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SIBERIAN SYNCHROTRON RADIATION CENTER

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"Terahertz Radiation: Generation and Application"

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INTERNATIONAL SYMPOSIUM

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Prospects for research on biological systems using THz radiation

Peter Weightman

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This talk will review the contribution that research in the terahertz (THz) region of the electromagnetic spectrum can make to the study of biological systems. It will be argued that THz modes may play an important role in the mechanism of biological organisation. Biological systems evolved at room temperature and kT at room temperature is 6THz so these modes would be available for use in the evolutionary development of the mechanisms of self-organisation that systems operating out of thermodynamic equilibrium must develop in order to maintain themselves. The theoretical work in this field is controversial and inconclusive. What is required is experimental studies of biological systems in the THz region and these are now being made possible through the development of next generation accelerator based light sources. The talk will also include an account of recent developments on the THz beamline and tissue culture facility that is currently being commissioned on the ALICE energy recovery linear accelerator at the UK Daresbury laboratory.

Applications of Terahertz spectroscopy and imaging

Cunlin Zhang, Kaijun Mu

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We have examined application feasibility of THz time-domain spectroscopy (THz-TDS) to inspect 30 kinds of illicit drugs, 20 kinds of amino acid and 10 kinds of explosives and related componds. We also have got their fingerprints, established the corresponding database, and propose the reference-free methods to extract the absorption or reflection spectra, respectively. We also use optical pump THz probe to research the ultrafast dynamics of semiconductor. While, we also present some new THz imaging techniques, such as, focal-plane multiwavelength phase imaging, reference-free phase imaging, polarization imaging, and continuous-wave standoff distance imaging.

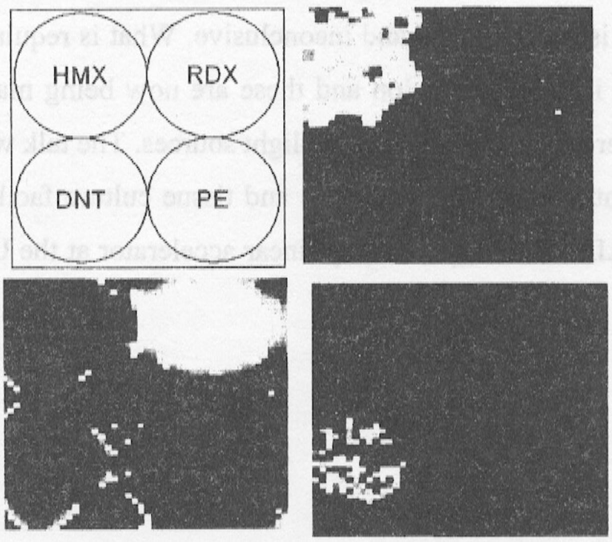

Figure 1. Reference-free identification of explosives, (a) the schematic illustration of the four imaging samples and the images of the sample targets formed by integrating the peak area around, (b) 1.80, (c) 0.82, (d) 1.08 THz. All the three explosive material samples can be identified at the images of their corresponding absorption peak frequencies.

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SENSITIVE DETECTORS OF TERAHERTZ RADIATION BASED ON $Pb_{1-x}Sn_xTe(In)$

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Sensitive detectors of the terahertz radiation are required now for many applications, such as ecological monitoring of pollutants, global weather observation, laboratory molecular spectroscopy, and many others. Some of these applications - such as infrared and terahertz astronomy, one of the fastest progressing fields in modern physics - require operation in space. Construction of more advanced space-borne telescopes operating in the terahertz spectral range implies some tough and specific requirements for photodetectors used in these systems. Many of the sensitive photodetecting systems operating in the terahertz wavelength range (20-200 μm) and used for infrared astronomy are based on doped germanium or silicon.

We propose to use alternative materials for the construction of sensitive photodetecting systems in the terahertz spectral region: narrow-gap lead telluride - based alloys heavily doped with some of the group III impurities. $Pb_{1-x}Sn_xTe(In)$ photodetectors have a number of advantageous features that allow them to compete successfully with the existing analogs:

- Internal accumulation of the incident radiation flux,
- Possibility of effective fast quenching of an accumulated signal
- Microwave stimulation of the quantum efficiency up to 10^2
- Possibility of realization of a "continuous" focal-plane array
- Possibility of application of a new readout technique
- High radiation hardness

We report on the physical principles of operation of sensitive terahertz photodetectors based on $Pb_{1-x}Sn_xTe(In)$. Beside other issues, we address a direct comparison of performance of the state of the art doped Si and Ge terahertz photodetectors and their counterparts based on $Pb_{1-x}Sn_xTe(In)$ using the same cryogenics and readout electronics. Performance of $Pb_{1-x}Sn_xTe(In)$ photodetectors operating in the regime of periodic accumulation and successive fast quenching of the photosignal with NEP values down to 10^{-16} $W/Hz^{1/2}$ is demonstrated. It is shown that the spectral response of a $Pb_{1-x}Sn_xTe(In)$ photodetector spreads out at least up to 500 μm.

These features make application of the $Pb_{1-x}Sn_xTe(In)$ photodetecting systems especially attractive for the space-borne applications, for instance, in astronomical observations.

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Terahertz Research Activities at Seoul National University

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Terahertz research activities at Seoul National University include the generation of tearhertz radiation using microfabrication, tearhertz metamaterial and terahertz interaction with biological systems. The activities will be reviewed at the conference.

