Book of Abstracts

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Scope

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Nuclear photonics

Extreme fields physics

Ultra high intensity facilities

Investigation of pre-pulse influence on high-Z plasma formation in experiments with high intense up to 10^{22} W/cm^2 femtosecond laser pulses by means of X-ray spectroscopy

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In experiments with laser fluxes on target reached $I_{laser} \geq 5 \times 10^{21}$ W/cm^2 the becomes very designed to control the pre-plasma [1]. Since pre-plasma plays an important role at these intensities and directly effects to physical processes in plasma and following experimental aims as consequence. In this work we demonstrate that x-ray spectroscopy diagnostic can be used for estimation target integrity at the time of main laser pulse coming. That becomes possible because appeared spectral features may indicate the interaction of main laser pulses as with pre-plasma or solid target. We report about x-ray spectroscopy measurements that were done at recent experiments on the J-KAREN-P laser facility. First experiment was aimed to achieve efficient coherent soft x-ray generation via high-order harmonics [2] and second was aimed to the investigation of proton acceleration mechanisms in ultra-relativistic laser plasmas [3]. In both cases, we measured x-ray emission from stainless steel plasma generated at the rather different experimental conditions and observed the high sensitivity of x-ray emission spectra to laser pulse contrast. As a result, we have been able to distinguish the existence or absence of pre-plasma in interaction of laser pulse with target. We found that x-ray emission intensity increases by power low with laser intensity on target as of $\sim I^{4.5}$ when the laser contrast $K \geq 10^{10}$ and as of $\sim I^2$ for $K \sim 10^6$. We also shown the strong influence of plasma states formation on the laser focusing.

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Compact laser-plasma sources of ultra-relativistic electrons

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High energy electrons and hard X-rays, produced in the interaction of relativistically intense laser pulses with matter, open a new approach to creation and diagnosis of extreme states of matter. The elaboration of compact sources of ultra-relativistic electrons and hard X-rays requires the development of advanced acceleration methods based on high gradient acceleration mechanisms. In view of current and future experiments, various methods of electrons acceleration in plasma are discussed.

One of the actively developing approach is based on the use of wake fields generated in rarified plasma under the action of relativistically intense femtosecond laser pulses. Acceleration of electrons to ultra-relativistic energies up to the TeV range with a large acceleration gradient, much higher than that available in conventional radio frequency accelerators, can be achieved in a multistage laser wakefield accelerator, operating in a moderately nonlinear mode. The properties of accelerated electron bunches are investigated on the base of analytical models and numerical simulations [1].

In the case of denser plasmas, the effective transfer of the laser energy to hot electrons was demonstrated by the use of structured targets. The direct laser acceleration mechanism in a plasma channel, created by a relativistically-intense subpicosecond laser pulse in a plasma with a near critical density, is analyzed for the laser and target parameters in recent experiments on the PHELIX laser system at GSI (Darmstadt, Germany). The efficient generation of high-energy electrons with an energy of tens of MeV demonstrated experimentally was supported by numerical modeling. These collimated beams of high energy electrons reach effective temperatures, which are many times higher than those predicted by Wilks ponderomotive scaling and carry mega-ampere current with charges of hundreds of nC [2].

This work was partially supported by the Presidium of the RAS (Fundamental Research "Programm Extreme Light Fields and Their Interaction with Matter") and RFBR (Grant No. 19-02-00908).

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Tuning laser wakefield acceleration at few-mJ kHz laser by varying pulse duration and tailoring gas profile

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Laser wakefield acceleration or simply laser-plasma acceleration (LPA) of electrons is a process, in which an ultrashort laser is focused into a gas, and ionising it drives the plasma waves with strong accelerating fields. Today, we can distinguish the LPA concepts based on the highest possible laser powers $\gtrsim 1$ PW, and the alternative ones which involve the kHz laser systems with few-TW power. The existing multi-mJ kHz laser systems are now able to compress the pulses into almost single-cycle beamlets, and with tight focusing to reach intensities suitable to drive wakefield acceleration [1-5]. Operating in the kHz regime, such sources provide a very high average current, which makes them of a great interest for ultrafast electron diffraction [6-8], irradiation experiments for radiation harness studies [9] or radio-biology [10,11].

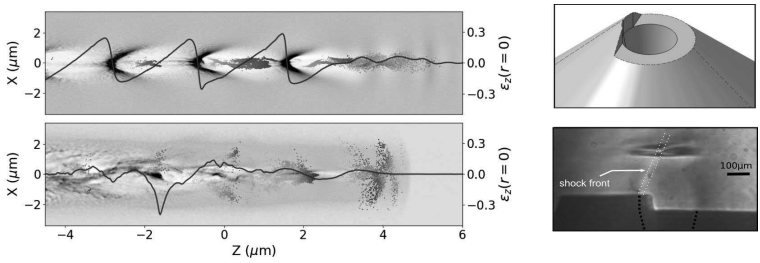

Figure 1: LPA with 4 fs (upper left) and 10 fs (lower left) laser: plasma density (gray), accelerating field (blue), electrons from self-injection (red) and ionization injection (green). Design of the nozzle with asymmetric shock (upper right), and shadowgraphic image of the plasma (lower right).

Wakefield acceleration and associated electron injection in the case of a few-cycle few-mJ laser may occur in a wide range of regimes providing beams with different charge, energy spectral and angular profiles. In this contribution, we present recent experimental and modeling results obtained at Salle Noire kHz laser system of LOA. We discuss transitions between the self-modulated and matched LPA modes by tuning laser duration from 4 fs to 10 fs (Fig. **??** left), and tailoring of gas density profile for enhanced stability (Fig. **??** right).

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Amplification of high harmonics and attosecond pulse trains with linear or elliptical polarization by a plasma-based X-ray laser, dressed by an IR laser field

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The attosecond pulses of extreme-ultraviolet (XUV) and soft X-ray radiation, produced via high order harmonic generation (HHG) of optical and infrared (IR) laser fields in gases have opened up qualitatively new opportunities in study and control of the electronic processes in atoms, molecules and solids at their intrinsic time scales. However, the energy of high-order harmonics (HHs) is quite limited, especially in the X-ray range (for the photon energies above 200 eV), as well as for the harmonics with circular and elliptical polarization.

Recently, we suggested a technique to amplify a train of attosecond pulses, produced by HHG of an IR laser field, in hydrogen-like active medium of a plasma-based X-ray laser. This technique is based on modulation of frequency of the inverted transition of the X-ray laser by the same IR field, as used to generate the harmonics, via linear Stark effect, which results in redistribution of the resonant gain and joint amplification of a wide set of high order harmonics. It was proposed an experimental implementation of the suggested technique in active medium of C^{5+} ions at wavelength 3.4 nm in the "water window" range, and the possibility to amplify by two orders of magnitude a train of attosecond pulses with pulse duration down to 100 as was shown [1].

In the present contribution we generalize this technique to the Ne-like and Ni-like collisional X-ray lasers. We show the possibility to amplify a set of HHs with circular or elliptical polarization, as well as to strongly increase the ellipticity of harmonics during their amplification in the Ne-like or Ni-like active medium of an X-ray laser, dressed by the IR field of the fundamental frequency with linear polarization. We discuss the possibility of an experimental implementation of the proposed technique in the wavelength range 20-30 nm in the active medium of Ne-like Ti^{12+} ions, irradiated by 3.9 um IR laser field.

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Synergic synchrotron-Cherenkov radiation

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The photon emission by an ultrarelativistic charged particle in the extremely strong magnetic field is analyzed, with vacuum polarization and photon recoil taken into account. The vacuum polarization is treated phenomenologically via the refractive index. The photon emission occurs in synergetic (cooperative) synchrotron-Cherenkov process[1] which is similar to synchrotron emission rather than to Cherenkov one. For electrons, the influence of the vacuum polarization on the emission spectrum is not evident even beyond the probable onset of non-perturbative quantum electrodynamics (QED). However, the evidence of the vacuum polarization in the emission spectrum can be reached for muons already at $\gamma B/B_S \simeq 30$, with γ the muon Lorentz factor, B the magnetic field strength and B_S the critical QED field, respectively. However, vacuum polarization leads to only 10% enhancement of the maximum of the radiation spectrum.

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Magnetoactive plasma processes and nuclear fusion resulting from the action of relativistic laser radiation

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The results of modeling space jets on a laser installation are presented. The spatial and energy distribution of proton fluxes accelerated from the back of a flat metal target when exposed to laser radiation with an intensity of $\sim 5 \times 10^{18}\mathrm{W/cm}^2$ was experimentally studied. A power-law dependence of the decrease in proton flux divergence with an increase in their energy is obtained. The minimum proton beam divergence recorded in experiments is $\phi \simeq 0.05^o$. The constructed theoretical model of the studied processes is in good agreement with the experimental results, describes the MHD - the process of collimation of plasma flows simulating space lies.

The results of a study of magnetized plasma flows with the aim of using them as a driver to initiate nuclear fusion reactions based on the p + 11B reaction are presented. It is of interest to compare the yield of alpha particles in cases of magnetized and free of magnetic field proton fluxes incident on a boron-containing target. The maximum measured yield of alpha particles is 10^9 in 4π steradian at a laser radiation intensity of $\sim 5 \times 10^{18}\mathrm{W/cm}^2$. The experiments showed exclusive results, both in obtaining and extremely small divergence of plasma flows, and in achieving an abnormally high yield of alpha particles in a boron-hydrogen reaction of nuclear fusion.

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Electron acceleration and secondary radiation emission from sub-micro-sized targets

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The use of sub-micro-sized targets in interaction with intense femtosecond laser pulses is considered to be uniquely convenient approach for the development of a compact versatile pulsed source of secondary radiation. Innovative nano- and micro-sized targets, including sub-microwires or sheets on the target surface and cluster media, allow effectively absorb laser energy, generate high energy electrons and, as a result, increase the production of accelerated electrons and ions, X-rays, neutrons [1,2].

Whereas for laser radiation of nonrelativistic intensity, increased absorption and heating have been explained in the framework of linear theory, then for lasers of relativistic intensity an understanding of the physics of these effects has not yet been fully achieved. As in the case of the interaction of a laser pulse with nano/micro structures [1,3], we can expect that in a cluster (or nano/micro droplet) plasma, the determining mechanism of a large energy gain by electrons is the stochastic heating in the combined field of the laser pulse and the Coulomb field of the clusters.

We focus on study of hot electron generation and particle acceleration to energies beyond the ponderomotive limit. The model describes the high energy particle generation as a result of multiple elastic electron scattering on an expanding charged cluster. As in the case of collisions of electrons with ions in a strong laser field [4], the model of collisions of electrons with clusters predicts the formation of a broad energy distribution with a tail of suprathermal electrons, which is characterized by power-law scaling. The expected appearance of supra-ponderomotive electrons should lead to an increase in the hardness of X-ray radiation.

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Target chemistry and engineering to provide multiplication effect on the laser plasma sources of particles and rays

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Target technology is a straightforward way to work out target design and to realize the target capable of optimal efficiency in laser-driver interaction. The purposes may range from inertial fusion energy (IFE) complex aims to more up to date needs of bright laser-initiated sources of particles and e.-m.beams, extreme matter studies for astro-objects physical modeling, other high-energy density (HED) experiments. Chemistry and engineering in the course of target creation resulted in wonderful progress of making powerful physical processes brighter in HED experiments.

Though the interaction experiments started several decades ago the investigations with inertial fusion targets present new physical findings every year, tending to transfer to even more interesting structurally diverse packages of targets, fitting multiple desired applications.

The IFE-aimed studies came across many new effects, so that many of the above-enumerated fields receive new impacts (even in the times of cheap oil).

Here we will stress on the further target material studies emerging from the observed effects (of higher x-ray and particle yields found earlier with foam targets) found in powerful interaction experiments in the context of IFE.

Low-density gold as bright emitter and polymer aerogel as multiplication layer [1, 2] could serve examples of such target chemistry and engineering application. The characteristic present stage strongly depends on the new materials and compounds, designed for the necessary physical realization, professionally synthesized, profoundly characterized, super-critically- and freeze-dried, optimally aged and thermally treated.

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Transient surface electromagnetic fields in laser-target interaction

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Strong ultra-fast surface fields and electric currents in the interaction of short intense laser pulses with solid dense targets are currently of great interest in both fundamental and applied sciences [1]. However, till now they were associated either with charge-neutralizing current [1] or with electromagnetic surface wave. Here we present theoretical model [2], which described generation of a fast transient surface field and the corresponding lateral skin current in the form of a polarization wave due to a laser-accelerated electron bunch crossing the target-vacuum boundary. Such a traveling-wave skin current naturally appears as near-field solution in the same approach that was used in the theory of transition radiation and is a fundamental effect for a high-conductivity half-bounded medium, for example, a solid dense plasma. The presented theory demonstrates transition from polarization field in a form of a quasistationary dipole field of two charges (the real charge and its mirror image) in the nonrelativistic limit to the radiation field in the ultrarelativistic case. We also complement our theory with two simulation models using FDTD and PIC methods. Distinctive features of the proposed theory are clearly manifested in both of these models.

We also show that transition field may be generated by switching on a charge-separation field when an ultrashort laser pulse quickly pushes electrons out of the target. It provides a hot-spot electromagnetic field spreading over the target surface to large distances at the speed of light. The surface transition field propagates in the form of a bipolar video pulse. Its amplitude significantly dominates the conventional surface wave amplitude.

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Experimental study of optical magnetic field generators in picosecond regime with proton radiography

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Laser-driven approach [1] to strong magnetic field generation is an interesting and promising technique that potentially has a number of applications in different areas of science and technology - from producing magnetized plasma for laboratory astrophysical studies to controlling high-energy charged particles transport in Inertial Confinement Fusion experiments. This method of magnetic field generation is compact and does not require expensive and cumbersome capacitor banks. It implies irradiating targets with intense short laser pulses in order to create strong discharge currents, which with use of modern laser systems are able to induce magnetic fields well in excess of 100 T [2], beyond the limit for conventional methods relying on non-destructive resistive and superconductive electromagnets. The structure and magnitude of the generated fields highly depend on the target geometry, which thus can be considered as a subject for optimization.

In this work, picosecond magnetic field generators of different geometries are studied. Various diagnostics can be employed to characterize laser-driven magnetic field generation both qualitatively and quantitatively. One of them is proton radiography. It allows performing spatially- and temporally-resolved measurements of magnetic and electric fields induced around the target by recording deflection of a probe proton beam with use of radiochromic films. Information about electromagnetic fields generated by the target can be extracted from experimental radiographs by performing numerical simulations of the proton beam flight through the studied region. By comparing the simulated radiograph with the experimental one it is possible to scale the fields and iteratively adjust their structure in simulations until the difference between radiographs becomes small enough. Then the fields around the target are assumed to be reconstructed with admissible error. In this study, characteristic features of radiographs are analyzed for several model targets and probing geometries. The simulation results are, where possible, compared with experimental radiographs obtained with real targets at PHELIX laser facility. The comparison confirms efficient generation

of magnetic field in some targets. Further steps for more precise analysis are discussed.

Some of the results are based on the experiment P171, which was performed at the PHELIX facility at the GSI Helmholtzzentrum fuer Schwerionenforschung, Darmstadt (Germany) in the frame of FAIR Phase-0. The research leading to these results has received funding from LASERLAB-EUROPE (grant agreement no. 654148, European Union's Horizon 2020 research and innovation programme).

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Orbital angular momentum exchange between laser beam and particle

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Generation of quasistatic magnetic field in numerical simulation is observed in interaction of spatially structured laser beams carrying orbital angular momentum (OAM) with dilute plasma.The magnetic field is directed along the axis of the laser propagation, which means it is caused by the rotation of charged particles. Indeed, electrons absorb part of the orbital angular momentum of the laser field [1]. Numerical simulations and the detailed analysis of the process show that it may be considered as a single particle effect.

Analytical consideration of the process may be simplified by using the paraxial approximation. It is widely used to prescribe propagating electromagnetic fields with moderate focusing. An arbitrary laser beam, which was numerically calculated for given initial conditions, may be decomposed in terms of Laguerre-Gaussian beams with a reasonable accuracy. In order to describe interaction of such a laser beam with a charged particle, a perturbation theory was developed. The momentum gain is determined by the ponderomotive force, however the symmetry in azimuthal distribution of the charged particles of the plasma leads to the zero net OAM transfer [2]. Hence further consideration beyond the perturbation theory is to be developed for understanding the process of orbital angular momentum exchange.

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Quantum fluctuations as a plasma

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Strong field QED effects have been thouroghly discussed by theoreticians for more than 60 years, initially with mostly astrophysical applications in mind. Yet nowadays they raise a substantial revival of interest due to a notable progressive development of potential experimental capabilities to probe them in a laboratory. The recent proposals include direct or indirect experiments with high-power lasers, propagation of ultrarelativistic electrons through aligned crystals, heavy ion collisions and beamstrahlung at lepton colliders. A few experiments of this kind have been already implemented, a number of others still remain under preparation or discussion.

Strong external field can modify the rates of the known QED processes, open the new channels and even modify the properties of the vacuum. A key point is that a strong field can substantially influence the properties of virtual electrons and positrons, in particular bringing them onto a mass shell thus transforming them to the real ones. It is often stated in the literature that with respect to light propagation a vacuum polarized by a strong field somehow resembles the material dielectric medium.

Here we review this point and discuss a number of additional illustrations of mapping the properties of virtual particles onto the properties of a real plasma. We believe that in a view of complexity of the conventional direct formal QED calculations this particular analogy can be extremely useful for developing various heuristic arguments for qualitative considerations of the actual higher-order QED processes and will eventually result in development of the novel profound calculation techniques.

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X-ray and optical time-resolved diagnostics of hot electron generation in shock ignition relevant experiments

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Inertial confinement fusion (ICF) is one of the actively developing scientific branches. Particularly, in the "shock ignition" scheme the gain of energy is supposed to be reached by a separation of the laser irradiation stages with a matter compression and a heating of the fuel in time. However, this approach is not fully proved yet, since the alternate mechanisms of the hot electron generation including parametric instabilities (SRS, TPD, SBS) and resonance hot electrons (HE) generation are not fully understood. Thus, the complex investigation of detailed mechanism of HE generation is needed in order to control the preheating of the DT fuel before the laser spike.

The experiments dedicated to the generation of hot electrons in a shock ignition relevant conditions were conducted at the PALS facility in Prague, Czech Republic. Bare and layered copper targets were irradiated by a laser at shock-ignition relevant intensities of about 1.5×10^{16} W/cm^2. We used an x-ray streak-camera with ps-scale temporal resolution and spherically bent Bragg quartz crystals with 2d = 1.5414 $\AA$ to obtain time-resolved images of Cu Kα emission from the front side of the target. The use of the time-resolved spectrometry allowed us to reveal the timing between Kα emission and SRS or TPD instabilities. As a result, we demonstrate the obtained temporal and spatial dependencies of Cu Kα emission vs laser energy, pulse maximum and material thickness. The absolute calibration of fiducial in the experiment allowed us to obtain the real delay of the HE emission regarding the laser pulse maximum.

Thin foil transparency threshold and optimal conditions for ion acceleration by an ultra-intense laser

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One of the most foreseeable applications of high power lasers is laser plasma ion acceleration. The radiation pressure (or Light Sail, LS) acceleration of a thin opaque foil [1,2] is probably the most promising among the acceleration scenarios under consideration. It is singled out by the two unique features, the highest possible efficiency (laser energy is almost totally transferred to ions) and monoenergetic spectrum of the ions. Due to them the energy gained by the ions accelerated in the LS regime is estimated as

$$\mathcal{E}_i \sim \frac{IT}{\sigma_0}, \tag{1}$$

where I and T are the intensity and duration of the incident laser pulse and σ_0 is the areal density of the foil target.

According to (1), the ions energy is higher the lower is σ_0. However, areal density controls the crossover from foil opaqueness to its transparency [3,4]. Below a certain limit the foil becomes transparent and cannot be accelerated by means of the LS mechanism. We refine the opacity threshold established in [3] and show that for ultraintense ($I \gtrsim 10^{22}$ W/cm^2) laser pulses the threshold areal density value is more sensitive to pulse duration and ions charge to mass ratio than to laser intensity [4].

We generalize the conventional 1D model for LS acceleration [1] by including such multidimensional effects as laser diffraction and target transverse expansion. We investigate the impact of these effects on foil opacity and determine the optimal laser and target parameters for LS ion acceleration in the ultrahigh intensity regime.

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Semi-analytical model for laser pulse spot size evolution in the bubble regime of plasma wakefield

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Plasma based acceleration methods have drawn much attention in the recent decades, as they provide acceleration gradients orders of magnitude higher then in conventional radio-frequency accelerators. Since the development of the chirped pulse amplification which made femtosecond laser pulses widely available, the efficient generation of plasma wake waves by using such pulses have become possible. Their intensity is often sufficient to make the motion of plasma electrons relativistic and to excite a strongly nonlinear wake wave in which a cavity free of plasma electrons (known as a "bubble") is formed behind the pulse. Background plasma electrons can be trapped and accelerated to high energies in the bubble, which makes obtaining accelerated electrons much easier in experiments.

The description of the laser pulse propagation in plasma is of utmost importance for laser-wakefield accelerators. In vacuum or a linear medium, a focused laser pulse can propagate only for its Rayleigh length before diffracting, which would limit the acceleration length. However, the nonlinear response of the medium can guide the pulse over longer distances. In a relativistic plasma, such nonlinearity stems both from the change of the effective electron mass due to the oscillations in the high-frequency laser field and from the excitation of plasma wake wave resulting in local density perturbations, which makes the description of the plasma response in the bubble regime challenging.

In this work, we propose a new semi-analytical model for the description of laser pulse propagation in plasma in the strongly nonlinear (bubble) regime. The model is based on solving the equation for the spot size w of an axisymmetric Gaussian beam in the medium with the parabolic refraction index $\eta = \eta_0 + \eta_2 r^2$ in the transverse direction,

$$\frac{d^2 w}{dz^2} = \frac{4}{k_{\text{laser}}^2 w^3} + \frac{\eta_2 w}{2}. \tag{2}$$

In the self-consistent approach, η_2 is a nonlinear medium response determined by the plasma density and the parameters of the laser pulse. In the strongly nonlinear wake, no sufficiently good models for self-consistently calculating the wake wave exist so far. So, in order to build a model for η_2, we use the results of quasistatic particle-in-cell (PIC) simulations instead. Under the ponderomotive approximation, the laser frequency does not influence the excited wake. Thus, the plasma density is a scaling parameter, and the simulations can be done

for one density only. In addition, the duration of the pulse has a very minor influence on η_2, so we limit ourselfs to one duration. In this case, the response η_2 becomes a function of only two variables: the laser amplitude and the spot size. The analytical form of this function is constructed by a numerical fit from the results of quasistatic PIC simulations for various amplitudes and spot sizes. The function is then used in Eq. (1) to describe the evolution of the spot size. It can also be used to independently obtain the matching condition when the spot size does not change during the laser pulse propagation. The predictions of the model are compared to the results of full-scale PIC simulations of the laser propagation in plasma.

Collimated MeV electron beam generation in the interaction of intense ultrashort laser pulse with a dense plasma and its applications

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The interaction of intense laser radiation with matter is one of the key areas of research in modern laser physics. Currently the main efforts aimed at creating unique laser complexes with peak power in PW range. However, for many applications such as low-energy nuclear physics studies and x-ray imaging it is important to have a large electron beam charge (∼nC) and a source size of several microns. This can be achieved using small femtosecond laser systems with a peak power of 1-20 TW, which are now commercially available. Such systems can provide an intensity on the target of $10^{18} - 10^{19}$W/cm^2, high beam charge can be obtained using laser-solid interaction. In this work we used a table-top Ti:Sa laser system to create an electron beam and used it for nuclear physics studies.

Experiments were carried out at the 1 TW Ti:Sa laser facility of the International Laser Center of Lomonosov MSU (800 nm, 50 mJ, 50 fs, 10 Hz). The peak vacuum intensity was 5×10^{18}W/cm^2. We used additional Nd:YAG laser (1064 nm, 10 Hz, 200 mJ, 10 ns) to create a preplasma. Prepulse intensity was varied from 5×10^{11} to 5×10^{12} W/cm^2.

We had shown experimentally that using an artificial prepulse with controlled parameters we can generate electron beam with a sufficiently small divergence (0.05rad for E>1 MeV), a charge of 30 pC, and a temperature of 2 MeV [1]. The charge was confirmed measuring neutron yield from Be(γ, n) photonuclear reaction with threshold of 1.7 MeV. We also found out that spatial alignment of two beams (main fs pulse and ns prepulse) is critical for obtaining such regime. This is due to the difference in preplasma profile, which is formed by ns prepulse. If these beams are aligned properly, electron beam exhibits great spatial and energy stability and is present for a wide range of other parameters (time delay between ns and fs pulses, angle of incidence onto the target, etc.) We also used this beam for nuclear physics studies (namely neutron and positron generation)[2].

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Efficient forward direct laser acceleration of electrons in subcritical plasma

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Efficient injection of electrons into a propagating relativistic laser pulse with normalized vector potential $a_0 \sim 2$ is demonstrated experimentally in thin plasma layer with density 0.15-0.3 of the critical value. This plasma configuration was obtained by evaporation of 16 μm thick audio tape by an artificial nanosecond prepulse. Numerical simulations suggest that injection mechanism is wavebreaking of parametric plasma waves. The trapped particles gain multi-MeV (up to 20 MeV) energies by the Direct Laser Acceleration (DLA) in the plasma channel formed by the laser pulse in the lower density plasma tail.

Experiments were carried out at the 1 TW Ti:Sa laser facility of the International Laser Center of Lomonosov MSU (800 nm, 50 mJ, 50 fs, 10 Hz). The peak vacuum intensity was $5 \times 10^{18} W/cm^2$. We used additional Nd:YAG laser (1064 nm, 10 Hz, 200 mJ, 10 ns) to create a preplasma. Prepulse intensity was $5 \times 10^{12} W/cm^2$.

We experimentally observed electron beam with divergency of ~ 0.05 rad, charge of ~ 50 pC for particles with $E > 1.7$ MeV with the pulse energy as low as 30-50 mJ. This value is 5 times higher than reported in our previous work [1] and 1nC/J efficiency was reached on table-top laser system.

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The role of stochastic electron acceleration in ultrashort subrelativistic laser interaction with cluster targets

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Laser-driven acceleration of charged particles and the generation of secondary radiation is a topic of great interest for fundamental research and possible applications in applied nuclear physics, medicine, inertial confinement fusion, and high energy density physics. These issues have motivated a worldwide search for different particle–acceleration mechanisms and laser–target interaction schemes aiming to boost the yield and energy of accelerated electrons and ions. An important role in this context is played by innovative micro- and nanoscaled targets, including sub-micro-sized wires, multi-sheet (slab, groove) targets and also clustered media [1-3].

Our previous studies of the laser-plasma interaction of a subrelativistic femtosecond laser pulse with micro-sized wires showed that the stochastic mechanism for efficient volume heating and generation of supra-ponderomotive electrons for a geometrically optimized target plays a decisive role [4]. Using 3D PIC simulations, we examined the interaction femtosecond laser pulse of moderate intensity ($> 10^{18}\ W/cm^2$) with other promising structured targets with a lower average density – a submicron-sized cluster plasma. The angular energy distributions of accelerated particles were analyzed. An analysis of the trajectories of high-energy particles in PIC simulations showed that the particles gain high energy by wandering around individual clusters and jumping from one to the other in a complex field consisting of combinations of induced Coulomb field of the cluster and the laser field. Effective electron heating occurs if the value of the Coulomb field on the surface of the clusters is of the order of the laser field amplitude.

To explain generation of supra-ponderomotive electrons (with energies significantly larger than the ponderomotive energy) we applied the test particle approach, tracking of electron trajectories in 3D PIC simulation, and methods of stochastic dynamics. Using the stochastic dynamics method particularly Lyapunov exponents, we demonstrated that the generation of super-ponderomotive particles in laser submicron sized cluster plasma is due to the stochastic instability of electrons moving in a complicated laser-plasma field structure in the interspatial regions between clusters.

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Acceleration and ionization of charged particles at high contrast relativistically intense laser-plasma interaction with structured and thin targets

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In this report we present recent results on generation and acceleration of charged particles at interaction of relativistic femtosecond laser pulse with various type of structured and thin targets. The connection between the experimental results on electron, hard X-ray diagnostics and fast ions measurements is made in order to elucidate the role of structures size and displacement as well as thickness of target in the absorption of laser light, particles acceleration mechanisms, ionization of ions. The experiments were carried out with the use of high contrast laser pulse delivered by a TiSa laser system (50 fs, 100 mJ, 800 nm, 10 Hz, ASE contrast $> 10^9$, $I_{peak} > 10^{18}$ W/cm^2). Complex diagnostics including optical plasma emission analysis, fast electron measurements, time-of-flight ionic detection technique were introduced to obtain an all-round data on plasma parameters. Experimental results are supported by numerical PIC simulations of laser-plasma interaction.

We found that the fast electron beam from plasma strongly depends on the size of the structures onto the surface. For nanostructured target the spatial emission diagram enlarges and overall flux of particles increases several times. The effect is related to the complex field near the tips of the targets. At the same time the flux of high charge ions is enhanced when micro-scale structures are involved. According to our assumption it may be explained by the increased interaction surface and penetration of laser into the gaps between the structures. At interaction with thin film target we obtained a collimated electron beam with energy up to MeVs both from front and back surface of the target.

Ionic diagnostics revealed, that ultimately ionized (+14) Si particles are registered from plasma of nanostructured target. The effect is related to the quick expansion of hot structures within the time of ions acceleration providing enhanced collisional ionization in the hot (1 keV) and dense (over-critical) plasma.

The part of the work dedicated to structured targets was supported by RSF grant 18-79-10160. The data on thin targets was obtained within the RFBR grant 20-32-70194.

Formation of high-intensity X-ray laser beam on a mask-target using travel-wave excitation of the multitude of the X-ray lasers

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X-ray lasers (XRL) with wavelengths in the region of the high reflectance multilayer optics are studied elsewhere; see our work [1], where a model of the XRL radiation with $\lambda \sim 13.4$ nm with high conversion factor is presented. XRL works on the transition $3d^9_{3/2}4f_{5/2}[J=1] - 3d^9_{3/2}4d_{3/2}[J=1]$ of Ni–like tin ions (Sn^{22+}) in plasma formed during the interaction of a nanostructured tin target with an intense ultrashort pump laser: intensity $I_{pump} \sim 8 \cdot 10^{17}$ W/cm^2, the pump pulse energy is assumed $E_{pump} \leq 1$ J, its duration $t_{pump} \approx 120$ fs. On the assumption that the target diameter $d = 40$ μm, the maximum length is ~ 0.4–0.5 cm, the XRL emission duration t_{las} is $\sim$ 12–15 ps. The plasma parameters for achieving the maximum energy yield of $\leq$0.3% of E_{pump} are as follows: the atomic density $n_i = 1.4 \cdot 10^{19}$ cm^{-3}, the electron density $n_e \sim 3 \cdot 10^{20}$ cm^{-3}, $T_e \approx 2000$ eV. Under these conditions XRL pulse energy with $\lambda \sim 13.4$ nm can reach several milli-joules. We emphasize that for projection nanolithography the XRL energy at the mask-target should be more than 200 J/sec. In this report we suggest the optic system based on the excitation by a travelling wave of many nanostructured tin. Targets of nanostructured tin are located on a multistage mirror, so that the rays of XRL are delayed relative to each other.

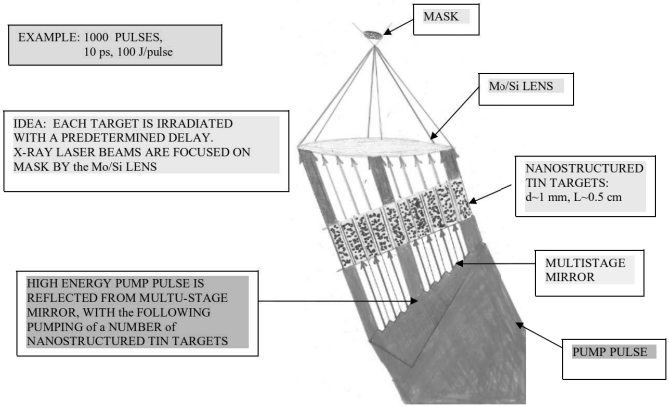

Figure 1: Simplified installation for converting the energy of high power pump laser to the multitude of XRL beams at 13.4 nm, followed by focus on the mask. Mo/Si lens are used for focusing.

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Efficient ultra-short X-ray laser at 32.8 nm produced by optical field ionization in krypton cluster jet

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The available experimental measurements of quantum yields of X-ray lasers with $\lambda = 32.8$ nm at the $3d^9\ 4d\ (J = 0) - 3d^9\ 4p\ (J = 1)$ transition in Kr^{8+} are interpreted. In various experiments, plasma was pumped in gaseous krypton and in krypton cluster jet. Using our model, an original scheme of the X-ray laser with $\lambda = 32.8$ nm, implemented in the krypton cluster jet is proposed. An unexpected result is the achievement of quantum yield saturation at a plasma length of ~ 300 μm at the krypton atom density $n_{Kr} \sim$ (4-9)$\cdot 10^{19}$ cm^{-3} and electron temperature $T_e \geq 5000$ eV. In this case, the conversion efficiency reaches $\sim 5 \cdot 10^{-3}$ of the pump pulse energy. The experimental setup of the highly efficient X-ray laser of subpicosecond duration, implemented in the krypton cluster jet is described in detail.

Mutual amplification of high-order harmonics and sub-femtosecond pulses in active medium of a plasma-based X-ray laser dressed by a strong IR field

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Attosecond pulses formed by high-order harmonics (HHs) of an infrared (IR) laser field is a powerful tool for study and manipulation of the intra-atomic and intra-molecular electron processes at their intrinsic attosecond time-scale. However, in the X-ray range the HH radiation energy is rather limited. Therefore, their amplification is an important problem.

Recently, there has been proposed a method for HH amplification in an active medium of a recombination hydrogen-like plasma-based X-ray laser irradiated by a replica of the IR field, which was used for the HH generation [1]. Due to the linear Stark effect, the IR field leads to the gain redistribution of the active medium on the combinational frequencies, separated from each other by twice the frequency of the IR field. If the harmonics are resonant to the induced amplification lines, in a dense (strongly dispersive at the frequency of the IR field) plasma medium they will be independently amplified with preservation of their relative phases during the propagation through the medium. On the other hand, as it was shown in [2], in the case of a low density plasma medium a single resonant harmonic is not only amplified but also efficiently generates the sidebands, which allows for the formation of attosecond pulse trains.

Here we study amplification of a set of HHs in the active medium with low electron density. We demonstrate the possibility of constructive interference between the amplified harmonics and the sidebands, which are generated by each of the harmonics at twice the frequency of the IR field, due to their mutual rescattering in the active medium driven by an IR field. This constructive interference leads to mutually enhanced amplification increasing the peak intensity of the pulse train up to an order of magnitude.

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Laser Wake Field Acceleration (LWFA)-based phase-contrast X-ray imaging: Applications and progress towards zero-dose radiography

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Laser-based X-ray sources offer the potential of performing X-ray Phase Contrast Imaging (XPCI) with small source size (1 μm range) and high throughput. Our group demonstrated the potential of laser-based X-ray sources based on K-alpha radiation [1]. Recently, it was demonstrated that LWFA-based synchrotron X-ray sources were opening new horizons in X-ray imaging with the demonstration of single shot XPCI with high contrast [2,3].

We recently upgraded our laser system which can deliver up to 700 TW power with 17 fs pulses and 2.5 Hz. I will review the most recent results obtained with our laser system, operated with power up to 200 TW on target, on LWFA-based X-ray yield (10keV-40keV) and present the X-ray scaling [4] to the PW laser power range, which is now available at several laser facilities worldwide. As an example, our results indicate that a 1 mW X-ray average power can be obtained in a 50 mrad^2 beam at 20 keV with a 500 TW/100 W ultrafast laser system.

The LWFA-based X-ray phase contrast technique is appropriate for both high spatial resolution (μm range) 3D tomography with a fast scanning time (720 images in a few mn) and also femtosecond time-resolved (100 fs range) phase contrast imaging. I will discuss various applications, some being pursued at INRS, which include Cancer [5], Global Food Security [6], non-destructive sensing and Inertial Confinement Fusion [7]. I will present our technical roadmap and effort to reduce the dose deposition for, as an example, early detection of breast cancer and to realize a LWFA-based X-ray machine allowing near-zero dose 3D X-ray phase contrast tomography.

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Vis-NIR transparent ZrBN hard films for protection of optical devices

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Protection of optical devices (portholes and solar cells, solar collectors, etc.) from abrasive effects can be provided by the use of wear - and erosion-resistant ion-plasma coatings, including those based on oxygen-free ceramics. The use of hard and optically transparent Zr-B-N films is promising.

Ceramic nanocomposite films were deposited by DC and pulsed DC magnetron sputtering of ZrB_2 target in the $Ar + N_2$ gas mixtures. The targets were manufactured by means of self-propagating high-temperature synthesis. The structure, chemical and phase composition of films were studied by high resolution transmission and scanning electron microscopy, X-ray diffraction, X-ray photoelectron spectroscopy, Raman and infrared spectroscopy, energy-dispersive analysis, and glow discharge optical emission spectroscopy. The films were characterized using nanoindentation, sliding pin-on-disk, impact ball-on-plate, abrasive calowear, and scratch tests. The refraction index, coefficients of transmittance (Tr) and reflectance were measured by Cary 5000 Agilent + UMA attachment for wavelength range from 200 to 2500 nm.

Results obtained show that films deposited at low nitrogen partial pressure predominantly consist of nanocrystallites of hexagonal ZrB_2 -phase, 1-20 nm in size and amorphous regions. N-rich films exhibit amorphous structure (a-BN) with nanograins of Zr-contained phases. Specific optical properties were observed for these Zr-B-N coatings including Tr=70-100%. The hardness of 15-37 GPa and Young's modulus of 150-470 GPa were determined for films deposited onto alumina substrates. Coatings demonstrated friction coefficient 0.2-0.4. The addition of nitrogen significantly increased wear resistance in sliding and impact conditions.

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On the complex interferometry of quasi-axisymmetrical plasmas

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The complex interferometry, the idea of which dates back to beginning of spontaneous magnetic field studies [1], combines classic interferometry and polarimetry combined as a one diagnostic tool and allows to record and subsequently reconstruct several sets of independent data from a single data object - a complex interferogram. This method has its advantages compared to the standard approach for SMF measurements, that implies usage of two separate diagnostics and subsequent combination of experimental data, which may cause certain interpretation problems due to different optical paths and magnifications of aforesaid systems. However, due to technical complexity of the setup itself and data processing techniques the method of complex interferometry was not widely used. Recently, a femtosecond complex interferometry system had been tested and implemented at the PALS facility in a single-frame regime [2,3], and then was upgraded to the 3-frame system [4].

Under irradiation of a single Gaussian-like laser beam, a plane target demonstrates an expansion, normal to the target plane. In a symmetric situation, assuming only small deviations from axisymmetrical plasma profiles, no holographic setup is necessary to characterize plasma parameters. Ideally, in the presence of axial symmetry in the plasma it is possible to reconstruct entire B(r) distribution by a path-integrated projected data using Abel inversion. However, in a realistic situation, even a small uncertainty and non-ideality of the plasma expansion may considerably increase the error of the measurements, especially around the plasma axis.

The error analysis was based on the processing of synthetic complex interferograms, which were created using analytical expressions. Some of the most important error sources (unstable laser intensity distribution, plasma absorption, Cotton-Mouton effect etc) were considered. It was found out that all of the considered factors lead to a common consequence - to the increase of a shift between symmetry axes, attributed to the observed plasma density distribution and to the distribution of the angle of rotation of the polarization plane. This can lead to a substantial error in magnetic field reconstruction around the plasma axis. Possible error handling algorithms, based on compensation of axes difference,

were proposed and tested [5]. The reconstruction accuracy in different plasma regions was estimated.

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On the Landau damping of plasma waves carrying Orbital Angular Momentum

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Electrostatic plasma waves, carrying Orbital Angular Momentum (OAM), are cosidered in the kinetic framework using Vlasov-Maxwell equations in the paraxial approximation [1]. The solutions are written as an expansion over the Laguerre-Gaussian basis, which for plasma modes may be numbered similarly to the electromagnetic waves, by the radial $p \geq 0$ and azimuthal l indices, where azimuthal number l relates to the OAM of the wave. The spatial structure of the Laguerre-Gaussian basis does not allow it to be an eigenfunction set of the Vlasov equation, and the modes with different p and l are coupled depending on the value of the paraxial parameter. The paraxial approximation allows to consider only a finite number of modes and to sum them up. Further analysis shows, that the mode coupling of plasma waves carrying OAM results in modification of their dispersion relation. In particular, the expression for the collisionless (Landau) damping rate of such plasma waves is modified compared to the case of the plane wave [2].

The Landau damping of an OAM plasma wave and particle dynamics are considered in linear and nonlinear regimes [3,4]. Although the OAM plasma waves are electrostatic, a quasi-static magnetic field is induced as the second order effect on the wave amplitude. Absorption of the orbital momentum by the resonant particles may result in a more efficient magnetic field generation. The efficiency of this process and the achievable magnetic fields are discussed.

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Generating terahertz and XUV pulses by multiterawatt laser interaction with gas targets

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Laser pulse interaction with gas jet targets provides a lot of interesting effects resulting in generation of intense electromagnetic radiations in a wide frequency band. Below, two important examples of such processes will be considered using 2D particle-in-cell simulation. The first one is formation of relativistic electron mirrors from gas jets by accelerating laser pulses and generation of coherent ultrashort XUV pulses through Thomson backscattering of a probe laser pulse off such mirrors. The second example considers generation of intense infrared and terahertz radiation by strong nonlinear currents generated in plasma during wakefield formation.

An idea for synchronous acceleration of electrons from a nanofilm with a longitudinal component of the Lorentz force of a superintense nonadiabatic laser pulse was considered in [1,2]. The same physical mechanism can work for the gas targets. If the target is thin enough and its density is moderate then full evacuation of electrons from a gas plasma near the laser beam axis takes place and a relativistic electron mirror is formed. For thick targets, relativistic boundary of the gas plasma can be produced providing for effective Thomson backscattering of a probe laser pulse. Parameters of produces relativistic electron mirrors and generated coherent ultrashort XUV pulses are studied.

Emission of intense infrared and terahertz radiation by laser generated wakefield in inhomogeneous plasma is also studied. The main frequency of radiation in this case is defined by a plasma frequency so the terahertz and infrared bands can be covered by this source. Characteristics of generated radiation are found, the role of plasma inhomogeneity is elucidated.

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Generation of electron bunches by an ultrarelativistic laser pulse crossing the plasma boundary

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An important problem in the practical implementation of a laser plasma accelerator providing monoenergetic acceleration of electron bunches is the generation of short electron bunches for acceleration. An interesting phenomenon in the generation of electron bunches of attosecond duration was discovered in [1] in the numerical simulation of the propagation of a high-power laser pulse in an inhomogeneous plasma. It was supposed that the laser pulse is incident normally on a diffuse plasma boundary comprising a transition layer in which the plasma density varies linearly with plateauing out. It turned out that, when the laser pulse amplitude exceeds a certain threshold value in the neighborhood of the point at which the plasma density reaches the plateau, a quasi-onedimensional process of generation of electron bunches develops. For the case of a sharp plasma boundary, a theoretical analysis of this phenomenon in one dimensional geometry is proposed in [2, 3] on the basis of a simple physical model in which plasma electrons are considered as plasma oscillators whose one-dimensional motion is excited by a laser pulse. A generalization of the theory [2, 3] for the case when the plasma boundary as in [1] has a linear transition layer is presented in [4]. The good agreement between the analytical results and the numerical simulation confirms the adequacy of the physical model used for the analysis of the phenomenon of electron bunch generation in the presence of a transition layer in the plasma.

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Proton beam self-modulation and electron acceleration in AWAKE experiment

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AWAKE experiment (Advanced WAKEfield) is aimed at studying excitation of the plasma wakefield by high-energy proton beams and acceleration of electrons by this wave. The drive beam comes from SPS synchrotron and has the proton energy of 400 GeV. For efficient wave excitation, the initially long proton beam self-modulates in the plasma, that is, transforms into a train of short micro-bunches, which resonantly drive the wakefield [1]. The self-modulation process is initiated and controlled by a short laser pulse that co-propagates with the proton beam and creates an ionization front approximately in the middle of the beam. The front part of the proton beam propagates in a neutral rubidium vapor and does not collectively interact with it. The main (rear) part of the beam propagates in the plasma, gradually breaks into micro-bunches, and transfers energy to the wakefield. For coherent addition of the wakefields from a large number of microbunches, the plasma density should be constant with an accuracy better than 0.2%, which is achieved by thermal stabilization of the rubidium vapor and the chosen method of its ionization with the intense laser pulse [2]. In the process of self-modulation, a part of the proton beam is defocused by the wakefield. The experimentally measured deflection angle of defocused protons coincides with theoretical predictions and indicates the presence of a strong transverse electric field in the plasma [3]. When electrons with the energy of 19 MeV are injected into the wakefield, a bunch of accelerated electrons with energies up to 2 GeV appears at the exit of the 10-meter plasma section [4], which proves the presence of a strong longitudinal electric field in the plasma.

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Effect of plastic coating on the density of plasma formed in solid targets irradiated by ultra-high-contrast relativistic laser pulses

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Obtaining, maintaining, and studying high energy density matter is important for in inertial confinement fusion, astrophysical, and high energy density physics. In this context, the role of a buried (or so-called "sandwich-type" [1]) target structure influencing the plasma condition in the interaction with ultra-high contrast ultra-intense laser pulses was studied and results were recently published in Ref. [2] and [3]. The experiment was carried out on the Vulcan (UK) petawatt laser facility with a laser intensity of up to 6×10^{20} W/cm^2 and an ultra-high laser contrast exceeding 10^{10} provided together by OPCPA amplification technology and by use of a single plasma mirror [4]. The densities and temperatures of the generated plasma were measured based on the analysis of X-ray spectral lines profiles and relative intensities. It is shown that switching from uncoated foil to buried one enhances the energy density in relativistic plasma from 3 to 5×10^{20} J/cm^3, despite the ultra-high laser contrast in both cases.

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High-Z front surface ion acceleration in relativistic femtosecond laser-plasma interaction at different contrast level

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The experimental results on the relativistic laser-plasma interactions of femtosecond laser pulse with nanoscale structured and flat targets with contrast control are presented. In our experiments we used an ultrafast pulse from the Ti:Sa laser system (pulse duration - 50 fs, energy on target - up to 30 mJ, wavelength - 800 nm, repetition rate - 10 Hz, peak intensity - up to 5×10^{18} W/cm^2). The experiments were conducted with contrast control by special controlled prepulse with different delay relative to the main pulse. The controlled prepulse was created by Nd:YAG laser with active Q-switching, a wavelength of 532 nm. (second harmonic - 1064 nm.), pulse duration - 6 ns., pulse energy - up to 250 mJ at the main harmonic. Also, experiments were conducted with ultrahigh (with XPW contrast level $< 10^{-10}$) contrast level. Ions were registered with the use time-of-flight magnet spectrometer with the charge-to-mass (Z/M) separation and Thomson parabola mass spectrometer.

In experiments with low contrast level there are no high energy ions. Also, it was demonstrated that with high contrast level there is no significant difference between flat bulk and nanoscale structured target. In experiments with ultrahigh contrast high-Z ions (up to Si^{12+} and even fully stripped Si^{14+}, which not registered in experiments with high contrast level) were registered. Also it was demonstrated significant increase in ion energy and ion flux depending on nanostructured target compared to experiment with flat target.

Experiments with nanostructured targets was supported by Russian Science Foundation grant No 18-79-10160. Ion diagnostic development and experiments with contrast control by the artificial prepulse were supported by Russian Fund for Basic Research under grants No 18-32-00416 and 19-02-00104

Ultrafast-ultrahigh-fieldgeneration by intense-laser-driven microbubble implosions

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Microbubble implosion (MBI) is a novel concept [1], which is expected to achieve ultrahigh electrostatic fields close to the Schwinger limit [2]. The core of MBI occurs in an extremely short period on the order of attosecond and in a nanometer-scale volume. In MBI, the bubble wall protons are subject to volumetric acceleration toward the center due to the spherically symmetric electrostatic force generated by hot electrons filling the bubble. Such an implosion can generate an ultrahigh density proton core of nanometer size on the collapse, which results in an ultrahigh electrostatic field to emit energetic protons in the relativistic regime.

Three-dimensional particle-in-cell and molecular dynamics simulations are conducted in a complementary manner. As a result, underlying physics of MBI are revealed such as bubble-pulsation and ultrahigh energy densities, which are higher by orders of magnitude than, for example, those expected in a fusion-igniting core of inertially confined plasma. MBI has potential as a plasma-optical device, which optimally amplifies an applied laser intensity by a factor of two orders of magnitude.

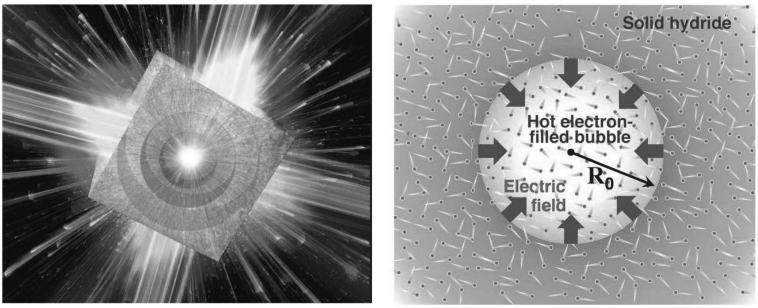

Figure 1: Schematic pictures of the microbubble implosion

We show that electron-positron pair production from the vacuum is possible via the strong Coulomb fields generated by micro-bubble implosions induced by ultra-high inten- sity lasers. Even in the case where the Coulomb fields are lower than the pair creation threshold, externally injected high energy electrons or photons could be used to generate pairs. [3].

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Perspectives of relativistic pulse compression with lambda-cubed laser systems

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Recent laser developments toward the highest intensity have indicated a natural path - the shortest pulse duration and the minimal focal spot on target. With single-cycle focused to a single- wavelength spot size such laser systems, so-called lambda-cubed, may encompass pulse energy in near-wavelength-cubed volume. Laser-plasma interaction in such regime is sensitive to carrier- envelope-phase. In this talk we will review the related developments in modeling and experiments.

Experimental validation of ionization potential depression models in over dense silicon plasma created by PW optical laser pulses

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Warm dense matter states are extensively studied now experimentally with the use of X-ray free electron lasers and high-power high-contrast optical lasers. Correct understanding of atomic processes in WDM is required to describe many exotic phenomena such as double core hole states, bond hardening, electoron degenerancy, saturable absorption. There are several and often contradictory models being developed particularly describing the depression of ionization potential (IPD) in a dense and over-dense plasma. Here we validate IPD models in experiments with high-contrast optical laser pulses of 1 ps duration irradiating Si solids with the flux of up to 6×10^{20} W/cm^2. X-ray emission of Si XIII ions existed in a near solid-density ∼500 eV plasma is examined. The shift of photorecombination continuum edge is traced in X-ray spectra along the variation of plasma density in the range of $(0.2-4.2) \times 10^{22}$ ion/cm^3 (or $(0.3-5.4) \times 10^{23}$ electron/cm^3). The analysis clearly validates the consistency of IPD models dealing with the average interionic distance as the key parameter, while the approach focused on average interelectron distances greatly overestimates IPD effect. The results complement the recent studies of WDM pumped by intense X-ray FEL beams.

Laboratory analogy of celestial dynamos with intense lasers

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It is widely observed that many celestial objects posess magnetic fields [1]. The fields are presumably generated and maintained by dynamos from the convection of electrically conducting fluids in the object interior [2]. While dynamo theory is successful on the whole, detailed dynamics of celestial dynamos is still unclear. Plentiful mysteries urge further studies [3,4]. Unfortunately, the extreme environment at the interior of objects is almost inaccessible in terrestrial laboratories, thus investigations have been limited to observations and theoretical work over the past decades.

Here we present proof-of-principle studies on the laboratory analogy of celestial dynamos [5]. Supercomputer simulations show that by irradiating femtosecond laser onto plasma targets, one can obtain convecting plasma flows. These flows drive a plasma dynamo and amplify a seed magnetic field on the ion time scale within hundreds of femtosecond. The dynamo then persists for a picosecond or more as long as the convection is maintained. Such a process shares similar nature of celestial dynamos. At high laser powers, the laser-plasma dynamo can generate magnetic fields at gigagauss levels. Our results open the prospect of all-optical experiments on celestial dynamos. It might also be useful for wider areas such as inertial confienement fusion.

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High current well-directed beams of super-ponderomotive electrons for laser driven nuclear physics applications

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We report on new findings in a laser driven enhanced electron beam generation in the multi MeV energy range at moderate relativistic laser intensities of 10^{19} Wcm^{-2} and their applications. In our experiments, an intense subpicosecond laser pulse propagates through a plasma of a near critical electron density (NCD) and a direct laser acceleration (DLA) of electrons takes place. The breakthrough became possible due to application of low-density polymer foams [1]. A sub-mm long NCD-plasma was produced by sending onto a foam a well-controlled ns laser pulse forerunning the relativistic main pulse and initiating a super-sonic ionization process [2]. This provided a substantial increase of the electron acceleration path compared to the short scale of the NCD region by irradiation of foils and resulted into $11 \div 14$ MeV effective electron temperature and up to 90 MeV electron energy measured in the laser pulse propagation direction. Compared to the shots onto standard foils at 10^{19} Wcm^{-2}, we measure a strong increase of the number of relativistic super-ponderomotive electrons and a well-defined directionality of the electron beam that propagates along the laser pulse direction in a $12 \pm 1^{\circ}$ divergence cone. This acceleration regime at 10^{19} Wcm^{-2} laser intensity was compared with shots onto conventional metallic foils at the ultra-relativistic laser intensities of 10^{21} Wcm^{-2}. The measured electron effective temperature ($11 \div 14$ MeV) and the maximum of the electron energy (90 MeV) were higher for shots onto pre-ionized foams at 10^{19} Wcm^{-2} as for direct laser shots onto standard foils at the ultra-relativistic laser intensity of 10^{21} Wcm^{-2} (7 MeV and 40 MeV correspondingly). The difference in the electron spectra for these two cases became visible in the isotope production yield. Using activation probes of Au, Ta and In, we measured higher yields of gamma-driven nuclear reactions demanding high energy MeV photons and neutrons in shots onto pre-ionized polymer foam layers than in the case of shots onto foil targets at 10^{19} Wcm^{-2} laser intensity. A good agreement between experimental data and results of the Particle-in-Cell and GEANT4 simulations was obtained. This

allows for the further optimization of the experimental set-up toward record values of gamma and neutron fluxes in laser experiments at moderate relativistic intensities.

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Perspectives of nonlinear compton scattering for nuclear photonics

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Nuclear photonics has emerged in the last 2 decades mostly due to the rapid development of laser technology. It is a multidisciplinary field studying the methods of generation of bright gamma-ray sources and their usage in fundamental physics, material science, nuclear non-proliferation and other areas. One of the main methods that is being discussed and used for the generation of bright gamma-ray sources is Compton backscattering - a process in which laser photons get significantly upshifted while scattering off the relativistic electrons. The main problem of the Compton scattering is a very low cross-section. After a general introduction to Nuclear Photonics, in this talk we will discuss Nonlinear Compton Scattering that can be used for orders of magnitude increase in photon yield, and obstacles that arise when using strong laser pulses. Several novel, easy-to-implement methods of increasing the brightness of the gamma-ray sources will be presented. Perspectives to achieve compact ("table-top") X- and gamma ray sources for Nuclear Photonics having higher peak brightness and similar average brightness as compared to traditional facilities will be discussed.

Investigation of the effectiveness of the interaction of laser beams with a magnetized target

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The scheme of the interaction of plasma target with high energy pulse laser beams in the externally applied magnetic field, so-called laser-driven magneto-inertial fusion is considered. [1-3]

A mathematical model of the interaction of high-energy-energy laser beams with a plasma target located in a seed magnetic field is developed by authors. [4-6] The theoretical calculations of the processes of compression and energy release in the target when combined with a system of pulsed jets and intense laser radiation in a magneto-inertial plasma confinement are carried out. The results of the calculation of the combined effect of intense energy flows on a single-layer cylindrical target are obtained.

Estimations of magnetized target compression and heating by high energy pulse laser beams for neutron and particle sources are presented [7,8].

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Analytical model of the QED cascade development in the plane wave

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Interaction of the extremely intense plane wave with the solid target is considered. It is shown by full 3D PIC simulation that above some threshold intensity the interaction leads to the formation of the quantum-electrodynamical (QED) cascade in the form of the electron-positron plasma cushion propagating towards the source of the radiation [1] which is similar to the propagation of the ionization front in the microwave gas discharge. The mechanism of the cascade self-sustentation is described qualitatively.

Development of such a QED cascade is also studied analytically. A phenomenological 1D model is developed based on the peculiarity of the particles motion in the strongly radiation-dominated regime [2, 3]. The model predicts the key features of the cascade development observed in full 3D-PIC simulations, that are the magnetic field predominance and electromagnetic energy absorption inside the generated electron-positron plasma and almost constant velocity of the cascade front propagation. Equations of the model are written in the closed form and can be solve numerically. The model is in a decent agreement with the results of the 3D-PIC simulations.

Experimental evidence of the phenomenon can be obtained with the upcoming laser facilities, hence these results can be important for their applications. The developed model can be probably applied to the astrophysical phenomena like pair cascade in magnetospheres of neutron stars where the cascading has complex space-time dynamics and can be also accompanied by generation of dense pair plasma.

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The effects of ASE contrast and beams alignment on the γ-ray yield in laser-plasma interactions with artificial prepulse

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Femtosecond laser plasma is a brilliant source of ultra-short bursts of high energy electrons, which lead to the generation of hard X- and γ-rays. Preplasma layer created by prepulses or ASE have a significant influence on electron acceleration mechanisms. In our experiments, for changing of the preplasma length and density we used a nanosecond duration ($\sim$ 10ns) artificial prepulse with a short (50fs) high-contrast (10^{-7}) main pulse of relativistic intensity ($2 \cdot 10^{18}\mathrm{W/cm^2}$) [1]. Two γ-ray yield maxima were observed depending on the time delay between the pulse and prepulse (0-10 ns - "first" and 20-40 ns - "second"). In maxima γ-ray temperature and maximum energies increased up to 1.6 and 7.5 MeV. Also dependence of γ-ray yield on main pulse duration was observed [2].

Presence of the artificial prepulse is critical for the described phenomena of the increasing γ-rays yield or energies, but the ASE impact is also significant. In this work we present experimental results on γ-emission from plasma in the case of different ASE contrast levels ($10^{-9}, 10^{-7}, 10^{-6} - 10^{-5}$) and different coincedence of the artificial prepulse and main pulse beams on the target surface. In particular, it was shown, that the "second" γ-ray emission maximum disappears at a high ASE contrast (10^{-9}). For lower ASE contrast ($> 10^{-7}$) γ-ray yield is minimal when the beams coincide and increases when they are separated. Comparison of the obtained data with the interferometry results clarified the laser-plasma interaction processes.

In our experiments we used Ti:Sa laser system (p-pol, pulse duration - 50fs, energy on target - 25mJ, wavelength - 813nm, repetition rate - 10Hz, ASE level - $10^{-9}-10^{-5}$). The ASE level was changed by adjusting the master oscillator. The contrast level was measured using a third-order autocorrelator (picosecond scale) and a pin-diode (nanosecond scale). The controlled pre-plasma layer was created using Nd:YAG laser (8ns, 130mJ, 1064nm) locked with Ti:Sa laser system.

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Application of Geant4 toolkit for modeling of experiments on laser-driven neutron and gamma generation.

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High luminous neutron and gamma sources play an important role in many reserch fields such as high energy density physics, material science, and nuclear astrophysics. Well-directed high current relativistic electron beams are perfect candidates to drive (γ, xn) disintegration reactions by penetration in high Z materials. This is a basic concept of the laser driven nuclear physics program at the ELI-NP [1]. The threshoulds of such reactions lay in MeV gamma energy region, so that for the effective MeV gamma production a high number of relativistic electrons is neccesery. In experiments at the PHELIX-facility Darmstadt, high current well directed beams of MeV electrons were generated when a short laser pulse of 1-2 $\times 10^{19}$ Wcm^{-2} laser intensity interacted with a sub-mm long plasma of the near critical electron density (NCD). Such kind of plasma was produced by a super-sonic ionization mechanism when a well-controled ns pulse was send onto low density polymer aerogels forerunning the main relativistic laser pulse [2]. As a result, beams of super-ponderomotive electrons with effective temperatues above 10 MeV and maximum of the measured energy up to 90 MeV were detected in the laser pulse propagation direction. In the experiment, high yield of Ta, Cr and Au isotopes as well as neutron yield from the In probes were measured.

The experiment was simulated by the PIC and Geant4 Monte-Carlo codes. The GEANT4 code includes comprehensive physical processes and databases of the particle-matter interactions [3, 4]. Simulations were made to bench mark the Monte-Carlo code using experimental data. In the experiment and in simulations, the electron beam propagates through 1mm thick Au-radiator producing MeV bremsstrahlung radiation. MeV gammas and electrons that escaped the radiator interacted with a stack of high-Z materials placed at 5^o to the laser propagation direction at the distance of 15 cm from the laser-foam interaction point. For the simulation of the photonuclear reactions, the ShieldingLEND (Low Energy Nuclear Data) [5] physics list was used. This physics list ensures a high precision cross section data for photonuclear reactions below 20 MeV, which shows a good agreement with experimental data. For energies higher than 20 MeV, one of the standards physics lists was taken into account. Good agreement between the experimentally measured and simulated isotopes yields allows

for further optimizations of the experimental set-up toward record values of the neutron fluxes.

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Weibel instability in expanding plasma plume created by intense femtosecond laser pulses

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We studied both experimentally and theoretically the expansion of a laser plasma created by irradiation of a solid target with intense femtosecond pulse. The combined use of interferometry and optical depolarization diagnostics allowed us to determine the spatial distribution of the plasma density and revealed the development of smallscale instabilities accompanied by megagauss magnetic field generation. The nature of the observed instabilities is discussed and modelled numerically.

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Effects of quasi-phase matching in high-order harmonics generated in perforated extended gas media

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One of the most powerful and modern sources of photons are X-Ray Free-Electron Lasers (XFEL). The radiation of existed XFEL upconverted by the inverse Compton scattering can be a perspective tool for nuclear photonics. For this reason, it is important to increase the number of photons generated by XFEL. There are a few possible ways for that. One of them is to use the spontaneous incoherent emission from ondulator as a seed in another ondulator [1]. Another and a more prospective one is to use the coherent radiation of harmonics generated in the process of intensive laser field interaction with gas as the seed in the ondulator [2]. This method was realized for the wavelength of 160 nm; the enhancement of the efficiency of the FEL generation up to 3 orders of magnitude was shown. The possible development of the method is to use high-order harmonics [3] as a seed to achieve XUV and soft X-Ray FEL radiation. Therefore, it is important to increase the relatively low efficiency of the high harmonics generation (HHG).

Here, we discuss the methods of control over the quasi-phase matching of the HHG in periodically modulated extended media [4,5]. Basing on the numerical calculations of extended gas media with periodically modulated density response on the action of two-color laser field formed by the fundamental and the second harmonic of femtosecond laser we have studied possible ways toward incensement of the HHG efficiency. In simulations, we used the 1D model described in [5]. Within the model, the nonlinear medium is simulated by a chain of atoms oriented along the propagation direction of laser field. The response of each atom in the chain is calculated using the non-perturbative theory [6].

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Electromagnetic pulse generation in experiments on high power laser facilities

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The interaction of high energy and high power lasers with matter produces broadband particle and electromagnetic radiation. In particular, a significant portion of the incoming laser energy is transformed to powerful transient electromagnetic pulses (EMPs) mainly in the range of radiofrequencies and microwaves. Such fields depend on laser energy and intensity [1] and they are so powerful that present a danger for any electronic device placed inside or even outside the experimental vacuum chamber. For this reason, understanding of the origin and mitigation of these electromagnetic fields is of primary importance for the operation of the existing laser facilities for inertial confinement fusion and laser-plasma acceleration, and EMP represents a severe issue for future laser facilities with higher energy and power.

A recognized main source of the EMP fields is the target positive charging caused by the fast-electron emission due to the laser-plasma interaction. This fast charging induces high neutralization currents from the conductive walls of the vacuum chamber [2]. Other mechanisms related to the laser-target interaction are also capable to generate intense electromagnetic fields. The complete and complex picture of the field distribution within the experimental chamber strongly depends on the physical localization and on the characteristics of each of the source processes, but is also affected by the expanding plasma and particle beams emitted from the target. Several possible mechanisms of EMP generation will be discussed and compared in experiments with high energy and intensity lasers, typical for inertial confinement fusion and laser-plasma acceleration.

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Electron acceleration in the laser produced plasma channel with injection through the breaking of plasma waves of parametric instabilities

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In recent years, many scientific groups observed beams of fast electrons from laser plasma created at a solid target. In this work, we show that by using an artificial nanosecond prepulse one can prepare a specific preplasma profile providing for the high charge, high energy, low divergence electron beam in the specular direction.

The electron bunch was produced in oblique (45 degrees) relativistic laser pulse interaction with the specific plasma profile containing arbitrary sharp, ~0.5λ, gradient at the vicinity of 0.1-0.5 critical density and a long tail of a tenuous preplasma. Such a preplasma profile was formed by an additional nanosecond laser pulse (Nd:YAG laser, I=10^{12}W/cm^2). In the case of optimal preplasma parameters femtosecond laser pulse (I=5×10^{18} W/cm^2 τ=50 fs FWHM, d = 4λ FWHM) generates a collimated electron bunch with divergence of 50 mrad, exponential spectrum with the slope of ∼2 MeV and charge of tens of pC [1]. The 2D PIC simulations confirmed beamed electron's acceleration in the plasma channel (so-called direct laser acceleration, or DLA). This channel is formed in a long tail of teneous preplasma by the laser pulse specularly reflected from the arbitrary sharp gradient. Simulations of a test electron's motion in the complex electromagnetic field consisting of the laser pulse and static fields showed that an electron acquires maximum energy at the channel exit if its initial energy amounts to several hundred keV and it is injected at the instant of the maximal field of the laser pulse. Simple estimates showed that plasma waves of the hybrid SRS-TPD instability are capable of injecting electrons with required energies in the channel. This instability generates two groups of waves: one moves along the plasma surface and the other - approximately in the perpendicular direction toward lower densities. Analysis of electron's trajectories obtained from the PIC-modeling showed that the first group of waves accelerates electrons, while the field of the second group pushes electrons into the plasma channel. These waves were evidenced experimentally and numerically from the scattered $3/2\omega_0$ harmonic.

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Diagnostics of ultra-intense femtosecond laser pulses via ponderomotive acceleration of protons and electrons

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Development of high-power laser facilities requires new methods of diagnostics of high-intense femtosecond laser pulses, since the direct measurement of such extraordinary intensity is challenging using conventional techniques. There are some different approaches to satisfy this demand including ones based on multiple tunneling ionization of high Z atoms [1], nonlinear Compton scattering [2], temporally resolved intensity contouring by a chirped probing scheme [3]. At the same time, the highest intensities are achieved in the case of ultratight focusing, which allows accelerating charged particles (electrons [4–6] and protons [7]) without needing subsidiary devices or beams of high-energy particles. Thus a new method of laser diagnostics can be based on this effect.

Here we discuss angular-spectral characteristics of both accelerated particles. The laser pulse focused by off-axis parabolic mirror is described by Stratton-Chu integrals, which allows simulating laser pulse with different spatial-temporal profiles focused down to the diffraction limit. Particle trajectories are calculated by the test particle method, which consists in the solution of relativistic equation of motion with Lorentz force for electrons and nonrelativistic one with ponderomotive force for protons. This model neglects plasma effects, thus characteristics of the distributions are determined by the laser parameters, that is needed for the laser diagnostics. This condition can be experimentally implemented by ultrathin nanofoil or rarefied gases. We have analyzed impact of the laser peak intensity, the focal spot size and the pulse duration on the angular-spectral distributions of particles (electrons and protons) to propose a method of simultaneous measurement of these laser parameters.

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Optimizing and understanding experiments on electron acceleration in dense laser plasma with numerical methods

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Recently generation of powerful (up to petawatt) short (5 to 50 fs) laser pulses with intensities more than 10^{18} W/cm^2 became possible on a small-scale systems. On interaction with plasma, these pulses cause acceleration of electrons. This offers a possibility of creating tabletop laser accelerators, which would have various advantages over conventional ones – such as, compactness, lower construction cost, lower maintenance cost.

We study laser acceleration of electrons in plasma on the surface of dense solid target. One of the problems is the interpretation of experimental data, as real experimental conditions include complex geometry, and various physical processes taking place. This renders analytical approach difficult at best.

Numerical calculation, on the other hand, is sensitive to neither the physics, nor the geometry involved. Application of the modified Geant4 Monte-Carlo code allowed for optimization of an existing experimental scheme for accelerated electron beam spectrum measurement. Additionally, a scheme for measuring said beam's charge via gamma-nuclear reactions is analyzed, taking real neutron counter geometry into account.

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Section 2: Ultrafast phenomena in condensed matter and ionized gases

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Scope

Optical properties of heated solid conductors

Instabilities and high-frequency phenomena in photoionized plasma

Non-linear phenomena in nonequlibrium plasma and metals

Kinetics of rapidly heated electrons in metals and plasma

Ultrafast control of magnetization and magnetophotonics

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All-optical magnetization reversal with femtosecond laser pulses facilitates the fastest and least dissipative magnetic recording [1], but writing magnetic bits with spatial resolution better than the wavelength of light has so far been seen as a major challenge, making the application of optical techniques in recording technically challenging or even impossible. Here we experimentally demonstrate that using light with the wavelength of 800 nm and without any magnetic fields, it is possible to obtain full control over two magnetic bits separated by just 80 nm [2]. In particular, two bits in our experiment are represented by two 10-nm thick GdFeCo layers separated by a 80-nm thick layer of Si_3N_4. Using a single femtosecond laser pulse, we can toggle the magnetization exclusively within a single magnetic nanolayer, without affecting the other one. The choice of the toggled layer is enabled by the excitation of a plasmon-polariton at a targeted interface of the nanostructure, and realized merely by rotating the polarization-axis of the linearly-polarized ultrashort optical pulse by 90°. The underlying mechanism is robust, well reproducible and relies on the polarization-dependent excitation of plasmon-polaritons in the magnetic nanostructure. Our results unveil a new tool that can be deployed to switch magnetization in targeted nanolayers of heterostructures, and paves the way to increase the density of opto-magnetic recording.

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Momentum and energy relaxation in femtosecond-scale energy transport in metals

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Since the development of femtosecond lasers multiple experimental and theoretical works were devoted to the energy relaxation in metals on a femtosecond time scale and its influence on heat transfer. Most of these papers handled the process of heat transport using various energy-averaged macroscopic models such as two-temperature model, Cattaneo equation etc.

In a current report we consider the processes of heat transport and energy relaxation in aluminium using Boltzmann transport equation for the electron distribution function, simultaneously accounting both energy and momentum relaxation. Mutual influence of electron-electron and electron-phonon energy relaxation on the electron distribution function are considered using linearized integro-differential collision integrals. These energy exchange effects provide main contribution to the difference between the results obtained using Boltzmann equation solution and widely considered two-temperature model. .

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Limitations of the semiclassical approach for the problem of single atom and atomic ensemble emission in a strong resonant laser field

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The interaction of high intensity laser field with a quantum system (atomic or molecular ensemble, electronic subsystem of solids, etc) results in a lot of nonlinear processes accompanied by radiation emission of various frequency band from the radio-frequency and THz to the VUV and soft X-rays. The emission of a quantum system driven by the strong laser field is typically studied in the framework of so-called semiclassical approach [1] when the atomic dynamics is described quantum-mechanically while the radiation field is described using the classical laws. However, the limitations of applicability of the semiclassical approach to analyze the emission of atoms driven by laser fields were discussed in [2]. In reality, each process of emission at frequency that does not coincide with the laser frequency starts with the spontaneous emission and, hence, should be considered taking into account the interaction of atom with the quantized field vacuum modes. Such approach was developed in [3]. It takes into account the interaction of an atom with a set of quantized field modes being in a vacuum state in the first order of the perturbation theory while its interaction with laser field is assumed to be classical and considered beyond the perturbation theory.

In this work we generalize the approach [3] for the study of spontaneous emission of the atomic ensemble driven by the classical laser field. The cases of resonant and nonresonant laser radiation interaction with a single two-level atom and two-level atomic ensemble are studied. The comparative analysis of QED and semiclassical study is performed. It is found that semiclassical approach has serious limitations for the description of the emission of the ensemble as it is not sensitive to the phases of wave functions of different atoms. As about the single atom the agreement of both approaches was obtained for the case of interaction with a nonresonant rather weak external field when the atom is dominantly in the initial (ground) state.

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Ultrafast depolarization in gases induced by focusing femtosecond laser pulse

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We report on experimental observation of the ultrafast depolarization induced by propagation of an intense laser pulse through the ionizing gas media. It has been previously demonstrated that during filamentation in gases a birefringence occurs that could also lead to depolarization [1,2]. Here we show that the depolarization is strongly dependent on the intensity of the laser pulse.

The experiment is based on pump-probe scheme with transverse directions of the beam paths. The pump pulse (2.5 mJ, 50 fs, 12 mm dia. $1/e^2$) is focused by a 5 cm focal length parabolic mirror producing ∼2 mm long plasma channel. The polarization of the beam is vertical. The probe beam goes through a controllable delay line and thereafter through the region of plasma formation. To visualize the depolarization, the probe beam polarization is turned to 45 degrees. It passes a 45 degrees oriented polarizer, the plasma region and an analyzer rotated in the vicinity of 135 degrees (crossed polarizers). The plasma channel region (and depolarization) is imaged on a CMOS-camera by a telescope. By changing of the delay we can scan the position of the pump pulse in the focusing region and so the intensity conditions. The depolarization pattern changes from the spot-like to ring-like structures with the increase in the intensity. The most intense depolarization occurs in the vicinity of ionization threshold.

The investigation of this depolarization could be useful for modelling of plasma formation processes.

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Generation of low-frequency radiation under the influence of a laser pulse on a thin metal film

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The work [1] is devoted to the study of the generation of low-frequency radiation arising from the action of femtosecond s-polarized laser pulse on a metal film. Two generation mechanisms are considered. The first of them is associated with effective heating of electrons [2], which leads to the appearance of electron pressure gradient, and the second is associated with the action of a drag force generating directional motion of electrons along the metal surface [3].

The expressions were given for the high-frequency field in a film produced by an s-polarised femtosecond laser pulse. Under conditions of weak nonuniform heating of electrons, an equation was written for a small pressure perturbation and the source of the drag current was found. Equations were also formulated for the Fourier transforms of low-frequency electric and magnetic fields. Using the general solution of these equations and the continuity conditions for the tangential field components at the film boundaries, the Fourier transforms of the low-frequency magnetic field generated by a pressure gradient and drag force was found.

The expressions for the Fourier transforms of the magnetic field on the surface of the film were analyzed. It is shown that in the case when the high-frequency field is localized at the surface and the low-frequency field is slightly inhomogeneous in the film thickness, the amplitude of the low-frequency signal grows inversely with the film thickness. In the case when the film thickness is less than the depth of the skin layer at the laser radiation frequency the amplitude of the low-frequency signal grows inversely with the square of the film thickness.

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Nonlinear excitation of solids and transient band gap dynamics upon femtosecond laser irradiation of semiconductors: Insights from first principles simulations

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Time-dependent density functional theory (TDDFT) is an efficient method to predict excitation dynamics of electrons in laser-irradiated band-gap materials.

In this work, the transient excitation of silicon was studied by performing extensive TDDFT simulations. The density of conduction band electrons, the total electronic current and the electronic energy were calculated for a wide range laser intensities and for different laser wavelengths. The approach has enabled to achieve a detailed description of the transition from the multiphoton to the tunneling regime of photoionization, characterized by a decrease of the number of photons required for the excitation of valence electrons to conduction bands. The nonlinear absorption rates were calculated as a function of laser intensity for several wavelengths. The dependence of the free-electron energy on wavelength revealed resonance peaks, which shift with increasing the laser field strength. This confirms the applicability of Keldysh theory for describing direct transitions of electrons in semiconductors.

To gain better insight to the observed effects, the dynamics of electron energy levels in the laser field was studied using a Floquet-Stark Hamiltonian. At low laser intensities, replicas of the electronic bands are found at energies shifted in comparison to the ground state that is explained by the interaction between the electronic bands. With increasing intensity, the replicas can cross, manifesting a transient closure of the band gap. This effect is related to the electron tunneling and can be described by the dynamic Floquet-Stark metallization [1-3].

This work provides quantitative information that is of high importance for the improvements of theories describing excitation, metallization and damage of laser-irradiated bandgap materials.

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Excitation of terahertz surface modes in plasma layer under action of two-frequency laser radiation

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Interest in the problem of generation and detection of terahertz (THz) radiation is connected with the possibilities of its wide use in scientific research and practical applications. In the modern experiments [1], THz pulses with energy near several hundred microjoules and the conversion efficiency several percent were obtained. The increasing the energy of THz pulses can be associated with the excitation of eigenmodes in a matter under the action of a laser field, when the medium itself makes a significant contribution to the energy of the THz signal. Such a mechanism for the excitation of low-frequency leaking modes under the action of laser radiation was previously considered for a rarefied plasma layer in [2]. The excitation of the plasma layer eigenmodes under the action of two-frequency laser radiation is investigated in [3]. We study an oblique incidence of two constant-amplitude laser waves with close frequencies on a rarefied plasma layer in a symmetric irradiation scheme, when along the layer boundary the waves propagate towards each other [3]. In the case, the excitation of the surface eigenmode of the layer occurs under conditions of direct resonance, when the frequency difference between the laser fields coincides with the eigenmode frequency of the plasma layer. This leads to the fact that in the considered irradiation scheme, the expression for the energy of the low-frequency mode contains in the denominator the square of the small imaginary part of the dispersion function. This allow to considerably increase the energy of low-frequency radiation in comparison with the result obtained in [2], where the energy contains in the denominator a small imaginary part of the dispersion function only in the first degree, due to the integration over the whole spectrum of the excited oscillations. The estimates show that under the conditions of modern experiments, the considered mechanism for the excitation of the plasma layer low-frequency eigenmode makes it possible to obtain radiation in the terahertz frequency range with an energy flux density comparable to the intensity of laser radiation.

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Theory for the laser induced transition from nonthermal to incoherent thermal lattice dynamics in condensed matter

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In laser excited solids, the produced hot electrons are at easiest described in the canonical ensemble in terms of the Helmholtz free energy, which in turns determines the potential energy surface (PES) for the ions $U(T_e) = E_e - T_e S_e$, where T_e, E_e and S_e are the electronic temperature, total energy and entropy after laser excitation and thermalization, respectively. On the other hand, the motion of the ions on the laser excited PES fulfills energy conservation as long as T_e does not change and can be treated in the microcanonical ensemble. Now, when the electron-phonon coupling is active and there is energy exchange in both directions, the mixed canonical-microcanonical usually leads to inconsistencies and wrong results. So far, different approximate approaches have been used to overcome this problem, but a microscopic theory is still lacking.

In this talk, we present a theory for the coupled description of the laser induced ultrafast dynamics of the electronic temperature and the ions from first principles. The theory yields and generalizes the equations of the two-temperature-model-molecular-dynamics (TTM-MD) method in a natural way and can be used either in ab-initio simulations or in large-scale MD simulations based on T_e-dependent force fields.

We apply this theory to study the ultrafast lattice dynamics in graphene, amorphous carbon and graphite performing ab-initio simulations and the dynamics of Sb and Si using large-scale MD simulations based on force fields derived using our recently proposed self-learning algorithm[1]. Remarkably good agreement with experiments is obtained. The importance of using T_e-dependent force fields in MD simulations is discussed.

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Intensity clamping and controlled efficiency of X-ray generation under femtosecond laser interaction with solid target in air and helium

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The generation of line X-rays with femtosecond laser pulses is stimulated much interest in due to its applications for time-resolved studies. Due to known difficulties in using a vacuum chamber system to line X-ray production there is a need for an efficient X-ray source capable of operating in air with a tabletop femtosecond laser. In that conditions ionization of air molecules in the near-surface area of the target is accompanied by depletion of laser energy, as well as self-induced defocusing of the laser beam [1]. These processes with increasing laser energy cause a restriction of the laser beam intensity level (compared to the "vacuum" level). The conversion efficiency to X-ray under the conditions of exposure to the target in a gas environment stabilizes at a lower level than under vacuum conditions. One of the ways to increase the efficiency of interaction with intense femtosecond laser radiation with a target is the use of local "blowing" of gas (helium) with a large ionization potential into the interaction area.

The purpose of this work is to study the conditions for overcoming the limitation of achieving effective generation of hard x-ray radiation, which occurs when a focused femtosecond laser beam of mJ- level interacts with a solid target in the air or in the presence of helium.

TiSa and Cr:forsterite lasers with an output energy not exceeding 4 mJ were operated in the performed experiments. As a target we chose a copper foil and a rotating copper rod. We found an intensity clamping effect with an limit about 3×10^{14} W/cm^2 in experiments with Cr:forsterite laser using the target placed in the air. Blowing helium with the jet into the interaction area allowed increasing the laser intensity by about 4 times compare with the air. We found that an increase in the pulse duration of the femtosecond TiSa laser interaction with the target leads to an enhanced in the output of X-ray radiation from the minimum recorded level (at a duration of 250 fs) by an order of magnitude compare with optimum pulse duration of 1500 fs. At the same time, ionization losses decreased from 25% to 5%.

We have performed theoretical calculations aimed at modeling the propagation dynamics of a focused laser beam in a nonlinear gas medium. It was

obtained that when helium is blown into the focal area, the intensity clamping level is about 4 times higher than when air is present (see.Fig.1). The conditions for optimal placement of the target relative to the position of the vacuum focus and, accordingly, achieving the maximum intensity are found, and the possibility of increasing the fluence in the conditions of the clamping effect with an increase in the pulse duration and focusing conditions is shown. It is theoretically shown and experimentally confirmed that when the pulse duration increases ionization losses during the propagation of the laser beam in air and helium are reduced and the effect of defocusing on the induced plasma nonlinearity is minimized. As a result, this leads to a significant increase in the fluence on the target surface and, consequently, to an increase in the output of X-ray photons. Theoretically, it is shown that an increase in the wavelength from 800 nm to 4000 nm with comparable laser parameters and focusing mode provides an increase in the product $I\lambda^2$ by almost an order of the magnitude (see Fig.2). We will present the results of the conversion efficiency of the laser energy for 8 keV copper line.

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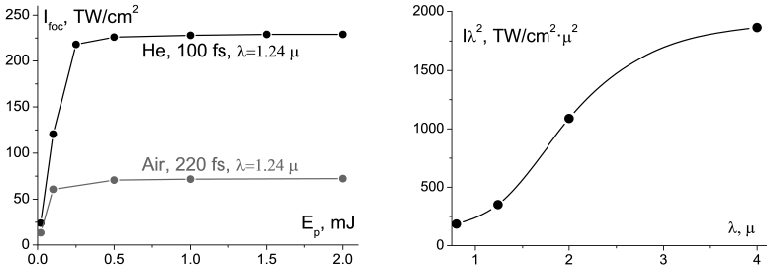

Figure 1: Fig.1, left. Intensity clamping depending on pulse energy (NA=0.021). Fig.2, right. Intensity product depending on laser wavelength (100fs, 1 mJ, NA=0.021)

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Cyclotron resonance amplification of THz radiation in a nonequilibrium plasma created by UV laser in the presence of external magnetic field

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From [1] it is known that in a plasma channel with a nonequilibrium electron spectrum created in a gas with a growing transport cross section, the effect of amplification of low-frequency radiation ($\omega < \nu_{tr}$, where ν_{tr} is the transport frequency of electron-atom collisions) can be observed. In particular, it was shown in [2,3] that upon photoionization of inert gases (argon, xenon) of atmospheric pressure by UV femtosecond laser pulses, the required conditions for the appearance of the amplification effect of THz radiation are fulfilled. In [2], it was shown that at atmospheric pressure it is possible to amplify low-frequency radiation up to the sub-terahertz radiation, and to shift the gain boundary to a higher frequency range it is necessary to increase the pressure in the plasma channel.

In the present study we analyze another approach that makes it possible to increase the frequency of the amplified radiation and reach the frequencies up to several THz without increasing the gas pressure. We propose to apply the static magnetic field along the nonequilibrium amplifying plasma channel to reach the regime of the cyclotron resonance. We perform the analysis for situation when external magnetic field B_0 is directed along the wave vector $\vec{k}$ and assume the linearly polarized THz wave field $\vec{E_0} = [E_0\, exp(-i\omega t),\, 0,\, 0]$ as a superposition of two counter-rotating waves with the polarizations along vectors $\vec{e}^{(\pm)} = \vec{e}_x \pm i\vec{e}_y$ correspondingly ($\vec{e}_x, \vec{e}_y$ are the unit vectors along x and y axes). Obviously, one of the counter-rotating waves interacts effectively with plasma electrons if $\omega \approx \omega_B$ ($\omega_B = \frac{eB_0}{mc}$ is the cyclotron frequency) and the arising electric current with circular $\vec{e}^{(-)}$ polarization will dominate near the resonance frequency. Hence, in magnetized plasma we can resonantly enhance only THz field with circular $\vec{e}^{(-)}$ polarization. Our calculations predict that for the wave with $\vec{e}^{(-)}$ polarization the resonance amplification ($\omega \approx \omega_B$) is possible even when $\omega > \nu_{tr}$. For the case $\omega_B \ll \nu_{tr}$ amplification of low-frequency radiation occurs ($\omega < \nu_{tr}$) which corresponds to the results for an unmagnetized plasma [2,3]. An increase in the magnetic field leads to a shift of the amplified frequencies to a higher frequency range. Hence, the presence of a magnetic field makes it possible to control the range of amplified frequencies in a nonequilibrium inert gas plasma, thereby removing the low-frequency limitation. Moreover, by changing the relationship

between ν_{tr} and ω_B, one can control the bandwidth of the resonantly amplified frequency range: the more ω_B compared to ν_{tr}, the narrower the resonance range becomes.

Thus, the presence of a magnetic field in the framework of the problem of amplifying (sub) terahertz radiation in a plasma removes the frequency limitation $\omega < \nu_{tr}$ and leads to absolute gain increase. In addition, it allows efficient amplification of the THz radiation of the selected frequency band, which can be used in the future for signal filtering.

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Fragmentation of a liquid droplet by a short laser pulse

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Fragmentation mechanisms of a micrometer-sized liquid tin droplet irradiated by a short laser pulse are studied. Our experiments show either symmetric or asymmetric expansion of the droplet depending on laser pulse intensity. To reveal the underline processes we perform simulations complying with the experiments using the smoothed particle hydrodynamics. It is demonstrated that, as a result of fast laser energy deposition, a strong shock wave followed by a tensile wave is formed and propagates from the frontal side to the rear side of droplet. Convergence of such waves inside the droplet induces cavitation nearby the center, which causes the droplet to expand symmetrically. Reflection of a shock wave from the rear side of droplet may lead to spallation producing a thin layer moving in the laser pulse direction, which results in the asymmetrical expansion. The calculated laser intensity threshold for the rear-side spallation is higher than a threshold required for the central cavitation. The corresponding expansion velocities and thresholds agree well with the experimental results in both regimes of droplet expansion. Special attention is made for fragmentation of a droplet irradiated by polarised laser pulse.

Generation of terahertz radiation under the action of short laser pulse focused by cylindrical lens on a dielectric-metal layered structure

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The generation of THz radiation under the action of a femtosecond laser pulse focused by a cylindrical lens on a metal that is in contact with a nanolayer of wide-bandgap dielectric was studied. In this case due to the incident and reflected high-frequency waves interference in the dielectric, a multiple increase in the amplitude of the high-frequency field at the metal surface occurs. The low-frequency magnetic field, the total energy of the THz radiation and radiation pattern is found. It is shown that the total energy of THz radiation is proportional to the strip length into which the laser radiation is focused, which makes it possible to significantly increase the total energy of THz radiation in comparison with the case of laser radiation focused into a spot (see [1]).

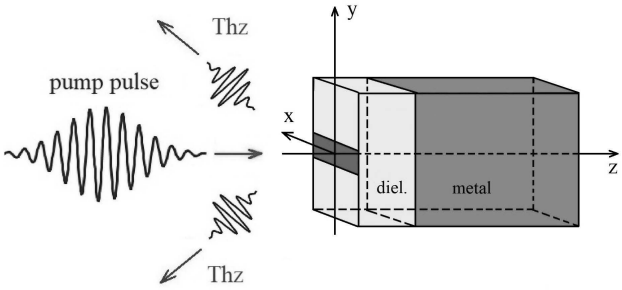

Figure 1: THz radiation generation scheme.

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Processing of semitransparent materials with fs laser pulses

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We report on the experimental observation of new type of processing of semitransparent materials upon femtosecond laser processing with highly-overlapping laser pulses. Overlapping laser pulses enable accumulation of heat and defects, which open possibilities for selective delamination [1] and recrystallization [2] of the processed samples. Analysis of the delaminated layer indicates that the material undergoes melting on its both surfaces. The mechanism of delamination is identified as a complex interplay between the optical response of laser- generated free-electron plasma and nonlinear effects upon laser beam propagation in semi-transparent ceramics.

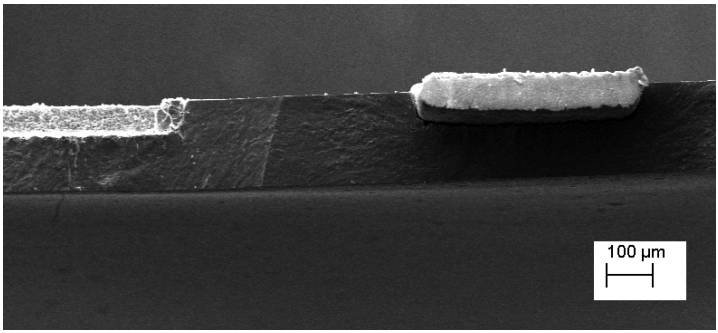

Figure 1: SEM image of the laser-delaminated area kept attached to the substrate (right) and substrate with removed delaminated area (left).

Heat accumulation is shown to play key role for laser-induced recrystallization of amorphous metal oxides. Laser-processed of oxide layers increase the efficiency of water-splitting cells by approximately 200% [3], however the recrystallization can be only one of the mechanisms along with increase in the light absorptivity and specific area of the electrodes due to formation of the laser-induced periodic surface structures (LIPSS).

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Structuring of polystyrene surface with ultrashort ps and fs laser pulses

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Biocompatible polymers, such as polystyrene (PS), are still in the centre of interest for wide range of applications, such as microsystem technology, micro-optics, fabrication of lab-on-chip devices or investigation of cell growth behaviour [1-4].

Required polymer modifications can be operated by laser-assisted ablation with chosen appropriate conditions. Pulsed laser ablation (PLA), as a well established method for surface processing and modification, then allow us to study and established new approaches and functionalities of polymers of different kinds. Polystyrene, as many other polymers, has been extensively investigated mainly for UV region of electromagnetic spectra. Polymer ablation in infrared region, especially in the regimes of ultrashort laser pulses, is still not widely studied despite that the non-linear absorption phenomena in IR region offer different material response.

This work presents complex approach to ablation of polystyrene (PS) polymer from ultraviolet (UV) to mid-Infrared (mid-IR) part of electromagnetic spectra. The ablation was performed with different pulse durations (ps and fs) and the single shots thresholds have been determined as well as the investigation of crater/grooves profiles. Accurate structuring of this biocompatible polymer is of importance for direct applications in study of collective cell behaviour and cell growth. ould change [1].

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Comprehensive study of the wave-scattering problem applied to fine-structured electrical sparks visualized via laser probing techniques

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In [1], a novel surprising feature of natural electrical spark discharges has been unveiled. By using simultaneous multi-frame laser interferometry, shadow and schlieren imaging, it is discovered that single spark channels developing in ambient air turn out to consist of tens closely packed thin filaments of highly-ionized plasma. Single filaments have characteristic diameters of $\sim$ 10–50 μm and are organized themselves into a cluster with a characteristic diameter of $\sim$ 200 μm, which forms a resultant spark channel. The microstructure of such channel is somewhat similar to a bunch of multiple optical fibers. Being a somewhat uniquely organized dynamic plasma system, the filament cluster is also an optical medium of immense complexity governed by stochastic fluctuations of the plasma dielectric permittivity. These fluctuations are caused by single filaments characterizing the internal scale ($\sim$ 10 μm) of the medium turbulence. It is found that the incident laser radiation undergoes a complicated scattering by the filament cluster, the visualization of which is accompanied by strong accumulation of diffraction effects. When solving the wave-scattering problem, these effects cannot be easily accounted for in terms of either wave absorption or strong refraction.

Herein we present the comprehensive analysis of the wave-scattering problem applied to the fine-structured sparks visualized via laser probing techniques and support it with simulated results. We justify the employment of the smooth perturbation theory for solving the direct and inverse wave-scattering problems in the case of strong accumulation of diffraction effects. We also reveal fundamental discrepancies of the simulated results obtained by the first Rytov and geometrical optics approximations used to solve the scalar Helmholtz wave equation and define possible accuracies of data acquisition for the filament clusters. The analytical approaches and created program codes for modeling the wave-scattering problems have been additionally tested on axisymmetric plasma inhomogeneties (fine-scale plasma spots at electrodes and homogeneous sparks).

The study is supported by the grants of the Russian Foundation for Basic Research (no. 20-08-01156) and President of the Russian Federation (no. MK-703.2020.2).

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Control of ionization and generation of secondary radiation in two- and multicolor fields

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Strong-field ionization and associated generation of secondary radiation are of great interest due to unique features (ultrabroad spectrum, extremely short duration, high peak intensity) of the generated emission, which can be used for spectroscopy and wide range of other applications. An important question here is how one can control the ionization processes and characteristics of generated radiation by changing the parameters of ionizing pump pulse. The ways of such control are quite rich, though understudied, when one employs two- and multicolor pulses, where the spectral composition, phase and group delays between one-color components and the polarization structure may be changed. Here, we report results on generation of low- and high-frequency secondary radiation (in THz [1], mid-infrared and ultraviolet range [2]) by multicolor pulse consisting of fundamental field and one or more of its harmonics. We discuss how additional harmonics may affect the ionization rate and the generated radiation and propose new ways of controlling spectrum, efficiency and polarization of generated radiation through manipulating phase and polarization structure of the multicolor pump.

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Linearly polarized Alfvén solitary waves in astrophysical plasmas

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The Alfvén electromagnetic waves are low-frequency magnetohydrodynamic plasma oscillations which propagate only in the presence of the external constant magnetic field [1]. Charged plasma particles are moving at the propagation of Alfvén waves. Therefore the velocity of their propagation is small in comparison to the light speed. Alfvén waves exist only in plasma with the high conductivity. Their phase velocity c_A is determined only by the external magnetic field strength H and by the plasma density ρ: $c_A = H/\sqrt{4\pi\rho}$. Small dispersion of the Alfvén waves is produced by the motion of atomic ions. We have the relation between the frequency ω of the wave and the wave number k:$\omega^2 = c_A^2 k^2(1 - a^2k^2)$, $ka \ll 1$. The dispersion length a is determined by the relation $a^2 = m_i c^2/4\pi ne^2$, where n is the plasma number density. In this talk we consider analytically the propagation of the *linearly* polarized transverse Alfvén solitary waves in cold plasmas. *Circularly* polarized Alfvén solitons in cold plasmas were investigated in [2].