Novosibirsk free electron laser: instrumentation development and experimental achievements

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The Novosibirsk ERL has rather complicated magnetic system. One orbit (11-MeV) for terahertz FEL lies in the vertical plane. Other four orbits lie in the horizontal plane. The beam is directed to these orbits by switching on of two round magnets. In this case electrons pass through RF cavities four times, obtaining 40-MeV. At the 4th orbit the beam is used in FEL, and then is decelerated four times. At the 2nd orbit (20 MeV) we have a bypass with another FEL. When bypass magnets are switched on, the beam passes through this FEL. The length of bypass is chosen to provide the delay necessary to realize deceleration at the3rd pass through accelerating cavities. In 2008 two of four horizontal orbits were assembled and commissioned. The electron beam was accelerated twice and then decelerated down to low injection energy. First multi-orbit ERL operation was demonstrated successfully. In 2009 the first lasing at the second FEL, installed on the bypass of the second track, was achieved. The wavelength tunability range is 40 - 80 micron. Energy recovery of a high energy spread used electron beam was optimized. Third and fourth orbit assembly is in progress. In 2010 radiation of the new FEL was delivered to the existing user stations. Experiments with THz radiation are described briefly.

Status of the THz/XUV pump probe beamline at FLASH: challenges and opportunities

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At the free electron laser in Hamburg (FLASH) a dedicated beamline [1] transports coherent terahertz (THz) pulses to the experimental station at of one of the XUV beamlines. The wavelength of the THz pulses is tuneable in the range from 1.5 – 30 THz (200 – 10 um) and the pulse durations scale from few picoseconds down to few hundreds femtoseconds. The pulse energies are the micro Joule range, rivalling that of dedicated THz-FEL facilities. A long period undulator uses the same electron bunch as the XUV undulators to generate the THz pulses. These pulses are thereby synchronized to the ultrashort XUV better than 10 fs [2]. In this contribution we present the current layout of the beamline. We discuss recent results of the beamline commissioning, analyzing the THz pulses with different novel techniques in the time and frequency domain. We give an outlook on the status of currently prepared first user THz pump XUV probe experiments and discuss plans for future upgrades of the beamline.

[1] M. Gensch et. al., Infrared Phys. Technol. 51 (2008) 423 -425.
[2] Fruehling et. al., Nature Photonics 3, 523 - 528 (2009)

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TERAHERTZ GYRODEVICES

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Gyrotron is the most effective and widespread variety of Cyclotron Resonance Masers (CRMs), i.e., devices, whose operation is based on stimulated cyclotron radiation of electron beams. In a gyrotron, the electrons move along helical trajectories in a uniform magnetic field $\vec{B}$ and interact with a wave propagating almost perpendicular to their longitudinal motion. Correspondingly, resonance line broadening that is caused by an inevitable spread in longitudinal electron velocity is negligibly small, and the condition of cyclotron resonance of particles with an electromagnetic wave can be written in the form

$$\omega \approx s\omega_c, \tag{1}$$

where ω is the wave frequency, $\omega_c = eB/m\gamma$ is the cyclotron electron frequency, and $s = 1,2,...$ is the number of the resonant harmonic. At the same time, due to relativistic dependence of the cyclotron frequency on particle energy, $mc^2\gamma$, particles are bunched in the transverse direction, namely, by the azimuthal angle at each Larmor circle. Thus, the bunching mechanism is relativistic even if the particle energy is small. Under certain conditions, the arising electron bunches are able to impart a significant part of their transverse kinetic energy to the wave.

To date, gyrotrons provide a 1-MW power level for millimeter waves. As is clear from Eq. (1), a very strong magnetic field, 11-36 T, is needed for generating at the frequencies of 0.3-1 THz when the gyrotron operates at the fundamental (s=1) cyclotron resonance. Nevertheless, recently, under conditions of increasing interest in the terahertz range, gyrotrons operating at frequencies of up to 1-1.3 THz were successfully tested [1-3]. It is important that these generators operated both at the fundamental and higher cyclotron harmonics. Operation at harmonics is especially attractive because of the much lower working magnetic fields, but is more difficult for realization due to the necessity for effective discrimination against parasitic modes. Selective generation at a high (s>2) cyclotron harmonic can, in particular, be obtained in a gyrotron with axisymmetric cavity, which is excited by an axis-encircling electron beam (the so-called Large Orbit Gyrotron) as well as in gyromultipliers of various types. The existing fairly perfect magnet systems comprising Liquid-He-Free cryomagnets can be used in terahertz high-harmonic gyrotrons, which makes the CW regime possible in such devices.

It is important that terahertz gyrotrons operate with particle energies many times smaller than those in the existing Free Electron Lasers (FELs) of the same frequency range. Moreover, the broadband frequency tuning, which is inherent in FELs, can presumably be realized in gyrotrons. Therefore, in comparison with FELs, gyrotrons can, despite the necessity for strong magnetic fields, be more compact and reproducible sources of powerful coherent radiation with a frequency of at least up to 1-1.5 THz.

[1] M. Y. Glyavin, A. G. Luchinin, G. Y. Golubiatnikov, Phys. Rev. Lett. 100 (2008) 015101.
[2] T. Idehara, T. Saito, H. Mori, et al., Int.J. Infrared Millimeter Waves 29 (2008) 131-141.
[3] V. L. Bratman, Yu. K. Kalynov, V. N. Manuilov, Phys. Rev. Lett. 102 (2009) 245101.

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Design Study of a Table-top THz Free-Electron Laser and Its Prospect for Security Inspection

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Design Study of a Table-top THz Free-Electron Laser and Its Prospect for Security Inspection

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Abstract

We have designed a table-top terahertz (THz) free electron laser (FEL). The main issue of the FEL design is to decrease radiation losses at a FEL resonator except outcoupling ratio. Also reducing the number of undulator periods and total undulator length is important to increase FEL conversion efficiency and to reduce its size. The FEL consists of a magnetron-based microtron having an energy of ~5 MeV, a strong electromagnetic helical undulator having the period of ~30 mm, and a circular waveguide-mode optical resonator. The total diameter of the microtron is approximately 50 cm and the macropulse current is more than 50 mA. The size of the system is expected to be 1x2 m^2. The condition for low-loss and high-gain oscillator of the table-top FEL has been studied by using a 2-D FEL code. Simple injection scheme of the electron beam to the undulator was optimized by calculating beam trajectories with a 3-D PIC code. The average THz power is calculated to be 1 W with the tunable wavelength range from 200 μm to 600 μm (0.5 to 1.5 THz). The FEL is expected to be used for the real-time imaging of security inspection.