We consider the propagation of nonlinear transverse electromagnetic waves along the axis X. The constant magnetic field H is directed along the axis Y. Let introduce the notation $h(x,t)$ for the perturbation of this magnetic field. This magnetic field is directed also along the axis Y. We solve the Korteweg-de-Vries equation for the electron velocity V which is directed along axis X [3]:

$$V(x,t) = \frac{3U}{2}\cosh^{-2}\left(\sqrt{\frac{U}{2c_A}}\frac{x-Ut}{a}\right)$$

This solution is the solitary wave which propagates with the large phase velocity $U \gg c_A$. The soliton height is $3U/2$. The small spreading of the soliton is equal to $a\sqrt{c_A/U} \ll a$. Thus, the soliton is narrow at the high intensity. We find the magnetic field h which is directed along the axis Y:

$$h(x,t) = \frac{3UH}{2c_A}\cosh^{-2}\left(\sqrt{\frac{U}{2c_A}}\frac{x-Ut}{a}\right) \gg H$$

We derive the electric field E of the solitary wave which is directed along the axis Z:

$$E(x,t) = -\frac{9U^2}{4c_A c}\cosh^{-2}\left(\sqrt{\frac{U}{2c_A}}\frac{x-Ut}{a}\right) \gg H$$

Thus, the transverse electromagnetic field of this Alfvén solitary wave propagating along axis X is linearly polarized. This study will provide a sound basis for further research on problems [4] relating to Alfvén solitons in plasmas.

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High-frequency skin-effect in a photoionized inert gas plasma

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The features of a monochromatic electromagnetic (EM) wave penetration during its normal incidence on the semi-bounded plasma, obtained as a result of multiphoton ionization of inert gas atoms, were studied when the conditions of high-frequency skin-effect are realized. The main characteristic determining the pattern of EM wave penetration into a plasma is the parameter α — a value determined by the average photoelectron energy and the type of energy dependence of the scattering transport cross section. Expressions for the surface impedance and absorption coefficient in different frequency ranges of the probe wave were obtained. Field absorption is mainly determined by collisions of photoelectrons with atoms. For frequencies noticeably lower than the Langmuir frequency, the absorption coefficient linearly depends on the collision frequency ν. When the field frequency approaches Langmuir's one, the absorption increases and depends on the frequency of collisions like $\sqrt{\nu}$. Taking into account the Ramsauer-Townsend effect leads to an increase in absorption over the entire range of frequencies under consideration. With a further increase in the frequency, the absorption coefficient ceases to depend on the collision frequency in the linear approximation and tends to unity. Fig.1 demonstrates absorption coefficients taking into account the dependence of the scattering cross section on the electron velocity (for xenon and krypton) and without it.

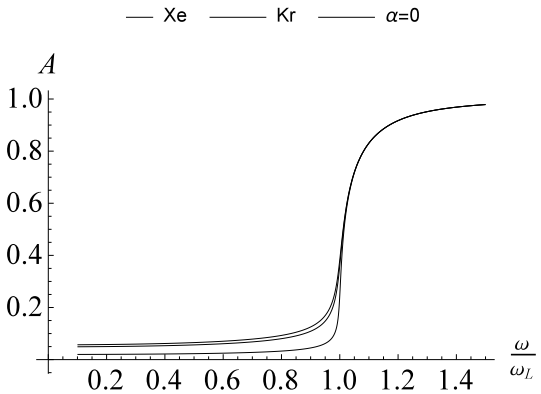

Figure 1: Dependence of the absorption coefficient $A(\omega)$ on the incident field frequency ω.

Shock wave induced ultrafast phase transition and amorphization of Si: an atomistic study.

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Silicon has a great importance as an optical, electronic, and structural material [1]. Modeling the impact of shock waves on silicon at room temperature is an important step toward understanding the various phenomena associated with phase transitions in Si [2]. Pressured silicon undergoes a series of phase transitions caused by stress, accompanied by large changes in cell volume ($\sim 25\%$). Under high pressures (more than 10GPa) Si undergo series of phase transitions. Si transforms from cubic diamond phase to a primitive hexagonal (b-Sn) structure around 11 GPa, and to hcp (Si-VII) around 50 GPa [3]. Such high pressures could be achieved in laser-matter interactions. We used molecular dynamics simulation to investigate the pressure-induced phase transitions in Si both in static (fixed pressures) and dynamic (shock wave propagation) case. The simulations were performed in LAMMPS software package over 360000 atoms (TERSOFF interatomic potential).

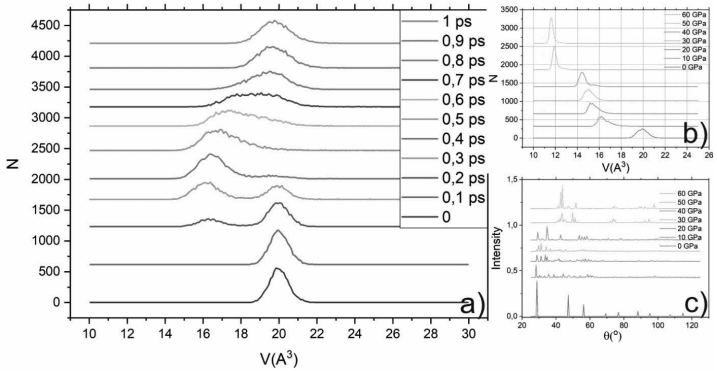

Figure 1: Histograms of atomic volume (a,b) during propagation of shock wave in Si (p=21.2 GPa) (a) and under constant pressures (b). XRD spectrum at constant pressure in Si.

In the static pressure conditions (Fig.1b,c) we demonstrated that the phase transitions leads to the change of atomic volume, centrosymmetry parameter and XRD spectrum. The cubic diamond phase is stable up to 11 GPa, β-SN is stable in the pressure range from 11 to 50 GPa. In the dynamic phase the phase transition takes place only on the shock wave front on the ps timescale under pressures above 10 GPa. The phase is not stable, and the structure returns to

the initial state with a small number of defects. If pressure overcomes 30 GPa the structure of Si becomes broken and it transmits to amorphous phase. The computed XRD spectra are useful tools for compassion a numeric modeling data with experiments on synchrotron facilities.

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Pump driven normal-to-excitonic insulator transition: signatures of BEC-BCS crossover in time-resolved ARPES

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Ultra-fast spectroscopy is a powerful tool for the observation of electronic and atomic dynamical processes. In a basic Pump and Probe experiment a first light pulse (the pump) resonantly triggers a photo-induced process exciting electrons from the valence to the conduction bands. This initial photo-excitation inevitably creates an avalanche of phenomena that drives the system dynamics. The description of this complex dynamics is really challenging. In this talk I will first review the Ab Initio Non Equilibrium Green's function (AiNEGF) method [1], which represents a new frontier in the realm of atomistic simulations.

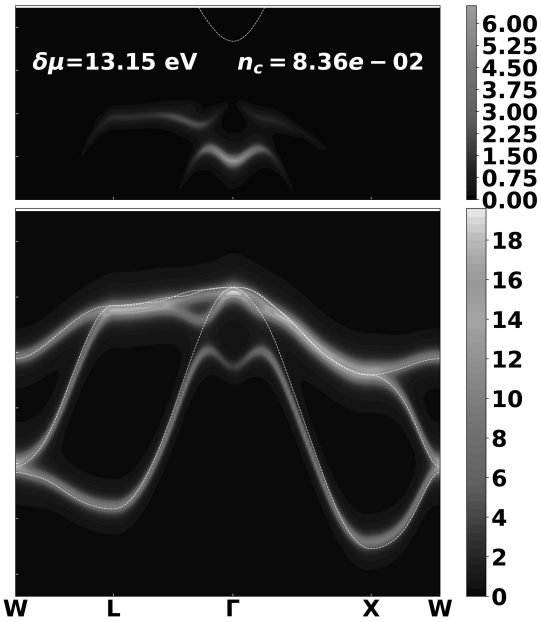

Figure 1: Occupied part of the spectral function of a bulk LiF for different values of Excitonic energy. The excitonic resonance clearly appears as a isolated band in the conduction energy region.

In the second part of the talk I will use the AiNEGF to describe a novel phenomenum: the photo–induced band insulator to excitonic insulator (NEQ-EI) transition in complex materials [2]. I will show that the NEQ-EI phase

is characterized by self-sustained oscillations of the complex order parameter. The peculiar fingerprints of the NEQ-EI phase in time-resolved angle-resolved photoemission spectroscopy spectra will be discussed in a simplified mode and in paradigmatic materials (See LiF figure below).

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Ultrafast dynamics of AF SDW and SC order parameters in doped cuprates

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A planar nanosystem in conducting CuO2 layers of doped cuprates, consisting of periodically alternating, highly conducting (charge) and semi-insulating (spin) stripes, arises near the pseudogap opening temperature T^* on the Fermi surface and becomes superconducting (SC) at $T = T_c$ [1]. The temperature interval $T_c < T < T^*$ corresponds to the region of the magnetic phase transition from spin-disordered state to a state of AF spin density wave (SDW), incommensurable with the lattice constant (pseudogap state) [1]. In view of the dynamic (fluctuating) nature of this nanosystem, a detailed study of its electronic and optical properties, which depend on the coupling of fermionic quasiparticles with phonons and bosonic excitations of electronic origin, is possible only with the help of local and fast methods. One such technique is broadband ultrafast spectroscopy (see, e.g. [2])), which makes it possible to reveal the subtle interaction between quasiparticles and electronic or phonon collective excitations due to various characteristic time scales and spectral responses. In this case, nonequilibrium optical spectroscopy of these materials is carried out with a resolution both in time and in energy. Based on the available experimental data on measuring the femtosecond dynamics of the optical properties of the CuO2 plane in the energy range of 0.5-2 eV, the report provides a detailed analysis of the role of electronic correlations in controlling dynamics on a femtosecond time scale. Analysis showed that the equilibrium absorption cross section for this energy interval in the CuO2 plane is determined by the sum of the Drude absorption (free carriers) and absorption due to a number of Lorentzian oscillators, (e.g. at energy of 2 eV), in the visible region (interband transition between O2p and Cu3d_x2-y2 states with charge transfer (CT transition)) [2] (cf. with [3]). Measurements of the planar reflection coefficient in cuprates made using a Ti: Sa laser (pump energy ~ 1.07 eV and probe energy ~ 1.55 eV) showed a characteristic change in its sign both at temperature T^* and at temperature T_c. The picture is consistent with our above results [1]. Another interesting effect is the appearance of a threshold value of the pump flux density of ~ 70 μJ/cm^2, above which two peaks appear on the dependence of the reflection coefficient on the delay in the SC-state - fast and slow, while only slow is observed below this threshold. The detailed comparison of results of ultrafast optical measurements in cuprates with magnetoresistive ones indicates to implementation of known idea of HTSC "Ginzburg sandwich" (in planar geometry) in these materials.

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Role of wavelength in photocarrier absorption under excitation of dielectrics by high-intensity laser field tunable from visible to mid-IR

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Nonlinear absorption associated with generation of free electron plasma is known as one of the main mechanism of laser-induced breakdown and damage of transparent materials by femtosecond pulses [1,2]. We have performed measurements of plasma formation threshold (PFT) induced by tightly focused femtosecond pulses in a wide range of wavelengths covering visible, near- and mid-IR regions (from 620 nm to 4.8 μm) in transparent dielectrics (SiO_2 and MgF_2), as a precursor of laser induced damage. We have observed non-monotonic behavior of PFT with wavelength. The uppermost value of PFT was observed around 1 μm in both materials, while additional local minimum around 3-4 μm was found in MgF_2. Our experimental results were compared to the predictions of numerical model based on multiple rate equations [3], which include photoionization and electron heating through direct electron-photon, as well as, indirect electron-photon-phonon interactions. This approach reveals that the appearance of local maximum around 1 μm is governed by an interplay between ionization mechanisms. Photoinization rate rapidly decreases with wavelength since multiphoton order increases, while influence of electron heating significantly increases with wavelength. At longer wavelengths (2-4 μm) inverse Bremsstrahlung process becomes extremely efficient and leads to lowering of the PFT. At high intensity of 10^{13} - 10^{14} W/cm^2 and driving wavelength of 4-5 μm multiple photon inverse Bremsstrahlung (strong field regime) comes into play decreasing the rate of electron heating and increasing PFT at longer wavelengths. Thus the presented results demonstrate transition between not only strong field ionization regimes, but also weak- and strong-field regimes [4]. Our findings pave the way for further optimization of two-color light matter interaction and controllable laser-induced material modification using mid-IR light.

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Nonequilibrium Auger-processes in targets

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The paper considers the possibility of excitation of nonequilibrium Auger transitions by corpuscular probes in a nonequilibrium Auger process, when a vacant place is filled with an electron from the inner shell of an atom. The authors give a diagram of the energy levels of how this Auger process proceeds. The presented calculations reveal the main idea of the report. It is shown that the speed of such a process will depend on the flux density of the incident particles and their energy. Indeed, when the first electron knocks an electron from the inner shell, a vacancy arises which fills in a very short time. It is necessary that the "second electron" has time to fill it, which means the participation of a sufficient number of electrons. An estimate is given for the electron flux and their energy at which the given process becomes competing with the ordinary Auger process.

Resonant signal transmission in optical structures with periodical profile of permittivity

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In this project we consider a general physical approach to enhancing the efficiency of terahertz and infrared bolometric detectors. The approach is based on the concept of resonant tunneling of an electromagnetic wave which is similar to quantum particle tunneling in quantum mechanics [1]. Placing resonator under nontransparent conductive layer (plasma, metal or superconductor) helps to increase under certain conditions the field intensity both beyond the nontransparent layer and within it, thus enhancing the detection efficiency [2]. If the frequency of the incident radiation matches with one of the eigenfrequencies of a resonator the effect of resonant tunneling through the conducting layer can be observed. Replacing single resonator with a resonator sequence separated with conductive layers result in formation of an absorption band instead of one resonant frequency [3]. To improve the absorption capacity of a bolometric detector it is proposed to place a periodic structure containing N resonators and conducting layers under the external absorbing layer. In this case, the field will penetrate much better both into dielectric and absorbing layers, which leads to increase in sensitivity of photodetection.

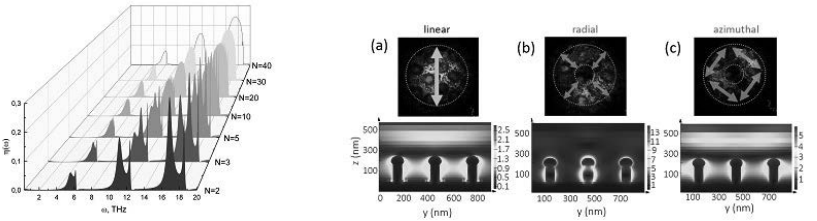

Figure 1: Fraction of the electromagnetic energy incident on the structure absorbed in the conducting layer $\eta(\omega)$ versus the radiation frequency ω for various numbers N of the conducting layers.

A sequence of doped (conducting) and undoped (non-conducting) GaAs layers with a thickness of 1 μm and 9 μm respectively deposited onto a metal substrate has been chosen as an investigated structure. Incident electromagnetic radiation with the frequency ω is on the right.

The numerical simulation of such a system has been carried out. As a result, spatial electromagnetic field distribution for a system with *N=1...100* layers

showed that the incoming radiation penetrates well into the structure if its frequency matches or almost matches the resonant frequencies of dielectric layers. The filling factor in dependence of transmitted signal frequency has also been calculated. It showed the formation of allowed zones (absorption regions) for incident radiation. The fraction of electromagnetic energy absorbed in the conducting layers was calculated as well (fig. 1). It was shown that such systems can provide absorption of up to 30-60% of the incident radiation of a given frequency range depending on the structure parameters.

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Edge currents inside the metal generated by anisotropic electronic pressure

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Interaction of femtosecond optical pulses with solids is usually accompanied by a variety of ultrafast phenomena like nonequilibrium heating, ballistic heat transfer, crystal lattice destruction, generation of optical harmonics and terahertz signal. In all of these effects dynamics of electron distribution function plays a key role. However, subpicosecond kinetics of charge carriers in solids is still a relevant problem both due to high computational complexity of numerical modeling and technical limitations of ultrafast measurements.

The talk will be focused on the electrodynamical phenomena caused by the anisotropic velocity distribution of electrons in metals. There are several physical mechanisms which may produce or keep the anisotropy of electronic distribution: Umklapp processes, ballistic transport, phonon drag effect and others. Contribution of the concreter effect depends on the metal and (mostly) on its temperature, while the electrodynamical features can be described in the general case.

We propose analytical description of the electron gas dynamics basing on modified Euler equation derived from the Boltzmann equation for free electrons. Anisotropic electronic pressure in the optical skin-layer of metal appeared to be non-potential external force (with $rot \neq 0$) exciting electric currents with nonzero vorticity. As a consequence, quite a strong magnetic field inside the metal is generated with a characteristic timescale of the pressure isotropization. In typical experiments with femtosecond laser pumping considered source produces magnetic field of a magnitude up to $\sim$1 Tesla even in non-damaging interaction regime.

It is shown that after the excitation magnetic field propagates inside the metal in accordance with the diffusion-like equation. All of the obtained analytical results are proved by numerical modeling which is also based on modified hydrodynamical equations and Maxwell equations. Besides the general interest to laser-metal interaction at femtosecond and subpicosecond timescales, developed theory can be useful for interpretation of experiments on optical-to-THz conversion, second harmonic generation and ultrafast demagnetization of metals.

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Propagation and amplification of ultrashort terahertz pulses in strongly nonequilibrium plasma channels formed in air by femtosecond UV laser pulses

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We consider a numerical model for the propagation of an ultrashort THz pulse in a highly nonequilibrium plasma channel created in air by third-harmonic radiation from a titanium-sapphire laser. The effect of amplification of a THz pulse is achieved due to the formation of a photoionization peak in the spectrum of electrons located in the region of growing with the energy of the transport cross section. The proposed model takes into account the time variation of the response function to an external THz field due to relaxation of the electron velocity distribution function (EVDF), which is determined mainly by vibrational excitation of nitrogen molecules. At the same time, we assumed that the THz pulse is rather weak and does not have an inverse effect on the EVDF in the channel plasma. It is shown that the spectrum of the initial THz pulse can be significantly red- shifted during the propagation, which leads to a significant distortion of the pulse shape and its duration. At gas pressures of several atmospheres, it is possible to achieve an increase in the energy of the THz signal by an order of magnitude or more over a length of ∼30 cm.

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Dynamics of expansion of near-electrode plasma in a high-voltage discharge in air

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The paper presents the results of experimental studies of the dynamics of expansion of near-electrode plasma in a pulsed high-voltage spark discharge in the air in the geometry of the tip plane. The generator that provides the supply of a voltage pulse to the discharge gap by means of a cable line had the following output parameters: voltage amplitude – 25 kV the duration of the front of the voltage pulse at the level of $0.1 - 0.9^{-7}$ ns. The interelectrode gap was 1.5 mm. A detailed description of the experimental stand, the method of registration and experimental conditions is presented in [1,2]

The results of the discharge registration by shadow photography show that semi-circular structures are formed in the near-electrode regions, starting from 30 ns and up to the exit of the spark channel boundary beyond the field of view of the optical registration system. Judging by their appearance, these structures can be identified with hemispherical shock waves, whose sources (energy release regions) are located on the surface of a flat electrode. The estimation of the wave front speed gives values from 1 to 10 km/s, which corresponds to the shock mode. These structures were registered with both negative and positive polarity of the tip.

The movement of the shock wave can be divided into two stages – a strong shock wave, which by the time 30 ns reaches a radius of 80 μm, then degenerates into a sound disturbance and then moves at the speed of sound corresponding to the temperature of the gas in the channel of about 10 kK.

The work was carried out with the financial support of the RFBR (project N 20-08-01043a).

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Dynamics of radial expansion of the channel in the initial phase of a spark discharge in the air

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The relevance of studying high-voltage nanosecond pulsed gas discharges is due to their wide practical application. At the same time, the experimental study of such discharges is often associated with a number of difficulties due to the need to ensure high temporal and spatial resolution, as well as the sensitivity of recording equipment and techniques. This question is particularly acute when studying the initial stage of the discharge. However, in many cases, it is at the initial stage of the discharge that the processes that determine its further evolution take place.

The paper presents experimental data on the development of a nanosecond discharge in atmospheric pressure air in the tip-tip geometry with an interelectrode gap of 1.5 mm [12]. The results of registration of the dynamics of the discharge structure, its electrical characteristics and electron concentration in it are presented.

Computational and theoretical interpretation of experimental data is performed. It is shown that gas-dynamic processes significantly affect the discharge parameters at times less than 100 ns. The kinetics of processes occurring at these times is considered and the electron concentration, drift velocity, temperature of electrons and ions, channel expansion rate and its conductivity are calculated. A satisfactory agreement of the calculation results with experimental data was obtained.

The work was carried out with the financial support of the RFBR (project N 20-08-01069a).

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Numerical simulation of giant enhancement in high-harmonic generation by xenon

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The high-order harmonics generation (HHG) during the interaction of intense laser pulses with gases is one of the most well-known phenomena of strong-field physics, which is of great interest in terms of numerous applications [1,2]. The physical mechanism of HHG is qualitatively explained in the framework of a three-step scenario [3]. At the first step, atoms or molecules are ionized by an intense field. In the second step, the electric field accelerated the free electrons in the continuum. At the final step, the electrons recombine on the parent ion with the emission of high-energy photons in a wide energy range [3]. In the first and final steps, multielectron effects associated with the motion of many electrons in an atom or molecule can play an important role [4].

A well-known example of the significant influence of multielectron effects at the recombination step is the giant enhancement of the HHG yield in xenon [5]. This phenomenon was associated with the interaction of the most active photoelectron, originating from $5p_0$ orbital, with the internal electrons of an atom. However, although several theoretical studies of this phenomenon have been carried out [5–7], the physical mechanisms underlying HHG enhancement remain partially unexplored.

In this paper, we, for the first time, study the giant enhancement of HHG in xenon based on the time-dependent density-functional theory [4]. We carry out numerical calculations of the HHG spectra, taking into account the dynamics of all subshells on the 4th and 5th shells of the atom. Our analysis of the contributions of various orbitals to the total atomic response shows that the giant enhancement mechanism is following. (1) The $5p_0$ electron recombines into its initial state with energy transfer to one of the photoelectrons in the 4th shell. (2) The latter electron recombines into its initial state with the emission of a high-frequency photon. Moreover, the strong interaction between the electrons on the 4th shell leads to the great influence of $4p$ and $4s$ subshells along with the $4d$ subshell in the giant enhancement of HHG yield.

This work was supported by RFBR (Grants Nos. 18-02-01150 and 20-32-70213).

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Extreme THz field induced bleaching and symmetry breaking in Si

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We studied the interaction of an intense THz pulse with the doped Si exploiting the new regime when the THz field strength is far above the breakdown threshold by the DC electric field.

Firstly, we consider self-induced transparency of a medium under the action of terahertz radiation (or bleaching) that was previously observed in semiconductors irradiated with a THz field of relatively low strength and increase in transmission was of a few percent only. In this work we reported that transmission by energy of the 700 fs THz pulse through n-doped Si sample increases almost two orders of magnitude to $\sim 8\%$ with field strength up to 5-7 MV/cm and then gradually decreases nearly twofold at higher electric fields of 10-20 MV/cm [1,2].

Secondly, we study an extreme few cycle terahertz (THz) pulses action at the p-doped Si wafer in transmission mode. The THz pump - weak infrared probe measurements revealed complex and unusual temporal dependence of the second order optical nonlinearity induced by the THz pulse. This was attributed to: (i) direct delayed transverse acoustic phonons' excitation at the maximal THz field strength of 2-6 MV/cm; (ii) anharmonicity of this process at higher fields leading to chaotic phonons' behaviour and (iii) modulation at the optical field frequency of the THz field induced impact ionization rate due to modulation of the free carriers' drift kinetic energy by the probe field at the THz field strength above 10 MV/cm.

Hence our study opens up new intriguing area of research, where an extreme ultrashort THz pulse changes medium's drastically.

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Laser-induced electron dynamics in graphene nanoflakes

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Similarly to nanoparticles made of noble metals, graphene nanoflakes support plasmonic excitations in the infrared and optical domain. In contrast to gold or silver particles, the optical response of graphene-based plasmonic nanostructures strongly depends on externally tunable parameters and can with that be controlled posterior to the fabrication. Among the parametres with which the response can be tuned are external field intensity, a level of doping, or temperature [1], suggesting a potential of graphene nanoflakes to provide a platform for dynamically tunable light-matter interactions at the nanoscale.

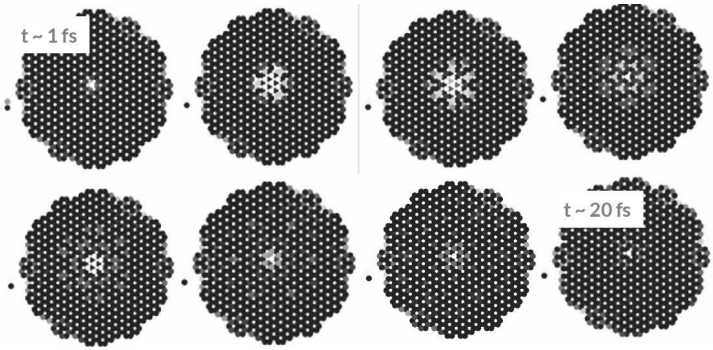

Figure 1: Spread of electron probability distribution, initially peaked at a centrally-located impurity, across a graphene nanoflake: coupling to a large number of carbon sites acts as a dissipation channel for the impurity population.

To account for the optical properties and the dynamics of graphene nanoflakes in presence of external electromagnetic field, we develop a numerical framework combining the quantum-mechanical tight-binding model with the master equation approach. The former allows one for a spectral characterization of the investigated system, while the latter provides access to dynamics of the electrons on the flake, similarly to as it has been proposed in Ref. 2. We additionally exploit the Anderson impurity model [3] and integrate it in the temporal picture. The impurity may represent an atom localized near the flake whose interaction with the electromagnetic field is radically enhanced by the plasmonic graphene nanoflake. The applied model allows one to describe electron exchange between the impurity and selected carbon sites and to study its influence on plasmon-mediated light-matter-coupling characteristics.

We apply the framework to reveal connections between basic quantum-optical models: by tuning the model parameters we study a smooth transition between (1) coherent two-level-system dynamics of a laser-driven impurity weakly coupled to the flake and (2) dissipation dynamics of an impurity connected with a large number of carbon sites. Our results suggest novel possible scenarios for nanoscaled control of light-matter interactions.

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Towards the analysis of attosecond dynamics in complex systems

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The progress in laser technology over the last decades has opened up new avenues for the exploration of properties of clusters and molecules. A laser pulse is characterized by its frequency but also by the laser intensity as well as the laser time profile. The latter can now be tailored up to time scales of the order of magnitude of electronic motion and even below. This allows the follow up of the detail of electronic dynamics at its own "natural" time. We shall focus in this presentation on the recent explorations of electron dynamics down to the attosecond time scale. We shall first present some experimental cases, whose characteristics can be well reproduced by time dependent microscopic theories. We shall then seek for a detailed explanation of observed trends and introduce a schematic model which surprisingly enough provides a remarkable account of experimental trends. It shows in particular that the response of the system is heavily biased by properties of the laser used for exciting and testing the system, especially its IR component. Using the ideas developed in the schematic model we shall reanalyze former computed data and show how much one can attain system's properties.

By recording observables of electron emission we analyze the response of small metal clusters and organic molecules to a pump probe setup using an IR fs laser pulse as pump followed by an attosecond XUV pulse as probe. As observables, we consider total ionization, average kinetic energy from Photo Electron Spectra (PES) and anisotropy parameters from Photo-electron Angular Distributions (PAD). We show that these signals can provide a map of the system's dynamical properties. The connection is especially simple for metal clusters in which the response is dominated by the Mie surface plasmon. The case of organic molecules is more involved due to the considerable spectral fragmentation of the underlying dipole response. But at least the dipole anisotropy from PAD provides a clean and robust signal which can be directly associated to system's properties even reproducing non-linear effects such as the change of spectra with excitation strength.

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Some problems of modeling the laser-induced filaments and optical breakdown

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The problems of self-focusing, generation of filaments [1] and optical breakdown [2, 3] are interconnected phenomena of Nonlinear and Relaxed Optics. According to [2, 3] the chain of this processes may be next: self-focusing, diffraction stratification, optical-induced Cherenkov radiation, interference of Cherenkov radiation and optical breakdown. A threshold of generation of self-focusing may be determined by electromagnetic methods (as rule, for Kerr media [1]) and physical-chemical methods [2, 3]. Physical-chemical method as more universal and may be used for all media (solid, liquid and gases). The diffraction stratification of laser beam in the prpcess of its focusing or self-focusing may be explained with help modified Rayleygh model of diffraction rings [2, 3] and Lugovoy-Prokhorov theory of moving foci [1, 2]. Each diffraction ring is source of Cherenkov radiation. This fact is described with help Golub nonlinear optical macroscopic and modified N. and A. Bohrs microscopic models of Cherenkov radiation [2, 3]. For the modeling the interference of Cherenkov radiation may be used modified I. Frank model [2]. The creation of filaments may be explained as process of self-trapping [1] or optical-breakdown [2]. In second case process of creation laser-induced microfilaments and nanovoids in 4H-SiC may be written with help modified Raylegh model and methods of continuum mechanics [2, 3]. These theories and models may be used for the shock (pure optical) processes of interaction light and matter. In this case we have basically electromagnetic nature of optical breakdown [3].

For more long-duration regimes of irradiation thermal and plasma mechanisms of optical breakdown may be realized [3]. In this case, the distribution of laser-induced second-order continuum radiation has uniform spatial form (star or other) [3]. Corresponding continuum spectra of irradiation may be explained as plasma radiation [3]. But in this case the processes of optical breakdown may be accompanied with processes, which are basic for the more short regimes of irradiation, too [3].

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Instability and quasi-potential electron waves in plasma formed by multiphoton ionization of rare gas atoms

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Exposure on gases by short laser pulses with an energy flux density $10^{12} - 10^{13}$ W/cm^2 leads to multiphoton ionization of atoms. In the case of atom ionization by a laser pulse of linearly polarized radiation, it is formed weakly ionized plasma is formed which has a strongly anisotropic discrete energy distribution of photoelectrons, consisting of a set of individual peaks, each of which corresponds to the absorption of a certain number of photons. In a rarefied gas over a wide time interval, rare electron collisions are not significant and this distribution changes only slightly. Under such conditions, we studied collective electron modes that can excited in plasma with one (the threshold case of multiphoton ionization) or several energy peaks in the distribution of photoelectrons.

It is shown (see also [1]) that in plasma with single energy peak in photoelectron distribution, along with the usual electromagnetic wave, there are two additional modes. In the region of large wavelengths, the higher-frequency mode is similar to the electron Langmuir wave. In the region of short waves, the dispersion law of this mode is close to linear, which corresponds to electronic sound. The group and phase velocities of this wave are close to the average electron velocity. The second mode, which has lower frequency, in the region of wavelengths smaller than the ratio of average electron velocity to the plasma frequency, corresponds to quasi-potential wave. Its dispersion law is also close to the linear one. The damping of both modes is determined by the Cherenkov mechanism of the interaction of waves and electrons, and in the short-wavelength region is relatively small. On the contrary, in the region of large wavelengths, this mode corresponds to aperiodic instability, the maximum growth rate of which is comparable to the plasma frequency. For the wave vectors directed along the anisotropy axis of the photoelectron distribution this instability is similar to two-stream instability. For the wave vectors directed across the anisotropy axis this instability is similar to electromagnetic Weibel instability.

In plasma with photoelectron distribution which has two energy peaks, in addition to the electromagnetic mode four extra modes are possible. In the shortwave region, all four modes correspond to the waves with linear dispersion laws. Two of these modes in the region of relatively long wavelengths are unstable. One of these unstable modes corresponds to quasi-potential wave which amplitude aperiodically increases with time.

The variety of types of electromagnetic modes and the peculiarity of their properties in photoionized plasma formed during the multiphoton ionization of gas atoms is a consequence of the anisotropic multi-peak form of photoelectron distribution.

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Theoretical and semi-empirical approaches for optical properties of solids in wide frequency range

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Ab-initio numerical simulations based on density functional theory and molecular dynamic codes are successfully used presently for calculation of optical properties of matter in wide-frequency range, see, e.g., [1]. Nevertheless, theoretical and semiempirical models of kinetic and transport properties of matter are also of great importance due to their applicability in long-range hydrodynamical simulations and also from the view point of understanding of fundamental physical processes in laser-heated solids.

We present theoretical analysis based on quantum statistical operator and linear response theory approaches [2] and semi-empirical models for high-frequency dynamical conductivity of laser-heated metals in a wide-frequency range, from infrared to X-ray. The role of individual electron-ion and electron-electron [3], as well as collective electron-phonon interactions and Umklapp scattering [4,5], as well as the role of short-range and long-range correlations and peculiarities of interband transitions at high frequencies are discussed.

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Section 3: Ultrafast laser nanofabrication and nanophotonics

Section Chair:

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(ITMO university; Lebedev Physical Institute, Russia)

Mini-workshop "Direct inscription in bulk dielectrics by ultrashort laser pulses" (co-chairs - Nadezhda Bulgakova, HiLASE Centre, Institute of Physics ASCR, Czech Republic; Vladimir Sigaev, Dep. of Glass and Glass-Ceramics, Mendeleev University of Chemical Technology)

Mini-workshop "Ultrafast laser-induced electron dynamics in metals and hot-electron applications" (co-chair - George Tsibidis, IESL FORTH, Greece)

Mini-workshop "Advanced laser ablation and nanoparticle generation in liquids" (co-chairs - Sven Reichenberger, Uni Duisburg-Essen, Essen, Germany; Ekaterina Barmina, General Physics Institute, Moscow, Russia)

Joint workshop "Ultrafast laser nanofabrication, nanophotonics and sensing" (co-chair - Harald Giessen, University of Stuttgart, Germany)

Scope

Direct inscription in bulk dielectrics by laser pulses

Ultrafast laser-induced electron dynamics in metals and hot-electron applications

Advanced laser ablation and nanoparticle generation in liquids

Ultrafast laser nanofabrication, nanophotonics and sensing

Heat dynamics in ruthenium thin films induced by ultrafast laser pulses

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Irradiation of ruthenium (Ru) thin films with femtosecond laser pulses is interesting because of its application as grazing incidence mirrors in XUV and X-ray optical systems[1]. Under sufficiently high fluences, irradiation by pulsed laser can cause melting of the Ru films. The process of melting together with the melting threshold of Ru are not yet extensively explored and understood.

Pump-probe experiments were carried out to measure the transient change of reflectivity of Ru thin films on Si substrate after irradiation with 800 nm femtosecond laser pulses with varying incident fluence. Saturation of the reflectivity change as a function of fluence was considered as an indication that the melting threshold is reached. The samples were rotated to exclude effects related to the accumulation of heat.

The main feature of the ultrafast heat dynamics in Ru thin films is the strong non-equilibrium state when the electronic temperature after laser irradiation is significantly higher than the lattice one. In order to explain the reflectivity behavior in the pump-probe experiment two-temperature modeling was used to calculate the laser-induced relaxation of the electron and ion subsystems in thin films of Ru on Si substrate. Transfer matrix method was used to calculate the absorbed energy profiles. The obtained results are in good agreement with the experiment, including correct values of the melting threshold for Ru films of various thicknesses. The good agreement between simulations and experiment validates the choice of the thermal parameters used to describe Ru in the two-temperature state.

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Machine learning approach for quantum photonic circuits optimization

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Random walks on graphs play an important role in current computational algorithms [1]. Due to interference, quantum walks can be employed as a tool for quantum information processing and quantum algorithms. Recently on-chip integrated photonic circuits are proposed for quantum walks and quantum photonic computing realization operating at a single-photon level [2]. Laser direct writing technology currently represents a tool to obtain on-chip waveguides and Mach-Zehnder interferometers for these purposes. However, low dissipation and decoherence conditions represent solid requirement for large scale photonic chips exploiting. We attack this problem by using a machine learning paradigm that helps to predict a speedup of noisy classical or quantum walks distinguishing them. Our approach is based on training a discriminative classifier, that is, a specially designed convolutional neural network (CNN) [3]. We have generated the training examples, each consisting of an adjacency matrix and a corresponding label ("classical" or "quantum"), by simulating the random walk dynamics of classical and quantum particles. The CNN is able to learn to classify the quantum speedup, and to match the results obtained by our simulations. The CNN was correctly classifying not only previously unseen graphs of the same size, but also of sizes that were never given to train the network. For the line graphs of the same size the average accuracy was shown to be above 90%, and 60%-85% in the case of the larger graph sizes. We found that it is possible to predict the existence of quantum advantage for the entire decoherence parameter range, even for graphs (representing photonic circuits) outside of the training set [4]. We discuss the obtained results in the framework of demonstration of quantum supremacy in experiments with "noisy" quantum photonic chips which may explore various materials for direct laser writing procedure.

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Surface chemistry of colloidal gold nanoparticles generated by laser ablation in liquids

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Laser-generation of gold nanoparticles (NPs) in liquids results in the formation of ligand-free NPs with a tremendous colloidal stability when chaotropic halide anions are added to the solution [1]. The resulting surface charge could be responsible of the electrostatic repulsion impeding their aggregation. However, the surface chemical composition of the laser-generated Au NPs remains a matter of debate [1,2], as well as the origin of the electrostatic repulsion [3]. An experimental investigation of their surface chemistry will be presented based on experiments conducted at SOLEIL synchrotron facility on the PLEIADES beamline. X-ray photoelectron spectroscopy measurements performed on free-standing [4,5] gold NPs will be reported addressing the questions of (i) the oxidation state of the surface gold atoms [6] and (ii) the chemical composition of the first's atomic layers of the NPs. Signatures of halide-ions and possible gold oxidized atoms on the NPs surface have been evidenced, demonstrating that this technique provides a promising new way to study bare gold surfaces and a complementary insight to their colloidal stability.

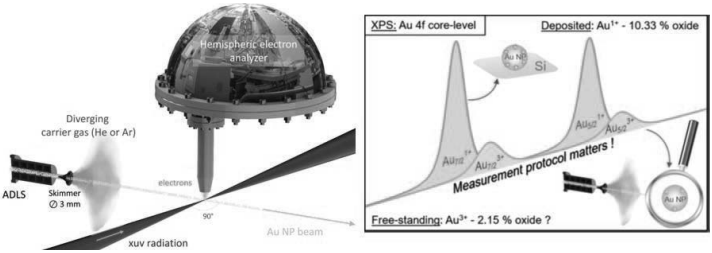

Figure 1: (Left panel) Experimental setup of the XPS measurement of the Au NPs beam generated by means of the aerodynamics lens. (Right panel) Surface oxidation states of the Au NPs as a function of the measurement protocol.

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TiO_2:Au nanocomposite formation under femtosecond laser irradiation

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Different nanocomposite materials based on organic and inorganic matrixes with metallic nanoparticles attract growing attention due to their unique physical, chemical, optical and magnetic properties [1,2]. One of perspective ways to control properties of such materials is laser irradiation, which allows extremely local modification and precise tuning. However, the processes during the interaction of focused laser irradiation with composites can lead to unexpected results or even the material damage.

In this work we study the processes taking place in thin nanocomposite films based on TiO_2 matrix with gold nanoparticles under femtosecond laser irradiation ($\lambda = 515nm$, $\tau = 190fs$, $f = 610kHz$, $F = 42 - 57mJ/cm^2$). Two different regimes were found: (i) the processing with the high scan speed (Vsc=1.6 mm/s) leads to visible change of optical properties, but does not involve the growth of gold nanoparticles (fig. 1a); (ii) after the low speed processing (Vsc=0.16 mm/s) optical properties were also modified, however rapid abrupt nanoparticles growth occurs accompanied with the formation of cavities in the film (fig. 1b).

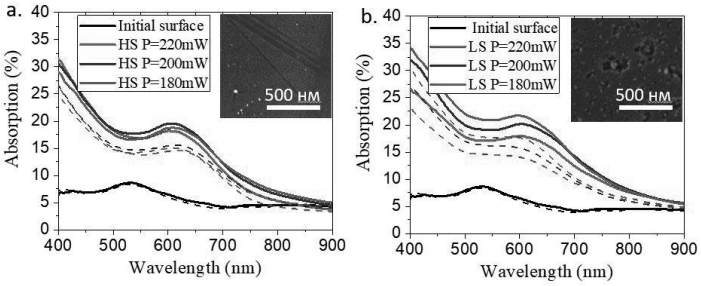

Figure 1: Absorption spectra of the nanocomposite, obtained in different fabrication regimes: (a) high speed mode; (b) low speed mode. Inserts show typical SEM images for such structures (F=47 mJ/cm^2)

To describe these effects the modelling of temperature distribution considering nanoparticle absorption, local field enhancement, photo-induced free carrier

generation, plasmon-assisted electron emission, and thermal heat transfer from nanoparticles towards titania matrix. It was shown that collective heating plays a critical role in nanocomposite formation. We also conclude that spall in solid state [3] is responsible for final matrix degradation if nanoparticles become large enough.The explained results are useful for production of chemosensors, photocatalytic devices and energy sources.

The reported study was funded by RFBR, project number 19-32-90247.

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Modification of Ni/Al multilayer nanostructure with femtosecond laser pulses

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Multilayered structures consisting of alternating nanometer-scale layers of two or more materials have been finding a wide range of applications in many fields of modern engineering and electronics. Over the past few decades, a significant progress has been made in modification of multilayer nanomaterials using femtosecond laser pulses (FLP) [1 - 3]. At the same time, the issues of selective laser processing have not been fully studied due to the difference in the thermodynamic properties of layers, adhesion, strength, etc.

In this work we report on the experimental study of the features of selective modification of the multilayer NiAl structure (layers thickness of 45 nm) using single FLP irradiance. The morphology of craters at different fluence has been investigated by the interferometric and atomic force microscopy. The occurrence of an intermediate spallation within the upper nickel layer has been detected. According to the simulations it is due to the tensile stresses caused by the reflection of the compression wave from the interface of the layers [4]. The results of measurements of the temporal dynamics of the upper layer expansion performed by spectral interferometry with a spatial and temporal resolution are presented.

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Investigation of the effect of Ni nanoparticle concentrations on laser breakdown of aqueous solutions

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The process of laser breakdown of aqueous solutions in the presence of various concentrations of Ni nanoparticles was studied. Known concentrations of Ni nanoparticles obtained by laser ablation in a liquid were added to aqueous solutions and irradiated with Nd:YAG laser radiation ($\lambda = 1064$ nm, $\tau = 10$ ns, $\nu = 10$ Hz, $E_p = 650$ mJ, $J = 65$ J/cm^2). During irradiation, molecular H_2 and O_2, hydrogen peroxide H_2O_2, and short-lived OH radicals were recorded by developed methodics [1]. In addition, acoustic signals of shock waves were recorded, and images of plasma flashes were made. As a result, the dependences of the generation rate of H_2, O_2, H_2O_2, OH, integrated acoustic signals, the number of breakdowns, the average distance between breakdowns, the breakdown brightness, and the total brightness of the plasma flash on the irradiation time and on the concentration of Ni nanoparticles were studied, fig.1. It was found that the dependences of the generation rate of chemical products, acoustic signals, and the total brightness of plasma flashes on the concentration of Ni nanoparticles are correlated with each other.

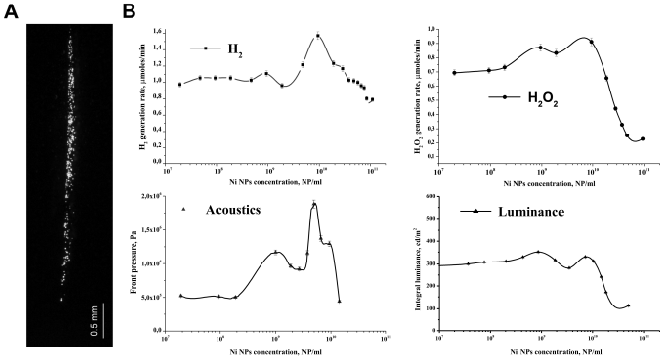

Figure 1: A – Image of laser breakdown plasma during irradiation of an aqueous solution of Ni nanoparticles. B – Effect of Ni nanoparticles concentration on generation rates of H_2, H_2O_2, integral acoustic signals and luminance of breakdown plasma.

The reported study was supported by the Russian Foundation for Basic Research (19-02-00061) and partly by a grant from the President of the Russian Federation (MD-2128.2020.11).

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Ultrafast laser enhanced optical fibres for sensing and metrology

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Optical scattering is usually treated as a negative process that is sought to be avoided in transparent media. However, in certain situations, optical scattering can become a key working principle in the operation of an individual component or the system as a whole. This talk will overview recent progress in exploiting femtosecond laser direct writing for optical scattering related applications.

The ability to modify optical fibers using a femtosecond laser has been well known and used for decades preferentially for Bragg grating inscription. Recently, the use of a femtosecond laser has been proposed to improve the optical response in backscatter-based distributed fiber sensing systems [1]. The issue with the conventional fibre is that Rayleigh scattering distributes light in all directions, whereas useful backscattered signal is confined to a small spatial angle. The purpose of laser irradiation is to locally alter refractive index increasing the portion of the backscattered light. The strength of the signal is enhanced by about 20 dB, while additional losses are smaller than 0.1 dB/km.

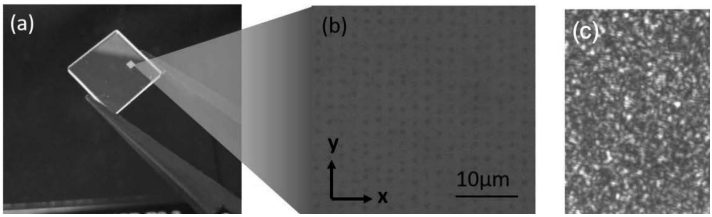

Figure 1: (a) Image of the laser inscribed 1x1 mm scattering chip. (b) Microscope close-up showing geometry of a single layer within the scattering chip. (c) Speckle pattern captured with the CMOS camera.

A compact spectrometric system can also be developed with the help of laser writing [2]. As light propagates through the scattering medium, each spectral component is decomposed into a large number of spatial modes that create a unique interference or speckle pattern. By matching speckle patterns to individual spectral components, the wavelength can be measured even with the accuracy of an attometer. In addition, it ensures the compactness of the system by effectively folding the optical path. A scattering spectrometer can essentially consist of two components: a scattering medium and a digital camera. Scattering centers can be created using micro-explosions induced by a femtosecond laser. A wavemeter implemented as a diffuse medium with 30 scattering layers allowed a 0.2 nm accuracy. The stability of the measurements was evaluated over

a period of 120 hours. The obtained results show that the standard deviation did not exceed 37 pm. The main reason for the deviation is the temperature change in the refractive index that can be compensated.

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Single-shot and multi-shot damage of metals and semiconductors induced by ultrashort laser pulses: Comparison of air and water environments

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Pulsed laser ablation in liquids (PLAL) is an efficient and flexible technique for nanoparticle production and surface nanostructuring. The PLAL technique is simple in realization but involves complicated physical and chemical processes which are still poorly understood. As a result, controllable PLAL fabrication of both colloidal nanoparticles and surface structures is still a challenge. In this work, we have systematically investigated damage effects in metals (gold, titanium) and semiconductors (silicon, germanium) induced by near infrared (1030 nm) ultrashort laser pulses in water. The experiments were carried out with pico- and femtosecond pulses in single-shot and multi-short irradiation regimes and the corresponding damage thresholds were determined. The results are compared with data obtained under identical irradiation conditions in air. The influences of the pulse duration, surface reflectivity, thermosphysical properties of the irradiated materials, focusing conditions, accumulation effects and nonlinear effects during laser pulse propagation in water will be discussed.

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On the perspectives of dual wavelength laser processing of bandgap materials

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Traditionally, monochromatic laser beams are used for material processing, modifications of structural, optical, mechanical, conductive, and thermal properties of different materials, and for designing new nanostructured material systems. So far, there is a limited number of studies, which however indicate considerable enhancement of bi-chromatic laser coupling with material surfaces as compared to single-color pulses. This includes improving the quality of surface nanostructuring [1], enhanced efficiency of nanoparticle production [2], improvement of the LIBS signal [3] and microfabrication of optical structures in hard materials [4].

In this work, we will report on theoretical and experimental studies of excitation of bandgap materials with dual-wavelength ultrashort laser pulses [5]. It will be shown that, by proper choosing the ratio between energies of two laser harmonics, it is possible to strongly enhance the laser energy absorption as compared to single pulses of one of harmonics with the same total energy. Simulation results will be presented on ultrafast laser excitation of fused silica with two laser pulses of different wavelengths in the regimes of volumetric modification, which have revealed the possibility of enhancing and controlling the highly localized absorption of laser energy. Experimental evidence of advantage of bi-color irradiation of silicon by two laser pulses with a variable time delay between them will also be provided.