Hot-electron superconducting nanobolometers-sensors and arrays of them for high sensitive terahertz frequency range imaging radiometers (abstract)

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The comparative review of investigations and development state of high sensitive superconducting nanobolometers-sensors for terahertz frequency range imaging array radiometers has been carried out. The following conclusions are made. (1) Hot-electron nanobolometers with combined radiation absorber and transition edge sensor (TES), the last are fulfilling the electron temperature measuring function, are most promising for the achievement of utmost high sensitivity as opposed to bolometers which radiation absorbers are made as suspended membranes and TES's are membrane temperature sensors. (2) Dimensions of TES have to be small to the limit – down to tens of nanometer, and operating temperature has to be super low – down to 30 – 40 mK. The networks of immersion lens, planar antenna, microstrip line and/or coplanar line with nanobolometer coupled into them have to be used to match THz radiation energy transfer to such small nanobolometers. Such nanobolometers and arrays of them are needed in the first place for the space astronomical applications where the cosmic background noise of order of 10^{-20} and less related to one nanobolometer does limit NEP. The electron-beam lithography technology is needed for fabrication of nanobolometers with said dimensions. The array structures of receiving elements with such nanobolometers are proposed. It is reasonably to be guided to such hot-electron nanobolometers and arrays of them in case of applications demanding the moderate sensitivity ($\geq 10^{-18}$W/Hz$^{1/2}$). In this case they have to have dimensions of order of microns and not too super low temperature (~ 0.3 K).

Матрицы сверхпроводниковых наноболометров-сенсоров на горячих электронах для сверхчувствительных изображающих радиометров терагерцового диапазона частот

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THz Radiation Detectors

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THz technologies play increasing role in different areas of human activities (e.g., security, biological, drugs and explosions detection, passive and active imaging, astronomy applications, etc.) (see, e.g., [1]). To be successfully implemented in these areas they require further improvements in *THz* detectors sensitivity to be used at given conditions. Here, issues associated with the development and exploitation of *THz* radiation detectors, are discussed.

Progress in *THz* detector sensitivity has been impressive during last 60 years when *NEP* values decreased by a factor of 10^{11}, from $NEP \sim 10^{-9}$ W/Hz$^{1/2}$ to sub-Kelvin operation (T<300 mK) $NEP \sim 10^{-20}$ W/Hz$^{1/2}$ (at low-temperature background fluctuations) (see, e.g., [2]). Here considerations on limited to some physical detector basis comparison detector characteristics and new propositions of detector designs are presented. The basic physical phenomena and the recent progress in both direct and heterodyne detectors are described. Their advantages and drawbacks are presented.

Comparison and discussion of implementation of low-temperature operation *THz* detectors (e.g., *SIS* and *SIN* junctions, *HEB* and *TES* bolometers, carbon nanotube, *SL* and *QD* detectors, extrinsic semiconductor detectors, *IV-VI* semiconductor detectors, etc.), which in some cases can operate in wide radiation frequency range between the radio and gamma rays, are presented. Problems associated with their use in large format multielement arrays are discussed.

Uncooled *THz* direct detection detectors, e.g., on the base of *2D* electrons in *FETs* or warm electron bolometers, which *NEP* should reach $NEP \sim 10^{-10} - 10^{-11}$ W/Hz$^{1/2}$ could be used in many low-resolution spectroscopy applications and low-cost active imaging systems. Properties of these *THz* detectors, which can be assembled in arrays with electronics embedded into the chip, are also discussed in comparison with conventional uncooled detectors (microbolometers, Golay cells, Schottky barrier structures, and others).

1. M. Tonouchi, "Cutting-edge terahertz technology", *Nature Photonics* 1, 97–105 (2007).
2. F. Sizov, "THz radiation sensors", *Opto-Electr. Rev.* 18, 10-36 (2010).

PROPAGATION OF FEW-CYCLE THZ WAVES: METHODS OF ANALYSIS AND PATTERNS OF EVOLUTION

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Peculiarities of few-cycle THz waves are discussed. Spectral method of analysis of propagation of light waves with ultrabroad spatiotemporal spectra is investigated. Spectral analogs of Maxwell equations for dielectric media are obtained. Equations for dynamics of spatiotemporal spectra of electric fields of light waves in linear and nonlinear dielectric media and their solutions are considered. Patterns of diffraction-dispersion spreading of THz wave packets in linear dielectric media are determined. Field method of analysis of propagation of light waves with ultrabroad temporal spectra is investigated. Principles of derivation of field equations for few-cycle pulses are described. Equations for field dynamics of waves with ultrabroad temporal spectra in dielectric media are considered. Patterns of generation of THz and IR few-cycle waves during interaction of intense ultrashort light pulses with different frequencies are determined. Patterns of reflection of paraxial THz wave packets with ultrabroad temporal spectra are obtained.

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Surface plasmon-polariton THz waves in optically active media

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Surface plasmon-polariton waves are known to propagate along interfaces of media with different signs of permittivity or permeability. While the dielectric permittivity is positive, metals possess negative permittivity for wavelengths above plasma wavelength. Recently artificial metamaterials with negative permittivity and permeability up to optical frequencies have been manufactured [1]. Metamaterial-dielectric interface also supports surface waves with properties different from metal-dielectric interface [2,3]. Remarkably, such interfaces support both TE and TM modes with different dispersion, which can be both forward and backward. One of the distinctive properties of both metals and metamaterials is their specific frequency dispersion that leads to surface pulse broadening.

In this work we investigate surface waves on the interface of metal or metamaterial and dielectric with optical activity. Our analysis shows that within the linear on gyration value approximation optical activity doesn't influence the propagation constant but changes transverse field distribution and polarization state. In optically active dielectric a surface wave is a combination of two coupled waves that correspond to eigenwaves of bulk medium. In metal/metamaterial a surface wave decays exponentially in the transverse direction.

We investigate surface wave beam diffraction while propagating along the interface between two media: metal or metamaterial with a negative index and an optically active medium or a nonlinear dielectric. The equation that describes surface beam diffraction [4] is:

$$\frac{\partial A}{\partial x} + iD_{dif}\frac{\partial^2 A}{\partial y^2} - i\alpha |A|^2 A = 0,$$

where $A(x,y)$ is the slowly varying amplitude, diffraction coefficient is $D_{dif} = \frac{1}{2\beta}$ and α is effective nonlinear coefficient, sign and value of which depends on the media permittivity, permeability, nonlinearity and beam localization coefficients. Thus optical activity doesn't influence surface beam diffraction. The transverse field distribution depends on the type of dielectric.

Taking into account diffraction phenomena the equation for surface plasmon-polariton pulsed beam of finite width and duration can be written in the form [4]:

$$\frac{\partial A}{\partial x} + iD_{dis}\frac{\partial^2 A}{\partial \xi^2} + iD_{dif}\frac{\partial^2 A}{\partial y^2} - i\alpha |A|^2 A = 0,$$

where $\xi = x - v_{gr}t$ is beam coordinate in the reference frame moving with the group velocity $v_{gr} = \partial\omega / \partial\beta$, dispersion coefficient is $D_{dis} = \frac{1}{2}\frac{dv_{gr}^{-1}}{d\omega}\Big|_{k=k_0}$. Equation (3) is the nonlinear Schrodinger equation having soliton solutions.

The work is supported by RFBR (projects No 08-02-00717, 09-02-01028, 10-02-90010) and Dynasty foundation.

References:

[1] V. Shalaev "Optical negative-index metamaterials", Nature Photonics 1, 41 - 48 (2006)
[2] Ruppin R. // Phys. Lett. A 277 61 (2000)
[3] Shadrivov I. V., Sukhorukov A. A., Kivshar Yu. S. et al. // Phys. Rev. E, Vol. 69, p. 016617 (2004)
[4] D.O. Saparina, A.P. Sukhorukov // BRAS: Physics, Vol. 73, No. 12, pp. 1701–1704 (2009)

Generation and detection of terahertz radiation by means of periodically poled crystals

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Development of the terahertz (THz) wave generation and detection methods based on non-linear optical frequency conversion processes stands as a fast developing research area during the past few decades [1]. Among the advantages of this approach there are high attainable efficiencies, room-temperature operation, coherent properties of the THz generation, and possibilities of subsequent synchronous time-sampling of the THz fields as well as usage of sensitive optical detectors for the THz detection. Different dielectric, semiconductor, organic materials with high second-order optical susceptibility, transparent both in optical and terahertz ranges, with instantaneous response, are considered as promising for the frequency conversion form the optical to THz range and vice versa. Nevertheless, only a small part of them is really used due to limitations caused by the phase matching conditions. Constructive collinear interaction between THz and optical waves in a spatially homogeneous non-linear medium can be provided only within the forward and backward coherence lengths, which are inversely proportional to the phase mismatches and can be too small for application in spite of high non-linearity of the material. From the beginning of the 2000s, the use of quasi-phase matching conditions was proposed for narrow-band collinear THz generation in periodically poled crystals [2]. An enlarged scope of the quasi-phase matching approach will be discussed in the talk, taking into account applications of periodically poled crystals in both generation and detection schemes, and using advantages of controllable disordering of quasi-phase-matched structures in nonlinear-optical crystals.

Two recently proposed experimental systems for quasi-phase matched THz generation and subsequent detection will be considered in detail, one operating under optical femtosecond pulsed pumping and the other operating in quasi-continuous (nanosecond pulsed) pumping regime [3]. The use of broadband laser pumping mode in combination with the specially designed aperiodically poled crystals opens a possibility of spectral shaping of the THz signals generated in the both schemes. The new quasi-phase-matched femtosecond EO detection scheme is performed, based on measuring of variation of the femtosecond laser pulse energy induced by a terahertz field [4]. Narrow-band OR generation and the probe-energy type of EO detection have been demonstrated at a number of terahertz frequencies using wide-aperture periodically poled Mg:Y:$LiNbO_3$ crystals with as-grown domain gratings.

A distinctive feature of the proposed nanosecond detection scheme is availability of the internal reference signals which can be used for absolute calibration of the THz radiation. The new method of absolute measurement of the THz radiation spectral brightness will be reported.

[1] G.Kh.Kitaeva, Laser Physics Letters 5 (2008) 559.

[2] Y.-S.Lee, T.Meade, M.DeCamp, T.B.Norris, A.Galvanauskas, Appl. Phys. Lett. 77 (2000) 1244.

[3] G.Kh. Kitaeva, A. N. Penin, A. N. Tuchak, Opt. and Spectrosc. 107 (2009) 521.

[4] G.Kh. Kitaeva, S. P. Kovalev, I. I. Naumova, R. A. Akhmedzhanov, I. E. Ilyakov, B. V. Shishkin, and E. V. Suvorov. Appl. Phys. Lett. 96 (2010) 071106.

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DETECTION OF PICOSECOND THZ PULSES BASED ON THE GENERATION OF ACOUSTIC WAVES IN NANOMETER CONDUCTIVE FILMS

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Possibility of use of effect of generation of acoustic waves in thin conductive films for registration picosecond THz pulses is considered. This effect has been applied by working out of sensor of high-power microwaves pulses of nanosecond duration [1]. Operation of the detector is based on effect of acoustic signal generation when microwave pulses are absorbed in the layered structure: radiotransparent substrate - absorber - liquid. Thin metallic film of nanometer thickness deposited on a substrate is used as an microwave absorber. Transformation of microwave radiation into acoustic pulse is produced in the film and in the liquid contacting with the film. The pulse is received by a wideband acoustic receiver and then recorded by a digital oscilloscope. Testing for frequencies 10 and 37,5 GHz have shown full working capacity of the sensor [2].