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Numerical simulations of the polarization-sensitive response in nanospikes array

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The high efficiency of SEPL (surface-enhanced photoluminescence spectroscopy), widely used for the detection of different analytes, is provided by the contribution of electromagnetic and chemical enhancements [1,2]. An enhancement of the electromagnetic field occurs because of the localized surface plasmon resonance, which amplify the field intensity around the structure. In our work we numerically simulate the interaction of laser radiation with the array of gold nanospikes. We use Gaussian beam with a linear polarization and Laguerre-Gaussian beam with radial or azimuthal polarizations. The results are compared with the experiment, and differences in electromagnetic response of the structure are discussed.

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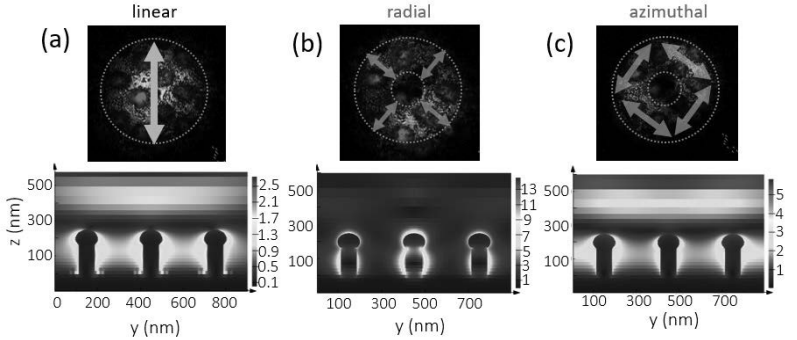

Figure 1: Numerical simulation of electric field distribution for laser radiation with λ=600 nm for different polarizations: linear (a), radial (b) and azimuthal (c). Color scale in $|E|/|E_0|$

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Effect of water-confined environment on nanosecond pulsed laser ablation of metal targets

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Water-confined laser ablation of solid materials is attracting the interest of researchers given changing laser interaction with the target and enhancing mechanical impulse in the solid substrate. In order to study the effect of a water-confined environment on nanosecond pulsed laser ablation of metal targets, Ti6Al4V alloy, AISI304 steel, silicon wafers, and Au-Pd thin film on glass were irradiated by nanosecond pulsed laser underwater and as a comparison, in air. Ablated target surfaces were characterized using scanning electron microscopy, contact rear-side ultrasonics, time-resolved optical emission and transmission of plasma measured by a calibrated fast photodiode and oscilloscope. The results show that for water-confined laser ablation generated mechanical shock waves in water are an order of magnitude stronger than in air and has a lower mass ablation rate. Further, the absorption coefficient of the plasma in water is calculated and compared to the experimental results. It is concluded that the generated plasma in the water-confined regime plays a dominant role in laser ablation efficiency and affects the value of mechanical shock waves and ablated mass.

Plasmon features of flat silver nanoparticle grown by combined laser ablation and LED irradiation in water solutions

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Laser ablation in liquids (LAL) is considered a formidable way to generate metal colloids with a green approach. The generated nanoparticles possess a number of different peculiar features such as the ligand-free and surface clean status. This renders laser generated colloids attractive candidates for many interesting applications in catalysis, biology, sensing, and clean energy generation and storage, even because it is possible to choose the proper liquid environment during the growth [1].

The intrinsic physics and chemistry of plasma evolution during a LAL process always gives spherical-like nanoparticles, thus one of the major limitations of the method is the difficulty to manage the size and shape of the metallic NPs in such a way to have selected plasmonic responses. In this work we demonstrate the "in liquid" formation of flat silver nanoparticles' colloids through a wise use of pulsed laser beams and monochromatic LEDs. As an example, a spherical to flat nanoparticles transformation can be driven and sustained by the addition of H_2O_2 and citrate during the light irradiation [2].

The initial "clean" status of the particle permits to understand better the action of added species with respect to the growth of some crystalline facets, yielding smaller plates with plasmon resonances of the final colloid confined to the visible region, while the use of lower concentrations results in the formation of large plates with resonances in the near infrared. Thus the manipulation of citrate concentration in the solution and the choice of the irradiation wavelength give the possibility to tune the position of the main plasmon resonance across the visible and near IR part of the spectrum. Plasmon sensitivity measurements show that nanoplates irradiated at the longest wavelenghts have the highest response to refractive index change. A number simulations of the plasmon extinction spectra, performed in the frame of the Boundary Element Method [3], support the experimental finding and the plasmon sensitivity towards the environment.

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Ultrafast electron dynamics and energy deposition during femtosecond laser ablation of fluorite

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Currently, there are two main directions in experimental studies of fs-laser photoionization mechanisms in dielectrics: (1) rather indirect measurements of threshold intensities for some distinct modifications (damage, ablation) on surfaces or in bulk for diverse laser wavelengths [2]; (2) dynamic measurements of nonlinear transmission for thin samples or of reflection for bulk samples [3]. Moreover, there is also a hybrid approach of single-shot fs laser ablation of dielectric surfaces, where the focused fs-laser pulse proceeds via nonlinear absorption in the surface layer and induces its ablation at a certain depth for the well-defined threshold local intensity (volume energy density) [4].

In this work, two-crater structure was studied in details on fluorite surfaces photo-excited by tightly focused 515- or 1030-nm, 300-fs laser pulses, were for the first time studied in single-shot surface ablation experiments by acquiring intensity-dependent crater profiles and accompanying self-phase modulation spectral broadening. Based on these results, we explain the different effective squared beam radii as fluence calibration slopes in their relationship to actual energy deposition mechanisms, which are crucial for sub-wavelength ultrashort-laser nanomachining.

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Assessment of the time-dependent density functional theory for investigating femtosecond laser energy absorption by several metals

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Measuring and predicting the absorption of laser energy by crystalline materials is of high interest for improving control in laser processing of solids [1]. Depending on the choice of laser parameters and of material, a wide range of phenomena can affect the absorption dynamics of the intense light [1]. As a result, several kinds of theoretical descriptions are being developed to investigate this problem [2-5], both classical and ab initio. In classical approaches, the models are based on the concept of the electron collisional frequency, thus considering electron and lattice atoms/ions as balls. Ab initio simulations, which are applicable for very short laser pulses due to requirement of high computer resources, enable however to gain an insight into a realistic dynamics of charge redistribution inside a material under the action of the external laser field. For investigating a dynamics of electrons in solids out of equilibrium during laser pulse action, the time-dependent density functional theory (TDDFT) can be efficiently employed both for semiconductors [6,7] and metals [5,8]. In particular, this technique was successfully employed for studying high intensity regimes beyond the Kubo-Greenwood approximation [8].

In this work, the TDDFT [9] was used to investigate the energy absorption of several metallic materials irradiated by ultrashort IR laser pulses. The energy absorbed and the current generated in the laser-irradiated metals were computed as a function of time for a wide range of laser intensities. The simulation results provide insights into the role of the fields induced by the oscillation of charge density in the material bulk and help to better understand the optical response of solids at high intensities, beyond usually employed approximations. A comparison of the obtained results with experimental data, which are available in literature, is provided.

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Dynamics of femtosecond laser-induced modification in nanoporous glass

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Nanoporous high-silica glass (NPG) is a subject of numerous studies due to its unique amorphous structure including elements of sponge-like and corpuscular types at different structural levels and to the favorable combination of significant optical transparency, mechanical and thermal strength and high open porosity [1]. For the first time, the formation of birefringent regions, with a slow axis of the perpendicular polarization of the laser beam, in the NPG volume under the action of ultrafast laser pulses was shown in 2018 [2]. This phenomenon made it possible to propose NPG as a storage medium with multilevel encoding of digital data [3].

NPG of the composition $0.4Na_2O \bullet 1.6B_2O_3 \bullet 98SiO_2$ was used in the performed experiments. The Pharos SP (Light Conversion Ltd.) regenerative amplifier operating at a wavelength of 1030 nm was used as a source of femtosecond laser pulses. The condition of laser exposure were 1 MHz repetition rate, 50 nJ pulse energy, 180 fs pulse duration and 3 pulses/dot. Laser pulses were focused on 30 μm below the glass surface with a microscope objective (NA = 0.65).

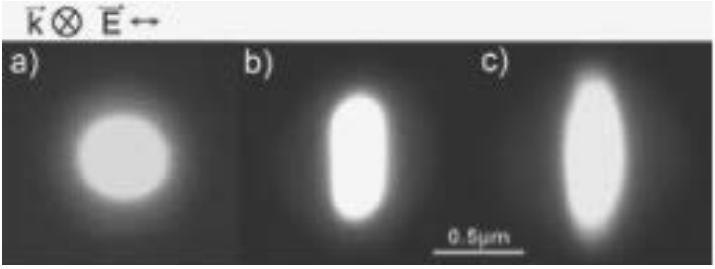

Figure 1: SEM images of top-view areas modified by 1) 1 pulse, b) 2 pulses, c) 3 pulses.

The effect of two or more fs laser pulses on a nanoporous glass induces the appearance of a birefringent structure with a slow axis perpendicular to the plane of polarization of the laser beam. SEM analysis showed that the modified region was a cavity with an elliptical cross-section with a large axis perpendicular to the plane of polarization of the laser beam. A layer of densified non-porous glass around the laser-written cavity. The study of the dynamics of the formation of an elliptical cavity revealed the possibility of controlling the shape of the cavity,

which can be tuned from circle to ellipse depending on the number of pulses (Fig. 1).

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Pulsed laser deposition and photoluminescent properties of Si films

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The work summarizes data from a series silicon film pulsed laser deposition experiment. The experiments were devoted to the research of PLD process of silicon films and study their photoluminescent properties. PLD process was carried out under conditions of adding buffer (He) and reactive (N2) gases. UV KrF laser was used as a source of radiation in PLD. The obtained films were studied by means of Raman scattering, the scanning electron microscopy, and photoluminescence (PL) spectroscopy. Production of silicon nanocrystals with photoluminescent properties is an actual goal, which solving open new opportunities in bioimaging [1].

The authors acknowledge financial support from the Russian Science Foundation (grant No.19-72-30012).

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Nano-, micro-structuring of bimetalic Ti and Al thin films with femtosecond laser pulses

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Results concerning modification of thin bimetallic films, by single femtosecond laser pulses, are presented. Experimental samples, composed of titanium (Ti) and aluminum (Al) bilayers, were deposited a silicon substrate. In our experiment, we used bimetalic Al/Ti and Ti/Al films of different thicknesses. In all cases, the first layer, either Al or Ti, was deposited on Si. The fs laser irradiations of the samples were done with an ytterbium-doped fiber laser (λ = 515 nm, τ = 300 fs) in the air. After the irradiations, the samples were analyzed by optical microscopy, scanning electron microscopy (SEM), X-Ray technique and profilometry.

Fs laser irradiation of metals is known to proceed via multiple stages as 1) absorption of photon energy including photo excitation of electrons, 2) energy transfer from electrons to the lattice, 3) melting and thermal expansion, 4) ablation and in some cases lift-off a surface layer - spallation, and 5) thermal relaxation [1,2]. The cases 1 and 2 highly depend on the specific metal zone structure and are the most important at low laser fluences [3,4]. Registered modifications revealed nano- and micro-structuring of the thin films surface. Different morphology depends on the pulse energy and on which metal was on the surface of the bimetallic film-aluminum or titanium that having simple and complex spectral zone, respectively. Consequently, fs laser irradiation induces different electronic dynamics, the most important for ablation at low pulse energy. In addition, damage threshold fluence, was calculated according to SEM images for the all samples.

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Terahertz optical components fabrication using femtosecond laser recording technique

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In spite of the rapid development of THz optoelectronics, its capabilities is largely limited due to lack of an effective element base of THz optics and, in particular, the lack of commercially available lenses, axicons, diffraction elements, etc. The main reason is primarily related to the limited range of THz optics materials with low losses and dispersion in comparison to visible and IR optics. Despite obvious advantages of materials such as high-resistance silicon, sapphire, various polymers, etc. [1-4], their production is complex, time-consuming and expensive. To date, THz elements are produced only on a scope of laboratories and are far from mass production. Thus, the research and development of new technologies for creating various elements of THz optics is a very relevant task of modern physics.

In this regard, many researchers are trying to find new materials, to develop obtaining and processing techniques. Among them are metamaterials in semiconductors [5], flat porous optical elements [6] etc. Meanwhile, the technology of direct laser recording of volumetric functional nano- and microstructures is known. It is implemented mostly on the basis of silicate materials that compact under ultrashort laser pulses induced by point oxygen defects (waveguides), get self-organized (volumetric nanolattices, birefringence), or the migration of impurity ions, which leads to the creation of various voids. As can be seen from [6], the creation of such planar elements is based on the superlens effect.

This paper presents a simple and effective method for obtaining voids in quartz glass based on femtosecond laser recording.

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Topological plasmonics: Watching the vector dynamics of plasmonic skyrmions on a nm length and fs time scale

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Plasmonic skyrmions are topological defects in the electromagnetic near-field on thin metal films, recently observed using scanning near-field optical microscopy [1-2]. However, only one spatial component of the electric field was measured and one of the most intriguing features of skyrmions, namely their dynamics, was not assessed. Using time-resolved PEEM, the intensity of the plasmonic electric field could be mapped with high spatial and temporal resolution [3-5]. However, the vector information until now had been lost.

Here we introduce a new technique, namely time-resolved vector microscopy, that enables us to compose entire movies on a sub-femtosecond time scale and a 10 nm spatial scale of the electric field vectors of surface plasmon polaritons [6]. Specifically, we image complete time sequences of propagating surface plasmons as well as plasmonic skyrmions on atomically flat single crystalline gold films that have been patterned using gold ion beam lithography.

This allows us to unambiguously resolve all vector components of the electric field as well as their time dynamics, enabling the retrieval of the experimental time-dependent skyrmion number, and indicating the periodic transformation from skyrmion number +1 to -1 and back on a few femtosecond timescale.

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Broadening the spectrum of precision femtosecond laser processing

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High-peak power compact femtosecond lasers allow strong-field interactions that are the basis for high-precision laser processing. However, a relatively narrow region of the spectrum remains exploited today in this field. In this work, we study femtosecond laser interactions in various bandgap materials at non-conventional driving wavelengths from the deep-ultraviolet to the mid-infrared part of the spectrum.

We present a complete study, together with a careful experimental metrology, on single shot ablation of fused silica, sapphire and other dielectrics induced by femtosecond pulses ($<$ 200–fs) ranging from 258 nm to 3500 nm. The determination of the wavelength- dependent fluence ablation thresholds with systematic measurements of ablated crater diameters and depths allow to discuss the effect of drastically changing nonlinear ionization responses on the ablation outcome. It serves also to fully evaluate the potential of the wavelength as control parameter to improve machining performances, including throughput, resolution and precision.

In particular, the range of nonlinear responses accessible by radiation tuning allows to revisit questions as important as the achievable resolution in laser machining technologies. From our data set, we establish that the concept of nonlinear resolution is not applicable for femtosecond laser ablation [1]. Independently of the nonlinearity of interaction, we find a systematic one-to-one mapping between femtosecond laser ablation features in dielectrics and beam contours at a strict threshold-intensity. This is because any observable based on a threshold-based response (as ablation) simply ruins all potential benefits that could be expected on resolution from the nonlinear confinement of absorption. A direct consequence is that the use of extreme UV, as in lithography, should not be overlooked for super-resolution applications because the same optical limits finally apply.

Another important consequence is that the achievable precision and repeatability can be directly derived from the level of determinism of the interaction. By comparing the results of a simple 'noise' model and statistical analyses of ablation experiments, we quantify the degradation of the level of determinism with increased pulse duration [2]. In this way, we derive and access the determinism and precision limits in laser machining. This allows to discuss potential directions to meet the remaining challenges for a reliable laser nano-machining technology.

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Space-time domain solutions for direct inscription in bulk silicon with ultrafast lasers

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High-peak power femtosecond lasers allow strong-field interactions that are the basis for three-dimension (3D) laser writing in transparent materials. However, a relatively narrow region of the spectrum remains today exploited in this field. In this work, we study interactions using long-wavelength laser pulses. These open new and exciting opportunities to tailor in the 3D some semiconductors inside which breakdown regimes were inaccessible until recent demonstrations.

Our first proposed solution to achieve permanent modifications in the bulk of silicon with sub-100-fs pulses was to rely on hyper-focused beams [1]. With this space-domain optimization, we circumvent the strong detrimental propagation nonlinearities in the pre- focal region that prevent enough energy localization for permanent modification with the conventional configurations used for 3D writing in dielectrics.

For more practical alternatives, we rely today on optimizations in the time domain. We investigate the picosecond regime limiting the nonlinearities and provoking progressive thermal band gap closure to assist pulse energy deposition [2,3]. We also perform multi- pulse irradiation experiments where femtosecond, picosecond and nanosecond pulses are synchronized. We identify by appropriate pulse combinations breakdown channels seeded by pre-ionization or local thermal pre-stimulation [4]. Another approach is to rely on transient accumulation strategies. To this aim, we generate and apply ultrafast trains of pulses at the highest achievable repetition-rates (up to THz) [5]. Taken these approaches together, we introduce unique multi-timescale control parameters exploited for improved energy deposition and for demonstrations of reliable 3D laser writing deep inside silicon chips that would not be possible otherwise.

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Time-resolved ablation dynamics of indium tin oxide

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Indium tin oxide (ITO) is commonly used a transparent electrode for various applications such as touch displays, LEDs, or solar cells. Selective removal of material is a necessary process step for many ITO applications that stands to be optimized by ultrafast laser ablation. Ablation threshold fluences for ITO thin films on glass substrates have been observed at an order of magnitude less than the ablation threshold for glass substrates, providing the desired selectivity for industrial processing. At a normal angle of incidence, ITO films displays an ablation threshold of approximately 0.3 J/cm^2 whereas glass substrates of float glass or quartz display thresholds of approximately 3 or 4 J/cm^2, respectively, for a pulse duration of 525 fs at a wavelength of 1056 nm.

A better understanding of the exact ablation mechanisms is required in order to optimize process parameters and avoid unwanted effects such as ridge formation. Pump-probe microscopy may be used to observe the physical phenomena that occur during the ablation process and allows for a specific determination of the driving mechanism of the ablation, whether it be a direct ablation process or resulting from a confined energy situation. Previous work has shown that ultrafast changes to the material that cause a confined energy situation or direct ablation process may be observed through pump-probe microscopy [1][2]. Laser parameters such as pulse duration, wavelength, focus radius, or fluence, may be methodically varied in order change the driving mechanism of the thin-film ablation.

The ablation dynamics of thin film ITO on glass substrates were investigated using pump-probe microscopy from femtosecond to microsecond time-scales. The change in reflectivity at the ITO surface was measured for several fluences both above and below the ablation threshold. The resulting crater morphology was thereafter examined. Spectrally resolved transmittance and reflectance measurements were carried out at low intensities to calculate the steady-state refractive index of the ITO. The strong nonlinearities inherent to ITO and its implications on the ablation dynamics of the thin-film system are considered. The prospects of micromachining for industrially-relevant applications are discussed.

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Nanostructured glasses and gelatins using a combination of the PLD and Sol-Gel techniques in the nanosecond and femtosecond regimes

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In this work we report on the synthesis of nanostructured glasses and gelatins by simple method that combines the pulsed laser ablation method (PLD) and the Sol-Gel techniques [1]. Two different laser sources operating in different regimes are used for this purpose. The first one produces pulses in the nanosecond scale using a Nd:YAG laser emitting at 532 nm, with an energy of 100 mJ focussed in a 2mm diameter laser spot. For the second one a mode-locked Ti:Sapphire laser (Vitara-T from Coherent) coupled to a regenerative amplifier (modified Legend-Elite-DUO, Coherent) was used; with this system produces pulses of 80 fs, 800 nm and 4.5 mJ at a 1 kHz repetition rate are produced. Metal nanoparticles (Np's) are generated by PLD using the corresponding target (Au, Ag, Bi). For the synthesis of glasses the target is immersed in a transparent solution made with tetraetilorthosilicate (TEOS) and water adding chloridric acid as a catalyzer. The solution was prepared before the ablation process. For the gelatins commercial transparent grenetin was employed. The ablation time was varied from 1 min to 10 min depending on the target. The Np's were uniformly dispersed in the solution. After the ablation process the gels were sealed and stored at room temperature for 24 hours and afterwards thermally treated at 3000C for 3 hours. The gelatins were stored in the refrigerator for a few hours in order to The samples were characterized by HRTEM, UV-Vis, and Raman spectroscopy.

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Laser ablation: ejecta, shocks, and structures

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Laser ablation through liquid or gas is an important process that have to be studied for applications which use laser ablation in liquid (LAL) [1] and laser shock peening (LSP) [2]. LAL is employed for production of suspensions of nanoparticles (NP), while LSP is applied to increase hardness and fatique/corrosion resistance properties of a surface layer. A bubble appears in liquid around the laser spot focused at a target surface after strong enough laser pulse. In the paper we connect the early quasi-plane heated layer created by a pulse in liquid and the bubble forming at much later stages. In the previous works these early stage from one side and the late stage from another side existed mainly as independent entities. At least, quantitative links between them were unknown.

We consider how the quasiplane heated layer of liquid forms thank to thermal conduction, how gradually conduction becomes weaker, and how the heated layer of liquid nearly adiabatically expands to few orders of magnitude in volume during the drop of pressure. Our molecular dynamics simulations show that the heated layer is filled by the diffusive atomic metalliquid mixture. Metal atoms began to condense into NPs when they meet cold liquid outside the edge of mixing zone. This process limits diffusive expansion of metal atoms, because the diffusivity of NP is less than that of individual atoms. Thus the mixture expands together with hot liquid, and the NPs approximately homogeneously fill an interior of bubble.

Femtosecond (fs) laser exposure has recently been used to increase strength of materials (fs LSP). Increase of strength is achieved through plastic transformations behind the front of a sufficiently strong laser shock wave (SW). Plastic transformations evolve in time to residual stresses and deformations. There is a threshold $p_{thr}|_{el-pl} \sim 1$ GPa of elasto-plastic transformations in terms of ultrashort shock wave amplitude. Below the threshold, plastic transformations cease. The article analyzes the factors that determine the attenuation of a shock wave during its propagation in a target. Thus thickness of the region covered by plastic transformation is estimated.

Nanosecond (ns) lasers are used for LSP for many years. A water layer is used to increase momentum transferred into target by a ns pulse. Thus in this

sense the LSP is similar to LAL. There are many experimental papers devoted to ns LSP, but a whole physical picture which includes descriptions of a ejecta in liquid and all stages of shock evolution in a target was absent. In the paper we will consider all aspects of laser-matter interaction in case of ns LSP down to 3D decay of a shock deep inside a target.

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Laser-induced nanocomposite and nanostructure formation: mechanisms and control possibilities

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Glass-metal nanocomposites containing nanoparticles have attracted a great attention due to their unique properties. However, both fabrication and a control of the nanoparticle growth remain challenging. Herein, we demonstrate that the use of a carefully chosen laser radiation provides not only unique possibilities of the fabrication of such materials, but also of a reliable control over their optical properties. As a result, a wide range of applications become possible in the fields of photonics, optoelectronics, security and catalysis.

In this study, we use mesoporous thin film containing of small (d<5nm) metallic (Au, Ag) nanoparticles and several laser sources ranging from continuous wave to femtosecond lasers. The performed multi-physical modeling demonstrates that, depending on target composition and laser parameters, an interplay of nanoparticle growth and decay sets in different ways for low and high laser scanning speeds. The involved phenomena are related to the temperature increase strongly depending on the nanoparticle size distribution. In particular, the presence of several nanoparticle populations and of the collective thermos-plasmonic effects are demonstrated to be crucial in the definition of the final nanoparticle distributions [1,2].

Additionally, based both on the experimental results and on the developed numerical modeling, we could efficiently control over the optical properties of the produced nanocomposite materials. Thus, the results of this work provide not only a better understanding of the nanocomposite formation mechanisms, but also ways of further development of such technologies for numerous industrial applications.

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Modeling of laser-assisted generation of nNanoparticles in iquids for bio-medical applications

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In this work we investigate the mechanism of nanoparticles (NPs) generation due to laser ablation of metals in liquid medium with numerical atomistic-continuum model. The mode is capable of addressing the mechanisms of non-equilibrium laser-induced phase transition processes at atomic level with Molecular Dynamics (MD) approach, whereas the effect of free electrons, playing a determinant role during short laser pulse ablation, is described in continuum with Two Temperature Model (TTM). Such the combined MD-TTM model [1] was utilized in a super large scale modeling of the process of Au and Al NPs generation in water. The obtained NPs are then characterized from the point of their size distribution and morphology [2]. These characteristics were studied as functions of the laser irradiation parameters (pulse duration and fluence), the ablated materials (Al and Au), and their porosity in the presurface region (in the case multipulse regime). The performed simulations enable a direct comparison of the modeling results with the experimental data [3] and allow for manipulations with the laser irradiation parameters for generation of the NPs with predesigned properties, demanded by Bio-medical applications.

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Ultrashort laser-ablative synthesis of functional nanomaterials for biomedical applications

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The presentation will overview our on-going activities on laser ablative synthesis of novel biocompatible colloidal nanomaterials and their testing in biomedical tasks. Our original approach is based on ultra-short (fs) laser ablation from a solid target or already formed colloids to fabricate "bare" (ligand-free) nanoparticles (NPs) with well-controlled size characteristics, as well as coating of nanomaterials by functional molecules (dextran, PEG etc.) during the ablation process or afterwards. The presentation will describe different approaches to achieve appropriate characteristics of plasmonic (Au, TiN), semiconductor (Si-based structures) and polymer dye nanomaterials and overview their biomedical applications. In particular, by performing in vitro and in vivo tests we concluded on safety of Au [1], TiN [2] and Si [3] NPs. We also found that bare Au NPs can provide unique opportunities as SERS probes for identification of biological species [4], as well as serve as electro-catalysts of glucose oxidation in biofuel cells [5]. We also revealed a strong photothermal effect under the use of TiN and Si TiN NPs and applied this effect in tasks of cancer hyperthermia [2,6]. We finally overview applications of Si NPs, which exhibit biocompatibility and biodegradability options [7]. In particular, we show that laser-synthesized NPs can be used as efficient markers in tasks of linear and non-linear optical bioimaging [8]. In addition, these NPs can be used in mild cancer therapies, e.g. as sensitizers of radiofrequency radiation-based hyperthermia [9] and safe carriers of therapeutic radionuclides in nuclear nanomedicine tasks [10].

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Laser ablation of a multilayer target with layers of nanometer thickness

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Multilayer products made of ultra-thin layers are widely used in modern science and technology. Laser exposure is used as one of the promising methods of processing such products. In this regard, we study the ablation of a layered target. A physical model is constructed, numerical simulation is performed, and experiments are carried out.

We study a layered target composed of alternating layers of nickel and aluminum. Nickel is the first layer on which the laser beam is incident. In the calculations, the first pair of layers has a thickness of 45 nm, then five pairs of thin layers with a thickness of 25 nm and a thick nickel layer with a thickness of 160 nm instead of a substrate. In the experiment there are more thin layers. The layers are sprayed onto a silicon glass substrate.

The experiments were conducted with two different lasers and various diameters of the focal spot. To estimate the absorbed energy the reflection coefficient was measured. The results of calculations and experiments are consistent with an accuracy of about 10%. This allowed us to refine the model of two-temperature states and determine the strength of nickel. It is explained why, with an increase in the absorbed fluence, first the upper layer breaks in the multilayer.

Surface and phase modifications induced by femtosecond laser pulses in multilayer amorphous $Ge_2Sb_2Te_5$ thin films

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In the present work amorphous GST225 thin films with thickness 100 nm on a W(140 nm)/TiN(30 nm)/SiO_2(1 μm)/Si(substrate) multilayer structure were fabricated via DC magnetron sputtering and were irradiated by femtosecond laser pulses (λ=1250 nm, ν=10 Hz, τ=125 fs, J=0.14-1.17 J/cm^2) after.

Ellipsometry measurements showed that the values of reflection and absorption coefficients at the irradiation wavelength are R=0.39 and $\alpha = 24500\text{cm}-1$, respectively. These parameters are appropriate to effective LIPSS fabrication [3]. Raman spectroscopy revealed amorphous structure of initial samples, as well as partial crystallization of irradiated regions. Scanning electron microscopy (SEM) and atomic force microscopy (AFM) analysis revealed formation of one-dimensional lattices oriented orthogonally to the polarization vector of modifying laser radiation. After irradiation at the fluence $J = 0.14\text{J/cm2}$ ripples with the period $\Lambda_1 = 1.17 \pm 0.02$ μ m and the depth H_1=10-20 nm are observed. In turn, the laser pulses with the higher fluence $J = 1.17\text{J/cm}^2$ induce formation of LIPPS with the period $\Lambda_2 = 0.91 \pm 0.02$ μ m and the depth H_2=100-200 nm. Estimated induced non-equilibrium charge carrier concentrations during initial stage of irradiation are $N_1 = 6 \cdot 10^{21}$ cm^{-3} and $N_2 = 2.8 \cdot 1021\text{cm}^{-3}$ and are in accordance with a hypothesis about LIPPS formation on account of interference of a laser beam and photoinduced surface plasmon-polaritons [3].

The obtained results enhance the understanding of the surface and phase modification mechanisms in amorphous GST225 thin films under femtosecond pulsed laser treatment and seem useful for new device design for data-storage applications and polarization optics.

DC magnetron deposition of amorphous GST225 thin films and ellipsometric measurements were supported by RFBR project N 20-03-00379 and were performed using equipment of Core facilities center "MEMS and electronic components" and "STI Sensory" of MIET. Experiments on femtosecond laser treatment, as well as SEM, AFM and Raman spectroscopy investigations were supported by the program of Competence Center of the National Technology Initiative "Big Data Storage and Analysis Center" according to the contract of Ministry of Science and Higher Education of RF No 7/1251/2019 on 15.08.2019 between Lomonosov MSU and Russian Venture Company.

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Laser-induced structural changes in chalcogenides: the role of electronic excitation

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Chalcogenide semiconductors represent a large group of functional materials, which include chalcogenide glasses, phase-change alloys [1] and transition-metal dichalcogenides [2]. Among their various useful properties in their ability to change the structure in a reversible way under the action of external stimuli, such as light. In this talk we cover laser-induced phenomena in chalcogenide glasses (reversible photosructural change and photo-induced anisotropy), phase-change alloys (reversible crystallisation-amorphisation) and transition-metal dichalcogenides (semiconductor-metal transitions [3,4]).

The three classes of materials are characterised by different electronic structure of chalcogen species (lone-pair electrons in chalcogenide glasses, resonant bonding in phase-change alloys, and bonding that involve *d*-electrons in transition metal dichalcogenides). The effect of different bonding nature on structural response to electronic excitation will be discussed based on experiments and ab-initio simulations [5].

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Hierarchical surface microstructures made using ytterbium fiber laser

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This paper presents the production of hierarchical surface structures on a copper foil substrate coated with a polyvinyl chloride (PVC) film using an ytterbium fiber laser (1064 nm wavelength, 100 NS pulse duration). The resulting surface structures were studied using optical microscopy and scanning electron microscopy. The optical properties of the surface after laser irradiation was determined by the method of IR spectroscopy of attenuated total internal reflection (ATR). Wettability was assessed by the lying drop method. The threshold value of the energy density required for complete removal of the polymer from the substrate was determined. It is shown that an increase in the energy density of laser radiation leads to superhydrophilicity of the surface. The results allow us to produce gradient structures for such operations as sample preparation, transport, mixing, separation, detection, dosing, etc. [1-2].

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Femtosecond-laser lithography on halide perovskite thin films for advanced nanophotonic applications

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Light-emitting active nanophotonics based on resonant nanostructures and metasurfaces made of semiconductors have become an active direction for creation of multifuctional designs for light manipulation at subwavelength scale via structural coloration, photoluminescence, and lasing. At the same time, halide perovskites are a prospective class of light-emitting materials providing optical contrast that is high enough to support resonances in broad spectral range. Although perovskites allow for their low cost synthesis and subsequent thin films deposition, their nanostructuring is limited to their sensitivity to various chemicals. We demonstrate a novel concept for 3D micropatterning of perovskite films via direct femtosecond laser projection lithography. Whereas the majority of previous works used laser processing only for rough cutting/scribing of perovskite materials at microscale level, here by using advanced laser beam engineering and delicate multi-pulse processing we showed the capability of flexible non-destructive 3D processing of perovskites at sub-diffraction resolution down to 250 nm. The elaborated optimized laser processing regime allowed to control 3D surface morphology preserving optoelectronic properties of the irradiated perovskite material, thus opening a pathway for high-performing inexpensive and large-scale fabrication of nanostructures and surface textures suitable for advanced light-emitting, surface coloring, and information encryption applications [1,2].

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Pulse-width dependent spatiotemporal nanostructuring in bulk dielectrics by ultrashort laser pulses

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Moderately short (picosecond-range) laser pulses were shown to be more advantageous in some ultrashort-pulse laser processing in dielectrics [1,2]. Meanwhile, the underlying fundamental physics is still far from to be well understood.

In our studies, we demonstrated that pulse variation from 0.3 till 12 picoseconds during direct 515-nm and 1030-nm laser writing of birefringent nanograting arrays inside fluorite slabs has optimal pulsewidth for maximal retardance per irradiated spot of 15-micron (half-width) thickness. At both these laser wavelengths, the optimum comes as the trade-off between the pulsewidth-decreasing laser intensity and the increasing interference region of incident and reflected (backward) waves, making a light standing wave with the following formation of nanogratings.

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Analysis of filamentation effect in liquids during ablative pulse-width dependent laser generation of colloidal nanoparticles

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Laser generation of colloidal nanoparticles in liquids has matured as a high-throughput, semi-industrial, eco-green technology, providing nanophotonic building blocks, key-enabling nanoagents for biomedicine, components of advanced nanomaterials. Meanwhile, novel opportunities to increase throughput and range of colloidal nanoparticles in liquids through elaborate laser technologies are still in need.

In our studies, we performed single-shot-per-spot laser ablation of bulk gold and silicon in water and carbon disulfide at different pulsewidths (0.3-12 ps) of 1030-nm laser pulses in water, analyzing UV-NIR spectrally characterized optical density of colloidal solutions and ablation rate per pulse. Our results indicate the dramatic increase of ablation rate and nanoparticle yield versus laser pulsewidth occurs for supercritical peak laser powers, saturating for subcritical peak powers. Analytical expression was developed to quantify the laser pulsewidth effect in terms of ablation rate and ablative yield of nanoparticles.

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Direct laser writing of depressed-cladding waveguides in ultra-low expansion glass-ceramics

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Transparent glass-ceramics with an ultra-low coefficient of thermal expansion (CTE) based on precipitation of nanosized crystals with negative CTE such as spodumene or β-eucryptite-like solid solutions in lithium aluminosilicate glass is widely applied in engineering from telescope mirrors and ring laser gyroscopes to household appliances. Recent progress in ultrafast laser-induced micromodification of transparent dielectrics increases the topicality of the investigation of direct laser writing of channel waveguides and other integrated optical components inside materials with ultralow or near-zero CTE. However, very few experiments on the laser-induced modification of ultralow thermal expansion glass-ceramics including commercial Zerodur and Robax glass-ceramics have been reported so far and mainly qualitative evaluation of the induced effects has been performed [1]. Recently, we have studied ultrashort laser pulse-induced effects in Sb-doped lithium aluminosilicate glass-ceramics with near-zero CTE and have shown noticeable negative refractive index change up to -0.002 due to partial amorphization of the glass-ceramics [2]. This result opens an opportunity for direct ultrafast laser writing of depressed-classing waveguides in the glass-ceramics under study.

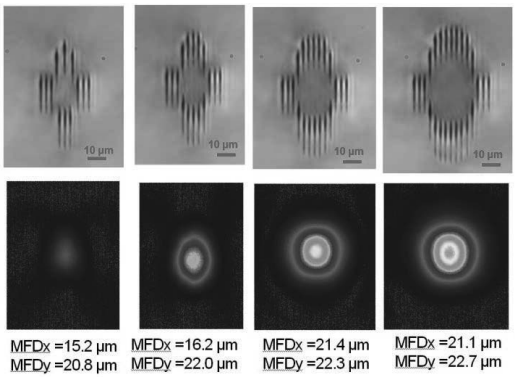

Figure 1: Cross-sections of the laser-written channel waveguides (top row) and corresponding pseudocolour images of the near-field mode intensity profiles (bottom row); d is for the calculated core diameter, MFDx, MFDy are for horizontal and vertical mode field diameters, respectively.

The depressed cladding waveguides with different geometries (Fig. 1) were fabricated by direct laser writing of the cladding as a set of parallel tracks at the pulse energy of 200 nJ, the pulse repetition rate of 10 kHz and scanning speed of 200 μm/s. Dependence of the propagating mode profile on the waveguide diameter was examined. The minimal propagation losses for the waveguides were estimated as low as $\sim$ 4 dB/cm at 1030 nm wavelength. The further optimization of the writing conditions is expected to improve the performance of the waveguides.

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Direct femtosecond laser writing of crystalline waveguides inside oxide glasses

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Femtosecond laser-induced crystallization of glass provides precipitation of microcrystals with high spatial resolution and opens the opportunity for the direct laser writing of crystalline waveguides in the inside of glass. It is considered to be promising method to fabricate 3D integrated optical circuits, microlasers and new photonics architectures based on space-selective precipitation of functional crystalline phases, possessing second-order optical nonlinearity, significant electrooptical properties, enhanced luminescence efficiency ets.

However, the way from crystallized tracks in the inside of glass to crystal-in-glass channel waveguides with nearly single-crystal, highly oriented structure requires accurate selection of glass-forming system and glass composition and coping with fundamental problems of the growth of homogeneous, smooth, and continuous tracks. At the moment, femtosecond laser-written crystal-in-glass waveguides with evaluated propagation losses were reported only for lanthanum borogermanate glass in which a ferroelectric $LaBGeO_5$ phase can be precipitated [1,2]. Here, we describe direct laser writing of β-BaB_2O_4 crystal waveguides in $47{,}5BaO$-$5Al_2O_3$-$47{,}5B_2O_3$ glass. β-BaB_2O_4 crystals have significant second-order optical nonlinearity and have excellent optical transparency in the visible and near-IR ranges. The waveguiding properties of extended crystal tracks of β-BaB_2O_4 were evaluated. In comparison with lanthanum borogermanate glass, the writing of crystal waveguides in barium aluminoborate glass can be performed at significantly lower pulse energy and higher scanning speed of the laser beam.

A major problem of performance of the crystalline waveguides written in the inside of glass by the Gaussian femtosecond laser beam is their strongly elongated, asymmetrical cross-section, often horseshoe-shaped or split into two parts (so-called bilateral growth), which is determined by the shape of the temperature distribution around the beam waist and can be further aggravated by the aberration of the focused laser beam increasing with the focusing depth under the glass surface. Successful correction of this aberration by the spatial modulation of the wave front profile with the spatial light modulator reducing the elongation of the crystallized track cross-section was reported earlier [1]. Here, various opportunities to control and further improve the shape of the cross-section of the laser-written tracks are described. By example of $LaBGeO_5$ crystalline track laser-written in lanthanum borogermanate track, we have shown that careful exposure to the femtosecond beam moving along the helical or sinusoidal path

along the crystal-in-glass track enables its partial amorphization, thus forming a track with a smaller, nearly circular cross-section. Another opportunity is using the optical vortex beam for growth of crystalline tracks inside glass. The Laguerr-Gaussian beam formed by LG_{01} mode induces the smoother temperature distribution near the focal region than the Gaussian beam. At appropriate laser beam parameters, smaller temperature gradients avoid the effect of the bilateral growth and form a single crystalline track with the oblong cross-section having the better aspect ratio.

The study was financially supported by the Ministry of Science and Higher Education of Russia, FSSM-2020-2003.

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Nanoantennas for light harvesting and ultrafast energy conversion

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Metallic and dielectric nanostructures provide distinct and unique means for shaping the electromagnetic near field, and for channelling radiation from the far field to the nanoscale. The associated electromagnetic field hot spots can be exploited for the enhancement of interactions between light and matter, most prominently for surface-enhanced spectroscopy and sensing, the boosting of non-linear interactions, and also for nanoscale spatial control over chemical reactions.

In my lecture I will approach plasmonic and dielectric nanoantennas from the viewpoint of being a means for ultrafast energy conversion at the nanoscale. With example materials systems such as gold and silver (plasmonic), gallium phosphide (dielectric), and silicon carbide (polar dielectric), I will highlight applications such as non-linear optics, photon-phonon interactions for the launching of acoustic surface waves, and the plasmon-assisted triggering of redox reactions.

Laser ablation for nanophotonics based on halide perovskites

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Recently, the study of halide perovskites has attracted enormous attention due to their exceptional optical and electrical properties. As a result, this family of materials can provide a prospective platform for modern nanophotonics and meta-optics, allowing us to overcome many obstacles associated with the use of conventional semiconductor materials. Namely, the perovskites provide simple and cheap wet-chemistry methods of nanofabrication, high quantum yield and pronounced excitonic properties at room temperature, broadband and reversible spectral tunability, high defect tolerance, high enough refractive index for light confinement at subwavelength scale, as well as flexibility regarding integration with various nanophotonics designs.

Here, we review the recent progress on laser ablation for application in halide perovskite nanophotonics starting from single-particle light-emitting nanoantennas [1,2] and nano/micro-lasers [3,4] to the large-scale designs working for surface coloration, anti-reflection, optical information encoding [4], and enhanced solar energy harvesting [5].

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Thermo-optical effects in spherical microresonators based on different glasses

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Microresonators with whispering gallery modes (WGMs) can be used for optical frequency comb generation and are demanded in various applications including optical filtering and switching, remote diagnostics, spectroscopy, precision metrology, telecommunications, etc [1]. Thermal nonlinearity is known to play a huge role in microresonators, which can lead to dramatic changes in nonlinear dynamics of the systems and can be used for controlling comb parameters [1]. A lot of attention is paid to the study of thermal nonlinearity, but, as a rule, as applied to silica microresonators. Here we contribute to the study of thermo-optical effects in spherical microresonators based on different types of glasses, which are promising due to their large Kerr nonlinearity and wide range of transparency in the near- and mid-IR.

To simulate thermo-induced shift of WGMs under laser pumping at 1.55 μm, we developed a theoretical model which takes into account uneven heat distribution over the microsphere caused by small WGMs' effective mode volume and overall experimental geometry. Temperature distribution calculated by the finite element method was used in characteristics equations for eigenfrequencies through thermal expansion and thermooptic effects. Silica, tellurite (TeO_2-WO_3-La_2O_3) [2] and chalcogenide (As_2S_3) glass-based microspheres of different radii were studied for various parameters. It was found that for silica and tellurite spherical microresonators calculated thermal frequency shifts are approximately similar for the studied model parameters, while for chalcogenide-based microspheres the shifts are significantly larger than for the two other glasses. Attained theoretical results are in a good agreement with experimental ones [2].

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Research of proton transfer photodynamics in tetrahydroacridin-1(2H)'s derivatives

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The charge transfer reaction (proton and/or electron) is the most important stage in a wide range of energy conversion processes in chemical and biological systems. Due to the fundamental nature of these reactions, an interest of its comprehensive study of both experimenters and theorists is constantly growing. The purpose of this work is to develop a model for proton transfer kinetics description in tetrahydroacridin-1(2H)'s derivatives systems and to evaluate the main energy parameters of molecular systems by experimental steady-state absorption and fluorescence spectra fitting of tetrahydroacridin-1(2H)'s in a set of aprotic (dimethylformamide (DMF), acetone (ACE), methylene chloride (DCM)) and protic (alcohols) solvents. Knowing the basic energy parameters will allow us to study the kinetics of charge transfer in the framework of the developed multichannel stochastic model.

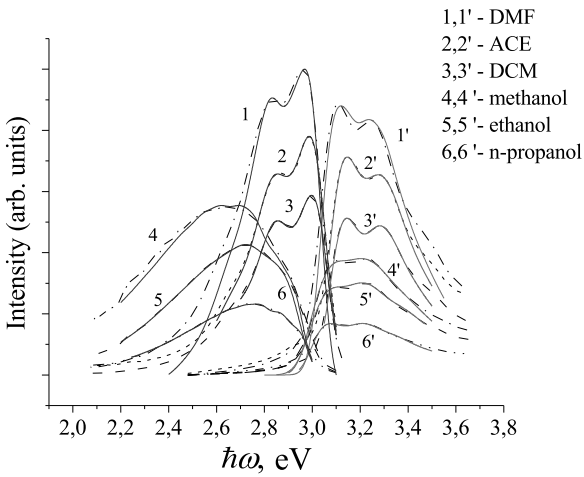

Figure 1: Fitting of experimental stationary absorption and emission spectra in a set of solvents. The experimental data are shown by black colour, the data obtained with the fitting are presented by red and blue lines.

In the framework of our research, it is proposed to use the multichannel stochastic approach which was previously successfully used to describe the multistage electron transfer in donor-acceptor complexes [1–3]. Such model takes into account the dynamics of solvent relaxation and the reorganization of intramolecular high-frequency vibrations. A quantitative description of charge transfer kinetics in the framework of a multichannel stochastic model requires knowledge of the basic energy parameters (exergonicity parameter and medium reorganization energy at each stage, reorganization energies of high-frequency intramolecular vibrational modes, as well as their frequencies), which may be determined on the basis of a fitting of experimental stationary absorption and fluorescence spectra [3, 4]. It was found that in aprotic solvents, when changing from the ground state to the excited state, the frequencies of high-frequency modes change insignificantly ($\sim 10 \div 15\%$). In protic solvents (methanol, ethanol, propanol) when changing from the ground state to the excited state, the frequencies of high-frequency modes can change by a factor of 2. These modes are assumed to be directly related to the vibrations of the hydrogen atom involved in the hydrogen bond.

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Ultrafast ablation of ruthenium: from visible to hard X-ray irradiation

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Interaction of intense ultrashort laser pulses with solids creates highly excited non-equilibrium states of matter with high electron temperatures, but still at solid state density. Relaxation of such an excited system may lead to significant changes in the lattice structure of the irradiated target. Understanding such processes is necessary, e.g., to manufacture long lasting reflective optics for the rapidly developing X-ray free-electron lasers (XFELs).

We study the interaction of fs laser pulses with Ru films in a wide range of incident photon energies ($\sim 1 - 10^4$ eV). Since at XFELs reflective thin metal films operate at grazing incidence conditions, absorption of light occurs in the top part of Ru mirrors ($\sim 1 - 10$ nm). Hybrid multi-scale modeling of target evolution after irradiation is performed. The model takes into account photoabsorption and non-equilibrium electron cascading occurring on a fs timescale, thermal diffusion and electron-phonon energy exchange on a ps timescale and lattice dynamics up to ns timescale.

Different photon energies result in qualitatively different absorbed energy profiles by the time of thermalization of the electronic system. The effects of such a difference on the hydrodynamic evolution and eventual damage of Ru are discussed [1]. Details of processes such as melting, cavitation, ablation and recrystallization are revealed on the example of 92 eV photons [2]. The results show a good agreement with the experimental observations on Ru ablation [3].

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Writing and rewriting laser-induced periodic surface structures on stainless steel for optical properties control

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Laser-induced periodic surface structures (LIPSS) can be produced in a wide range of pulse durations from continuous to femtosecond exposure on almost any material, such as metals, semiconductors, and dielectrics [1,2]. This phenomenon is usually associated with the interference between an incident electromagnetic wave and an excited surface electromagnetic wave. LIPSS usually appear as a periodic surface relief that correlates with the laser irradiation parameters, polarization, and wavelength [3,4].

In this work, the nature of LIPSS formation induced by short laser pulses (100 ns) on the surface of AISI 304 stainless steel is studied. LIPSS were generated using an ytterbium fiber laser (IPG Photonics) with a maximum power of 20 W, a wavelength of 1064 nm, and a pulse repetition rate from 20 to 99 kHz. A step by step process of LIPSS formation is considered. The effect of the laser irradiation polarization on the LIPPS writing and rewriting is revealed. A change in structure direction due to the repeated laser irradiation with another polarization direction is demonstrated. Thus, the control of the LIPPS formation during multiple laser irradiation process is shown. This technology can be applied for information recording and colorful image formation with various visual effects such as image movement or color switching.