The similar scheme is supposed to be used for registration THz of radiation picosecond duration. Registration of an acoustic pulse picosecond duration will be carried out by a method of an interference of a basic pulse with an pulse which phase changes owing to the mechanical deformations caused by an acoustic wave.

For registration of an acoustic pulse picosecond duration the small trial part of THz pulse is used. The basic part of THz pulse goes on a conductive film for generation of an acoustic signal. Trial part of a THz beam is split on two beams, one of which is basic, and another measuring. The phase of a measuring beam changes owing to interaction with an acoustic wave and the mechanical deformations of a substrate caused by it. The pulse in a measuring shoulder is late concerning basic by means of an optical line of a delay with discrecity of an order of picosecond. Both coherent beams are added and intensity of a total signal and measured. On a target photocurrent it is possible to judge size of correlation of basic and measuring beams for the fixed value of time of a delay. Spending measurements for a set of values of size of a delay, it is possible to detect the form of an acoustic pulse which corresponds to the shape of the envelope of THz pulse. In the report schemes of modulation of a phase of a measuring beam are analyzed.

[1] V.G.Andreev, V.A.Vdovin, Instrum. Exp. Tech. No. 2 (2009) 226.
[2] V.G.Andreev, V.A.Vdovin, K.V. Afanas'ev, et al. Radiophys. Quantum Electron. 52, 8 (2009) 587.

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OPTICAL PROPERTIES OF CARRIER PLASMA AND GENERATION OF THZ WAVE RADIATION IN INHOMOGENEOUS SEMICONDUCTORS

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In THz range optical properties of semiconductors are mainly determined by an interaction of radiation with charge carriers – semiconductor plasma. Processes of non-coherent generation of THz-range radiation during optical-range laser irradiation are also determined by the interaction with carriers. Carrier plasma is susceptible to the external fields, which can be both a wave field and a quasi-static external electric field. Specific features of carrier plasma dynamics and kinetics (processes of scattering and relaxation during the interaction with internal local fields in semiconductor) determine a non-linear response from the semiconductor, effect of static fields on its optical properties, intensity and spectra of THz radiation.

Main processes of carrier scattering which influence on linear in field and non-linear contribution to the optical properties of semiconductors in THz range are analyzed in the paper. Numerical results for spectral dependencies of non-linear susceptibilities of AIIIBV semiconductors at different temperatures and carrier concentrations are presented. Dependencies on external quasi-static field for real and imaginary parts of permittivity as well as for reflection and transmission coefficients are presented.

Local internal semiconductor fields play an important role in non-coherent generation of THz-range radiation. Besides the surface layer inherent to homogeneous materials, such fields can be introduced due to the specific conditions of semiconductor growth or during its processing. The experiments carried out on semiconductors irradiated with high-energy heavy ions showed a significant increase in efficiency of generation of THz radiation and an influence of inhomogeneities on it.

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PLASMONIC DEVICES FOR DETECTION AND GENERATION OF TERAHERTZ RADIATION

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Terahertz (THz) plasmonics is a newly emerging field of THz physics and technology studying the processes of detection and generation of THz waves by plasmon excitation in semiconductor microdevices. Terahertz response of semiconductor microdevices with two-dimensional (2D) electron channels such as field-effect transistors (FETs) and akin devices is strongly affected by plasma oscillations exited in the device channel. This phenomenon can be used for the detection, frequency multiplication and generation of THz radiation [1-4] as well as for THz imaging [5]. Plasmonic devices are practically attractive because they are extremely fast, electrically tunable through the entire THz frequency band by changing electric potentials at metal contacts of the device, and exhibit sub-THz-wavelength response (which is important for THz imaging and near-field THz microscopy). The latest experimental studies show that plasmonic THz detectors demonstrate the responsivity exceeding 100 V/W along with deeply sub-THz-wavelength spatial resolution.

In this paper the physics of plasma oscillations in semiconductor microdevices with 2D electron channels is considered. Detection and generation of THz radiation by plasmons in such structures is based on the hydrodynamic nonlinearities of free-electron movement in 2D channel. Special attention is given to the problem of electromagnetic coupling between plasmons in 2D electron channel and THz radiation. This problem is very important for designing high-performance plasmonic devices but it is a non-trivial problem, however, because the wavelength of plasmons is typically two or even three orders of magnitude shorter than the wavelength of THz radiation. It is shown that plasmons can be effectively coupled to THz radiation by using a metal grating coupler of large area (comparable with the cross-section area of focused THz beam) placed in close proximity to 2D electron channel [6].

[1] M. Dyakonov, M. Shur, IEEE Trans. on Electron. Devices 43 (1996) 380.

[2] W. Knap, J. Lusakowski, T. Parenty, S. Bollaert, A. Cappy, V.V. Popov, M.S. Shur, Appl. Phys. Lett. 84 (2004) 2331.

[3] К.В. Маремьянин, Д.М. Ермолаев, Д.В. Фатеев, С.В. Морозов, Н.А. Малеев, В.Е. Земляков, В.И. Гавриленко, В.В. Попов, С.Ю. Шаповал, Письма в ЖТФ 36 (2010) 39.

[4] D. Coquillat, S. Nadar, F. Teppe, N. Dyakonova, S. Boubanga-Tombet, W. Knap, T. Nishimura, Y.M. Meziani, T. Otsuji, V.V. Popov, G.M. Tsymbalov, Opt. Express, 18 (2010) 6020.