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Nanodot array deposition via laser interference pattern using laser-induced forward transfer

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Laser-induced forward transfer (LIFT) is a direct-writing technique capable of depositing a portion of material. In addition, the size is smaller than the laser wavelength at small shot energy through the laser-induced dot transfer (LIDT) technique[1-4]. To deposit a single nanodot in a single shot of laser irradiation, a liquid nanodrop is transferred from donor to receiver and finally solidified via a solid-liquid-solid (SLS) process[5].

In this study, a femtosecond laser interference pattern was first applied to LIDT, and an array of nanodots was successfully deposited in a single shot[6]. The LIDT technique produces high-purity, catalyst-free that do not require post-cleaning or alignment processes. Given these significant advantages, LIDT can expand the usability of nanodots in a wide range of fields.

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Femto-nanosecond laser ablation of gold target in liquid

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Laser ablation in a liquid is well-known and popular method for obtaining nanoparticles due to number of advantages [1-2]. The choice of the generation regime has a great influence on the characteristics of the produced particles.

Colloidal solutions of gold nanoparticles were generated in water from gold films of variable thickness and bulk target at different intensities both of a nanosecond fiber laser marker HTF Mark on Yb^{3+} ions (1064 nm, 120 ns, E_{max} up to 1mJ) and Yb-fiber femtosecond laser Satsuma (1030 nm, 0.3-10 ps, E_{max} up to 10 μJ). For comparison, different scanning speeds were chosen. Gold thin films were produced by magnetron sputtering in an argon atmosphere on SiO2 substrates. The target was arranged in a glass beaker with deionized water of a volume $\simeq$ 2.5 ml (height above the target $\simeq$ 1 cm). The laser beam was focused through the liquid layer onto the target surface. The obtained colloidal nanoparticles were characterized by scanning electron microscopy, optical transmission spectroscopy, and dynamic light scattering. The chemical composition was confirmed by energy-dispersive x-ray spectroscopic chemical microanalysis (EDS) using the INCA module (Oxford Instruments, England) of the electron microscope.

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Graphene transistors functionalization using femtosecond laser in air conditions

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Possibility of femtosecond laser pulses to affect on materials modification takes a big part of interest in ultra-fast processes research and technology investigations. In case of graphene surface modification and functionalization using femtosecond laser there are many effects, such as ablation, covalent bonding of different chemical groups [1], re-crystallization in three-dimensional shapes [2].

CVD grown graphene was transfered on Si/SiO_2. Through several lithography steps graphene-based field-effect transistors were formed with Cr/Au source-drain electrodes and with Si as back gate. For graphene modification processes we used 80 MHz laser with 780 nm wavelength.

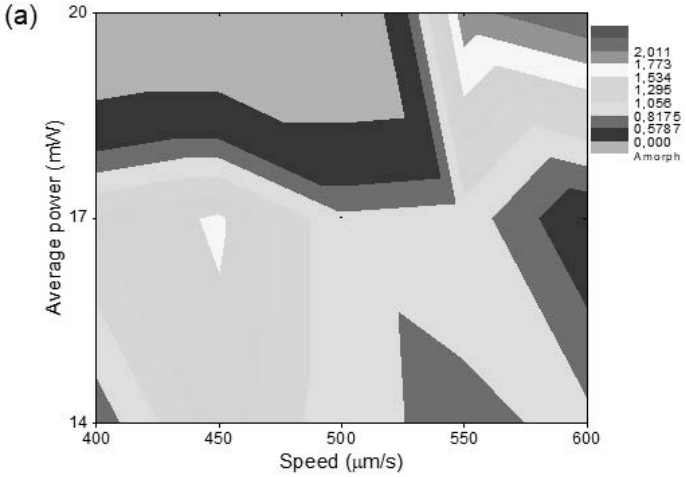

Figure 1: Ratio of D/G Raman peaks mapping, showing functionalization level.

Parameters of laser treatment were calibrated to have different total modification dose. From ablation to slight functionalization of graphene $10\,\mu m \times 10\,\mu m$ squares parameters of laser treatment calibrated as can be seen from peaks intensity ratio (D/G), that shows amount of defects and functional groups, recorded using Raman spectroscopy (fig. 1). Semiconductor characteristics analysis was

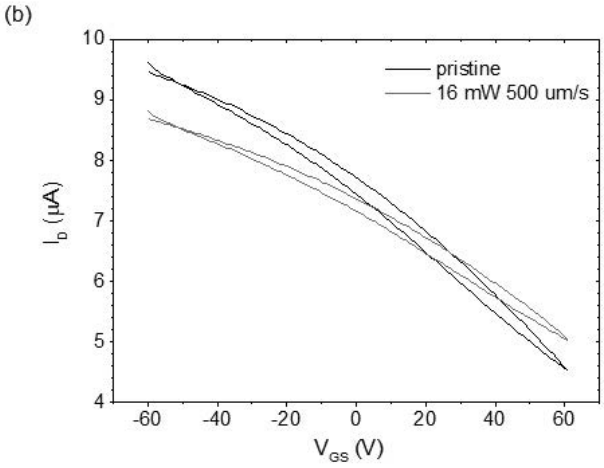

Figure 1: Changes in transfer characteristic after functionalization of graphene (b).

also performed to see changes in doping level of graphene, as can be seen on slope change of transfer characteristic (fig. 2).

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Femtosecond micromachining of bulk Si: effect of pulse duration and chirp

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Spatial localization of laser pulse energy during process of micromachining is achieved due to the tight focusing of laser beam. Under tight focusing conditions laser pulse energy is localized and the deposited energy density (DED) can exceed micromodification formation threshold [1]. Unfortunately it is extremely difficult to achieve high DED inside semiconductors [2].

We have investigated the effect of pulse duration and focusing conditions on the energy delivery under nonlinear propagation of tightly focused Cr:forsterite laser radiation in bulk silicon. The numerical simulation (Unidirectional Pulse Propagation Equation) shows that pre-focal losses of femtosecond IR pulses are associated with two-photon absorption and plasma defocusing. Increasing the duration of the tightly focused laser pulse by introducing a negative chirp leads to a decrease in laser pulse intensity, which promotes mitigation of the undesirable losses. Figure 1 (a) shows the pulse duration dependence of the maximal fluence for tightly focused (NA=0.5) 240 nJ pulses which confirms more efficient energy delivery to the focal volume by longer laser pulses. Nevertheless, it is still not possible to achieve the micromodification formation threshold in bulk silicon in this regime.

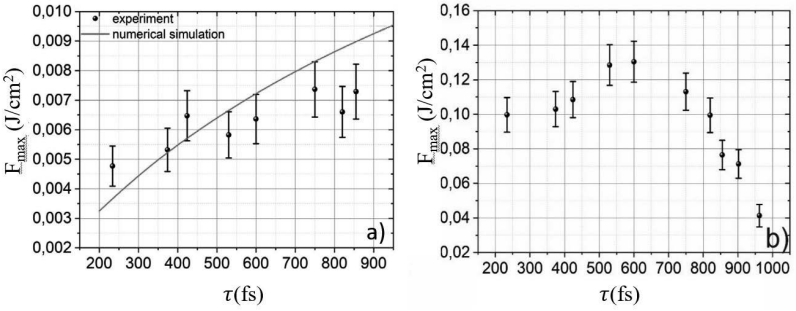

Figure 1: Dependence of maximal fluence on laser pulse duration, a) laser pulse energy 240 nJ, NA=0.5, b) laser pulse energy 650nJ, NA=0.85.

Figure 1 (b) shows the pulse duration dependence of the maximal fluence for 650 nJ pulses focusing with a numerical aperture of 0.85 in bulk silicon. It was

determined that for the pulse duration of $\tau \simeq 500 - 600$ fs and a negative chirp the maximum fluence has a local maximum of 0.13 J/cm^2. This maximum is attributed to the up-chirp compensation by the self-phase modulation and the positive dispersion of the material what leads to pulse compression. We experimentally (using 3D propagation imaging) demonstrated that with this approach DED about 5.5 kJ/cm^{-3} was achieved, that overcomes the micromodification formation threshold (3.2 kJ/cm^{-3}).

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Helical microstructures by irradiation of ultrafast optical vortex pulses

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Structured light beams, such as optical vortex, vector beam, and non-diffractive beam, carry various physical properties, for instance, ring-shaped spatial form, self-healing and orbital angular momentum.

Recent works have shown that irradiation of structured light beams offer many unique structured materials and novel fundamental light-matter interactions. In particular, irradiation of a single nanosecond to femtosecond optical vortex pulse with orbital angular momentum twists a variety of materials to form helical structures, such as helical metal or silicon microneedles, and helical surface reliefs, on a nano/micro scale [1-6].

This presentation reviews the state-of-art of the helical nano/microstructures formed by the irradiation of a single picosecond optical vortex pulse. Such light induced helical structures will open the door towards advanced materials science and technology, for instance, chiral meta-surfaces, sensitive detection and collection of the chiral chemical composites, and chiral chemical reaction at high time and cost efficiencies.

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Waveguide laser writing in porous glass for molecules detection

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Nowadays direct laser writing of waveguides has found a wide application in photonics applications [1]. For example, a waveguide sensing demonstrates promising results in a refractive index determination of substances deposited on a glass surface [2]. However, the writing occurs inside toughened glasses [3] that strongly limits their potential applications in sensor industry. Thus, the concept of waveguide with a cladding sensitive to the environment and a core with optical properties close to a fused silica seems relevant. In this case the direct laser writing in a porous glass allows to implement the concept.

In this report, we fabricate waveguides inside the porous glass and research their sensor potential. The feature here that the waveguide is buried in a nanoporous framework that makes the shell sensitive to the external action. While the framework easily captures molecules of water, alcohol, or organic dyes that influence on the waveguide optical characteristics. The combination of the waveguide and such a porous glass may become a novel sensing platform with a wide range of applications, depending on the molecules captured.

As a result, three types of waveguides, namely, "comet-shape", "ectangular-sectioned" and "cylindrical-shape" are fabricated and their optical properties are measured. In particular, the "cylindrical-shape" waveguide is used for detection of molecules captured by the porous glass upon registration of time dependent changes in the near-field mode distribution of the waveguide output. The collected data of the influences homologated with different concentrations of a substance allowed us to build a data base, which is used by potential sensor devices for measuring unknown concentration by matching output data with the data base.

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Formation of in-volume plasma nanogratings in fused silica due to ionization instability of internal surface plasmon

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The periodic nanogratings formed in the volume of dielectric by fs laser pulses are already widely used in various fields of modern optics [1,2]. Nevertheless, a clear physical model that reveals the nature of their periodicity is still missing. In a number of calculations it was shown that multiple plasmoids formed around randomly placed ionization centers in fused silica show a tendency to formation of more or less ordered structure [3-4], however, being only based on the direct numerical integration of Maxwell's equations this studies cannot reveal the physical nature of periodicity and still do not allow to advance further some common references to wave interference.

To provide a sufficiently clear physical model that allows to identify the specific physical mechanism of the emergence of order from chaos in "multiplasmoid" discharge and calculate the main characteristics of the arising ordered structure, it seems natural to use approaches based on the concept of ionization-field instability of a medium exposed to electromagnetic radiation [5,6]. In this work a computer simulation of dynamics of an optical discharge produced in the volume of a transparent dielectric by a focused femtosecond laser pulse was carried out taking into account the possibility of developing small-scale ionization-field instability. The presence of ionization centers was taken into account with the model of a nanodispersed heterogeneous medium by using Maxwell Garnett formulas. The results of the calculations made it possible to reveal the previously unknown physical mechanism that determines the periodicity of the arising structure. Two main points are decisive in this mechanism: (i) the formation of a thin overcritical plasma layer at the breakdown wave front counter-propagated to the incident laser pulse and (ii) the excitation of the "internal surface plasmon" at this front, resulting in a rapid amplification of the corresponding spatial harmonic of random seed perturbations in the plasma and formation of a contrast structure with a period equal to the wavelength of the surface plasmon ($\sim$0.7 of the wavelength in dielectric).

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Prediction of fast chemical order-disorder transitions induced by laser for high-density magnetic recording

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Today magnetic recording is still the leading technology for mass data storage with data densities beyond 1 Tbit/in^2. Pushing the recording density in the terabit regime requires new storage materials, novel recording schemes, and media designs. We propose the design of magnetic memories upon the basis of thermally induced chemical order-disorder transitions (CODTs) in alloys of transition metals, which exhibit disorder-induced ferromagnetism. If the temperature T is higher than the critical temperature T_c for CODT, the alloy tends to chemically disorder and its state can remain ferromagnetic upon quenching to room temperatures. Contrary, at $T < T_c$, one expects the relaxation of the alloy to the chemically ordered state which is nonmagnetic. We report on our simulations of CODTs and demonstrate that nanosecond laser irradiation concentrated within a nanoscale zone on the sample surface is able to induce the reversible transitions in Fe-rich Fe_xAl_{1-x} alloys.

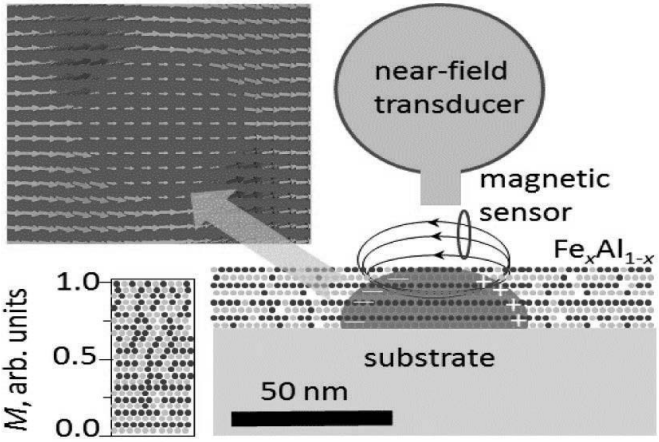

Figure 1: Design of magnetic memories based on chemical order-disorder transitions in intermetallic Fe-based alloys. Information bits are nanoscale regions with a reduced magnitude of magnetization written with near-field optical effects. The written information can be read out by detection of the stray field with a magnetic sensor combined with near-field transducer [1]. In the upper left corner, the simulated distribution of magnetization in the written bit is shown.

Figure 1 shows a magnetic memory nanodevice which can be realized upon that basis by using near-field optical effects, e.g., Ref. [1]. It is crucial for this approach that the bits can be written as erasable nanoscale entities in which the magnitude of magnetization differs from that of encompassing matrix. Therefore, contrary to the existing magnetic memories, the information here can be encoded in not the polarity of magnetization but in its magnitude. As a result, the difficult problems typical for current magnetic recording technologies, e.g., thermal upsets of magnetization and cross-talks between adjacent bits, can be circumvented by using the approach we propose.

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Engineering of laser beams for control of spin angular momentum

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Currently, spin angular momentum (SAM) of light is widely used in optical tweezers, laser material processing and spintronics [1-3]. It is well known that the transverse component of SAM occurs when there is a phase difference $\pi/2$ between the transverse and longitudinal components of the electric field of light, that is, its polarization state distribution of radiation must be inhomogeneous like, for example, in the case of cylindrical vector beams (CVBs). Here, we consider a new type of vector beam, vector Lissajous beams (VLBs), which are of double order (p, q) and a generalization of CVBs characterized by single order p. The ratio and parity of orders (p, q) affect the properties of different components of the electromagnetic field: these parameters define the type of components (whether they will be real, imaginary or complex) and the type of local spin angular momentum density (pure transverse or more complex). This allows one to engineer the imaginary part of the longitudinal component of the electromagnetic field and control the local transverse SAM density that is useful for optical tweezers and future spintronics applications.

We analytically show that SAM in the focal plane is transverse for all standard cylindrical polarizations (p=q) regardless of their orders. When $p \neq q$, all SAM components (longitudinal and transverse) are non-zero. Although due to symmetry, the total SAM in the focal plane will be zero, the local distribution of rotational forces is rather complex. Numerically, several examples show local directions of rotation of the electric field vector: in areas where all SAM components are present, a spiral rotation occurs (i.e., both in the longitudinal and transverse directions). In addition, we present a technique for the design of metalenses for the generation of the VLBs with the desired orders p and q.

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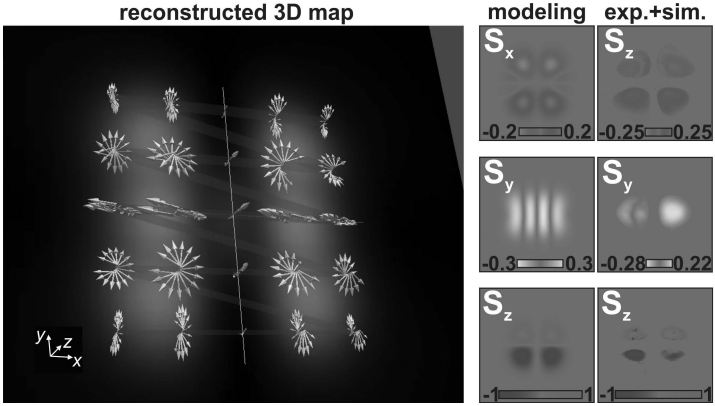

Figure 1: VLB with orders $p = 1$ and $q = 2$: reconstructed 3D map of the electric field vector (different colors indicate components of the electrical part of the electromagnetic field: red for $|E_x|^2$, green for $|E_y|^2$ and blue for $|E_z|^2$) and components of SAM of the beam.

Sub picosecond single pulse laser ablation of the high entropy alloy CrMnFeCoNi and comparison to stainless steel AISI 304

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The laser matter interaction of alloys, like industrial relevant stainless steels, with ultra-short pulsed (usp) lasers has been widely discussed. However, a new approach to alloy design, High Entropy Alloys (HEAs), is currently in the focus of many studies. HEAs show promising properties for technical applications. One of the most investigated HEAs is CrMnFeCoNi and although up to date a lot of research has been performed on this alloy, there is still a gap in the literature regarding subtractive usp laser micro-machining.

In this work, novel results for single pulse usp laser ablation of CrMnFeCoNi at a laser wavelength of 1056 nm and a pulse duration of 530 fs are presented and compared with commercial stainless steel AISI 304. The ablation threshold Φ_{thr} at the selected laser parameters is $0.24(1)\,\mathrm{J\,cm^{-2}}$ for CrMnFeCoNi which is slightly lower than for AISI 304 with $0.27(1)\,\mathrm{J\,cm^{-2}}$. The analysis of the crater morphology by SEM imaging and optical profilometry implies that photomechanical spallation can be considered as the driving ablation mechanism for CrMnFeCoNi and for stainless steel in the low fluence regime. The energy specific ablation volume (ESAV) was determined for both alloys and has a maximum at $4 - 4.5\,\Phi_{\mathrm{thr}}$. This result agrees well with the model of the fluence dependent ablation depth proposed by Smirnov et al. [1], but contradicts with the well-known linear absorption model [2]. The reflectance corrected ESAV at this maximum is $9.5\,\mu\mathrm{m^3/\mu J}$ and $7.0\,\mu\mathrm{m^3/\mu J}$ for CrMnFeCoNi and AISI 304, respectively. By comparing this values with the total energy needed to evaporate the solids, CrMnFeCoNi ablation needs approximately 25 % more energy and AISI 304 even 50 %. So while ablation mechanism and morphology of usp laser ablation of CrMnFeCoNi are comparable to AISI 304, CrMnFeCoNi shows in contrast an increased ablation efficiency.

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Scalable laser synthesis of surfactant-free oxidation catalysts

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The scalable, surfactant-free laser-based synthesis route has shown to complement the conventional catalyst preparation methods, enabling independent studies of the catalytic activity in terms of nanoparticle purity, functional properties (size, morphology, oxidation state) and material design (multi-elemental composition).[1,2] Furthermore, preadjusted nanoparticle properties are maintained due to subsequent nano integration onto support materials allowing mechanistic[3a-c] and applicatory studies like the implementation of laser-generated catalysts in real fuel cell systems.[3d] But gram-scale synthesis of nanoparticles with desired size (commonly below 10 nm to gain sufficient catalytic activity) is required for economical catalyst synthesis.[1] Yet up until now only the overall productivity is investigated in respective studies addressing the scalability of the laser ablation process.[4]

The presented talk intends to cover recent breakthroughs in scaling the synthesis of catalytically relevant Pt and PtPd alloy nanoparticles with particle size below 10 nm. First, the interplay between ablation rate and fragmentation efficiency during high-productivity laser ablation will be discussed allowing optimization of the yield of particles below 10 nm while maintaining g/h-scale production rate for the first time. While larger particles could not entirely be avoided, a continuously operating tubular bowl centrifuge removing these undesired particle fractions has been implemented downstream.[5] By varying the g-force and residence time, the cut-off was shifted to smaller diameters, consequently maximizing the cumulative mass-yield of NP below 10 nm to more than 90% at flow rates used for g/h-scale synthesis of nanoparticles.[5] Finally, catalytic activity of size-selected PtPd nanoparticles from gram-scale synthesis will be evaluated in CO and NO oxidation catalysis showing that the activities were in perfect agreement to literature reference values, even showing enhanced NO2 formation rates. These results solidify the scientific and economic relevance of laser-generated catalysts.

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Spatially modulated femtosecond laser pulses via bubble-scattering processes in liquid

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Nanostructured silicon interfaces provide a unique platform for the development of many advanced technologies. Femtosecond laser pulses at fluences near melting and ablation thresholds being focused onto a polished silicon surface immersed into liquid enable the control over the surface morphology at nano- and even subnanoscales [1, 2]. In liquids, however, the laser processing even at sufficiently low fluences is inevitably accompanied by generation of gas bubbles which strongly scatter the incident laser radiation preventing its interaction with a material. We demonstrate that under certain laser parameters and appropriate ambient environment one can benefit from such an adverse effect.

We report on a new technique of silicon surface nanostructuring in liquid with a pair of femtosecond laser pulses. The bubble, generated by the first pulse, serves as a dynamic microscale obstacle to scatter the second pulse off. As a result, a diffraction pattern is projected onto the surface resulting in annular concentric structures consisting of alternating maxima (protruding rims) and minima (microdimples), referred to as a circular ripple pattern [3]. Controlling the incident laser pulses' energy at constant time delay allows repeatable producing of a wide range of circular ripple patterns notable for their high surface-relief modulation of radial symmetry, undersurface nanocavities and interfacial smoothness. The oil with a dynamic viscosity of two orders of magnitude higher than that of distilled water is used in the experiment to control the bubble lifetime as liquid viscosity significantly effects the cavitation dynamics, in particular, at long timescales in the collapse phase [4]. Wavelength doubling of incident radiation (1028 nm) results in similar circular patterns but with half as much lower modulation frequency.

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Three-dimensional optoacoustic imaging of laser-induced plasma and deposited energy density under optical breakdown in water

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The nonlinear absorption of intense (up to 10^{14} W/cm^2) laser pulses is a powerful tool for the bulk modification of transparent media [1] and attracts the attention of scientific community as a subject of fundamental research [2,3]. The most important application of nonlinear absorption phenomenon is a plasma-mediated laser micromachining of inorganic materials [4] and ophthalmological surgeries [5]. In order to realize the precise control of the bulk modification process under laser micromachining in condensed matter it is principal to use a feedback, that gives information about the modification process with high spatial and temporal resolution. One of the possible types of this feedback is the spatial distribution of the deposited energy density (DED), that is the amount of energy absorbed per a unit volume of medium.

In order to provide the feedback with high spatial resolution, we propose a novel optoacoustic method aimed to retrieve the 3D distributions of plasma electron density and DED under plasma- mediated bulk modification. The method is based on photoacoustic imaging method [6] and shadowgraphy technique [7].

The experimental proof of the concept was done on the basis of optical breakdown in distilled water, that was induced by Cr:Forsterite femtosecond laser system pulses (central wavelength is 1240 nm, pulse duration is 170 fs (FWHM), repetition rate is 10 Hz, energy up to 2.5 mJ). The Cr:Forsterite radiation with energy E = 325 μJ was focused by lens with NA = 0.5 into the water in order to induce the optical breakdown.

The algorithm of 3D distributions retrieval is divided onto three stages. The first one is a retrieval of 3D distribution of absorbed energy fraction integrated along the probe beam path $A(x, y, z)$ on the basis of acoustic tomogram and shadowgraphy photo. The second one is a retrieval of 3D distribution of the plasma electron density $n_e(x, y, z)$ by recalculation of $A(x, y, z)$ on the basis of a model of laser pulse propagation in inhomogeneous plasma. The third stage is a retrieval of DED distribution $\epsilon(x, y, z)$ by recalculation of $n_e(x, y, z)$ on the basis of the experimental calibration of total laser pulse energy absorbed in the region of optical breakdown relatively to the total amount of generated plasma electrons. The obtained 3D distribution of the DED $\epsilon(x, y, z)$ is shown on Fig.1.

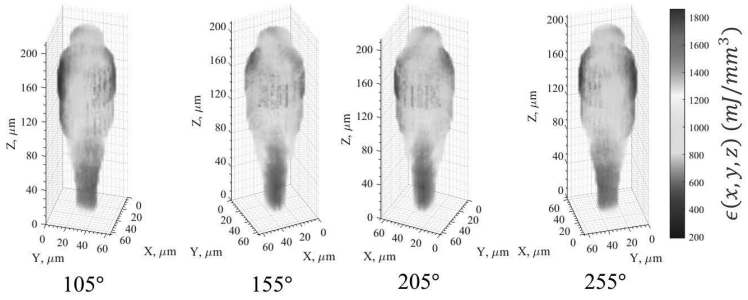

Figure 1: The obtained 3D distribution of the deposited energy density at the region of optical breakdown in water (105°, 155°, 205°, 255° are the azimuthal angles of view).

The advantage of the proposed method in comparison with another techniques (such as shadowgraphy itself [8], interferometric measurements [9] and spectral multiplexing [10]) is in the 3D resolution of the inner structure of the optical breakdown plasma. The proposed optoacoustic method can be applied both in the area of technological applications, such as micromachining of transparent materials, and in the field of fundamental science of laser-matter interaction.

The part of the photoacoustic imaging and shadowgraphy is acknowledged by Russian Foundation for Basic Research (RFBR) 18-32-00696. The part of the estimation of deposited energy density is acknowledged by Russian Science Foundation (RSF) 17-72-20130; The retrieval of photoacoustic tomograms is supported by NUST MISIS Competitiveness Program by the Ministry of Science and Higher Education of the Russian Federation [K2-2019-004]. B.V. Rumiantsev is the scholar of the Foundation for the Advancement of Theoretical Physics and Mathematics “BASIS”.

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Femtosecond-laser microstructuring in transparent materials

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Direct femtosecond recording in dielectrics allows you to create local constant modifications that can be used in various fields, for example, to create optical waveguides, splitters, resonators in the volume of active media, micro- and nanofluidics devices. By changing the radiation parameters, one can obtain various types of modifications or defects [1,2]. The following types of structures recorded by femtosecond pulses are distinguished: regions with a refractive index different from the initial material, birefringent structures, cavities, etc. Separately, it is worth noting an actively developing field, such as laser recording and long-term storage of information [3].

During the interaction of ultrashort laser pulses with a material volume and surface, periodic nanolattices can form [4]. These structures are parallel stripe-shaped regions, the direction of which depends on the polarization of the laser beam. The period of self-organizing nanogrids depends on the energy in the pulse and the number of pulses per point, the frequency of the bands varies within hundreds of nanometers, which is less than the wavelength of the recording laser [5]. The properties of these structures can be used for the manufacture of half-wave and quarter-wave plates, polarization converters, polarization-dependent devices, as well as moderators.

In the course of this work, using ultrashort laser pulses (wavelengths of 515 nm and 1030 nm) at various polarizations in the volume and on the surface of transparent materials, microstructures were recorded in the form of arrays of parallel microlines (with linear polarization) or perpendicular-parallel microlines (with circular polarization). Linear structures recorded in the volume of fluorite have birefringence.

In this work, we study the possibility of creating structures that can have different optical effects in direct femtosecond laser recording of arrays of microlines taking into account possible manifestations, self-organized nanogrids, and residual microscale voltages. A distinctive feature of this study is the preparation of structures in materials which are characterized by the presence of a significant amount of optical inhomogeneities and chemical impurities.

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Laser wettability control of metal surfaces for directional fluid flow

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The ability to control wettability of metal surfaces is of great interest nowadays and have various applications such as anti-corrosion treatment, oil-water separation, friction reduction [1]. One of the relevant applications is directional fluid flow, which can be used in microfluidics [2], biomolecular interactions [3], for creating chemical sensors [4]. The directional fluid flow can be achieved by creating wettability gradient with contact angle going from hydrophilic to superhydrophilic [5]. A one-stage method of laser formation of structures for a directional fluid flow on an AISI 304 stainless steel surface proposed. Structuring was performed using a nanosecond fiber laser with a wavelength of 1.06 μm.

To create a wettability gradient, laser exposure parameters were obtained with a change in fluence with small increments from 2 J/cm^2 to 18 J/cm^2, which formed a roughness gradient with rms value, changing from 0,15 to 42. Additional post-processing of the material was not carried out; wetting experiments were executed immediately after laser structuring. Thus, a wettability gradient was created with contact angles from 65 to 0 degrees, which allow the directional movement of a droplet with volume from 1 to 5 μl over a 15 mm distance at an average speed of 20 mm/s. The creation of patterns with complex shapes, such as branching, merging, turning, and bending around an obstacle, was also demonstrated.

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Laser-induced diffusion-controlled growth of nanoparticles in semiconductor films

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New functional nanocomposites have found numerous applications in such areas as optics, photonics, photovoltaics, catalysis and plasmoincs. Generally, laser irradiation forms a buried modified region in a nanoporous glass composite, more specifically a multilayer spherical plasmonic structure with the concentration of nanoparticle distributed across the cross-section [1]. Moreover, the growth [2], fragmentation [3], reduction or oxidation of nanoparticles occur in the irradiated zone, thus defining the structure's optical properties that are commonly measured after laser processing by contact examination. The ability to predict the optical properties of composites during their laser processing is crucial in the development of new functional materials. Commonly, such task requires the determination of stable phenomenological relationships between experimental and simulated results. In this work, we propose an combination of effective medium theory [4] for simulate of optical properties with diffusion-controlled model for simulate of nanoparticles growth [5] by laser annealing. Effective medium theory with Bruggeman approximation will be used for dielectric function determination in the case of composite with nanoparticles (silver/gold). The diffusion-controlled model will be used for correction of nanoparticles size and its concentration in the irradiated region. Will be presented the procedure to control the plasmonic structures formation inside a transparent composite with doped with silver/gold ions induced by laser irradiation. The theoretical and experimental investigation are demonstrated here to prove the procedure working ability.

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Synthesis of magnetic nanoparticles by laser ablation in a liquid and verification of their antibacterial properties

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Pathogens are a common cause of many diseases. Nowadays, the treatment of various types of bacteria is complicated by the development of resistance of these organisms to the use of antibiotics [1]. One of the promising directions in solving this problem is the use of magnetic nanoparticles obtained by laser ablation in a liquid. The magnetic properties of these particles can be used for their targeted delivery within the human body to problem areas using powerful magnets. In this study, we studied the process of obtaining magnetic nanoparticles, checking the possibility of their movement in viscous media (with a viscosity coefficient close to blood) and checking their antibacterial properties.

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Laser wettability control of metal surfaces for directional fluid flow

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The ability to control wettability of metal surfaces is of great interest nowadays and have various applications such as anti-corrosion treatment, oil-water separation, friction reduction [1]. One of the relevant applications is directional fluid flow, which can be used in microfluidics [2], biomolecular interactions [3], for creating chemical sensors [4]. The directional fluid flow can be achieved by creating wettability gradient with contact angle going from hydrophilic to superhydrophilic [5]. A one-stage method of laser formation of structures for a directional fluid flow on an AISI 304 stainless steel surface proposed. Structuring was performed using a nanosecond fiber laser with a wavelength of 1.06 μm.

To create a wettability gradient, laser exposure parameters were obtained with a change in fluence with small increments from 2 J/cm^2 to 18 J/cm^2, which formed a roughness gradient with rms value, changing from 0,15 to 42. Additional post-processing of the material was not carried out; wetting experiments were executed immediately after laser structuring. Thus, a wettability gradient was created with contact angles from 65 to 0 degrees, which allow the directional movement of a droplet with volume from 1 to 5 μl over a 15 mm distance at an average speed of 20 mm/s. The creation of patterns with complex shapes, such as branching, merging, turning, and bending around an obstacle, was also demonstrated.

The reported study was financially supported by the Ministry of Science and Higher Education of the Russian Federation Research Agreement No. 075-11-2019-066 of 22.11.2019 (within the framework of decree of the Government of the Russian Federation No. 218 of 09/04/2010).

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Electrophysical anisotropy of amorphous silicon surfaces irradiated by femtosecond laser pulses

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Femtosecond laser irradiation is a promising technique for modification of amorphous hydrogenated silicon (a-Si:H) films, as it increases conductivity and optical absorption of such films due to crystallization and surface texturing [1]. Also, micron-scale laser-induced periodic surface structures (LIPSS) can be formed in the a-Si:H films owing to excitation of surface plasmon-polaritons under effect of high-power femtosecond laser pulses [2]. Such way structured a-Si:H films demonstrate birefringence, dichroism [3], and electrical anisotropy [2] which can be used in design of polarization-sensitive optoelectronic and photovoltaic devices. However, these practical applications demand understanding the nature of the anisotropy arising in a-Si:H as a result of LIPSS formation.

In our work a-Si:H films with 600 nm thickness were irradiated by femtosecond laser pulses (λ = 1250 nm, τ = 125 fs, f = 10 Hz, F = 0.5 J/cm^2) in raster mode. The scan speed V varied from 2 to 50 μm/s during laser processing. After irradiation scanning electron microscopy revealed formation of LIPSS with periods close to the laser wavelength. At V = 50 μm/s one-dimensional gratings with 0.88 ± 0.03 μm period orthogonal to the laser polarization were formed. When V = 2 μm/s, the second LIPSS type formation was observed. The obtained ripples are directed along the laser radiation polarization and have the period of 1.12 ± 0.022 μm. Raman spectra indicate formation of crystalline silicon (c-Si) phase with the volume fraction from 17 to 30% inside the irradiated films.

Electrical measurements showed increasing specific dark conductivity of modified films by 3 to 4 orders of magnitude, up to $3.8 \pm 0.2 \cdot 10^{-5}$, $(\Omega \cdot cm)^{-1}$, due to formation of silicon nanocrystals by femtosecond laser pulses. Also, dark conductivity and photoconductivity of the modified a-Si:H films demonstrate anisotropy in the surface plane, when their values are higher along the LIPSS or the scan direction during laser irradiation. The ratios of these conductivities in mutually orthogonal directions differ up to 2.5 times. Observed electrical anisotropy is caused both by the LIPSS depolarizing effect in the effective medium theory framework and uneven c-Si phase distribution within the LIPSS and scan traces after laser irradiation. Additional analysis of photoconductivity

spectral dependences and absorption coefficient spectra revealed anisotropy of the charge carrier lifetime along and orthogonal to the LIPSS. This difference of the charge carrier lifetimes explains the observed dark conductivity anisotropy.

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Laser-induced backside wet etching in water using 3-μm laser sources

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Laser-induced backside wet etching (LIBWE) is an effective method for transparent materials processing. Compared to other conventional methods, it is characterized by a low threshold, low etching rate, and a high-quality surface with very low surface roughness. The etching process relies on the strong absorption of laser pulses energy by the buffer liquid. It allows the formation of submicron and nanoscale structures on the processed sample surface and efficient nanoparticle manufacturing. As a rule, nanosecond UV-NIR lasers are used in combination with strongly absorbing media: organic dyes, liquid metal, or nanoparticles formed from a solution upon laser pulses absorption [1]. The unique properties of water allow using it as an effective buffer medium in the etching process. At a wavelength of about 3 μm, there is a strong fundamental absorption line (1.3×10^4 cm^{-1}), resulting in several micron absorption depths. It makes 3-μm laser sources attractive for many applications where a high energy input into the liquid is required [2].

Up to now, the etching process at a high energy deposition is not totally understood. It includes a combination of complex physicochemical processes in water, including nonlinear bleaching, sharp increase in temperature and pressure, and corresponding supercritical water state formation. Extreme energy input is also accompanied by strong mechanical effects, including cavitation and shock wave generation, which are believed to play an essential role in the etching process. As a result of the processed sample mass removal, nanoparticles are formed in the solution, which can also affect the etching rate and mechanism.

We report the study of the surface structuring of crystalline dielectrics (CaF_2, Sapphire) during LIBWE in water under the excitation of powerful 3-μm laser pulses. The difference in etching mechanisms under nanosecond and femtosecond effects is considered. The composition of the buffer fluid for the presence of nanoparticles from the processed material is also studied. Methods for increasing the etching rate by using a liquid accelerating the rate of a chemical reaction are considered.

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Surface crystalline-amorphous alternating structure on a GST225 amorphous thin film under femtosecond pulses

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The formation of two-phase laser-induced periodic surface structures (LIPSS) on the surface of the initially amorphous $Ge_2Sb_2Te_5$ (GST225) thin films under the illumination by 180-fs laser pulses with the wavelength of 1030 nm has been studied in detail. The observed LIPSS were perpendicular to the light field polarization and their period was close to the wavelength. We have determined their parameters by several methods (optical microscopy, SEM, TEM, AFM) which correlate with each other.

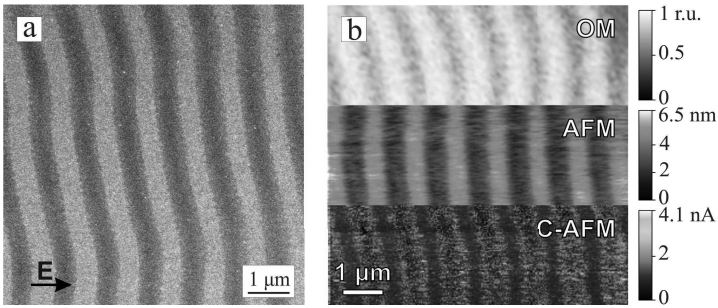

Figure 1: The results of the microscopy studies for the GST225 film after the exposure to laser pulses (duration 180 fs, repetition rate 200 kHz, average energy fluence 3.6 mJ/cm^{-2}, pulse number N = $5 \cdot 10^3$). (a) The SEM image and (b) the overlay of images (optical microscopy OM, AFM in topography mode, and conductive AFM) were obtained from the same spot..

It was found that the valleys consist of the crystalline phase, while the ridges remain amorphous. The LIPSS appearance can be explained by the formation of surface plasmon-polariton and its subsequent interference with the incident beam resulting in spatial modulation of the temperature on the film surface.

The height difference between the valley and the ridge is about 2-3 nm, according to the AFM data (Figure 1b, central panel). This value is significantly less than the height of the ripples observed in the similar film after the femtosecond laser irradiation with the wavelength of 515 nm, where the 20-nm height ripples were observed [1]. The significantly less pronounced surface relief for

crystalline-amorphous alternating structures induced by the wavelength of 1030 nm can be explained by the larger penetration depth of femtosecond pulses into the bulk of the GST film.

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Single-shot pulse ablation of silicon by ultrashort laser pulses of variable duration in air and water

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Silicon due to unique properties is widespread material and has applications in different fields, such as micro-optoelectronics, electronics, solar energy. Besides recently silicon become very widespread as a photon material and silicon nanoparticles are successfully used in theranostics [1, 2]. Since many of these systems operate at high optical intensities, an accurate understanding of the nonlinear characteristics of silicon is important for understanding and optimizing their performance. The paper presents the results of irradiating a silicon surface with femtosecond radiation with a wavelength of 1030 nm and laser pulse durations of variable duration in the range from 0.3–10 ps. A crystalline silicon plate 380 μm thick was used as a target. The target surface was irradiated in a single-pulse mode through a lens with a numerical aperture NA = 0.25. The treated surface of the sample was studied using methods of optical, scanning electron and scanning probe microscopy. The results were obtained on the efficiency of silicon ablation from the duration of radiation in air and in distilled water. The two-photon absorption coefficient for silicon was calculated.

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The perspectives of application of silicon nanoparticles formed by picoseconds laser ablation of porous silicon in liquids for localized and effective heating of a biological tissue

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Silicon is material of high biocompatibility, bioavailability, biodegradability and low toxicity [1]. For biomedical applications it would be better to employ silicon nanoparticles (SiNP) of spherical shape, with their size being less than 150 nm.

Photothermotherapy (PTT) techniques are based on using inorganic nanomaterials as a thermal coupling agents for a biological sample. Nanoparticles injected in a tissue play the role of additional elastic scattering and absorption centers. As a result stable and localized heating more than 40^oC can be achieved [2].

We developed a two-stage technique to obtain suspensions of SiNP in concentrations that are desirable for hyperthermia method. The first stage is the electrochemical etching of crystalline silicon wafers in order to obtain a layer of porous silicon (PS). The second stage is picosecond laser ablation of PS in ethanol or liquid nitrogen and SiNP formation as the result. Lower ablation threshold in PS results in higher yield of SiNP than ablation of crystalline silicon.

Atomic-force microscopy of obtained samples demonstrated formation of the SiNP with the size ranges of 5-100 nm and 7-60 nm for ablation in ethanol and liquid nitrogen , respectively. Relatively small sizes of the produced nanoparticles indicate low efficiency of agglomeration of the ablation products into nanoparticles in the used buffer environments. Scanning electron microscopy inspection indicated that all types of fabricated Si-NPs have a smooth surface, without noticeable surface roughness, and a shape close to spherical.

We used Monte Carlo simulation method to obtain initial thermal distribution as a result of light absorption from continuous laser source. Then we solved time-dependent heat equation through MATLAB Partial Differential Equation Toolbox. The simulation of heat maps was performed for a sample tissue with suspensions of SiNP taking into account the particles size distribution obtained previously in experiment .

This work was supported by Russian Science Foundation (grant 19-12-00192).

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You shall not pass: titanium nanospikes-based flow-through filter for liquid sterilization

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The cause of the majority of diseases, is the activity of pathogenic microorganisms. The use of antibiotics has led to the mutation of bacterial strains and their acquired resistivity. Such "lion in the way" of human well-being is nowadays bypassed with the use of micro- and nanostructures with a wide specter of functionality. One of the most eligible methods of such structure manufacturing is laser ablation in liquid, which allows fabrication of nano- and microstructures [1]. In this work, several Ti nanosctructures, fabricated with the use of ytterbium-doped fiber laser Satsuma, were tested as potential elements for liquid sterilization filter. We implemented the morphology (fig. 1a) and tested their antibacterial properties with standard live-dead viability kit, (fig. 1b). Nanostructured Ti was used afterwards for the construction of flow-through filter, with functional surfaces (fig. 1c, d). Such filter allowed reducing the bacterial population from 10^6 to 10^4, presumably due to the chemical toxicity of nanoparticles and mechanical damage caused by a sharp nanoscale relief on Ti.

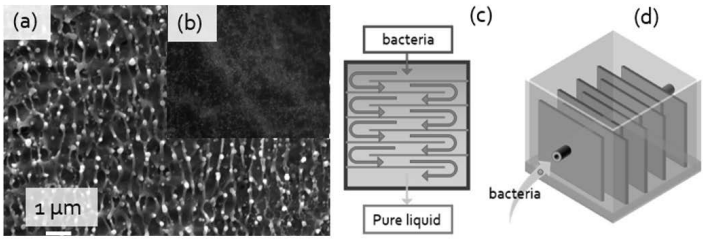

Figure 1: (a) SEM image of nanostructured Ti surface; (b) fluorescent photograph of the bacterial strains; (c) the upper view of flow-through filter and (d) its 3D model.

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Influence of pulse separation on the ablation mechanism of silicon: Spallation and phase explosion vs. melt ejection

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Ultrafast laser material processing with MHz to GHz bursts is a common technique to effectively leverage the high pulse energies provided by state of the art laser systems. Burst processing promises to increase the ablation volume compared to processing with single pulses, while at the same time it seems to decrease the residual heat remaining in the sample in the so called "ablation-cooling" regime [1]. However, this technique has the drawback of losing precision and ablation quality due to significant melt burr formation at the ablation edges [2].

In this study we focus on the melt dynamics of electronic grade <100> silicon after irradiation with ultrafast near-infrared pulses with varying inter-pulse spacing. First the melt dynamics, recorded after subjecting the sample to single pulses with varying fluence are determined using a pump-probe microscopy setup. Based on the measurement of the transient sample reflectivity, the resolidification times were measured to be 8 ns and 75 ns for fluences of 0.47 J/cm^2 and 4.73 J/cm^2, respectively. In a second experiment the sample was irradiated with multiple pulses of the same energy, exhibiting inter-pulse spacing of 10 μs and 12 ns.

We observe two different regimes of burst laser material processing. At fluences below 1.3 J/cm^2, subsequent pulses irradiate a solid surface. Here spallation and phase explosion are the driving ablation mechanisms. Within this regime, the ablation volume is comparable to single-pulse processing with an inter-pulse spacing of 10 μs and no melt ejection is observed. Above fluences of 1.3 J/cm^2 subsequent pulses irradiate a liquid surface. Here the ablation volume increases up to a factor of four compared to single-pulse processing with an inter-pulse spacing of 10 μs. Furthermore a large amount of molten material is ejected up to 20 μm across the ablation crater edges.

Based on this observation, the ablation volume increase in the burst mode can be attributed to ablation in the liquid phase. This is well known from nanosecond pulse ablation, which exhibits high ablation volumes with the drawback of reduces quality due to melt ejection.

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Volume gratings fabrication using ultrashort laser pulses with different intensity distributions

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A change in the refractive index in a silicate material can be achieved by focusing ultrashort laser pulses both on the surface and in volume of the material [1]. This technology allows producing of nano- and microstructures, such as waveguides [2,3], couplers [4] and gratings [5-6]. To a greater extent, such a structure is obtained using the direct laser recording method. Focused ultrashort pulses form a desired pattern in two or three coordinates on the surface or inside the material. The direct recording method can be implemented in two ways: parallel recording [2,3] and side recording [6,7]. In parallel recording, the sample is scanned parallel to the beam propagation axis, and the shape of the focused beam is highly symmetrical. In lateral recording, the sample is scanned perpendicular to the axis of beam propagation, but the shape of the scanning beam is usually asymmetric, for example, cylindrical.

The volume high-frequency grating is an important element in photonics due to the high diffraction efficiency, high selectivity for wavelength and large diffraction angles. Usually a micro objective is used as a focusing element. We suggest using an axicon as the focusing element. Then the quasiparallel laser beam after the axicon will have an intensity distribution described by the Bessel function of the first kind of the 0th order, i.e. a Bessel beam of the 0th order is formed. As a result, under the influence of ultrashort laser pulses, there will be a change in the refractive index of the silicate material along the entire length of the 0th order Bessel beam, which in turn will immediately allow the formation of nano- and microstructures of the required thickness.

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Laser-induced periodic surface structures formation on various materials

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The use of ultrashort laser pulses for surface nanostructuring is of great importance in technological and medical applications [1]. Thus, the understanding of the basic governing mechanisms of energy deposition to the irradiated material is very important. On a rough material surface, at grating structures or at a step edge, ultrashort laser pulses can excite surface plasmon polaritons (SPP), i.e. surface plasmons coupled to a laser electromagnetic wave [2,3]. One of the possible scenarios for the description of laser-induced periodic surface structures (LIPSS) is based on the SPP excitation and their interference with the incident beam.

The spatial and temporal evolution of the periodically modulated absorbed laser energy is studied after irradiation of various metals in the framework of the two-temperature model (TTM) [4]. We present a new analytical source term in the TTM, which takes into account the excited plasmon subsystem and therefore spatial periodicity [5]. The developed method can be used to study the mechanisms of laser energy absorption under controlled conditions and for investigation of the properties of the excited SPP.

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Synthesis of metal phyllosilicates and silicides via reactive laser ablation in liquid

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Reactive laser ablation in liquid (RLAL) combines "top-down" and "bottom-up" approaches to laser nanofabrication in liquid media through ablation of a solid target in metal salt solution. In this work, a high-power ultrashort pulsed laser is focused onto the surface of a silicon wafer immersed in aqueous solutions of one or more metal salts such as $KAuCl_4$, $Cu(NO_3)_2$, or $Ni(NO_3)_2$ [1-3]. This synthesis both produces ablated nanomaterials in solution and writes nanostructures onto the silicon surface. The specific composition and structures of both products are highly dependent on the solution pH. Under alkaline conditions, the solution products are comprised of metal phyllosilicates, a class of minerals built of alternating tetrahedral and octahedral coordination layers containing Si^{4+} and divalent metal cations such as Cu^{2+} and Ni^{2+}, respectively. We have found that phyllosilicate formation relies on the generation of deprotonated silicic acid ($SiO(OH)_3^-$) species from silicon atoms ablated off of the wafer, which react with the metal cations to self-assemble into phyllosilicates [2]. When $Cu(NO_3)_2$ is present, sub-2 nm Cu_2O nanoclusters supported on the copper phyllosilicate matrix are also formed (Figure 1) [1].

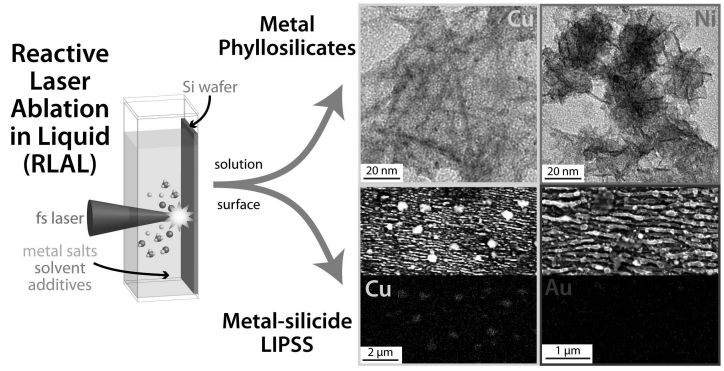

Figure 1: Scheme of RLAL of a silicon wafer in metal salt solution and representative products produced in solution and on the surface.

Under neutral pH conditions, high quantities of metal are deposited into the remaining silicon surface, producing laser-induced periodic surface structures (LIPSS) doped with Au or Cu silicides (Figure 1) [3]. Whereas the low wettability of copper on silicon results in large ∼400 nm Cu silicide particles on the

surface, the high wettability of Au produces small nanoparticles on the surface and a mixture of metallic Au and Au-silicide phasess to a depth of up to ∼150 nm [3]. Further characterization of both solution and solid RLAL products will be discussed.

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Effect of laser treatment with short and ultrashort pulses on the structure of near-surface layers of titanium alloys

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The report presents the results of original studies of the structural-phase state of the surface and near-surface layers of titanium and its alloys after irradiation with short (nanosecond) and ultrashort (femtosecond) laser pulses.

Features of realization of the effect of nanostructuring of thin (about 1 μm) surface layer on the example of titanium alloy of system Ti-Al-V (VT6) and commercially pure titanium brand VT1-0 in the initial submicrocrystalline and coarse-grained structural states in the result of laser processing are discussed. The change in the phase composition of technically pure titanium associated with the formation of a high-pressure phase is analyzed.

The possible mechanisms of the observed nanostructuring effect associated with the possibility of phase recrystallization and dynamic recrystallization under the studied conditions are considered.

The study in the main part related to the study of the structure of commercially pure titanium, performed with support from grant RFBR N 19-58-26005 and additional parts related to the study of phase composition, thematic maps of fundamental research IPCP No. 0089-2019-0017.

Ionisation processes and laser induced periodic surface structures in dielectrics with mid-infrared femtosecond laser pulses

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Ionisation processes and laser induced periodic surface structures in dielectrics with mid-infrared femtosecond laser pulses

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Irradiation of solids with ultrashort pulses and laser processing in the mid-Infrared (mid-IR) spectral region is a yet predominantly unexplored field with a large potential for a wide range of applications. In this work, laser driven physical phenomena associated with processes following irradiation of fused silica (SiO_2) with ultrashort laser pulses in the mid-IR region are investigated in detail. A multiscale modelling approach is performed that correlates conditions for formation of perpendicular or parallel to the laser polarisation low spatial frequency periodic surface structures for low and high intensity mid-IR pulses (not previously explored in dielectrics at those wavelengths), respectively. Results demonstrate a remarkable domination of tunneling effects in the photoionisation rate and a strong influence of impact ionisation for long laser wavelengths. The methodology presented in this work is aimed to shed light on the fundamental mechanisms in a previously unexplored spectral area and allow a systematic novel surface engineering with strong mid-IR fields for advanced industrial laser applications.

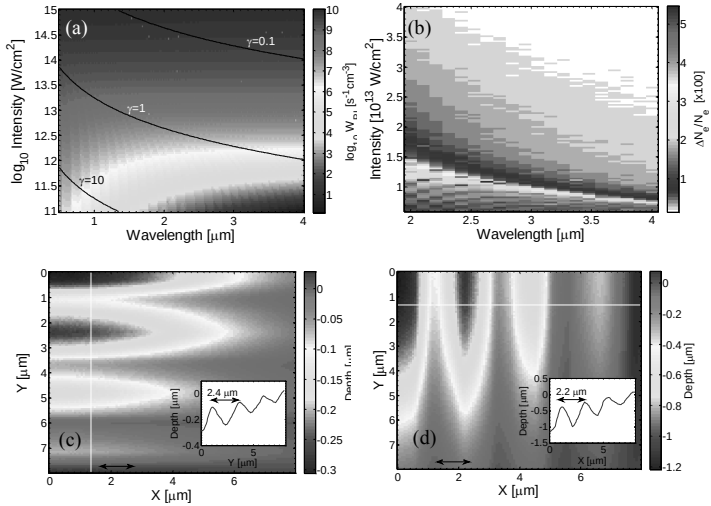

Figure: (a) Photoionisation rates at various wavelengths and laser (peak) intensities assuming excitation of electrons from the valence band, (b) Percentage change of maximum value of electron-density if Kerr effect is considered ($\Delta N_e = \left(N_e - N_e^{(Kerr)}\right)$), Top view of Parallel (c) and Perpendicular (d) to laser polarisation LSFL for laser (peak) intensities I=1.06×10^{13} W/cm^2 and I=1.4×10^{13} W/cm^2, respectively for NP=3 and NP=10, respectively.

Figure 1: (a) Photoionisation rates at various wavelengths and laser (peak) intensities assuming excitation of electrons from the valence band, (b) Percentage change of maximum value of electron-density if Kerr effect is considered ($\Delta N_e = \left(N_e - N_e^{(Kerr)}\right)$), Top view of Parallel (c) and Perpendicular (d) to laser polarisation LSFL for laser (peak) intensities I=1.06 ×10^{13} W/cm^2 and I=1.4×10^{13} W/cm^2, respectively for NP=3 and NP=10, respectively.

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[1] Tsibidis G.D. and Stratakis E., *Ionisation processes and laser induced periodic surface structures in dielectrics with mid-infrared femtosecond laser pulses (under review)*

Results demonstrate a remarkable domination of tunneling effects in the photoionisation rate and a strong influence of impact ionisation for long laser wavelengths. The methodology presented in this work is aimed to shed light on

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Laser-printed platform for ultrasensitive SERS-based identification

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We demonstrated a technology of fabrication and application of laser-printed platform for ultrasensitive SERS-based identification of various analytes dissolved in water droplets at trace concentrations. The device combines an analyte enrichment system comprised of properly arranged superhydrophobic micropillars that guide the water droplet with dissolved analyte molecules during its evaporation so that eventually the concentrated analyte gets deposited onto a hydrophilic central site with SERS-active nanostructures. The optimal parameters of the superhydrophobic area and special external electrostatic field distribution providing the most efficient transport of the analyte molecules from the solvent to the central site are found. The optimal design of the central SERS-active site and its laser fabrication technology are developed. The proposed platform showed remarkable performance, permitting to identify characteristic fingerprints of various model analytes including organic dye molecules and widely used medical drugs at concentration down to 10^{-12} M in a reliable manner.

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Influence of pulse separation on femtosecond laser ablation efficiency of Aluminium

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In recent years, several works have been investigating the temporal pulse spacing with the aim of maximizing removal rate by applying double pulses or pulse bursts. In the theoretical explanations, it was pointed out that the double pulse acts as a single pulse for double pulse spacing remaining below the electron-phonon relaxation time. When double pulse time spacing is exceeding the electron-phonon relaxation time, the second pulse suppresses the rarefaction wave induced by the first pulse resulting in a decreased ablation depth [1]. For a separation time in a nanosecond time domain it was argued that only the first pulse contributes to the formation of the ablation crater, while the second pulse is partly absorbed by the ejected ablation plume resulting in a re-deposition of ablation plume [2].

Here we study the energy specific ablation volume and ablation depth of double pulses in dependency of increasing pulse separation on aluminium bulk material. We focus especially on a pulse spacing range from tens of picoseconds up to one nanosecond to close an existing gap in the state of the art. Ultrafast pump-probe ellipsometry and microscopy are applied to study the surface material motion after single laser pulse impact. Additionally, a hydrodynamic simulation of double pulse laser ablation supports the experiments.

The comparison of time-resolved measurements and double pulse ablation depth confirm the suggestion that a double pulse acts as a single pulse for double pulse spacing below 5 ps. Between 5 ps and 50 ps the interaction of the second pulse with the rarefaction wave decreases removal rate. The propagation of ablation layer is clearly visible in time-resolved experiments resulting in the re-deposition of ablated material back to the surface for longer double pulse spacing up to 1 ns. This re-deposition is also confirmed with a hydrodynamic simulation with a pulse spacing of 100 ps.

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Laser ablation of silicon nanowires and silicon microparticles in liquids

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Pulsed laser ablation of silicon in different liquids is a powerful modern tool to produce a variety of nanoparticles with desirable size, physical and chemical properties [1]. Silicon nanoparticles (Si-NPs) fabricated by this technique have potential in different biomedical applications [2, 3] due to high biocompatibility and biodegradability of nanostructured silicon. Note that high-yield production of Si-NPs is quite time-consuming and requires employment of a powerful laser with high pulse repetition rate. To enhance the efficiency of Si-NPs fabrication, we suggest using preliminary nano- or microstructured silicon instead of traditionally used monocrystalline silicon (c-Si) targets.

In our work we use silicon nanowire (Si-NW) arrays [4] and mechanically grinded microparticles (1-6 mm in size) as targets for picosecond (1064 nm, 34 ps, 10Hz) laser ablation in water and ethanol. Measurement of the ablation thresholds for Si-NWs targets in liquids revealed that these values are several times less in comparison to the corresponding ones for c-Si. Thus, this approach allowed to increase the ablation product yield. Similar tendency is observed for laser fragmentation of the silicon microparticles.

According to scanning electron microscopy and atomic force microscopy studies, Si-NP sizes are in the range of 5-170 nm depending on the used target and buffer liquid. Raman spectroscopy analysis revealed almost perfect crystallinity of the formed Si-NPs. The Si-NPs ablated in ethanol exhibit fluorescence emission in the range of 600-900 nm. We assume that the observed fluorescence caused by defects in the studied nanocrystalline structures.

Spectrophotometry measurements of the ablated Si-NPs suspensions revealed that scattering coefficient reaches value of $\sim$1 mm^{-1} in the spectral range of 400-1000 nm indicating their potential as contrast agents in biomedical imaging.

Thus, pulsed laser ablation of Si-NW arrays and silicon microparticles provide high-yield fabrication of Si-NPs with relatively small size and high level of crystallinity, that are promising as fluorescence markers and scattering contrast agents in bioimaging.

This work was supported by the Russian Science Foundation (project N 19-12-00192).

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Femtosecond laser printing of single living mammalian cells

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According to the superior cell survival rates, laser-induced forward transfer (LIFT) has been used in recent years for the flexible and gentle 3D-bioprinting of cells [1]. One drawback of the state-of-the-art nanosecond laser based cell printing is the fact, that material from an inorganic sacrificial layer, which is required for laser energy absorption, is transferred to the printed target structure where it contaminates the printed construct [2]. Instead of an inorganic sacrificial layer, protein based donor films have been used in combination with nanosecond ultraviolet (UV) laser sources. However, UV radiation can introduce DNA double strand breaks, thereby imposing the risk of cancerogenisis [3].

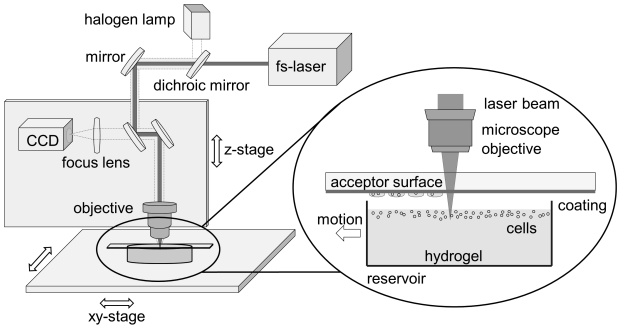

Figure 1:

Here we present a new femtosecond laser-based method for the efficient and precise cell printing which avoids the use of non-biological inorganic absorption layers. An ultrashort laser pulse (λ = 1030 nm, 600 fs, few μJ) is focused underneath a cell layer (cf. Fig.1), which is suspended on top of a hydrogel reservoir. Non-linear absorption leads to plasma ionization and rapid cavitation bubble expansion, which generates a jet of material, transferring cell-laden hydrogel from a gel/cell reservoir to an acceptor stage [4]. Fig.2 shows the transferred jet of pure hydrogel at a delay time of 50 μs after laser pulse. Fig.3 presents microscope image of transferred human mesenchymal stem cells (SCP1) on accepter slide (red Propidium Iodide (PI) staining indicates dead cells, live cells

are displayed in green). The transferred cells reveal a well-defined form and have survival rate around 95%, which is close to the vitality of non-transferred cells.

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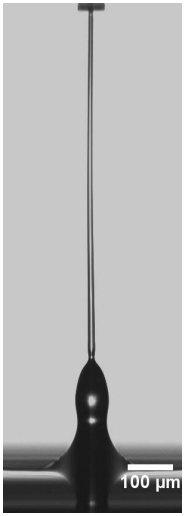

Figure 2:

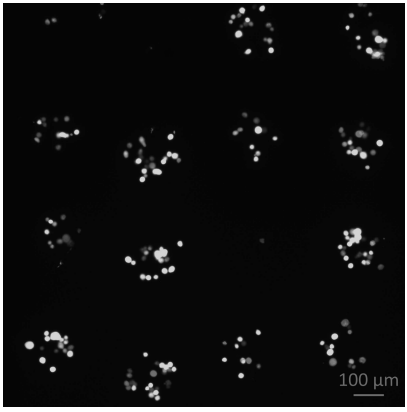

Figure 3:

Residual stresses in Ti6Al4V alloy after surface texturing by femtosecond laser pulses

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Femtosecond laser processing is one of the promising methods in surface modification of biomaterials because of the unique periodic surface nano- or microscale topography formed after irradiation [1]. The main features of relief formation on titanium alloy surface were extensively studied; however, the residual stresses in the surface layers of such titanium alloy exposed to fs laser pulses have not been sufficiently studied. The analysis of the residual stress state is of great technological importance because stresses can be beneficial or detrimental with respect to the mechanical properties of the material [2].

In this work, we study the formation of laser induces periodic surface structure (LIPSS) on Ti6Al4V titanium alloy, irradiated by 1030 nm femtosecond laser pulses, and investigate residual stresses in the near-surface layers after such laser processing. Multipulse femtosecond laser processing of Ti6Al4V titanium alloy with a single-pulse fluence in the range from 0.08 to 1.2 J/cm^2 leads to the formation of periodic surface structure. It is shown that laser processing with 0.08 and 0.4 J/cm^2 leads to the formation of compressive residual stresses in the surface layers (up to 2.3 μm). After processing with 1.2 J/cm^2, tensile residual stresses are formed in the surface layers of the Ti6Al4V titanium alloy.

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Generation of metallic nanoparticles by laser ablation in molten salts

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Laser ablation of metallic nanoparticles in various liquids is an active research topic [1-3]. Ambient media used for this purpose are typically liquid at room temperature. In this work, the generation of metal nanoparticles by ablation of solid targets in ionic liquids was studied. Sodium nitrate $NaNO_3$, sodium nitrite $NaNO_2$ and lithium nitrate $LiNO_3$ salts with a relatively low melting point were used as such liquids.

An ytterbium fiber laser with pulse duration of 200 ns and energy of 1 mJ at repetition rate of 20 kHz was used as a laser radiation source. The salts were brought to the melting point from 300 to 320^o C on a hotplate, then a solid target was placed in the resulting liquid. Laser ablation was then carried out at a constant temperature of 320^oC. X-ray diffractograms of pure NaNO3 matrix and $NaNO_3$ with Au NPs indicate that the size of Au NPs lies rather in sub-μm range that in nanometer scale. The spectrum of the resulting solid matrix after solidification turned out to lack the usual plasmon resonance peak at the wavelength of about 520 nm. Instead, an increase in the absorption in the IR region (wavelengths from 750 to 1000 nm) was observed, which can be associated with the elongation of Au nanoparticles under the influence of surrounding matrices. A similar effect was reported earlier in [4] in case of polymer matrix.

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Critical assessment of the problem of the boundary conditions for modeling of propagation of tightly-focused ultrashort laser pulses in transparent solids

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For fabrication of high-precision structures inside bandgap materials for photonics and optoelectronics applications, ultrashort pulse duration of tightly-focused laser beams is preferable to provide minimizing of the intensity clamping effect and, thus, to avoid delocalization of the absorbed laser energy [1,2]. Sophisticated numerical modeling of different stages of laser-materials interactions, from the laser excitation of the electronic sub-system of a solid to its thermal and mechanical response to the laser energy deposition, enables a deep insight into the dynamics of laser-induced processes and helps to reveal optimal conditions of the irradiation regimes for specific applications. However, in the case of tightly-focused beams, mathematical modeling faces the problem of setting up correct boundary conditions for the laser field entering a material sample.

It is usual practice that, in numerical models, that the spatiotemporal shape of an incoming laser beam at the sample surface is taken in the Gaussian form, that corresponds to a solution of the linear Schrödinger equation for the monochromatic case [2,3]. For the case of tightly focused laser beams, such boundary conditions can lead to unphysical results while the validity of a "smoothed" boundary conditions is still not well-proven [2]. For obtaining physically-grounded modeling results, it is necessary to elaborate boundary conditions for incoming tightly-focused beams, which correspond to real focusing systems. For this aim, a "parabolic mirror" boundary condition is seemingly one of the most reasonable approaches [4]. In this work, we investigate the "parabolic mirror" boundary condition in applications to the problems of propagation of tightly-focused laser beams in transparent dielectrics. We have applied the technique of the Stratton-Chu integral [5]. It is demonstrated that using the temporal Gaussian shape to describe tightly-focused ultrashort laser pulse propagation yields unphysical results. For obtaining the physically meaningful solutions, it is necessary to calculate temporal evolution of the beam in a special way. To do this, the generalization of the Stratton-Chu integral for the time dependence of the propagating laser pulse has been proposed. A numerical code has been developed for efficient calculations of the generalized Stratton-Chu integral.

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Femtosecond laser lithography of 3D-structures for photonic integrated circuits

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In contrast to electronic technologies, where well-studied metal interconnections are used, silicon photonics still does not have a proven and reproducible integration of radiation I/O elements with photonic chips. Available integration methods have high radiation losses, can be polarization-dependent, and have a high price. Recent studies have shown the existence of a new technology of low-loss photonic interconnections using three-dimensional polymer waveguides that are transparent to the telecommunication wavelength of 1550 nm [1].

In this work, we have investigated such photonic wire bonds (PWB) fabricated by femtosecond laser lithography for connection of two silicon nitride waveguides on a single nanophotonic circuit [2]. For this purpose, 3D optical interconnections have been designed and optimized for effective transmission of infrared radiation of the telecommunication wavelength on a photonic chip. Luminescence mapping and morphology analysis of the fabricated 3D-structures were performed by laser scanning confocal microscope upon the cw-excitation wavelength of 458 nm (argon laser).

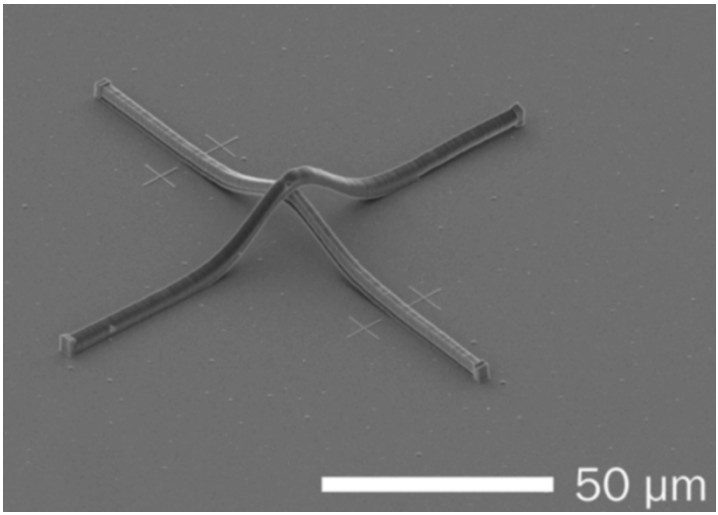

Figure 1: SEM image of the fabricated photonic junction containing two PWB.

The most important part of the work is to measure the optical functionality of the manufactured devices; the obtained loss values range from 3 to 15 dB depending on the geometric characteristics of the waveguides. Also, we presented, theoretically substantiated and experimentally confirmed the concept of photonic junctions that combine 3D-waveguides within a single photonic chip (fig. 1).

The authors are grateful to the MIPT Shared Facilities Centre for SEM measurements. Financial support was granted by the RFBR grant no. 18-29-20129.

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Section 4: Femtosecond non-linear optics. Filamentation. High field THz generation.

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Scope

Self-compression and self-focusing

Terahertz science

Filamentation in various media

Femtosecond nonlinear phenomena

Spectral and temporal characteristics of emission luminescence of solid matter and anthropogenic aerosols under the action of Ti:Sa laser pulses of femtosecond duration under the conditions of nonlinear optical effects

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The report presents the results of complex studies of spectral and temporal characteristics of the emission glow of control samples of several substances in a solid state (imitation of topographic targets) and in the form of a solid aerosol (imitation of a contaminated aerosol) under the action of Ti:Sa laser pulses of femtosecond duration (at a carrier wavelength of 800 nm) under the conditions of nonlinear optical effects (self-focusing, filamentation, supercontinual conical emission).

The experiments in the laboratory and controlled air path with a length of 8 m have shown the effectiveness of using femtosecond laser-emission spectroscopy for registration of substances in the solid state and solid aerosol. It is shown that this technique allows us to confidently detect a greater number of emission lines of the samples used, in particular due to the excitation of lines with low excitation energy. Controlling the length of the multiple filamentation region at the propagation distance by changing the focusing conditions allowed remote excitation of the emission spectra of the glow of control samples. Increasing the length of the filamentation area along the propagation path leads to an increase in the detected signal, which partially compensates for the losses associated with removing the sample from the receiver. The detected effect can be used as a simple way to increase the total intensity of the glow signal of the defined emission lines and, consequently, to increase the probability of implementing this method.

From uni-molecular to collective effects in air lasing from molecular nitrogen cation

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Control over a distant laser source in atmosphere is desired for various applications such as atmospheric studies and remote sensing. In the past decade a phenomena called "air lasing" caught a lot of attention as it provided an easy access to a remote bright source in air. Although the realization of such a source is relatively easy and has been observed in various pulse energies, optical frequencies and air pressure, understanding of its gain mechanism was quite challenging. Various proposals had been published in literature in explaining the high gain in N_2^+.

In this paper I will present some of the proposed description of observed high gain between $B_2\Sigma_u^+ \rightarrow X_2\Sigma_g^+$ in N_2^+ such as electron re-collision [1] and strong field ionization. I present how high precision spectroscopy [2] that is traditionally used for study of uni-molecular aspect of the emission can be used to show the collective contribution in realization of high gain in air lasing. I show how the gain decay has the same time scale as the Stark shift on the emission lines suggesting the effect of plasma fields in loss of coherence [3]. Moreover the high precision spectroscopy highlights the coherence contribution in observing the high gain [2]. A collective contribution in high gain with fast decay known as superradiance provides a complementary picture to the uni-molecular studies of air lasing [4].

A parallel comparison between uni-molecular and collective aspects of "air lasing" is provided.

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THz radiation in circularly- and elliptically-polarized multi-color strong fields

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Terahertz (THz) frequency range (0.1-30 THz) is extremely useful for many applications since transitions between rotational and vibrational levels of complex molecules lie in this range [1]. One of the useful methods to generate THz pulses is based on ionization of noble gases using strong two color fields [1,2]. In a most typical setup, a femtosecond strong pulse of fundamental frequency and its second harmonic are focused into a gas spot, causing photo-induced plasma. THz radiation is produced because ionization in an asymmetric pump field create a nonzero net asymmetric plasma current [3]. The efficiency of THz radiation can be increased significantly if using more than two color pump, for instance 3-color driving fields produced by optical parametric amplification [4-6]. Taking even more colors promises an increase of the optical-to-THz conversion efficiency to a percent level [7]. Recent researches showed that circularly-polarized pump pulses allow to produce THz radiation more efficiency than linearly polarized ones [8,9,10]. Besides, nontrivial polarization of the pump pulses allows to generate THz radiation of tunable waveshape [11].

In this talk I overview the mechanisms of increasing efficiency of THz generation provided by controlling polarization and number of frequencies of the pump pulses, suggested by different authors. I also show how particular THz waveshapes are formed if the pump of nontrivial polarization is used.

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Generation of continuously-tunable, narrowband THz pulses from phase-locked femtosecond pulse bursts

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We demonstrate generation of continuously-tunable, narrowband THz pulses from phase-locked multi-millijoule femtosecond pulse bursts by optical rectification in a tilted-pulse-front setup[1].

The femtosecond laser pulse bursts is formed using the Vernier technique [2] in a chirped pulse amplifier where the pulse spacing is given by the cavity roundtrip time difference $\Delta\tau$ of the master oscillator (MO) and a regenerative amplifier (RA), $f_{burst}^{-1} = \Delta\tau = |\tau_{MO} - \tau_{RA}|$. Due to the chirped pulse amplification together with spectral and temporal overlapping pulses in the cavity it is necessary to stabilize and control the phases of the intraburst pulses to suppress the formation of high intensity peaks in the spectral and temporal domain. We demonstrate stabilization of the regenerative amplifier cavity, control over individual pulse phases, continuous tuning of the intraburst pulse spacing in the ps-regime and amplification of the burst to multi-mJ levels.

As a proof of concept, THz bursts are generated by optical rectification in $LiNbO_3$ using a tilted-pulse-front pumping (TPFP)[1] resulting in μJ THz pulses with conversion efficiencies exceeding 0.1% for pump energies higher than 2mJ (Fig. 1).

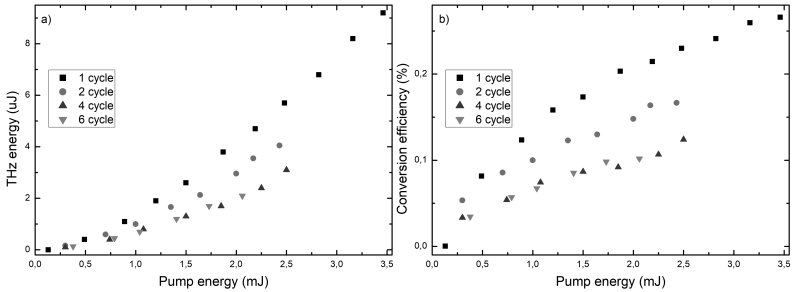

Figure 1: THz energy (left) and conversion efficiency (right) vs NIR pump energy for various intraburst pulse numbers (cycles) achieved in the TPFP-OR THz generation experiment.

SHG autocorrelations of the NIR driver and linear autocorrelations of the generated THz transients using a Michelson interferometer can be seen in Fig. 2.

In accordance with the prediction, the continuously-tunable intraburst frequency translating into the central THz frequency is given by the inverse pulse spacing and the bandwidth Δf of the generated THz signal is lower the higher the number of pulses N according to $\Delta f = 1/(N\Delta t)$. Higher-harmonics of the THz-signal can be seen as well, originating from higher-order side-bands in the original NIR burst spectrum

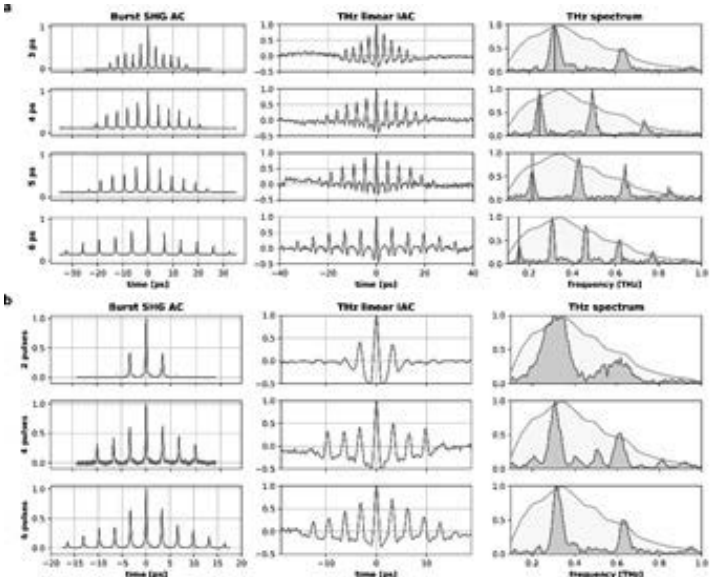

Figure 2: Intensity (SHG, burst) and linear (THz) autocorrelations and THz spectra for a) variable pulse spacing with a fixed number of pulses (N=6) with the respective THz-frequency marked as black vertical line b) variable pulse number with fixed pulse spacing (Δt=3 ps). The THz spectrum generated from a single pulse is depicted in orange.

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Dependence of the short-wavelength cutoff in the mid-IR pulse spectrum on the interaction length in a transparent dielectric

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Filamentation of high-power femtosecond laser radiation under conditions of anomalous group velocity dispersion leads to formation of a high-intensity wave packet, extremely compressed in space and time, — a light bullet [1]. Spatiotemporal transformation of the wave packet during the light bullet formation is accompanied by significant broadening of its spectrum — generation of a supercontinuum [2], the spectrum of which extends from near ultraviolet to mid-infrared region. The principal feature of the anti-Stokes region in the light bullet spectrum is the appearance of a narrow wing, separated from the central region by a broad spectral minimum, which is formed as a result of destructive interference of supercontinuum radiation [3]. Supercontinuum generation by light bullets is considered an effective method for obtaining coherent broadband radiation, therefore peculiarities of the light bullet spectrum are a topic of great interest.

This paper presents the results of experimental and numerical study of the anti-Stokes wing formation and the evolution of a short-wavelength cutoff in the mid-IR pulse spectrum during propagation of the pulse in fused silica and calcium fluoride. During the experiment, radiation with a close to Gaussian intensity profile was focused by the lens into wedge-shaped transparent dielectric samples. The samples were located on a movable stage, which made it possible to change the length of the nonlinear optical interaction with the dielectric, while the input radiation parameters remained the same. For numerical simulation of pulse filamentation and formation of light bullets, the slowly evolving wave approximation was used [4]; the model takes into account diffraction and dispersion effects, Kerr and plasma-induced variations of the refractive index, and also the attenuation of radiation. Our analysis of the results obtained at the filamentation of 1900 nm femtosecond laser pulses shows that the position of the short-wavelength cutoff of the supercontinuum spectrum was shifted to the region of shorter wavelengths when the increasing distance of nonlinear optical interaction of radiation with the medium remained shorter than the light bullet formation path. However, the short-wavelength cutoff did not change with an increase in the interaction length, already exceeding the length of the light bullet formation path. It is shown that the general picture of the anti-Stokes wing formation remains unchanged for various initial radiation parameters.

This work was supported by the Russian Science Foundation (Project No. 18-12-00422).

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Ultrashort laser pulse filamentation: The outlook from the nonstationary nonlinear diffraction-ray optics

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We present an uncommon outlook on laser pulse filamentation phenomenon based on the optical field representation as a self-consistent ensemble of specific spatio-temporally localized wave structures - the diffraction-ray (light) tubes. These light tubes are energetically independent from each other, but are in close coherent coupling through the phase front of optical wave. The spatial trajectories of light tubes follow the direction of the transverse component of the Pointing vector. The boundaries of light tubes do not intersect in space, and the tubes themselves do not exchange energy. Light tubes shape and cross-section can vary upon pulse propagation, thus reflecting the impact of the physical processes acting on optical radiation in the medium. This diffraction-ray approach brings together the features of pure amplitude and pure phase analysis to the problem of nonlinear nonstationary self-action of optical radiation and allows a new look at the conditions of the emergence and termination of laser pulse filamentation.

Some examples visualizing femtosecond laser pulse filamentation in air are considered in the framework of diffraction-ray optics. We show the filament is supplied and refueled by the light energy only of the part of laser pulse which is contained in the specific light tube having initial peak power slightly exceeding the critical power for pulse self-focusing. It is this light tube that serves as the energy reservoir for the filament. The residual peripheral part of the pulse does not directly refuel the filament but maintains it through inertial confinement of the "energy-supplying" ray tube by forming a virtual "diffraction" waveguide for the filament.

Nonlinear absorption measurements in CaF_2 and fused UV silica at 473 nm

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For the correct description of various light-matter interactions such as the self-focusing, filamentation, supercontinuum generation, ablation, the light bullet formation it is necessary to know the concentration of free charges. Correct calculations need the cross sections for multiphoton absorption, but for the coefficient of multiphoton absorption k>3, the measurements are difficult: corresponding cross sections are extremely small, which requires high intensities for direct observation and accompanied by the impact of additional scattering due to small-scale filamentation and etc. Consequently, to the best of our knowledge there are few articles about measuring the four photon absorption cross section, and for the five-photon absorption, there is only one article about measuring the five-photon absorption cross section [1], in which the cross section was estimated from the ablation threshold for Al_2O_3. However, plasma properties near the ablation threshold and critical density may be different. Recently we managed to obtain four-photon absorption cross section in UV fused silica [2] using direct transmission measurements by I-scan and z-scan open aperture techniques. The development of small-scale instabilities was avoided by using very thin (100 μm) samples. Using same technique we obtained five-photon absorption cross section for CaF_2 [3]. However, the contribution of plasma absorption was not taken into account and could be significant.

In this work, we improved this technique for measuring multiphoton absorption by adding variation of initial pulse duration. We carried out several series of I-scan absorption measurements for UV fused silica and CaF_2 with different pulse duration from 90 fs to 150 fs. Since multiphoton and plasma absorptions have different dependencies from pulse duration their contribution can be disunited using a numerical model based on the nonlinear Schrödinger equation to calculate sample transmission. Multiphoton cross-sections, collision and recombination time for density plasma below critical can be obtained after fitting to experimental data.

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High-efficient stimulated Raman scattering of femtosecond laser pulses in BaWO4 for a production of ultrashort longwave IR pulses

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A development of high-power ultrashort mid-IR laser systems is the important scientific object motivated by numerous applications, such as studies of ultrafast molecular dynamics, laser driven particle acceleration, atmospheric nonlinear optics, high harmonic and supercontinuum generation and other. A promising technology for producing of ultrashort 10-μm wavelength-range laser pulses is based on difference frequency generation pumped by a shortwave laser pulse and its Raman-shifted component via stimulated Raman scattering (SRS) [1,2].

In this work we experimentally demonstrated the high-efficient (up to 20%) SRS of 300-fs pulses in $BaWO_4$ crystal with Stokes wavenumber of 925 cm^{-1} in the very simple single-pass optical scheme. This anomalously high efficiency was achieved due to proper self-seeding of SRS induced by self-phase modulation. The spectral width of pump emission broadened by self-phase modulation reached $\sim$925 cm^{-1} which was matched the strongest Stokes frequency of $BaWO_4$ crystal. This emission acted as a seed for SRS and enhanced it. Also an applicability of output emission for $\sim$10.6 μm seed pulse production for high-pressure sub-picosecond CO_2 laser amplifier via DFG in $LiGaS_2$ crystal was numerically verified. A simple design of the developed Raman shifter and its high efficiency will allow one to increase an overall efficiency of the master oscillator for the longwave IR laser system proposed in [1].

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Dependence of the angular THz radiation distribution emitted by single-color filament plasma channel with different lengths

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The terahertz frequency range is attractive for use in various fields, for example, medical imaging, wireless communication, security, quality control, etc. To date, one of the methods for generating THz radiation is filamentation of ultrashort laser pulses in air. Mixing the first and second harmonics into one filament (two-color filament) is a popular way to generate THz radiation. However, medium dispersion leads to the spread of pulses in space and, as consequence, in time, which makes it difficult to obtain a remote source of THz radiation in this way. In this paper, we study the generation of THz radiation in the plasma channel of a single-color filament. There are not many articles on this topic and their result is the angular distribution of THz radiation dependence on the plasma channel length (L), as $\theta \sim (\lambda_{THz}/L)^{1/2}$ [1], where plasma channel length was varied by changing the focusing condition (the focal length of the focusing element), which leads not only to a change in channel length, but also to a change in plasma density, and as a result to a significant change in the THz radiation generation conditions by the filament plasma. In this paper, we present a study of the angular dependence of THz radiation from a single-color filament plasma at different plasma channel lengths under conditions of equal focusing.

In the experiments, the output radiation from Ti:sapphire laser system was focused. The central wavelength was 740 nm, pulse duration was 90 fs (FWHM), beam radius was 3.2 mm (at the level 1/e), the pulse energy was varied by a calibrated diffraction attenuator from 0.1 to 4 mJ. THz radiation was recorded by a superconducting bolometer operating on the effect of electronic heating in a thin NbN film. The spectral range of the bolometer operation is between 0.3 and 3 THz. To measure the angular distribution of the THz radiation, the bolometer was mounted on a special stand that allows moving it along an arc of a circle having a center in the geometric focus of the lens. Three series of experiments were performed. In the first series, plasma channel length was changed by changing the focus length of lens, and obtained angular distribution are consistent with the earlier obtained results [1] and confirm the correctness of the measurement method. In the second series, the plasma channel length was changed by varying the pulse energy from 0.25 to 4 mJ, and significant changes in the angular distributions were not observed. In the third series, the change in the plasma channel length was made by interrupting the filament by U-shaped

screen, and it did not result in noticeable changes in the angular distribution of THz radiation.

The results of the experiments show that the decisive role in the angular pattern of THz emitted by the plasma channel of a single-color filament is the initial focusing conditions of laser radiation, and not the length of plasma channel, since the plasma concentration strongly depends on the focusing conditions.

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Influence of optical pulse reflected from high absorption domain on developing of temporal contrast structure induced by laser radiation in a semiconductor

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We analyze the role of the optical pulse reflected from the boundary of the high absorption domain appearing in a semiconductor due to the nonlinear dependence of its absorption coefficient at the femtosecond laser pulse propagation [1]. Under this condition, the phenomenon of optical bistability occurs, and a gradient of the dielectric permittivity appears because of the inhomogeneity of the absorption coefficient [2]. Thus, this induced domain changes a propagation condition. In dependence on the relation between the pulse duration and time of the high absorption domain formation, the various parts of the pulse are reflected from this domain, and they propagate in the direction opposite to the initial direction of the pulse propagation.

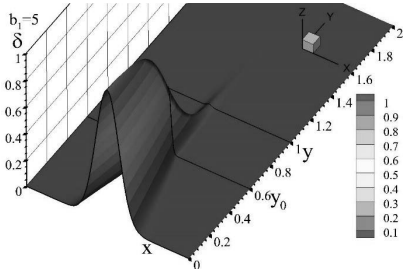

Figure 1: Fig.1 Fixed (stationary) high absorption domain.

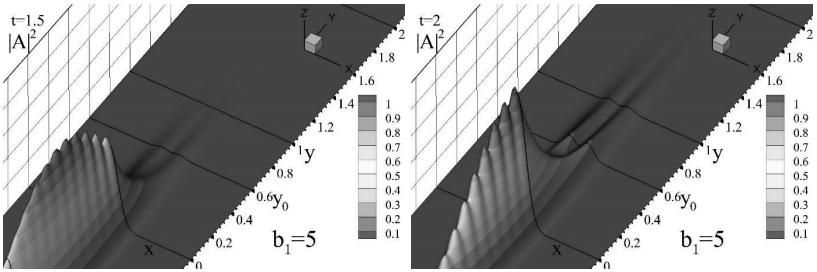

Figure 2: Evolution of the beam intensity profile at its interaction with fixed high absorption domain at time t=1.5 (a), 2 (b) dimensionless units. The incident beam profile is stated in the Gaussian form.

Mathematically the problem under consideration is described by the set of time-dependent nonlinear PDEs, which involves the Poisson equation concerning laser-induced electric field potential and equations concerning free electron and ionized donor concentrations. The laser pulse propagation in a semiconductor is described by the nonlinear Schrödinger equation with respect to the complex amplitude, slowly varying in time only. In this case, we can provide adequate modeling of a wave reflected from a high absorption domain.

In this study, we present the computer simulation results obtained on the base of specially developed finite-difference scheme [3]. To verify appearing of the reflected wave, we firstly consider the laser pulse propagation in a medium containing the stationary domain of high absorption (see Fig.1). Its spatial structure does not depend on the absorption of an incident laser energy. We investigate the influence of the reflected wave on the high absorption domain formation at different problem parameters: the incident beam profile, the width of the high absorption domain, the diffraction coefficients (Fig.2). After that, we provide a similar investigation for the induced domain of high absorption. The computer simulation results demonstrate that the reflected beam can change a dynamic of the high absorption domain and time of the switching essentially.

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Control of coherent radiation spectral properties in mid-IR by varying focusing conditions

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Harmonics and supercontinuum generation are the well-known and widely studied nonlinear phenomena both in gases [1,2] and in condensed matter [3,4]. The emission of harmonics in bulk solids is one of the possible ways to create compact sources of coherent radiation in the ultraviolet range [5]. Supercontinuum is used in time-resolved spectroscopy [6] and in seeding optical parametric devices [7]. The effect of focusing on the broadening of 800-nm pulse spectrum was studied in [8]. However, the influence of focusing on the efficiency of nonlinear processes in the mid-IR wavelength region is poorly studied.

In this work, we studied numerically how the focusing conditions control the harmonics and supercontinuum generation during the propagation of high power (up to $9\,P/P_{cr}$) mid-IR 200-fs laser radiation (4.4 μm) in fluorites (CaF_2). We simulated ultrashort pulse propagation using UPPE equation for electrical field calculations and single rate equation with multiphoton, tunneling, avalanche ionization and recombination for electron plasma dynamics.

When a laser pulse has relatively low power ($0.003\,P/P_{cr}$), only the low-order harmonics generation appeared. We observed that the larger harmonics efficiency is proportional to the 4th degree of the focal length. This indicates that the harmonics generation is determined by the confocal parameter – the interaction length for harmonics generation. When pulse power is more than critical one, the Kerr nonlinearity and plasma generation acted. It is shown that harmonics efficiency before the focal point is almost independent on focusing condition, that relates with the balance between the intensity growth during focusing and the interaction length increase (the first one is higher for tighter and the second one for looser focusing). At the focal point the intensity of the short-wavelength part of the spectrum increases under tighter focusing due to more intensive self-phase and cross-phase modulation.

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Theoretical and experimental estimations of nonlinear refractive index for various media in THz frequency range

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Despite the growth of interest to nonlinear devices and components for light by light control in the terahertz (THz) range, there still is a shortage of such media used for these purposes. Observation of nonlinearities in the THz frequency range is carried out without implementation of direct measurements of material properties in most cases. The important parameter characterizing the nonlinearity of the material response in the field of intense waves is its coefficient of nonlinear refractive index, usually denoted by n_2. Recently the theoretical prediction of an extremely large nonlinear refractive index for crystals at terahertz frequencies was made considering SiO_2 crystal only. The value of n_2 appeared to be about 10^{-12} W/cm^2 [1]. In this model the nonlinearity is associated with anharmonic vibrations of the lattice.

Due to its high transparency in the visible and IR, as well as in the THz frequency range (from 100 μm), crystalline quartz is undoubtedly a common material for components of terahertz technology. However, vibrational nonlinearity in the THz frequency range is worth considering as well, when working with electro-optical crystals used to detect and generate THz radiation. Therefore, in this work we estimate the nonlinear refractive index coefficients of ZnSe, ZnTe, CdTe, GaP, $LiNbO_3$ using the theoretical model mentioned. For instance, the model showed values for $LiNbO_3$ of the order of 10^{-11} W/cm^2, which is consistent with other experimental estimates [2].

These coefficients can be measured directly employing closed aperture z-scan technique, applicable for THz pulsed radiation if thin samples are used [3,4]. However, regarding the case when common intense pulsed THz sources based on $LiNbO_3$ with 10^8 W/cm^2 intensity [5] are employed, the difference between the peak and valley of closed aperture z-scan curve is less than system noise in such experiments.

Although, it was experimentally shown that liquid water has larger n_2 value in the THz range [4] (of the order of 10^{-10} W/cm^2). In this work, we present estimates of vibrational nonlinearity for various liquids such as water, heavy water, ethanol and α-pinene and eliminate the influence of different mechanisms inducing the refractive index.

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Pushing harmonics generation efficiency by resonant phase matching in mid-IR

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We demonstrate efficient generation of harmonics up to 11th order in a gas mixture containing 44 - 48 bar of xenon and 1 bar of carbon dioxide from mid-IR laser field. Obtained conversion efficiency reaches 1% into third harmonic and 0.3% into higher ones [1]. In previous papers harmonics were generated in conventionally accepted conditions of near- and mid-IR filamentation in low dispersive media such as air or noble gases with highest efficiencies into third harmonic of 0.5% [2] and 0.13% [3] for 2 and 4 μm drivers, respectively.

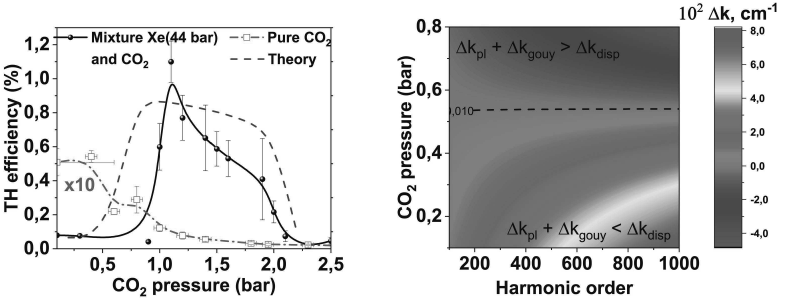

Figure 1: a) Evolution of third harmonic (TH) yield with CO_2 pressure in gas mixture (solid black) and pure gas (dash dot red). Blue dashed lines shows calculated data. b) Phase matching in XUV region.

In this contribution we show that efficient harmonic generation can be achieved in completely contrary conditions of strong dispersion provided by molecular resonance and moderate intensity of 1.8×10^{13} W/cm^2 eliminating influence of free-electron plasma. Manifold increase of conversion efficiency into harmonics is attributed to resonant interaction of mid-IR pump and carbon dioxide molecules, which absorption spectrum partially overlaps with pump one. We shed light on some aspects of resonant light-matter interaction showing that in the case of femtosecond pulses nonlinear refractive index does not increase by several orders near the resonant band as was reported recently for nanosecond pulses [4]. Even higher conversion efficiency was found in argon/carbon dioxide mixture, where pump experience lower losses due lower carbon dioxide phase matching pressure.

Moreover, our treatment shows that resonant molecules may also bring new opportunities for harmonic generation in XUV region, where efficient phase matching of particular importance. Fast change of the refractive index in the vicinity of pump spectrum allows for simultaneous phase matching of large number of harmonics, which has not been attained with plasma induced resonances yet.

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Energy deposition and terahertz radiation generation under the loose focusing femtosecond radiation in air in presence of electrostatic field

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Femtosecond laser filaments in air are the source of terahertz radiation and can provide a remote diagnostics of objects. The presence of static electric field can enhance the THz signal from the filament [1].

In our experiments we used laser system, based on Ti:Sa crystal (805 nm, 10 Hz, beam diameter (FWHM) 14 mm, energy up to 30 mJ, pulse duration 55 fs) to form filaments. The filament was created in air by a lense with focal length 262 cm.