[5] W. Knap, M. Dyakonov, D. Coquillat, F. Teppe, N. Dyakonova, J. Łusakowski, K. Karpierz, M. Sakowicz, G. Valusis, D. Seliuta, I. Kasalynas, A. El Fatimy, Y.M. Meziani, T. Otsuji, J. Infrared Millim. Terahertz Waves 30 (2009) 1319.

[6] V.V. Popov, M.S. Shur, G.M. Tsymbalov, D.V. Fateev, Int. J. High Speed Electronics and Systems, 17 (2007) 557.

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ELECTRICAL PARAMETERS of Si *n*-MOSFET THz-DETECTOR: MATCHING WITH EXTERNAL AMPLIFIER

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Uncooled or slightly cooled THz/sub-THz broadband direct detection detectors on the base of 2D electrons in FETs [see, e.g., [1]] are promising to be used in large arrays of the low-cost systems. Reaching *NEP* between 10^{-10} and 10^{-11} W/Hz$^{1/2}$ they could be used in many low-resolution spectroscopy applications and active vision systems. They can be manufactured as relatively large arrays with external or internal means for signal processing. Favorable semiconductor for these purposes is silicon.

Here, some characteristics of *Si n*-MOSFET transistors, as devices for registration of sub-THz radiation by linear arrays, designed and manufactured by 1 μm design rules were investigated. Typical dimensions of these transistors were rectangular and square form devices with different gate width W and length L from 1×1 μm to 20×20 μm. Parameters which are important for matching with signal processing devices, are input resistance R_L, amplifier intrinsic noise level U_n, amplification bandwidth Δf and gain factor k_{amp}.

In Fig.1 shown are voltage signals δU_D at different load resistances R_L which were measured at room temperature under radiation frequency ν=142 GHz with power ~10^{-3} W/cm^2. Current signals δI_D (Fig. 2) were calculated by $\delta I_D = \delta U_D / R_L$.

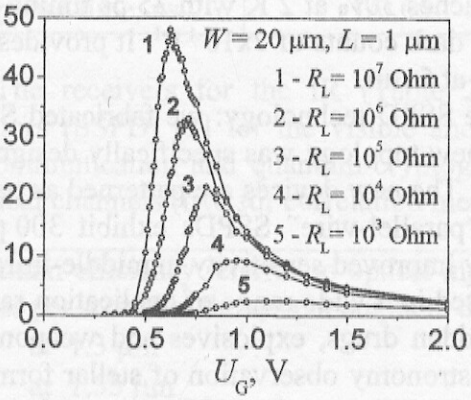

Fig.1. Drain voltage response δU_D of Si n-MOSFET vs gate voltage U_G. Drain voltage U_D = 0 V. Peak value: δU_D = 48 μV at U_G = 0.62 V and R_L = 10 MOhm.

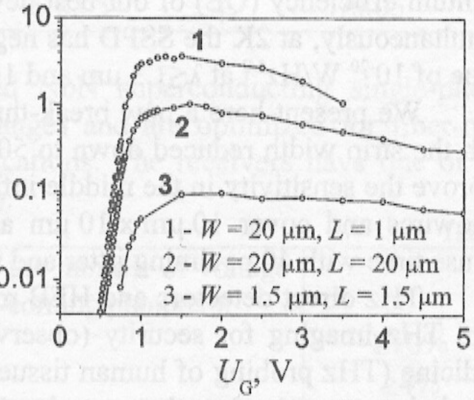

Fig.2. Drain current response δI_D of Si n-MOSFET vs gate voltage U_G at different W, L. Peak value: δI_D = 3.5 nA at U_G = 1.2 V and W =20 μm, L =1 μm.

For investigated transistors the amplifier input resistance should be $R_L > 10^5$ Ohm, noise level should be $U_n < 1$ mV. Gain factor is within $k_{amp} = 10^3 \div 10^5$ and depends on *n*-MOSFET transistor design and radiation power. Amplification bandwidth Δf ~ 8 kHz is chosen for frame frequency 25 Hz and number of lines in the frame N=320.

1. W. Knap, M. Dyakonov, D. Coquillat, et.al., "Field effect transistors for terahertz detection", J. IR, MM THz Waves, **30**, p. 1319 (2009).

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SUPERCONDUCTING NBN TERAHERTZ DETECTORS AND INFRARED PHOTON COUNTERS

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We present our resent achievements in the development of sensitive and ultrafast thin-film superconducting sensors: hot-electron bolometers (HEB), HEB-mixers for terahertz range and infrared single-photon counters. These sensors have already demonstrated a performance that makes them devices-of-choice for many terahertz and optical applications.

Hot-electron bolometers made from NbN and MoRe films are operated in 0.3-3 THz range exhibit response time as low as 50 ps and 1 ns respectively with noise equivalent power (NEP) of $3x10^{-13}$ W $Hz^{-1/2}$ (NbN) and $5x10^{-14}$ W $Hz^{-1/2}$ (MoRe). Another versions of these detectors have a broadband sensitivity in 0.1-30 THz range with the same response time and exhibit higher NEP but much higher dynamic range.

The HEB mixers based on ultrathin films of NbN combine the best sensitivity at the frequencies well above 1 THz and a gain bandwidth of about 5-6 GHz which make them suitable for most sensitive instruments being developed in the far IR region for astronomical and atmospheric studies.

A promising type of the photon counting detector is superconducting single-photon detector (SSPD). The SSPD is patterned from 4-nm-thick NbN film as 120-nm-wide and meander-shaped strip that covers a square area of 10 μm x 10 μm. At wavelength $\lambda \leq 1.3$ μm quantum efficiency (QE) of our best devices approaches 30% at 2 K with 35 ps timing jitter. Simultaneously, at 2K the SSPD has negligibly low dark counts of $2x10^{-4}$ s^{-1}. It provides NEP value of 10^{-20} W/$Hz^{1/2}$ at $\lambda \leq 1.3$ μm and 10^{-18} W/$Hz^{1/2}$ at 5 μm.