For the energy deposition diagnostics we used two independent methods. Firstly, the terahertz radiation was detected using a Golay detector (Tydex, GC-1P) with two teflon lenses (diameter – 5 cm, focal lengths – 15 and 5 cm). Golay detector with TPX lenses was mounted on a rotational rail. Since the Golay detector is intended firstly to record the power of quasi-continuous terahertz radiation, we had conducted a test experiment to calibrate the Golay detector in the recording mode of a single terahertz pulse. Secondly, to reveal multifilament transverse spatial structure and the relative plasma concentration we employed the novel high-resolution acoustic method [2].

We made acoustic measurements in the extensive number of longitudinal coordinate points thus acquiring filament evolution information. According to acoustic measurements the filament length was 32 cm.

To enhance the THz signal we placed two aluminum plane electrodes across the filament to create a static field in the filamentation zone. The electrostatic field was set 10 kV/cm. Width of the electrodes was 5,5 cm, length varied from 4,5 to 37 cm.

We measured dependence of the filament and electrode lengths and mutual position. For 4,5 and 37 long electrodes we also investigated the radiation pattern of the THz radiation with knife-edge method, diaphragm and rotating the rail with Golay detector and TPX lenses. Spectral dependencies were investigated with band pass filters and Michelson unterferometer.

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Red-shifted spectral hump generation during filamentation in atomic gases

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Spectral broadening of a femtosecond laser pulse propagating in a filamentation regime was observed almost at the very beginning of investigation of this phenomenon [1]. The spectral red-shift in this paper was attributed to the pulse self-phase modulation. In later studies the formation of spectral hump in the region of longer wavelengths was associated with Raman effect [2-4]. In this study we aim to find out what is the origin of this spectral hump formation. We conduct our experiments with the pulses from Ti:Sapphire laser system with the central wavelength of 744nm and the duration of about 90 fs. The laser beam has adiameter (FW at 1/e) of 3.2 mm and is focused to a gas cell with the lens f=115cm. In all cases we measure spectra of a bright spot in the transverse fluence distribution. The Fresnel reflection of this spot from a glass plate is directed to a spectrometer.

First, we compare the spectra after the filamentation in different gases (including atomic ones). The 196 cm long gas cell could be filled with different gases (air, Ar, Xe) or evacuated. The critical power of self-focusing, clamping intensity and peak plasma density can strongly depend on the propagation medium. Therefore the quantitative comparison of different gases is not valid. That is why we focused on the qualitative analysis of the spectra, namely on the presence or absence of the spectral red-shift in a form of a hump. Quantitative study of the spectral hump in air has been presented in [5,6]. Obtained spectra after filamentation in ambient air, xenon and 2 bar of argon are shown in Fig.1. We can observe the presence of several spectral humps shifted to the long wavelength region in comparison with the initial spectra in every case. That is why we doubt the Raman origin of this hump formation, as predicted in [5,6]. Second, we observe the dependence of spectral hump red-shift on the propagation distance in air and in atomic gas (argon). To carry out this experiment we place a glass plate inside the gas cell. Scattered light reaches the spectrometer through the transparent side window of the cell. Varying the distance between

the lens and the reflecting plate, we observe similar increase of the longer wavelength spectral wing shift with the propagation distance in air and argon. Thus, we discovered the formation of a red-shifted spectral hump during filamentation in both molecular and atomic (xenon and argon) gases. This hump cannot be attributed to stimulated Raman scattering due to rotational transitions in molecules. Indeed, it is the result of pulse self-phase modulation [5,6].

The research was supported by the Russian Foundation for Basic Research (grants 20-02-00114, 18-02-00954, 18-52-16020).

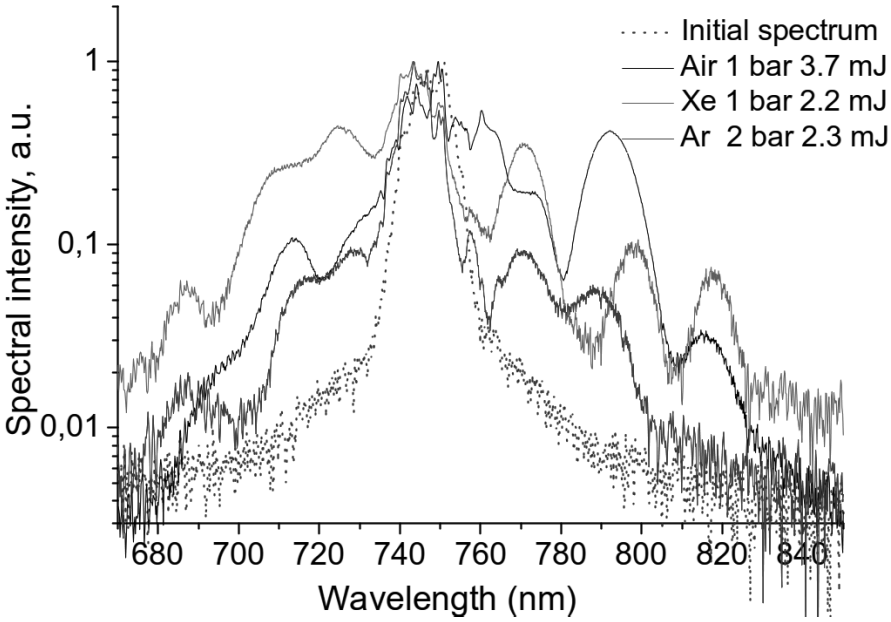

Figure 1: Normalized spectra after filamentation in different gases

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Study of THz and X-ray generation at TW laser pulses ablation of an Al foil

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Single-cycle terahertz (THz) pulses with a high-intensity electric field can be obtained by the conversion of multi-terawatt femtosecond laser radiation. Conversion into THz range via metal irradiation is one of the perspective methods. This process is known to be rather effective (up to 10^{-3}) at relativistic intensities, above 10^{18} W/cm^2 due to electron bunch acceleration[1]. For low intensities, below the ablation threshold, the efficiency of THz generation is below 10^{-7}, due to metal nonlinearity[2]. In the intermediate case of the sub-relativistic intensity of $5 \cdot 10^{16}$ W/cm^2 we observed the efficiency of THz generation in the order of 10^{-5} together with X-ray bremsstrahlung and characteristic radiation in the preliminary experiment. Possible generation mechanisms of THz radiation are discussed. We use the laser system "Pulsar 200 TW" installed in NRC "Kurchatov Institute", capable of generating 800 nm, 25 fs pulses with the energy of up to 7 J. In present work we used energy below 60 mJ. With 30 cm focusing mirror and 70 mm diameter beam we irradiate 10 microns thick Al and Cu moving foils. Laser intensity on the target surface is optimized by x-ray yield maximization. The ablation rate and hole diameter provide additional information about the actual beam waist size [3]. We compare THz and X-ray generation efficiency with the case of two-color gas plasma at low-pressure nitrogen. For tight focusing and 10 mbar pressure, THz generation from metal is comparable with a two-color gas plasma case, while maximal THz energy is obtained for loose focusing in the two-color scheme [4]. The advantage of metal THz generation - is the absence of saturation at energy increase.

This work was partially supported by RFBR grants 18-52-16024, and 18-02-40032

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3D structure of backwards-amplified UV radiation in Nitrogen plasma filaments

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Backwards amplification of UV radiation in atmospheric filaments has a huge potential as a source of intense, directional and coherent probe pulses for remote sensing applications. However, the swept-gain nature of these amplifiers strongly hinders backwards amplification. It is thus necessary to understand all the mechanisms involved in order to optimize backwards amplification.

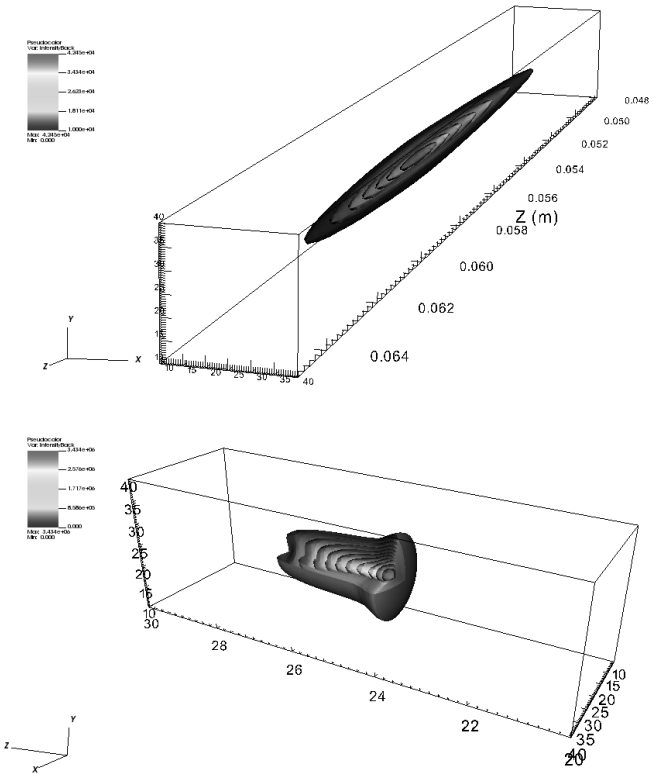

Figure 1: 3D structure of backwards-amplified UV spontaneous emission (top) and injected UV seed (bottom) in a 3 cm Nitrogen plasma filament.

In this presentation we will show 3D modelling of forward and backward amplification of UV radiation in Nitrogen plasma filaments and compare the results with previous experiments [1,2] and modelization [3]. Finally, we will show that the spatio-temporal characterization of the amplified beams allows to unveil some of the plasma and amplification dynamics.

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Diffraction-driven filament competition in focused femtosecond multifilament bundle

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The problem of filament interactions, playing the key role in superfilamentation and being of interest for multifilamentation control, has been tackled in a number of works [1-4]. However, the mechanism of the filament interactions in course of superfilamentation process, as well as the influence of additional focusing and beam modulation on this interactions, still requires further investigation. In this report, we have experimentally studied filament interactions in loosely focused multifilaments for numerical aperture (NA) ranging from $2.1 \cdot 10^{-3}$ to $1.3 \cdot 10^{-2}$, paying particular attention to the role of diffraction, self-focusing and self-phase modulation in the interaction process. The multifilament bundle was created by the radiation of a Ti:Sa laser system, delivering pulses with energy in the range of 1–20 mJ, 50±5 fs duration, 812 nm central wavelength, 10 Hz repetition rate and 8 mm FWHM beam diameter). We investigated two propagation modes: stochastic multifilamentation, when initial radiation transverse structure was defined by amplitude and phase inhomogeneities of the laser beam and regular multifilaments created using an amplitude mask. To obtain the data we employed a set of techniques including broadband acoustic diagnostics [5], luminescence and interferometric data (for 50 cm focusing), radiation mode measurements (for 310 cm focusing) and the radiation frequency angular spectra detection with simultaneous control of the laser pulse energy.

The measurements have shown that in amplitude regularized mode superfilament formation behaves rather like new filament emergence and growth during diffraction "competition" than like gradual merging of the seed filaments. This can be explained by diffraction-driven evolution of the energy reservoir and the intensive IR-shifted spectral components, which travels in the front of the pulse. Initial four-lobe beam (formed by the amplitude mask) gives one intense maximum in the Fourier plane of the lens accumulating most of the reservoir energy. Once the considerable amount of reservoir energy is concentrated around the beam center, the new central filament emerges and initial filaments fade away. This behavior substantially differs from the stochastic multifilamentation in which the reservoir gradually contracts to the propagation axis. There is no local minimum in energy deposition and luminescence signal dependencies

in this regime, pointing out at more gradual evolution of plasma concentration than in amplitude regularized mode.

Our study revealed that diffraction transformation of the laser beam plays the key role in femtosecond filament merging and energy exchange in the presence of additional beam focusing. In this case, conical emission ring structures do not make any significant contribution to the filament interaction process. The pre-defined beam pattern provides a way to influence not only the initial transverse multifilament structure but also energy deposition dynamics during the multifilament propagation.

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Comparative study of low-order harmonic generation in gas and cluster media at Ti:Sa femtosecond laser intensity up to 2000 TW/cm^2

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Low order harmonics of intense femtosecond laser in gas cluster media is of interest for creating efficient coherent UV sources with duration of 10^{-13}–10^{-14} s. The laser energy conversion efficiency to harmonic depends on its number and for the third and the fifth harmonics it can reach values of $\sim 10^{-3}$–10^{-4}. These sources open the possibility of studying ultrafast processes of molecular states photoexcitation and photodissociation. Low order harmonics can be used as seed radiation when amplified in femtosecond Kr2 and Xe2 excimer systems which have wide amplification bands and relatively high saturation energies. It should be noted that the photon energy at the frequency of the Ti:Sa laser fifth harmonic coincides with the energy of the 229mTh state that can be used for nuclear isomer excitation.

The subject of this work is a comparative theoretical and experimental study of the laser energy conversion efficiency of the third harmonic generation (THG) induced by femtosecond Ti:Sa laser in Ar gas and Ar cluster medium. Clusters were generated by the technique based on supersonic gas expansion through the conical nozzle into vacuum. Laser harmonics were generated under action of the femtosecond laser radiation: λ=810 nm, E=5 mJ, τ=300 fs, F=30 cm, I=2 PW/cm^2. Variation of laser intensity and THG optimization were provided by moving laser focus relatively to the cluster jet boundary (see Fig.1). Formation of the laser filament in a cluster jet is caused by nanoplasma nonlinearity, which leads to a significant decline conversion efficiency of THG. Comparison of the conversion efficiency of THG in a gas cell and cluster medium is shown in Fig. 2. The difference in the harmonic generation efficiency probably arises because in the case of the cluster jet, the third harmonic is generated only by the diverging part of the laser beam.

We also present the numerical calculation based on the model [1] in which the nonlinear gas medium is simulated as a chain of atoms oriented along the propagation direction of laser field. THG process was calculated in the paraxial approximation. Experimental and numerical results of the third harmonic efficiency as a function of the atomic density demonstrate quadratic growth in the low gas pressure region (see Fig.2) as a result of phase matching process. Then,

as the gas pressure increases the third-harmonic generation efficiency decreases due to the phase mismatching process (see dash curve).

We discuss the results of numerical calculations of the third, fifth and seventh harmonics generation process in a cluster environment, and compare the results of calculations for a free argon gas and argon cluster jet.

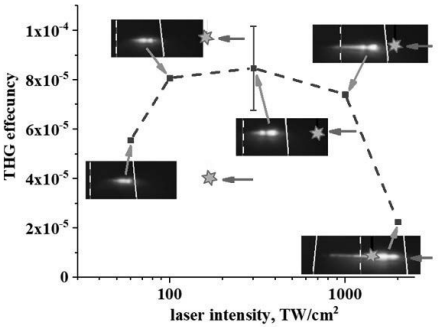

Figure 1: Efficiency THG in gas-cluster jet and the laser filament evolution versus laser intensity at the jet boundary. Ar backing pressure 30 bar, average cluster diameter $\sim$ 50 nm.

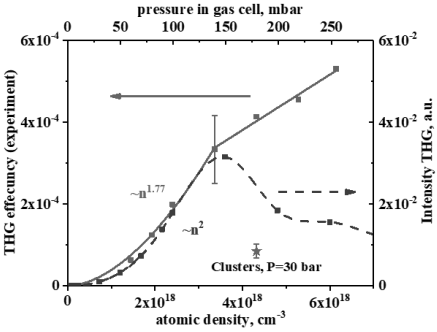

Figure 2: Efficiency THG and calculated TH intensity versus on the atomic concentration in gas cell.

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Generation of tunable mid- and far-infrared pulses during gas ionization by a chirped two-color laser field

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Generation of short and carrier-envelope phase (CEP) stable pulses of mid-infrared (mid-IR) radiation is essential for solving various problems in strong-field physics and time-resolved spectroscopy [1,2]. In the absence of broadband mid-IR laser gain media, coherent mid-IR sources usually employ difference-frequency generation [2, 3] and parametric downconversion [4] of ultrashort IR laser pulses in nonlinear crystals, supporting passive CEP stabilization. Despite the significant progress achieved in this direction, the generation of intense widely tunable few-cycle pulses in the mid-IR range remains a substantial and unsolved problem (particularly in the long-wavelength part). The main difficulties are caused by the limited operating frequency band due to the dispersion and absorption of the pump and the generated light [3, 4].

In this work, we propose and investigate a method for generating tunable and phase-controllable mid- and far-infrared pulses in gas ionized by an intense two-color laser field composed of the chirped fundamental and its second harmonic pulses with the group time delay. The generation frequency equals to the difference between the second harmonic and the doubled fundamental frequencies and is continuously tunable by varying chirp or time delay. The duration of the generated pulses is determined by ionization duration, which is much smaller than the duration of the ionizing field and is controlled by stretching or changing the intensity of the driving pulse. Our quantum-mechanical calculations and analytical description show that this method can provide a wide tuning range spanning from several to more than a hundred THz using femtosecond lasers.

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Nonlinear compression of high power ultrashort pulses from Cr:forsterite laser in hollow-core waveguides filled with argon

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High power ultrashort pulses in infrared (IR) spectral range are a key tool for intense laser-matter interaction, ultrafast diagnostics, highly nonequilibrium states formation, etc. They also open up possibilities for frequency conversion in hardly accessible spectral ranges. One of the most attractive fields is generation of coherent XUV radiation via high-order harmonic generation (HHG), which can be applied for free-electron laser seeding [1], coherent diffraction imaging [2], spectroscopy [3], etc.

Post-compression of IR pulses can be implemented via spectral broadening in hollow-core capillary filled with gas and further group velocity dispersion compensation. A plenty of results aimed on compression of Ti:Sapphire (800 nm) and Yb based ($\sim$1 μm) laser pulses have been reported [4]. The main challenge of millijoule pulse compression consists in occurrence of self-focusing and gas ionization. In terms of ponderomotive energy scaling, which is proportional to wavelength squared, and HHG cutoff frequency increasing, shifting wavelengths to mid-IR seems interesting, but the number of such high power sources is limited to date. Changing Ti:Sapphire laser to Cr:forsterite (1240 nm) allows HHG cutoff energy increase from 120 eV to 400 eV [3].

In this work, post-compression of 1240-nm 170-fs 2.5 – 8-mJ pulses in hollow-core capillary filled with argon has been studied. The capillaries with 220 μm and 250 μm core diameter, 100 cm and 50 cm lengths correspondingly have been considered. Dispersion compensation has been performed by chirped mirrors inducing group delay dispersion near -150 fs^2 per bounce. The generalized nonlinear Schrödinger equation containing attenuation, dispersion, Kerr nonlinearity and self-steepening terms has been solved numerically for optimal compression regimes revealing.

A compression of 1.24-μm pulses with 2.5 mJ input energy up to 20 – 25 fs (by a factor of 7 – 8) and threefold peak power increase with 65% of initial energy conservation in argon-filled capillary has been shown theoretically. The gas pressure has been varied between 0.5 – 1.5 bar and 1 – 5 reflections from chirped mirrors have been chosen. The main pulse contains 50% of output energy. Similar results can be obtained for 8 mJ pulse energy with pressure decrease to 0.1 – 0.3 bar.

Thereby, a possibility of 1240 nm and 2.5 – 8 mJ pulse compression in capillaries has been shown. In experiment one can expect spectral broadening and pulse shortening up to 20 fs.

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Femtosecond strong field ion excitation and subsequent lasing in N_2^+

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Delayed cavity-free forward lasing at the wavelengths of 391 and 428 nm was observed in recent experiments in air or pure nitrogen pumped with an intense femtosecond laser pulse at wavelength of 800 nm. The mechanism responsible for the lasing is highly con- troversial [1]. Two aspects of the results are particularly challenging to explain. First, how is optical amplification between the ground state $X^2\Sigma_g^+$ and the excited state $B^2\Sigma_u^+$ of singly ionized nitrogen molecules N_2^+ obtained under the given pumping conditions? Second, how can one explain a delayed amplified emission?

In this presentation we explain the delayed emission by the experimentally confirmed presence of long-lived polarizations in a three-level V-scheme coupling simultaneously ground state $X^2\Sigma_g^+$ to states $A^2\Pi_u$ and $B^2\Sigma_u^+$ of molecules N_2^+ without population inversion. Ionization of neutral nitrogen molecules in a strong laser field and subsequent ion excitation are described by a system of Bloch equations providing a distribution of ions in the ground and excited states A and B at the end of the laser pulse. The delayed signal amplification at the B-X transition wavelength is described by a system of Maxwell-Bloch equations in a V-scheme with polarization coupling maintained by a weak laser post- pulse. Two regimes of signal amplification are identified: a parametric amplification of a signal of a few ps duration at low gas pressures and a short (sub-picosecond) soliton-like signal generation at high gas pressures. The theoretical model compares favorably with available experimental results. The cavity-free lasing in air holds a unique potential for optical remote sensing applications.

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Spectral profiling of THz beams

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The studies of terahertz (THz) beam profiles [1] provide knowledge about physical processes of the generation and propagation of electromagnetic pulses. A specific interest to the THz beam intensity profile measurements is due to the study of nonlinear THz effects, for example with z-scan technique [2].

The results of experimental study of broadband terahertz radiation focusing by lenses and Fresnel zone plates are presented. It is demonstrated, that applying of lenses for the THz beam focusing leads to appearing of ring structure in spatial distributions of THz radiation intensity in beam waist region. This structure can be attributed to diffraction effects. The use of Fresnel zone plated for focusing of broadband THz pulses is demonstrated. The control of divergence of the radiation at selected frequencies is shown. Experimental results are in agreement with numerical simulations.

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Modulation of the anti-Stokes wing of the light bullets sequence spectrum

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The formation of high-intensity and extremely compressed light bullet during the filamentation of high-power femtosecond radiation is inseparably accompanied by super-broadening of spectrum, overlapping a wide band from the ultraviolet to the infrared region [1]. Under condition of anomalous group velocity dispersion the broadening of the spectrum towards Stokes and anti- Stokes regions relative to the carrier wavelength is significantly asymmetric. The spectral intensity curve in the Stokes band declines monotonically with increasing wavelength, while in the anti- Stokes region one forms an isolated wing, location and parameters of which depends on the assembly of characteristics of radiation and medium [2].

Experimentally, analytically and numerically one investigated features of transformation of the anti-Stokes band of radiation spectrum during the formation of a light bullet sequence in the filament. The propagation of a high-power femtosecond pulses focused in the SiO_2 and CaF_2 samples was considered.

Using the axicon as a focusing element leads to formation of a Bessel-Gaussian spatial transverse structure of radiation in the form of intense central maximum and surrounding rings with lower intensity [3]. Such intensity distribution provides a greater resistance to the occurrence of multiple filamentation in the medium compared to lens focusing. With that, variation of the axicon focusing parameters allows one to control the position and length of plasma channels during filamentation [4].

It is shown that the formation of the second and subsequent light bullets in a filament causes an appearance of high-frequency modulation of the anti-Stokes wing of the spectrum. The modulation period decreases as the wavelength of the corresponding spectral component decreases. It is established that the reason of spectrum modulation is an interference of broadband supercontinuum radiation, the source of which are light bullets.

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Bulk damage when structuring a diamond surface by ultrashort laser pulses: theory and experiment

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Optical breakdown and damage of the bulk is a serious issue when structuring a surface of diamond by ultrashort laser pulses [1]. To study the causes of the bulk damage and to find a way to eliminate it, experimental and theoretical investigations were performed.

Laser irradiation of diamond was carried out using a disk Yb: YAG laser (λ = 1030 nm, τ = 1 ps). The laser beam was focused at the surfaces of mono- and polycrystalline diamond samples. Surface graphitization and ablation, as well as the volume damage, were studied by optical microscopy. The geometry of the damaged areas suggests a filamentation of the laser radiation, which is observed for the first time for diamond.

Nonlinear Schrödinger equation for the electromagnetic field was solved numerically to simulate the propagation of laser radiation in the diamond bulk. An interplay of multiphoton absorption, diffraction and optical Kerr effect was found to be the cause of the focusing of the light and breakdown in the volume. Possible ways to eliminate this undesirable focusing during the diamond surface structuring by ultrashort laser pulses are discussed.

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Evolution of the frequency-angular spectra under superfilmentation of femtosecond laser radiation in air

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The superfilamentation regime, discovered in a recent work [1], is a special case of the multifilamentation that occurs under condition of additional weak focusing at a laser pulse power that is many times greater than the critical self-focusing power. To date, plasma channels transverse structure evolution and the spatial distribution of the radiation fluence (without frequency resolving) in the superfilmentation mode has been studied [2], but the evolution of the frequency-angular spectra (FAS) of superfilament radiation have not yet been studied in detail in the literature.

In this work, we have studied the evolution of the frequency-angular structure of radiation upon superfilmentation of femtosecond laser radiation in air. We focused our attention on the radiation FAS evolution in the process of coherent merging of four converging filaments. To create a regular (reproducible from shot to shot) spatial structure of the multifilament, an amplitude mask was used, which was an opaque plate with 4 holes [3]. The frequency-angular spectra were measured under the same filamentation conditions as in our works [4, 5, 6], where the acoustic signal and the spatial mode of multifilament radiation were studied.

When the filaments are formed, the radiation spectrum broadens compared with the initial pump spectrum forming new spectral maxima (in particular, the maximum in IR, which can be interpreted as corresponding to the light bullet [7]). During the filament fusion in amplitude-regularized multifilamentation mode, a maximum is formed in the center of beam near the geometric focus of the lens. The spectrum of this maximum is similar to the spectra of the initial filaments. As it is clear from the comparison of linear diffraction evolution of this beam mode with the multifilament bundle evolution, the decisive role in the formation of the spectrum on the main axis is played by the interference of the radiation of the initial filaments. CE components are almost absent at the FAS at these distances, therefore they can not make any significant impact on filament merging in this regime. When the critical power in the central maximum is reached, this radiation gives rise to a superfilament. Therefore, diffraction has a crucial impact on the superfilament formation at least at the amplitude-regularized regime, since the superfilament is "born" from the diffraction maximum. After the superfilament is formed, self-phase modulation

(with possible impact of the delayed Raman response of the medium) broaden the spectrum of its radiation in the IR spectral wing, resulting in significantly broader spectrum than one of the initial single filaments. In the postfilamentation mode, the self-phase modulation process does not stop and leads to an even greater IR-shift of the existing spectral maxima and the formation of the new ones.

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Temporal dynamics of air lasing from molecular nitrogen ions

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Air lasing created remotely in air has attracted much attention due to its promising applications in remote atmospheric studies [1–3].

In this report, the temporal and spectral characteristics of self-seed lasing effect corresponded to the $B^2\Sigma_u^+ - X^2\Sigma_g^+$ (0-1) transition of molecular nitrogen ions was investigated in forward direction. The experiments were performed by using a 10 Hz/60 fs/950 nm/10 mJ laser pulse from a Ti:sapphire laser complex. The laser plasma was created in air by different plano-convex lenses with 30, 40, or 50 cm focal lengths. The spectral-time parameters of lasing were recorded by a streak camera (Hamamatsu, Universal Streak Camera C10910) combined with a spectrometer (Acton Spectra Pro SP-2300). According to our measurements, lasing has linear polarization coinciding with the pump. Lasing pulse duration (3-5 ps) depends on the length of laser plasma, and lasing power depends on the pump peak power.

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Section 5: Femtosecond radiation in spectroscopy and optical frequency metrology

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Scope

Absolute optical frequency measurements

Femtosecond frequency combs for direct spectroscopy of ions and atoms

UV and HUV frequency combs

Frequency combs in astrophysics

Time and frequency transfer

Optical frequency combs applications

Spectroscopy of Rb atoms in a pulsed optical dipole trap

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We report on a study of the atom trapping in a pulsed optical dipole trap of femtosecond duration [1,2]. Pulsed laser radiation is regarded as a laser source for cooling and localization of atoms with absorption lines are in the ultraviolet range of the spectrum. This primarily refers to the atoms used in organic chemistry (oxygen, nitrogen). For basic research, the development of cooling and localization methods using radiation in the ultraviolet region of the spectrum is interesting for cooling and trapping of hydrogen and antihydrogen.

To study the spectral properties of atoms in a pulsed dipole trap, a spectroscopy method using selective resonant heating was developed [3]. This made it possible to compare the spectral properties of atoms localized in a pulsed trap and a trap formed by cw laser radiation. Experimental data show that at low intensities of localizing field the spectral properties of atoms are the same. Under such conditions, in both types of traps, there is a shift in the absorption line of the probe field caused by the ac-Stark effect induced by the trapping field. However, theoretical estimates show that increasing of average intensity of pulsed field leads to the more complicated spectral properties of trapped atoms. When the intensity is increasing, the spectral line splits. Moreover, there is an "appropriate" average intensity when the spectral shift of absorption line is absent [4]. Such properties of pulsed optical dipole trap open up the possibility for spectroscopy without optical shift with using of arbitrary wavelength of trapping laser.

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The particularity of WGM frequency combs applications to microwave signal generation for space and time metrology

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One of the most important tasks in the metrological support of time and frequency measurements is a development of an extremely stable microwaves sources. These devices are necessary for the transmission of the reference frequency signals and for use as part of mobile sources of time and frequency reference signals. They are also required for precision ultra-high resolution spectroscopy.

The possibility of the microwave generation using the optical frequency combs is a well known fenomena [1]. The microwave signal of tens GHz is formed between the teeth of the optical comb, which is the set of the equidistant spectral lines. In our research we are focused on the comb generation using whispering gallery mode (WGM) resonators. Combs are generated in WGM resonator using nonlinear effects, mainly Kerr or Blillouin effects. Usually, Kerr combs consist of tens or hundreds of lines, while Brillouin combs consist of several lines. Another difference is that Brillouin lines are generated one after one through cascaded process, while Kerr comb lines rise all simultaneously.

Previous researches showed the possibility of generation of microwave signal with Kerr combs with an instability up to 10^{-13} [2,3]. Almost the same instability (5×10^{13} at 1 s) was reached with Brillouin effect [4]. At the same time it was found, that the noise reduction up to -40 dB/Hz is achieved by cascading the Brillouin effect [5]. This is possible without additional stability circles in the setup. This is why the Brillouin combs are interesting for studies as the sourses of the stable microwave signal.

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Realization of a qudit readout in $^{171}Yb^{+}$ ion with complete state measurement

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The development of a quantum computer is one of the most important tasks of modern physics. At present, a quantum computer has already demonstrated supremacy over classical computers in solving certain problems [1]. An array of ions trapped ultracold ions in the Paul trap are among the most promising platform for quantum computing [2]. The internal state of each ion represents a unit of quantum information (qubit), and ions' state entanglement in the register occurs due to the Coulomb interaction. The advantages of this platform are robust trap lifetimes, long internal-state coherence, strong ion-ion interactions, the high fidelity of the preparation and readout [3], and the high fidelity of quantum gates [4]. The main technical challenge of the ion platform is its scalability. This problem can be solved by shifting from two-levels qubits to d-levels qudits. Qudit-based processors will be more efficient in simulations of higher-dimensional quantum systems [5], quantum error correction [6]. In this work, we present an experimental realization of encoding qudit states in hyperfine sublevels of a ground state $^{2}S_{1/2}$ of ultracold $^{171}Yb^{+}$ ion. Moreover, for the first time, the shelving technique using metastable state $^{2}D_{3/2}$ for measuring qudits is demonstrated.

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Surface and bulk scattering engineering in microresonators for enhancement of laser stabilization via self-injection locking

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Compact narrow-linewidth lasers and effective sources of optical frequency combs are important tools of modern optics, photonics and spectroscopy. Recent studies have demonstrated the possibility of using high-Q optical whispering-gallery-mode (WGM) resonators for realization of high-power single-frequency emission with sub-kHz linewidth [1] due to the self-injection locking effect [2] and for soliton comb generation from the compact multi-frequency diode laser locked to high-Q optical microresonator [3,4]. The laser is stabilized due to the resonant Rayleigh scattering on the internal and surface inhomogeneities, when a part of the incoming radiation is reflected back into the laser, providing fast frequency-selective optical feedback. In this work, we study in detail the stabilization efficiency of a laser self-injection locking to high-quality-factor WGM microresonator, crystalline or on-chip, for a wide range of Rayleigh scattering values.

It can be shown that the optimal parameters of the self-injection locking setup are mostly determined by the intrinsic microresonator parameter $\mu = \frac{\gamma}{\delta_0}$ that is backscattering coefficient. Here, γ is the backscattering rate (half of the mode splitting value) and δ_0 is the microresonator internal loss rate [5]. The parameters γ and δ_0 were divided into internal ("bs" - bulk scattering) and surface ("ss" - surface scattering) parts:

$$\mu = \frac{\gamma}{\delta_0} = \frac{\gamma_{\text{bs}} + \gamma_{ss}}{\delta_{bs} + \delta_{ss}}. \tag{3}$$

The surface scattering depends on the microresonator geometry and surface roughness, whereas the bulk scattering depends on the microresonator material and geometry. Theoretical analysis showed that normalized backscattering μ can be increased by decreasing surface roughness despite the fact at the same time both backscattering rate and intrinsic losses of the microresonator also decrease. To set the backscattering coefficient at optimal value, providing global maximum of the stabilization coefficient, the geometry and material of the microresonator can be selected at the manufacturing stage.

The results of the proposed model were tested on the experimental data [3,4], where the self-injection locking effect and soliton comb generation from the compact multi-frequency diode laser locked to crystalline MgF_2 [3] and integral Si_3N_4 [4] high-Q optical microresonator.

A detailed analysis of the presented model allows one to choose the optimal geometry and resonator material for high efficiency of laser stabilization in the self-injection locking regime.

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Stabilization of a frequency comb to an optical reference

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Optical frequency combs were developed two decades ago and now find applications in many areas of science and technology. They are indispensable part of modern optical frequency clocks, that allow connection of optical and radio-frequency domains to measure optical frequencies. In the same time, optical frequency combs referenced to ultrastable lasers are used to generate ultralow-noise radio frequencies.

In this work, we present our resent results on stabilization of a fibre frequency comb (from AVESTA) to a 1.14 μm utlrastable laser [1], which is locked to a high-finesse ULE cavity. Usage of an intracavity electro-optical modulator allows tight locking of a comb tooth to the laser, that results in transferring laser stability to full spectrum of the comb. We confirm this by observing narrow-line beat signal between the comb and another ultrastable laser at 871 nm.

A few-days-long continuous lock was routinely achieved, that paves the way for high-precision comparison of thulium optical clock to other optical or microwave clocks.

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Methane based femtosecond radio-optical reference oscillator and comb generator: stability, noise, applications

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State of the art of the Radio-optical Reference Oscillator and Comb Generator based on He-Ne/CH_4 Optical Frequency Standard and femtosecond Er fiber laser (Optical Frequency Divider) will be presented. The results of phase noise spectral density and frequency stability measurements characterizing the whole system as well as separate parts will be considered. Prospects of the development towards compact and reliable Reference Oscillator and Comb Generator as well as possible applications, for example interrogative oscillators for Cs, Rb cold atoms fountains, phase calibration of VLBI receiver equipment, detection of slowly moving objects by radars, etc will be discussed.

Clock laser systems based on half-meter long ULE cavities in vertical and horizontal mount

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Laser systems with spectral linewidth less than 1 Hz are the most vital instruments in most of high-precision spectroscopy experiments. Masterpiece systems now provide fractional frequency instability of 4×10^{-17} on 1-100 seconds averaging time [1]. Such sub-Hz systems are a key instrument in most accurate optical frequency standards: they provide spectroscopy of ultranarrow clock transitions in modern optical clocks. Moreover, "clock" laser defines stability of optical clock on short averaging times (less than ensemble preparation time) and limits stability on longer times due to Dick effect, that is determined by the level of laser noise as well. Accordingly, laser systems with a very low fractional frequency instability are more and more in demand, and our main goal is to improve their efficiency, and, as a result, to provide laser systems with fractional frequency instability about 10^{-16} on 1 second averaging time. Basic technique to obtain ultra-low fractional instability is locking laser frequency to the mode of a passive monolith ultra-stable high-finesse Fabry-Perot cavity. It has to be vibro-isolated and thermostabilized, is usually kept in ultra-high vacuum. Under those conditions fractional instability is fundamentally limited by thermal noise of cavity's mirrors (i. e. instability of length).

Allan variance of thermal noise can be used to predict best achievable fractional instability of cavity's eigenmode. In dependency on major parameters it is given as [2]

$$\sigma_y \propto \frac{\sqrt{T\times\phi_{coat}}}{L^{\xi/4}\times\lambda^{1/2}\times E^{1/2}}$$

Here, T - temperature, ϕ_{coat} - loss angle of mirror coating, L - cavity length, λ - laser wavelength, E - Young's modulus of mirror's substrate. Hence, main ideas of performing more stable laser systems are: using high-Q materials, low temperatures and enlarging base of reference cavity. The idea of enlarging cavity's base is realized by two half-meter long vertical and horizontal mount cavities made of Ultra-Low Expansion glass. Accurate calculations, proceeded for our systems, resulted in 7×10^{-17} fundamental fractional instability limit. These systems, operating on 698 nm will be used as clock lasers in Sr optical lattice clock [3].

Most recent features and difficulties for those systems like actual fractional frequency instability, vibrational sensitivity, doppler-caused instability, PDH

electronic circuit characterization, fiber lines instability and future applications are going to be discussed.

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Ultrastable lasers based on cryogenic silicon cavities

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Lasers with stable frequency are widely used in many fields of physics and technology, such as metrology, spectroscopy, astronomy and navigation. Moreover, ultrastable laser is essential for operation of modern optical clock and can limit its stability [1]. State-of-the-art laser system yields fractional frequency instability at the level of 4×10^{-17} on averaging times of 1-100s [2].

Most of the stable lasers are based on high-finesse Fabry-Perot cavities. Laser frequency can be locked to the eigenmode of a cavity viaa modulation Pound -Drever-Hall technique. Stability of laser is determined mostly by variation of distance between mirrors, which can be caused by various environmental perturbations, and imperfections in optoelectronic feedback loop. The fundamental limit on of laser frequency stability is imposed by thermal noise of cavity spacer, mirror substrates and coatings. To lower the thermal noise, one need to properly design geometry and materials of cavity.

We work on stabilization of 1.5 μm fiber laser by locking to 8-cm monocrystalline silicon cavity mounted in filled cryostat of original design. Very high mechanical Q-factor of silicon (108) and low temperature of zero CTE point (124 K) allow for reducing the level of thermal noise. Additional decrease can be provided by crystalline mirror coatings made of GaAs/AlGaAs. Towards reaching of the thermal noise limit we managed to stabilize cavity temperature at zero CTE point, isolate cavity from vibrations, and control the residual amplitude modulation in optoelectronic stabilization system.

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Optical frequency comb spectroscopy for trace gas and intermediate species detection

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In spite of the fact that optical frequency combs (OFCs) have been have been developed as precise optical frequency rulers for precise atomic spectroscopy, it was successfully used directly as a broadband light source in molecular spectroscopy. This combination creates spectrometers with a high frequency resolution and precision and highly sensitive spectral acquisition over the broadband OFC spectrum. Furthermore, comb-based Fourier-transform spectroscopy delivering spectra with no instrumental function has been demonstrated [1] and recently we have verified the precision of the comb-based spectrometer to 100 Hz level [2]. Such capabilities enable developments of broadband versions of cavity enhanced absorption spectroscopy (CEAS) [3,4], cavity mode-width spectroscopy (CMWS) [2,4-5], and cavity mode dispersion spectroscopy (CMDS) [2,4-5]. These spectroscopic methods provide background free spectra, and are less prone to the intensity noise of optical frequency comb. Therefore the comb-based cavity spectroscopies are useful to broadband determination of collisional line-shape parameters which is crucial for future spectral databases.

Apart from the fundamental studies on optical collisions, relatively easy frequency conversion to the mid-infrared wavelength range make it powerful tool for trace gas and intermediate species detection [6], which helps to determine pathways of chemical reactions relevant to atmospheric science and astrophysics. With this goal recently we have developed OFC in the mid-infrared, based on femtosecond optical parametric oscillator, working in 3-5 μm range and delivering more than 200 mW of optical power. In the presentation the ideas behind the approach will be presented altogether with the measurements of the target molecular species.

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Simultaneous optical pumping to the central magnetic sublevels of the hyperfine components of the thulium atoms ground state.

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Optical clocks have a various applications in fundamental and applied science [1]. Some of them requires transportable systems. Thulium atoms seem to be a suitable platform for transportable optical clock due to an inner-shell optical transition at a wavelength of 1.14 μm with 1.2 Hz linewidth. This transition has a low sensitivity to external static electric field and blackbody radiation the environment [2]. Other effects that cause frequency shifts in thulium optical clock were discussed in [2], with the most significant one being quadratic Zeeman effect.

To avoid frequency shift due to linear Zeeman effect we use the transition between central magnetic sublevels of ground and clock states ($|m_F = 0\rangle \rightarrow |m_{F'} = 0\rangle$). To eliminate the second-order Zeeman shift we plan to use so-called synthetic frequency technique. In this approach we are interrogating with both hyperfine components of the clock transition. These components have the same absolute value of second-order Zeeman shift but with different signs. Because of that, second-order Zeeman shift for the mean "synthetic" frequency of clock transitions between two hyperfine components cancels out (see fig.1).

In order to use this scheme we need to prepare atoms in the central magnetic sublevels of both hyperfine states. In this work we demonstrate simultaneous optical pumping into these states.

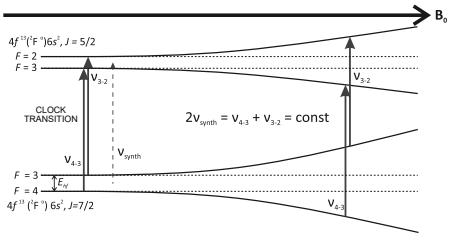

Figure 1: Concept of synthetic wavelength

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Ion traps for a scalable quantum computer

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Quantum computation is one of the hottest topics in physics today. Ion platform is one of the most promising candidates for realisation of a useful quantum computer. High fidelity gates and long coherence time using ultracold ions were already demonstrated. The next key step towards ion-based quantum computation is to overcome the scalability problem.

In this talk, an overview of approaches to scaling ion quantum computation and our contribution in this field will be presented including analysis of computation with arrays of micro point traps.

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Characterization of a microresonator in the self-injection loking regime

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Narrow-linewidth laser sources are of special demand for science and high-tech indus- trials. Microresonator-based photonics provides an effective method to make such sources less expensive by using commercial laser diodes locked to high-Q optical microresonators. Self-injection locking (SIL) of a laser diode to a whispering gallery mode (WGM) res- onator was proved to be an efficient instrument of the linewidth narrowing [1]. During SIL the laser resonator is coupled to the WGM resonator by Rayleigh backscattering as a passive frequency-selective optical feedback. Under such conditions, laser linewidth the result linewidth of the SIL laser diode can be determined by the fundamental thermore- fractive noise in WGM if the Q-factor is high enough [2]. It was found out that the SIL of a laser diode is sufficient for a Kerr comb generation in the microresonator [3, 4] resulting a solitonic pulse formation. High attainable Q-factors and small mode volume allow to decrease the soliton generation power threshold to several μW . Thus, microresonator quality factor is a crucial parameter for such devices. However, its accurate measure- ment can be a challenging task, especially in SIL regime, when traditional linewidth or ringdown time measurement isn't applicable.

In this work we proposed and tested an original technique allowed us to determine unloaded and loaded quality factors and vertical mode number p of the microresonator in the SIL regime using the dependence of the locking range $\delta\omega$ on the gap between the WGM resonator and the coupler d. Using linear theory of the SIL from [2] one may obtain that

$$\delta\omega = \frac{3\sqrt{3}}{2}\gamma\frac{\kappa_{mc}}{\kappa_m^2}\bar{k}_{d0}$$

where $\kappa_m = \kappa_{mc} + \kappa_{mi}$ is the microresonator's mode decay rate with κ_{mi} determined by the intrinsic losses and κ_{mc} determined by the external coupling, γ is the forward- backward wave coupling rate, and $\bar{k}_{d0}$ is the laser output beam coupling rate. Knowing the maximal value of the locking range, realized at critical coupling ($\kappa_{mc} = \kappa_{mi}$), we calculated $\kappa_{mc} = Q_c/\omega$ using the well-known formulas for $Q_c(d)$ from [5] and, thus, determined κ_{mi} and intrinsic resonator quality Q_i . The proposed technique was verified for the resonator with known parameters and showed good accuracy.

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Synchronisation of microoscillators in microresonators

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We report that the instability boundary of the single-mode state in Kerr ring microresonators with ultrahigh quality factors breaks the parameter space span by the pump laser power and frequency into a sequence of narrow in frequency and broad in power instability and synchronisation domains - Arnold tongues. The instability tongues are located between the Lugiato-Lefever (lower) and universal (higher) thresholds. Close to the universal threshold, the system shows a striking transition between the synchronisation and the frequency-domain symmetry-breaking regimes of operation. Both narrow and board (soliton) frequency combs can be interpreted using an interdisciplinary concept of oscillator synchronisation.

Optical frequency transfer via an ultra-stable free-space link

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The development of a network of optical clocks connected with links [1] for coherent transfer of frequency and time signals create great opportunities in such fields of science and technology as the formation of national and international time scales, satellite navigation, relativistic geodesy, very-long-baseline interferometry, tests of fundamental theories, search for dark matter. The state-of-the-art frequency standards have reached the level of relative uncertainty and instability of 10–18. Transferring signals from these standards with conservation of their characteristics using radio frequency methods is impossible, because the latter cannot provide frequency transfer instability better than 10^{-16}. One can reduce the level of the phase noise introduced by the communication link by transferring signals at optical frequencies. The development of stationary and transportable optical frequency standards shows the necessity of designing both fibre [2] and free-space [3] links for the transfer of highly stable signals.

We report the results of developing a laboratory 5-m free-space link with a system for active compensation of phase noise. We have showed that the noise introduced by the link into the signal is determined by the influence of atmospheric turbulence for Fourier frequencies f $<$ 1 Hz, and its spectrum is described by the function $f^{-2.3}$.3. The phase-noise compensation system makes it possible to reduce the link contribution to relative frequency instability and uncertainty of the transferred signal to a level of several parts of 10^{-19} for 5000 s of averaging; thus, the link can be used to compare transported frequency standards [4].

In continuation of this study we are going to increase the link length to 500 m and use an unmanned aerial vehicle with a mirror fixed on it as a moving receiver model.

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Quantum state inversion in a two-level system driven by a sequence of amplitude chirped ultrashort laser pulses

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Quantum state control is a highlight of considerable research interest nowadays [1]. Population transfer between the quantum states induced by electromagnetic fields is successfully exploited in atom optics as well as Bose-Einstein condensation and quantum information [2]. In the light of developing new generation of ultrafast sources of coherent radiation, such as femtosecond and attosecond lasers, study of the light-matter interaction is getting a tremendous boost.

In the last three decades, many efficient schemes, such as stimulated Raman adiabatic passage (STIRAP) and adiabatic rapid passage (ARP), for controlling the quantum transport among the states have opened new ways to get control on various atomic or molecular processes [1]. In order to attempt to speed up the adiabatic process, Shapiro et al. (2007) [3] proposed a technique, named piecewise adiabatic passage (PAP). It produces a STIRAP-like population transfer by sequences of a large number of pulses. The amplitudes of pulses changes adiabatically forming envelopes reminiscent of the so-called P (the Pump) and S (the Stokes) pulses in STIRAP. The interesting aspect of PAP that the individual pulses can be shorter than the durations allowed by the adiabatic condition in STIRAP, which makes it possible to implement this STIRAP-like process with ultrashort pulses [1].

We study the dynamics of the quantum two-level system in dipole approximation driven by series of ultrashort pulses.

We show that even in the case of single nonresonant ultrashort laser pulse it is possible to find such a value of amplitude that a complete population transfer occurs. However detuning from the perfect amplitude value leads to incomplete population transfer. To understand the underlying properties better we expose the quantum system by a train of ultrashort pulses. We demonstrate that the quantum state of the atoms may be controlled by varying the intensity of each different pulse, by controlling the overall phase and phase difference among the states between different pulses. The robustness of the scheme against the variation of the pulse train parameters is also investigated. Based on the interpretation of the parameters, we discuss possible working algorithm that leads to state inversion scenario. We show that contrary to commonly accepted PAP protocols [1, 3] the fastest regime of population transfer can be realized be means of essentially asymmetric envelope of pulse amplitudes.

Series of implementations of the described phenomena may be possible, for example in the design of magnetic field sensors, quantum gates or in the field of metrology.

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Characterization of a compact ultrastable laser system via optically referenced frequency comb

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Ultrastable lasers play an important role in many areas of modern physics and technology. Scope of their applications includes manipulation of quantum states of ions or atoms for quantum logic experiments, precision spectroscopy and optical frequency standards. Ever growing interest in performing such experiments outside laboratories, for example for chronogeodesy, spaceborn tests of general relativity, commercial quantum computation and quantum sensors setups and improving accuracy of satellite navigation systems, demand development of compact, robust and transportable laser systems. In this work we present results of stability measurements of a compact ultrastable laser system at 871 nm for manipulation of an optical qubit encoded in quadrupole $,^2 S_{1/2}(F = 0) \rightarrow ,^2 D3/2(F = 2)$ transition in $,^{171} Yb^+$ ion. The system is based on a diode laser frequency locked to an ULE cavity with high-finesse fused silica mirrors. The stability was characterized by comparison with a frequency comb referenced to another ultrastable laser source for clock transition interrogation in Thulium atoms at 1140 nm. The measured relative modified Alan deviation of the beatnote between the developed laser system and a frequency comb achieve level below 3×10^{-15} at the averaging times in the range from 0.5 s to 50 s. This result shows that despite significant reduction in mass and volume of the vacuum package of the ultrastable cavity in comparison with our previous laser systems (7 kg and 3.5 l in comparison with 20 kg and 10 l, correspondingly), metrological characteristics of the developed system did not degrade.

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Section 6: Physics and technology of ultrafast lasers and ultrashort laser pulses.

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Scope

Solid-state, parametric, fiber, and hybrid laser systems
Stretchers, compressors, and phase control
Measurement and characterization of ultrashort pulses
Laser design and related issues
Innovative femtosecond technologies

Modified frequency resolved optical gating method utilizing spectral interferometry for complete direct ultrashort pulse characterisation

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Measurements of the shape and phase of optical signals are of great importance for numerous applications. There are methods that allow direct algorithms for pulse retrieval [1-3], and methods with iterative algorithms, e.g., frequency resolved optical gating (FROG) [4] that has become a standard tool for ultrashort pulse characterization. We review the pulse measuring methods paying attention to the ambiguities and convergence issues of the pulse retrieval algorithms. In particular, the most used version of FROG based on the second harmonic generation (SHG) has several ambiguities (direction of time, $\pm\pi$ phase between pulses) and limited convergence of its iterative algorithm for complicated pulses and noisy data.

We present a novel unambiguous method based on an upgraded SHG FROG scheme and direct pulse retrieval algorithm. A conventional FROG trace, which is a set of spectra of a sum frequency signal generated by an input pulse and its delayed replica, contains only intensity information. In our method a relative spectral phase between the FROG signal and some initially unknown sufficiently broadband pulse is measured in addition. In our experimental realization we used the second harmonic of the input pulse as the reference and extracted the phase information from the spectral interference. We developed fast non-iterative pulse retrieval algorithm utilizing a two-dimensional data set, which greatly improves the pulse reconstruction compared to the known methods utilizing one-dimensional phase retrieval algorithms [1,2]. We also developed a simple and robust iterative algorithm with extremely fast convergence ($\sim$ 10 iterations for almost any pulse in exhaustive numerical tests).

We experimentally tested our method using asymmetric pulses with a pedestal and complicated phases, as well as double pulses with controllable relative amplitudes and phases. All these pulses were successfully retrieved with correct direction of time by our algorithm.

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Mode locking of diode-pumped dye laser

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Dye lasers are a convenient tool for generating radiation in a wide spectral range from 0.3 to 2 μm, and obtaining ultrashort pulses due to their wide gain spectrum. They are especially in demand for the region of $500 - 700$ nm, which is not available for Ti:Sapphire and Cr:Colquiirites lasers and their harmonics. The use of semiconductor lasers for pumping would significantly simplify and reduce the cost of dye lasers. Previously it have been shown that exciting dyes with powerful green laser diodes allows one to obtain high efficiency and wide tuning ranges. Our goal in this work was to obtain ultrashort pulses in a dye laser using either passive or active mode locking with 400 ns duration diode pumping.

The use of a saturable absorber only made it possible to achieve partial and unstable mode locking. This was due to the fact that with diode pumping of total pulse power $4 - 6$ W, it was not possible to achieve the desired intensity inside the laser cavity for sufficient bleaching of the saturable absorber. As a result, the mode locking did not have sufficient time to establish during the pumping. Synchronous pumping was provided by pulsed modulation of the current through laser diodes with a pulse duration of 1 ns and a repetition rate of $200 - 250$ MHz. As a result, a stable and reproducible mode locking with a single pulse in the axial period was ensured.

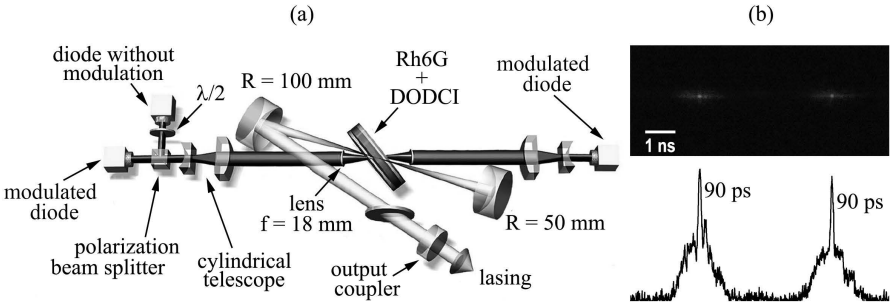

Figure 1: a) Experimental setup of tunable diode-pumped dye laser; b) temporal profiles of dye laser pulses using mixture of Rhodamine 6G and DODCI in ethanol.

The laser active element was a cuvette with 0.2 mm inner thickness filled with a mixture of Rhodamine 6G and DODCI (a saturable absorber) dyes; pumping was carried out by three NDG7475 laser diodes ($\lambda = 513$ nm) in the region of 20×40 μm. The radiation of two diodes were modulated through changing of

the supplied current, the power of the third diode was not modulated (fig. 1a). The duration of the generated pulses was measured by a high-speed streak-camera, and the typical half-width was $90 - 100$ ps. Further research will focus on increasing the pulsed current through laser diodes and achieving a shorter duration of pulses.

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Stimulated Raman scattering in diamond microcrystals

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Diamond crystals are one of the most studied solids, which are obtained from natural deposits or as a result of synthesis in laboratory conditions. The most widely used are artificial diamonds obtained at high pressures and temperatures and the chemical vapor deposition method. Using Raman scattering (RS) methods allowed obtaining some characteristics of diamond particles. Previously stimulated Raman scattering (SRS) was studied in bulk single crystals, diamonds or films. SRS observations in artificial diamond microcrystals grown at high temperatures and pressures have not yet been carried out. In this work, we set the task of studying the spectra of stimulated Raman scattering in microcrystalline diamond particles, as well as comparing these spectra with the spectra of spontaneous Raman scattering in a diamond microparticles of similar sizes.

Samples for research were commercial (Shenzhen Adiamond Technology Co., Ltd) microcrystals of diamond with sizes of 250-300 μm, obtained at high temperatures and pressures. The stimulated Raman spectra were excited by a YAG: Nd^{3+} laser with a wavelength of 532 nm, pulse duration of 60 ps, and a pulse repetition rate of 20 Hz. The maximum energy in each pulse reached 20 mJ, the maximum power $\sim$ 0.2 GW. Laser radiation was directed to the sample surface with a lens with a focal length of 30 cm. The OS-12 filter reduced the intensity of the exciting laser radiation and suppressed the secondary radiation arising in the anti-Stokes region of the spectrum. The Stokes SRS spectra were recorded with forward-scattering geometry by the FSD-8 fiber-optic minispectrometer with a spectral resolution of $\simeq$ 1 nm. During experiments on recording Raman spectra, focusing modes were used to ensure that there was no visible damage to microcrystals due to intense laser irradiation. As a result, 3 Stokes SRS components with a frequency shift of 1331 cm^{-1} were recorded.

Thus, in this work, we recorded the spectra of spontaneous and stimulated Raman scattering of diamond microparticles with sizes of 250-300 μm. As a result, the diamond fundamental F_{2g} mode ν=1331 cm^{-1} was detected in the spectra of spontaneous RS. When SRS is excited by a pulsed ultrashort laser several Stokes lines with frequency shifts of ν=1331 cm^{-1} are detected.

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Generation of two photons bound states under resonance excitation of Raman active media by ultrashort laser pulses

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The appearance of intense ultrashort laser pulses opened the opportunity to observe the different nonlinear phenomena: Parametric Light Processes [1-4], Second Harmonic Generation, Stimulated Raman Scattering and others. In this work, the two-photons bound states (boundtons) [5-7] appearance is predicted under resonance excitation of Raman active dielectric media by ultrashort laser pulses. The frequencies ω_b of the waves, corresponding to boundtons are $\omega_b \simeq 2\omega_0$, where ω_0 is the exciting line frequency. The most possibility of boundtons generation in media is predicted when the strong photon-phonon interaction takes place and the frequency of exciting laser emission is close to the absorbance edge of dielectrics. In this case the group velocity of the exciting emission in media is close to zero and a probability of two photon bounding sharply increases. The another preferable condition of boundtons appearance is the Resonance Fermi presence. In this case, the exciton state with energy and type of the symmetry, close to the boundton, exists in dielectrics. Boundtons in media may destruct with generating of biphotons (entangled photon states) and gravitons, emitted into vacuum. Simultaneously, as a result of destruction of boundtons in dielectrics, paraphotons and axions [8] may be emitted from the media into vacuum. For discovering of paraphotons, axions or high frequency gravitational waves we propose biphoton detection and also "Light shining through wall experiment", when the same media, in which boundtons were excited, is used for registration of the secondary emission. The experimental results of nonlinear phenomena observing in various dielectric media (ZnO, $Ba(NO_3)_2$, $Pb(NO_3)_2$ $NaBrO_3$, KNO_3, $NaUO_2(CH_3COO)_3$, antracene, POPOP, PPO), excited by short and ultrashort laser pulses, are presented.

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Anti-Stokes multi-frequency stimulated Raman scattering of light in light and heavy water

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The analysis of the molecular composition and structure of water molecules was effectively carried out using various optical methods, in particular infrared absorption spectroscopy [1] and Raman scattering [2]. The use of stimulated Raman scattering (SRS) methods opens up new possibilities for studying nonlinear processes in heavy and light water. To excite multi-frequency anti-Stokes SRS in water, we used a YAG: Nd^{3+} pulse-periodic laser, generating ultrashort (60 ps) pulses with a wavelength $\lambda = 1064$ nm. Four equidistant anti-Stokes satellites are observed in the Raman spectra of light water with a frequency shift 3024 cm^{-1}. Moreover, for the Raman components of higher orders, additional intensity peaks are found near the fundamental lines (Fig. 1a). The Raman spectrum of heavy water consists of five anti-Stokes peaks (Fig. 1b) with a frequency shift 2200 cm^{-1}, the half-width of which increases significantly when moving into the short-wavelength region of the spectrum. According to the laws of conservation of energy and momentum for four-photon processes, each anti-Stokes component corresponds to a Stokes satellite in the infrared region of the spectrum. The anti-Stokes multi-frequency Raman lines in light and heavy water correspond to the fundamental internal fully symmetric mode of a water molecule.

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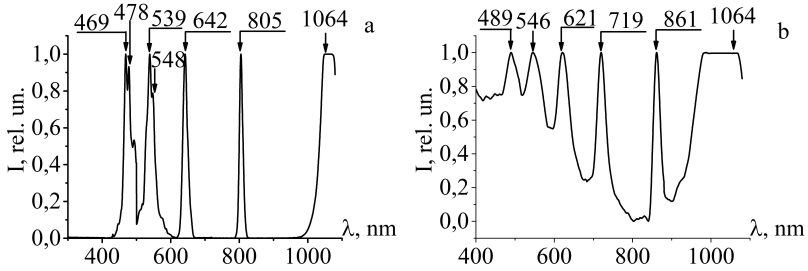

Figure 1: Figure. 1. Normalized spectra of anti-Stokes multifrequency SRS in light (left) and heavy (right) water.

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Highly efficient tiled aperture coherent beam combining

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Coherent beam combining (CBC) is a promising route for increasing peak and average power of laser systems. It is especially attractive for fiber laser systems (including ultrafast fiber systems) since they may be scaled to an extremely large number of channels. Apart from the problem of beam phasing, which can be solved by well-developed active feedback techniques, an efficient optical scheme is required to combine many emitters into one coherent beam. There are different concepts of CBC, but no methods have been demonstrated by now that would provide high combining efficiency, and at the same time would be easily scalable for a large number of channels and support large spectral bandwidth and ultrashort pulse duration [1].

The tiled aperture approach is the most promising one for scaling to large number of channels. In this scheme many parallel beams (beamlets) are arranged side by side and a combined beam is formed in the far field. However, for non flat-top beamlets there are fundamental limitations on the combining efficiency. Theoretical estimates show that efficiency at the level only of 50–70% can be achieved, while in experiments only lower values below 60% were reported so far [2].

We propose a modification to the tiled aperture approach that pushes combining efficiency close to 100% even for bell-shaped (e. g., Gaussian) beams with low aperture fill-factor. The scheme relies on changing the beam phasing paradigm from the commonly used in-phase pattern (where the phases of all channels are the same) to the out-of-phase pattern (interleaved $0/\pi$ phases in the neighboring channels). Such a pattern results in the formation of two (in one-dimensional arrangement) or four (in two dimensions) beams in the far field. These beams can be further combined by ordinary beamsplitters due to equal amplitudes and mirror symmetry. The major difference from the in-phase pattern is that the higher-order lobes contain much lower energy since they are shifted further away from the center and their amplitudes drop down quickly, leading to significant efficiency improvement.

In a proof-of-concept experiment with one-dimensional 9-channel fiber array we achieved 89% of the power in the main combined beam using the out-of-phase pattern. In numerical modeling we found optimal conditions leading to 98% efficiency for unlimited number of channels and arbitrary small initial aperture fill factors. The scheme is highly tolerable to the effect of sub-aperture clipping and suitable for combining ultrashort pulses.

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Dispersion management in free-space chirped-pulse amplification systems.

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Femtosecond lasers based on the chirped-pulse amplification (CPA) technique [1] have become a powerful tool in modern science and industry. In any CPA laser, dispersion management is a crucial factor determining the quality of the output pulse [2]. Uncompensated residual spectral phase can significantly deteriorate the pulse shape, reduce the peak intensity, and degrade the pulse contrast.

The dominant role in dispersion management in CPA systems belongs to stretchers and compressors [3]. Design requirements for stretchers and compressors can be substantially different depending on the application of the laser. Industrial lasers use robust designs optimized for low cost of manufacture, ease of service and overall reliability. Many scientific systems are designed to achieve outstanding goals, e.g. ultrahigh peak intensities or extremely short pulse durations. Such lasers employ highly-customized solutions, some of which require advanced auxiliary equipment and a team of PhD-level professionals to operate and maintain the device.

Despite having the mutual goal of achieving high-fidelity pulse reconstruction at the system's output, stretchers and compressors differ greatly in their performance specifications. Compressors are designed to withstand high energy pulses, have high throughput, and preserve beam quality without introducing angular chirp. Stretchers are operated with low-energy seed pulses and can have rather complicated schematics with more degrees of freedom. This allows their designs to be focused on tuning high-order dispersion terms to obtain transform-limited pulses at the recompression stage.

In this report, various aspects of dispersion control in CPA systems are discussed, including sources of dispersion, tools, optimization strategies and criteria. An overview of methods for the analysis of free-space dispersive subsystems is presented. Advantages of aberration-free and aberrated stretcher designs are discussed. Finally, a few of the current intriguing solutions and advanced techniques are provided.

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Numerical modeling of pulse-pumped ultrafast amplifier with unstable pump laser

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Femtosecond chirped-pulse amplification (CPA) systems face severe stability problems originating from the performance of their components. Crucial factors deteriorating the stability of a CPA system are fluctuations of the energy, beam-pointing stability and timing jitter of the pump laser. Frequency-doubled Q-switched neodymium lasers are widely used as pump sources for both regenerative and multipass Ti:Sapphire amplifiers. Cr:Forsterite amplifiers are usually pumped with fundamental-frequency neodymium lasers. Typical beam-pointing stability of commercially available Nd pump lasers is $\pm$25-50 μrad, while typical energy stability is around 0.3-1% (r.m.s.) for diode-pumped lasers and 1-3% for lamp-pumped lasers. Another stability problem associated with lamp-pumped lasers is that their output intensity distribution in the beam cross-section can notably vary from shot to shot. Despite poor stability, lamp-pumped lasers are widely used as pump sources for amplifiers with low pulse repetition rates (1-20 Hz) due to their low cost and high energy as compared to the diode-pumped lasers.

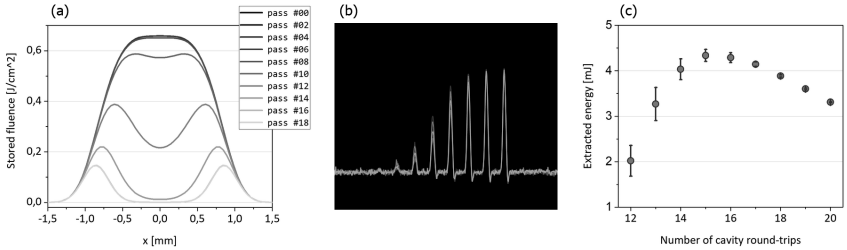

Figure 1: (a) Depletion of the stored energy in the active medium with Brewster geometry. (b) Simulated oscilloscope trace of an intracavity build-up signal of a Ti:Sapphire regenerative amplifier. (c) Extracted energy as a function of the number of cavity round-trips. Error bars display the energy stability (STD) at each round-trip.

A numerical model of a regenerative amplifier pumped by an unstable pump laser with fluctuating beam and energy has been developed. The model takes into account spatial distribution of the pump energy across the active medium and its fluctuations from shot to shot. Using spatially-dependent Frantz-Nodvik equation [1], we can calculate amplification of the laser pulse at each consecutive pass through the active medium and thus obtain the entire intracavity build-up signal. Using this model, we analyze the influence of the input parameters

(number of cavity round-trips, cavity losses, seed energy, diameters of the pump beam and the cavity mode, etc.) and their fluctuations on the extracted laser energy, accumulated B-integral, and their statistics.

This research was supported by the Russian Foundation for Basic Research (RFBR) (20-52-00036).

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High power laser system in visible spectrum range

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Nowadays, the creation of multyterawatt and petawatt laser systems is based on solid-state titanium-sapphire or parametric amplifiers using CPA technology. In this technology, a low-energy femtosecond pulse is extended to a subnanosecond duration then it is amplified in high-power amplifiers and compressed to its original duration in a diffraction grating compressor. All these laser systems operate in the infrared (IR) spectrum region (0.8–0.9 μm). The expansion of their spectral range makes it possible to find new application and, in case of wavelength shortening, to improve the interaction efficiency of high-power radiation with matter.

In this report, the focus will be on high powerful laser systems operating in the visible spectrum. The methods currently known for producing multi-terawatt laser pulses will be described, as well as the laser systems and the resulting radiation parameters. It will be noted that the method of converting high-power laser pulses of IR radiation in the visible range does not allow forming a high-quality beam. And only the method of direct amplification of visible spectrum laser pulse in booster amplifier makes it possible to obtain high-quality laser radiation.

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On uncertainty principle in laser pulse shaping

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The uncertainty principle is among the fundamental relations of information theory and signal processing. In classical Gabor's formulation, it restricts the minimum time-bandwidth product of a communication system [1].

We discuss implementation of this principle for ultrashort laser pulse shaping analyzed from the information-theory point of view. It is demonstrated that the product of time-domain resolution and modulation contrast can be maximized for a laser pulse shaper of generic architecture. The optimal shaper bandwidth is found to be twofold laser pulse spectrum. The results are applied to acousto-optic dispersion delay lines and spatial-light-modulator-based pulse shapers [2,3]. Experimental validation is performed with a high-definition acousto-optic dispersive delay line.

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Picosecond high peak and average power lasers and pulse-burst laser systems

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High peak power picosecond lasers are widely used in a variety of scientific, technological and medical applications such as time-resolved and time-domain nonlinear laser spectroscopy, coherent anti-Stokes Raman microscopy and two-photon bioimaging, laser ablation and micromachining, photo-guns equipping in electron accelerator injectors, precise satellite and lunar laser ranging, aesthetic cosmetology and dermatology, clinical surgery etc. Then, practical and reliable, highly stable and compact picoseconds laser schemes providing single pulse energy of mJ and multi-mJ level operating at different repetition rates, typically within kHz, are required to develop. Key modern approaches are briefly observed.

We develop advanced schemes of highly effective picosecond pulsed-periodic diode-pumped lasers of high peak and average power based on Nd-doped crystals. The schemes comprise active-passive mode-locked and negative feedback controlled master oscillators combined with regenerative and linear amplifiers. Problems of effective power scaling, generated mode structure analysis and enhancement, fast electro-optical operation control and Pockels cell crystals stability are discussed in the present paper.

We realized approach to generation of high-peak-power picoseconds pulse bursts based on use of master laser and electro-optically controlled regenerative amplifier with partial radiation output. Regenerative amplifier allows to obtain submillijole level energy picoseconds pulse trains with profiled envelope shapes which can be further enhanced in output amplifier stage. The envelope profile can be specially shaped to compensate amplification decrease from the beginning to the end of the train that allows operation at near saturation regime and most effective use of pump power.

The new design of frontend laser for high intensity parametrically pumped laser systems

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Further scaling of high intensity OPCPA based femtosecond lasers and their appications, require a significant increase in stability, the possibility of flexible control of both the amplified fs pulse and the pump pulse, high-precision synchronization with other experimental setups. This work presents the new design of a frontend system for a Pearl PW laser [1].

The new frontend laser is based on the approaches partially presented in [2]. The femtosecond fiber laser with 65 MHz pulse repetition rate with and its high precision tuning by PZT is used as a seed source, that will allow synchronizing Pearl laser system with other setups. This seed signal is divided into the femtosecond channel and the pump channel, which provides optical synchronization between them. In the femtosecond channel, the pulse energy is amplified up to mJ level with 250 fs pulse duration at 1kHz repetition rate. Further, these pulses, using approaches of white-light generation and parametric convertions [2], are transformed into ∼20 femtosecond pulses and an energy of more than 20 μJ. Due to the flexibility of parametric convertions, both the central wavelength (750-950 nm) and the pulse spectrum width (30-150 nm) can vary within wide range. Pulse-to-pulse stability is near 1% rms. This signal will be used as a seed in a Pearl system, which will significantly reduce the amplified pulse duration and increase its contrast due to the DFG stage in the new frontend. The radiation of the pump channel is stretched by the Bragg grating up to 1 ns in the 1 nm spectral range and is amplified up to 1 mJ with the pulse-to-pulse stability near 0.5%. This signal will be amplified in Nd:glass pump laser of the Pearl system. The presence of the spectral-temporal distribution allows using the spectral methods of temporal profiling [3]. The pulse temporal profiling of U-shaped laser pulse with an adjustable modulation depth has been elaborated to compensate the pulse rolling effect (one of the important limitations of high-energy pump lasers). Note that the use of a chirped pulse for amplification in a pump laser can potentially be used to compress it in the ps range, which also greatly expands the applications of Pearl system.

The developed frontend laser will significantly improve the Pearl system performance and expand its application possibilities. Moreover, the flexible design of the frontend laser will allow it's using as a seed for other femtosecond laser systems, based on the both OPCPA and CPA approaches.

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High power diode pumped solid-state femtosecond laser systems

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Ultrafast laser systems generating optical pulses shorter than 100 femtoseconds in duration are important tools both in science and technology. Their applications include chemically-selective microspectroscopy, metrology, time-resolved diagnostics of various physical processes, generation of coherent pulses from THz to X-rays, industrial and medical applications based on high precision processing of materials and biological tissues. In the family of ultrafast lasers, Ti:sapphire systems remain indispensable due to their extremely broad gain spectrum which provides tunability over more than 300 nm in near-IR as well as capability to generate pulses as short as 5 fs directly from the laser.

Spectral properties of Ti:sapphire determine a linearly polarized laser with wavelength near 500 nm as its pump source. Since femtosecond operation of Ti:sapphire lasers is based on Kerr lens modelocking (KLM) and longitudinal pumping [1], the focusing properties of the pump beam are important both for laser efficiency and for robustness of its femtosecond operation [2, 3]. External lasers commonly used to pump Ti:sapphire systems earlier resulted in high costs and complexity of such systems. The situation changed with the advent of compact and inexpensive blue-green laser diodes [4]. Output intensity of these lasers is currently approaching 3W at $> 20\%$ energetic efficiency opening a possibility to build a compact and efficient diode pumped solid state (DPSS) femtosecond laser. Recently passive KLM operation of Ti:sapphire laser has been demonstrated employing single diode pumping schemes [5, 6] However, further development of high power DPSS Ti:sapphire laser systems requires solutions to upscale average pump beam power while preserving its polarisation and focusability.

This talk reviews experiments with a femtosecond DPSS laser built from a commercial set of components "TiF-Kit-20" (OOO "Avesta-Project") and pumped by multi-diode laser modules [7]. The beam combining scheme preserves polarizations and focusing properties of individual laser diodes beams. This femtosecond laser generated ≈ 30 fs pulses at >100–300 mW average power. Possibilities to implement diode pump of other laser media are discussed. A numerical model of a DPSS KLM laser is used to optimize the laser and to generalize earlier results [2] to include pump beam astigmatism and its focusing properties along with non-linear Kerr lensing in the gain medium. These results open possibilities to replace existing Ti:sapphire pump laser sources with new compact and efficient solutions based on laser diodes and to develop compact and efficient

DPSS femtosecond lasers for applications in science, industry and medicine in the future.

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Nonlinear-optical conversion and light absorption effects in KTP-family Pockels cells employed in picosecond lasers

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Practical and reliable, highly stable, compact and easy maintaining laser sources generating picosecond pulses of mJ and multi-mJ energy levels at repetition rates within kHz are subjects of multiple requests nowadays.

Key elements underlying high-speed schemes of picosecond pulses gating and beams redirecting are electro-optical modulators (EOMs), i.e. Pockels cell (PC) plus polarizer that are utilized for operational control of generation since the early laser era.

Demands for better energy and temporal stability, effective shortening of picosecond pulses seed and it further amplifying are stimulating development of electro-optically governed combined schemes based on active-passive mode-locking, cavity Q-factor control, negative feedback (NFB), switching and dumping cavities.

Crystals of KTP-family (KTP and RTP) meet basic requirements for advanced electro-optical materials and are characterized by a unique combination of physical parameters that are needed for high EOM performance: low absorptivity at the laser wavelength, high damage threshold, low piezoelectric coupling of electric field to acoustics and relatively large electro-optical coefficients. In fact, they outperform most of other crystals by combination of its characteristics.

PCs based on KTP/RTP are assembled as a rule by the thermal compensated scheme with two equal lengths crystals. There are two variants of PC assembling that characterized by largest electro-optical coefficients values with corresponding light propagation along X (X-cut) or Y (Y-cut) axes.

High-peak power picosecond pulses propagation through PCs based on KTP/RTP crystals may be accompanied by noticeable nonlinear conversion to second (SH) and third harmonics (TH) despite the lack of synchronism conditions. TH for Nd:YAG fundamental is out of KTP/RTP crystals transparency ranges then its conversion efficiencies may be rather high due to resonance vicinity. Since KTP/RTP crystals effectively absorb TH radiation this may cause additional heat loading. When influence was increasing on EOMs due to repetition rate growing it leaded to unwanted depolarization, disturbance of the operating mode and also to crystal degradation.

SH and TH conversions efficiencies for KTP and RTP crystals were estimated based on literature data and were compared with measured ones. Generation efficiencies of SH and TH in PCs based on KTP and RTP crystals was evaluated using output of an independent supplementary Nd:YAG picosecond laser as a pump. Figure 1 shows the complex picture of SH and TH intensities distributions that was observed in the case of Y-cut RTP PC using. The minimal conversion efficiencies to SH and TH were obtained for PC based on Y-cut KTP. Results details will be discussed.

Y-cut KTP PC was successfully used in pulsed-periodic picosecond Nd:YAG laser. Oscillator - regenerative amplifier scheme based on common end-diode-pumped Nd:YAG crystal generates pulses with energy up to 1.2 mJ, duration of 25 ps at repetition rate up to 100 Hz.

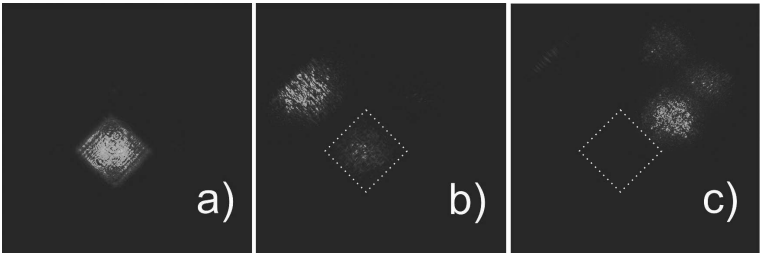

Figure 1: Harmonics intensity distributions at the distance of 15 cm behind Y-cut RTP PC (a) fundamental radiation; (b) SHG; (c) THG. Dotted line shows PC's aperture location.

Dye lasing in a slurry-like medium with the properties of a Christiansen filter

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The Christiansen filter (CF) — a known device for the spectral selection of radiation. The "classical" CF is a cuvette with a dense slurry-like mixture of glass or crystal particles in an immersion liquid, which has a maximum transmission in that part of the spectrum where the refractive indices of particles and liquid coincide. In addition to many publications on CFs for spectral selection, CF-like mixtures of particles of solid-state laser materials and liquids were studied as laser active media. Such compositions attract attention because allow the removal of heat generated in the laser by the mixture circulation. To create a CF-like laser medium, one can use also non-doped solid-state particles and transfer the function of gain to the liquid. In the present work the slurry laser on a dense mixture of LiF crystal particles and an immersion liquid with pyrromethene 567 (PM567) dye dissolved in it is reported.

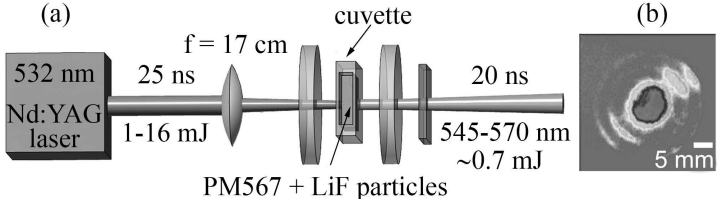

Figure 1: a) Schematic of the slurry laser; b) photograph of a slurry laser beam imprint.

The rectangular quartz (2 mm gap) cuvette with LiF microparticles ($70 - 140\,\mu$m) in an ethanol/toluene immersion mixture with PM567 was installed in a 2 plane mirrors resonator of ≈ 2.5 cm length, fig. 1a. The cuvette was pumped by single 25 ns pulses of the 2-nd harmonic of the Nd:YAG laser through the mirror with $\approx 99\%$ reflection ($\lambda = 545 - 625$ nm) and $\approx 85\%$ transmission of pump radiation. The pump intensity reached 100 MW/cm^2. The output mirror reflection was 64% ($\lambda = 530 - 650$ nm) . This slurry laser emitted 20 ns pulses with energy of up to 0.7 mJ tunable in the wavelength range of $\lambda = 545 - 570$ nm. The spectrum consisted of a group of narrow lines with a total width of up to 5 nm. The slurry laser efficiency was $\approx 5\%$ and only near twice as less than that of the particle-free PM567 dye laser. A laser beam profile at a distance of 190 cm is shown in fig. 1b. The beam consisted of a bell-shaped near-axis core with a divergence of ≈ 6 mrad, containing up to 80% of the energy, and several concentric rings with a divergence over 10^{-2} rad. The angular coordinates of the

rings corresponded to the directions for the maximum transmittance of radiation by the Fabry-Perot interferometer formed by 2 parallel resonator mirrors. The experiments performed allow us to state that the dye lasing was demonstrated at first in a dense disordered mixture of solid-state particles and a liquid similar to the optical medium of the Christiansen filter. The laser output was formed due to amplification of the dye radiation in the liquid component of the slurry under conditions of incomplete immersion and small-angle scattering in the medium. Possible applications of the slurry laser are discussed.

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Multi-frequency stimulated Raman scattering of light in sodium bromate crystals

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One of the effective methods for converting laser radiation into the long-wave or short-wave spectral range is stimulated Raman scattering (SRS). The stimulation of SRS by powerful radiation from a pulse periodic laser in nonlinear optical crystals ($Ba(NO_3)_2$ [1], BaF_2 [2]) can lead to the generation of a large number of equidistant Raman satellites in a wide spectral range. In this work, we recorded the multi-frequency SRS spectra of a polycrystalline sodium bromate powder (see Fig. 1) upon excitation of scattered radiation by a second harmonic YAG:Nd^{3+} pulsed periodic laser with a generation wavelength $\lambda = 532$ nm. The multi-frequency Raman spectrum was characterized by five Stokes and five anti-Stokes fundamental lines of a sodium bromate crystal with an average frequency shift between spectral components of $\nu = 790$ cm^{-1}. In this case, the frequency shift of the Stokes components exceeded the frequency shift between the anti-Stokes components of the Raman scattering.

This work was supported by Russian Science Foundation, grant 19-12-00242.

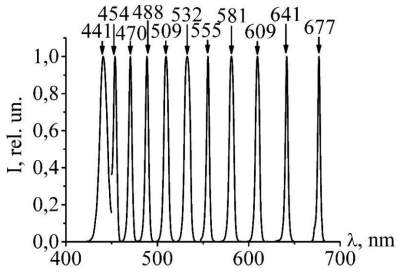

Figure 1: Figure. 1. Normalized spectrum of multi-frequency stimulated Raman scattering in sodium bromate crystals.

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Beam structure analysis at aberrational thermal lens in end-diode-pumped Nd:YAG crystals

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High peak- and average power picosecond lasers based on Nd:YAG crystals are used in a number of scientific and applied tasks, such as spectroscopy, pump-probe experiments, parametric amplifier pumping, ablation, photoinjector pumping, laser ranging (artificial satellites, the Moon), laser medicine, cosmetology, etc [1]. Easily implemented end diode pumping provides, in some pumping power limits, high energy efficiency and high beam quality due to optimal overlapping of lowest resonator mode with pumped region. At the same time, end pumping is accompanied by non-homogeneous temperature distribution inside laser crystal that brings to aberrational thermal lens formation. Aberrational thermal lens in laser resonator or in amplifier may cause growing energy losses and beam quality degradation under pump power increase. Since aberrational part of thermal lens could not be eliminated by conventional optics, then knowing its specific form is ought to be recognized for possible further compensation.

To reconstruct thermal lens profile, we primarily measured intensity profiles of He-Ne laser probe beam passing through end diode pumped Nd:YAG crystal. Beam structure before and after thermal lens was evaluated in terms of embedded Laguerre-Gaussian beams superposition [2]. Simulations of probe beam propagation are fulfilled to fit measured profiles by calculated ones at variation of aberration thermal lens shape. Accuracy of aberrational thermal lens reconstruction is discussed.

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Mid-infrared laser amplification of parametric seed in Fe:ZnSe crystal pumped by continuous wave Er:ZBLAN laser

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The creation of a mid-IR (3–7 μm) femtosecond sources is of great interest for solving numerous scientific and applied problems, such as the generation of a broadband supercontinuum, spectroscopy and multispectral tissue imaging, since a large number of molecules undergo strong characteristic vibrational transitions in this domain [1,2,3].

The paper considers the possibility of creating a hybrid source of femtosecond mid-IR (3-7 μm) radiation at a high repetition rate (20 kHz - 1 MHz). Such a system consists of a difference frequency generation unit between two femtosecond oscillators of the near-IR range with subsequent amplification in active media based on chalcogenide Fe:ZnSe crystal.

Pulses with an output power of the order of 1 mW in the wavelength range of 4 - 5 μm was experimentally obtained during the difference frequency mixing between tunable Ti:sapphire (800-860 nm, 200-330 mW, 50 fs, 71.8 MHz) and Yb oscillators (1032 nm, 7 W, 150 fs, 71.8 MHz) in a 4-mm-long LGS crystal. The spectral bandwidth of the generated pulses was up to 270 nm (at a central wavelength of 3980 nm). According to our simulations further increase of the output power can be achieved using a 0.5-mm-long PPLN crystal, which supports generation of 50-fs pulses with 14 mW average power around 4 μm. The amplification properties of a Fe:ZnSe crystal pumped by a continuous wave 3-μm Er:ZBLAN laser were experimentally studied. Amplification of 2.5 was obtained under cryogenic cooling of the crystal up to 77 K at a 71.8 MHz repetition rate, which corresponds to a gain of 1.06 cm^{-1}. Based on the obtained results, evolution of the gain in a multi-pass amplifier was calculated using the Frantz-Nodvik model [4] for low (15 - 20 kHz) and high (1 - 71.8 MHz) repetition rate cases (compared to inverse upper-state lifetime of 57 μs [5]) to figure out the influence of the seed repetition rate on the maximum achievable output average and peak powers. Our findings open new perspectives for the development of compact and efficient mid-IR sources for time-resolved experiments, as well as, for generation of a broadband supercontinuum.

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Towards efficient 10-mJ class mid-IR optical parametric amplifier pumped by Ti:sapphire laser

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Single cycle terahertz (THz) pulses of high field strength have attracted large attention since they allow for exploring electronic subsystem dynamics far from equilibrium, ultrafast magnetisation, imaging and others. Efficient generation of intense THz transients at a hundred MV/m field strength under optical rectification of the optical pump has appeared only recently with advent of organic crystal [1]. These crystals (such as DAST, DSTMS and OH1) provide high nonlinearity and transparency for both optical pump and THz field. However, dispersion properties of these materials requires near-IR (1.2 - 1.5 μm) pump. On the other hand, efficiency of the plasma based sources was also greatly increased with near- and mid-IR sources [2], while the optimal wavelength for two-color filamentation-induced THz sources was predicted around 3.2 μm [3]. Therefore, in this paper we consider wavelength conversion of terawatt Ti:sapphire laser system available in M. V. Lomonosov Moscow State University into infrared spectral region of 1.3 - 2.2 μm via optical parametric amplification.

For the development of high energy efficient optical parametric amplifier (OPA) nonlinear properties of the available transparent crystals were analyzed (BBO, BiBO, YCOB). Parametric process was simulated using SNLO package [4], which took into account diffraction, dispersion and group velocity walk-off and was performed for 800-nm, 50-fs, 90-mJ pump radiation. We have found that despite of higher nonlinearity of the type I phase matching in BBO and BiBO crystal, higher efficiency is reached with type II crystals since no parasitic processes (such as signal/idler second harmonic) are presented. In three stage configuration conversion efficiency around 24% in two waves (in total) has been achieved with more than 8 mJ in idler wave around 2 μm. Even higher conversion efficiency of 31% may be reached using BiBO crystal, which besides favourable dispersion provides higher nonlinearity (2 pm/V) compared to BBO crystal (1.55 pm/V) for type II phase matching. One may expect up to 11 mJ in idler wave with this crystal. Finally, low nonlinearity of YCOB crystal (1.1 pm/V) prevents efficient frequency conversion. The developed concept will be also compared to double chirped OPA [5].

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Stimulated Raman scattering in barium nitrate powder excited by ultrashort laser pulses

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We have observed for the first time stimulated Raman scattering in microcrystalline powder of barium nitrate under excitation by ultrashort (60 ps) pulses of a YAG:Nd^{3+} laser operated at the wavelength of 532 nm [1]. The experimental setup was similar to the one used in [2,3]. First and second Stokes components with the frequency shift of 1047 cm^{-1} were observed in the stimulated Raman scattering spectrum of the powder. The comparison of the corresponding spectra of spontaneous and stimulated Raman scattering in a $Ba(NO_3)_2$ single crystal and powder is presented in Figure 1. The studies performed open the possibility for creating frequency comb lasers in wide spectral region (from IR to UV) based on stimulated Raman scattering in microcrystalline powders.

This work was supported by Russian Science Foundation, grant 19-12-00242.

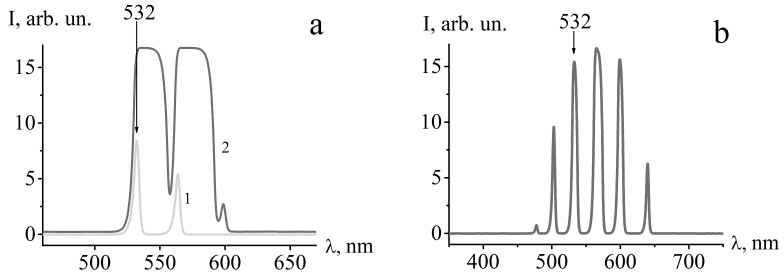

Figure 1: Stimulated Raman scattering spectra in a barium nitrate microcrystalline powder (left) and single crystal (right) under excitation by a picosecond YAG:Nd^{3+} laser at the wavelength of 532 nm in the forward scattering geometry. Curves 1 and 2 correspond to different pumping intensities.

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Attosecond Photoelectron Spectroscopy

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Time resolved spectroscopy is concerned with the generation, amplification, manipulation, and applications of short laser pulses. Extreme ultraviolet (XUV) light pulses with duration below 130 attosecond can be produced in tabletop experiments [1].

The attosecond pulse trains are generated based on high-order harmonic generation using Ti:Sa femtosecond technology. The isolation of a single pulse is achieved exploiting various gating technique e.g. amplitude gating and few-optical-cycle driving pulses with stabilized carrier envelope phase. Such short pulses allow us to investigate electronic dynamics in gases and solids via photoelectron spectroscopy.

In this report I will present the experimental setup for time resolved photoelecton spectroscopy in attosecond range as used at the University of Bielefeld.

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Pulse shaping with randomized transmission combs

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Ultrashort laser pulse shaping and tailoring is an essential part of numerous light-matter interaction experiments. Acousto-optic pulse shaping is a direct time-domain technique relying on synthesis of arbitrary complex-valued transmission of ultrasonic Bragg gratings [1]. A common approach driven by simplicity of signal generation is to represent the spectrum as a periodic frequency grid [2]. However, constructive intrapulse interference between the teeth of a periodic grid gives rise to satellite pulses that reduce contrast and usable group delay range.

We propose an aperiodic frequency grid to suppress undesired intrapulse interference and minimize the satellite pulses [3]. The first step of aperiodic frequency grid generation is optimization of the tooth width distribution. This optimization provides minimum satellite amplitude in average. The second step of the grid generation is stochastic permutation of the grid. This step eliminates spikes in the pulse pedestal that may occasionally appear in a random aperiodic frequency grid.

The new pulse shaping technique was demonstrated experimentally with a high-definition acousto-optic dispersive delay line designed and fabricated in-house. Autocorrelation traces in Fig. 1 were obtained for a wavelength-domain grating with the duty cycle of 2. The case in Fig. 1a corresponded to a periodic grating with all comb tooth width equal.The total number of teeth was 175 covering the bandwidth of 150 nm centered at 795 nm. The peaks with the period of 1.2 ps are the satellite pulses. The case in Fig. 1b was obtained with a stochastic grating having 405 teeth with the width randomly varying from 0.24 to 0.96 nm with the increment of 0.04 nm. The satellites suppression by an order of magnitude is demonstrated compared to the regular wavelength grid.

The research was supported by the Russian Foundation for Basic Research (Project 18-29-20019).

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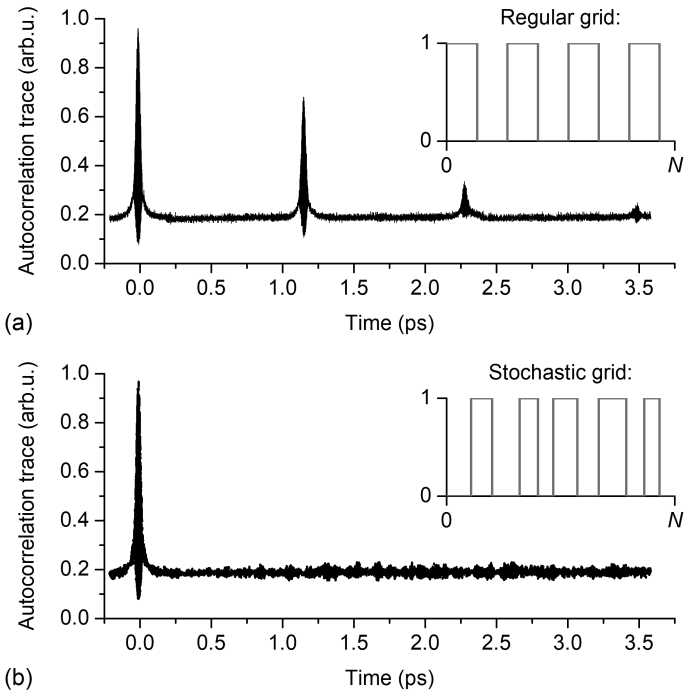

Figure 1: Experimental autocorrelation traces of a sub-15-fs pulse: (a) the satellites are produced by a periodic frequency grid; (b) the satellites are suppressed by a stochastic frequency grid. Insets: schematic grid transmission vs. sampling point index.

Formation and evolution of mid-IR femtosecond laser pulses ($4-5$ μm) in a mode-locked Fe:ZnSe laser cavity

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High-power mid-IR ultrafast lasers are in demand in many fields of science and technology including high harmonics and attosecond pulses generation, filamentation in air and remote sensing. New laser media based on transition-metal-doped II-IV chalcogenides made it possible to develop powerful, efficient and compact broadband mid-IR sources [1]. Recently, significant advances have been achieved in ultrafast laser systems development based on Fe:ZnSe operating at a central wavelength of about 4.3 μm [2], [3].

We report numerical simulation of the formation and propagation of ultrashort laser pulses in the Fe:ZnSe laser cavity in the mid-IR range. This laser medium has some unique properties which affect the formation of a soliton in a laser cavity. They are high nonlinearity, long lifetime under cryogenic cooling, high gain saturation energy. The nonlinear equation of pulse envelope dynamics is solved with the split-step method. Passive mode locking is based on saturable absorption in graphene. For cavity dispersion management, the dielectric plate (CaF_2) with an anomalous group velocity dispersion at the generation wavelengths is used. The dynamics of the generation at steady-state is considered. It is found that the minimum pulse duration is achieved by overcompensating the net GDD at -780 fs^2. The simulation states that the use of a larger anomalous dispersion leads to larger pulse energy but also to a larger pulse duration, which is consistent with the Soliton area theorem. The possibility of pulse generation with the energy from 14 nJ to 43 nJ and duration from 90 fs to 65 fs is shown.

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150 MHz passively mode-loked erbium fiber laser

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Ultrashort pulses laser sources find different applications in many scientific and technology fields. These sources can be used as part of supercontinuum [1] or terahertz [2] sources, microscopy setups [3] and etc. Current field of the special interest is generation of sub-gigahertz ultrashort pulse trains. In our work, to obtain ultrashort pulses with a high repetition rate, we used a linear cavity based on composite Er-doped fiber. The scheme is shown in Fig. 1(a). Mode-locking regime was realized by adding to the scheme 3 layers of aerosol-synthesized single-walled carbon nanotubes SWCNTs [4]. A stable pulsed oscillation mode with a repetition rate of 150 MHz was observed. The pulse duration was 0.5 ps. The average output power was 9.15 mW. The temporal and spectral characteristics of the output radiation are shown in Fig. 1(b).

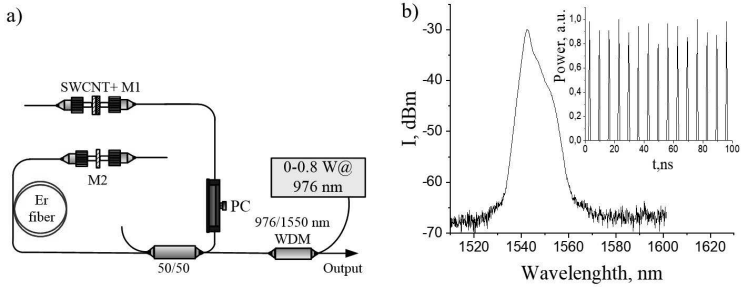

Figure 1: (a) Schematic of an Erbium fiber laser. SWCNT+M1 - Connected pigtails, between which there is a Al-foil with SWCNTs. M2 - Connected pigtails with Al-foil. PC - polarization controller. (b) The temporal and spectral output radiation characteristics.

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