We present here a new break-through in the SSPD technology: we fabricated SSPDs with the strip width reduced down to 50 nm. This new topology was specifically designed to improve the sensitivity in the middle infrared range. The new devices are patterned as parallel nanowires and cover 10 μm x 10 μm area. Such "parallel-wire" SSPDs exhibit 300 ps response time with 40 ps timing jitter and significantly improved sensitivity in middle-infrared.

THz direct detectors and HEB mixers are used in a wide range of application ranging from THz imaging for security (observation of hidden drugs, explosives and weapon) and medicine (THz probing of human tissues) to radioastronomy observation of stellar formation and dark matter (space observatories Herschel and Millimetron). SSPD due to their high quantum efficiency and picosecond timing resolution has already been successfully applied for study of quantum dot luminescence and for quantum key distribution (recent result is 250-km-long distance).

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TERAHERTZ AND INFRARED RECEIVERS BASED ON SUPERCONDUCTING NANOSTRUCTURES

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Rapid development in the fabrication and processing of ultrathin superconducting films resulted in significant progress in the field of superconducting receivers. Currently such receivers are used radio astronomy, quantum-correlation-type quantum cryptography and telecommunications, for VLSI testing and etc.

Here we present the results of developing receivers for the infrared (IR) and terahertz (THz) wave ranges. The receiver systems are based on superconducting detectors fabricated from thin MoRe and NbN films [1,2]. Table 1 shows the main types and characteristics of the THz receiver systems mounted inside optical helium cryostats.

The response time of these systems is determined by the cooling-down rate of the heated electron gas, in our case is the electron-phonon interaction rate, which is more effective in ultrathin NbN films than in MoRe ones.

Table 1.

Detector type	1/1a	2/2a	3/3a
Frequency range, THz	0.3-3	1-30	25-70
NEP, $W \cdot Hz^{-0.5}$	$5\text{-}7\times10^{-14}/3\text{-}5\times10^{-13}$	$4\text{-}6\times10^{-11}/1\text{-}2\times10^{-10}$	$1\text{-}2\times10^{-12}/4\text{-}5\times10^{-12}$
Response time, ns	1/0.05	1/0.05	1/0.05

The receivers for the IR (Table 2) are based NbN superconducting single-photon detectors (SSPD) [2] for the visible and infrared ranges and are optimized for fiber-optic telecommunication and quantum-cryptography applications. The receivers have one or two identical channels (two for correlation measurements).

Table 2.

Quantum efficiency referred to optical input (ratio of the number of voltage pulses per second at the system output to the flux of in-coming photons): at 1.3 µm at 1.55 µm	 ≥10% ≥4%
Dark counts rate (number of voltage pulses at the system output per second in the absence of in-coming radiation)	$\leq 1\ s^{-1}$
Output voltage pulse duration	≤5 ns
Jitter	≤40 ps

[1] M.I. Finkel, S.N. Maslennikov and G.N. Goltsman // Terahertz heterodyne receivers based on superconductive hot-electron bolometer mixers, Radiophysics and Quantum Electronics, v.48, n. 10-11 pp. 859-864, (2005).

[2] G. Goltsman, O. Okunev, G. Chulkova et al., App.Phys.Lett., v.79, p. 705-707, (2001).

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DESIGN AND APPLICATION OF UNCOOLED MICROBOLOMETER ARRAY FOR TERAHERTZ SPECTRAL RANGE

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In the latter several years to the uncooled matrix microbolometer detectors on the basis of the vanadium oxide are manifested great interest in the connection by their high sensitivity to the terahertz (THz) radiation.

The developed matrix microbolometer photosensitive devices with the format of the matrices of 320x240 and 160x120 pixels (pixel size 48x48 μm^2) possess the noise equivalent power (NEP) of 30 nW/pixel in THz range, and they are at present the unique highly sensitive terahertz detectors of high spatial and time resolution [1]. However, THz radiation is weakly absorbed in the thin layers of the vanadium oxide and silicon nitride, utilized as the design materials, which specifies larger noise equivalent power in comparison with the infrared region, in which it amount of 160 pW/pixel.

Report presents the theoretical and experimental results of investigating the possibilities of further increase in the sensitivity of microbolometer in THz range by using the additional thin metallic absorbing layer, deposited on the membrane of thermosensitive layer. It is known that the thin free metallic films with the layer resistance to the equal to 188 Ω/sq. absorb to 50% of incident radiation independent of wavelength in the submillimeter range. With the presence of reflecting mirror, located at a distance equal to quarter wavelength of incident radiation, the absorption can amount 100% during the layer resistance of metallic film equal to 377 Ω/sq. In matrix microbolometer designed for IR range this metallic film is located above the mirror at a distance 2-3 μm, that much less than the wavelength of THz radiation, and therefore it is located closely to the node of standing wave, which substantially weakens the absorption. It can be increased via the utilizing of the optimum layer resistance of metallic film.

The results of measuring the transmission and absorption of the layers of silicon nitride, vanadium oxide and different metallic films, used in microbolometer are presented. Obtained data are used with the simulation, whose purpose - the determination of the optimum design parameters, which ensure the maximum absorption value of THz radiation. It is experimentally shown that the modification of the construction of microbolometer leads to an increase in its sensitivity by several times. The results of the registration the objects with the use THz radiation of Novosibirsk free electron laser are presented.

[1] M. A. Dem'yanenko, D. G. Esaev, B. A. Knyazev, G. N. Kulipanov, and N. A. Vinokurov, Appl. Phys. Lett., **92**, 131116 (2008).

CURRENT STATUS OF "MILLIMETRON" MISSION MM & SubMM RECEIVER'S DEVELOPMENT

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We present recent advances in development of "Millimetron" mission receiving complex, which include medium resolution spectrophotometer/polarimeter arrays operating in 0.3-3 THz range (~10k pixels arrays of detectors with $10^{-(19-18)}$ W·Hz$^{-0.5}$ NEP are required), heterodyne receivers for high resolution spectrometer operating in 1-5 THz (several pixels arrays of receivers with noise temperature of several quantum limits, ~6-8 GHz bandwidth are required), VLBI receivers for Space-Ground interferometry operating at several bands within 18-950 GHz range. The Millimetron Space Observatory (the "Spectr-M" Project) is a 12 m telescope dedicated to the investigation of various objects in the Universe in the millimeter and infrared wavelengths (from 20 □m to 20 mm). It provides both super high sensitivity (in the single-dish mode) and super high angular resolution of up to $4 \cdot 10^{-8}$ arcsec in the interferometer mode. This is billion times better than the human eye resolution.

The super high sensitivity is achieved due to the deep cooling of the receivers, and the telescope as a whole. The high angular resolution is obtained by the Space-Ground interferometer which includes the Millimetron space telescope located in the L2 Lagrangian point, and a set of the largest ground telescopes. Since emission at the wavelengths shorter than 300 □m is screened by the Earth atmosphere, the 20–300 □m range will be explored only in the single dish mode. In the future, it would be possible to launch several additional space observatories and to realize a Space-Space interferometer which will provide a super high sensitivity and, also, a super high angular resolution including shorter wavelengths screened by the atmosphere.

Current development status of medium resolution spectrometer/polarimeter concept and recent advances in THz detector technology with ultra low NEP required for BLIP performance of the instrument are presented. Heterodyne instruments concept and recent achievements in THz hot-electron mixers performance are also presented.

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GENERATION OF HIGH PEAK POWER THz RADIATION BY OPTICAL RECTIFICATION AND THz NONLINEAR SPECTROSCOPY

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Terahertz (THz) waves have attracted considerable interest in recent years owing to their prospective applications in different scientific and industrial fields. Some of these applications require high-power ultrashort THz pulses. In particular they can be used for THz imaging and spectroscopy of large-scale remote objects for security purposes. One of the most challenging scientific applications of high-power THz radiation is nonlinear spectroscopy. The characteristic energy of many fundamental processes in molecules and condensed matter lies in the THz range; examples include the rotation of small molecules, biologically important collective vibrations of proteins, crystal lattice resonance oscillations, transitions between excited electronic states in semiconductor nanostructures, and formation of Cooper pairs in superconductors, among many others. Nonlinear THz spectroscopy can provide new information about these processes that is difficult to obtain via traditional methods such as Raman scattering and Fourier spectroscopy. However, very few studies on nonlinear THz spectroscopy have been published to date, in contrast to the large number of studies on nonlinear spectroscopy in the visible and middle IR ranges. One of the main reasons restricting the development of nonlinear THz spectroscopy is the lack of available sources of high-power THz radiation. Many previous studies on THz nonlinear spectroscopy have been performed using accelerator-based sources, which can provide single-cycle THz pulses with energy of up to of 100 μJ and corresponding peak power of up to 100 MW [1]. However, these sources present the typical drawbacks associated with large-scale facilities. Several table-top techniques based on femtosecond lasers have been used to generate near-single-cycle THz pulses. For a long time the peak power of the THz radiation delivered via these schemes remained significantly lower than that of accelerator-based sources. In 2002, Hebling et al. proposed a new velocity-matching technique based on femtosecond laser pulse-front tilting for large-area THz generation via optical rectification [2]. Recently, using this technique in combination with the *Teramobile* laser [3] we demonstrated the first mobile source of high peak power THz radiation [4].

In this report we review recent progress in generation of ultrashort THz pulses with high peak power based on the use of femtosecond lasers. Moreover, we outline the main research on THz nonlinear spectroscopy starting from early works in the 1960s up to the latest THz pump/probe experiments.

[1] Y. Shen, et al., Phys. Rev. Lett. 99 (2007) 043901.
[2] J. Hebling, G. Almási, I. Z. Kozma, and J. Kuhl, Opt.Express 10 (2002) 1161.
[3] H. Wille, et al., Eur. Phys. J. – Appl. Phys. 20 (2002) 183.
[4] A. G. Stepanov, S. Henin, Y. Petit, L. Bonacina, J. Kasparian, and J.-P. Wolf, to be published.

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HIGH-PRECISE SPECTROMETRY OF THE TERAHERTZ FREQUENCY RANGE: THE METHODS, APPROACHES AND APPLICATIONS

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The application of the microwave approach to the developing of the terahertz (THz) frequency range allowed producing the set of precise methods and devices for various applications. The midpoint of the development was the using of the mixers and multipliers on the quantum semiconductor superlattices which allow more effective signal transformation in comparison with usually used devices based on Schottky diodes. As a result the unique family of the frequency synthesizers based on the backward wave oscillators operating in the frequency range of 667 ÷ 1100 GHz was produced. Besides, the application of the non-stationary microwave spectroscopy together with the components of solid state nanoelectronics allowed to realize the solid state spectrometer of the THz frequency range, working in the phase switching of the frequency. The high sensitivity and spectral resolution allows using the spectrometer developed for various applications. The results of the spectrometer applications for the purposes of medicine and biology, as well as for hi-tech and safety systems are presented.

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ПРЕЦИЗИОННАЯ СПЕКТРОМЕТРИЯ ТЕРАГЕРЦОВОГО ЧАСТОТНОГО ДИАПАЗОНА: МЕТОДЫ, ПОДХОДЫ И ПРИЛОЖЕНИЯ

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Применение микроволнового подхода к освоению ТГц диапазона позволило создать серию прецизионных методов и приборов для различных приложений. Ключевым моментом в разработке стало использование смесителей и умножителей на квантовых полупроводниковых сверхрешетках, позволяющих осуществлять более эффективное преобразование сигнала, чем традиционно используемые приборы на основе диодов Шоттки. В результате было создано уникальное семейство синтезаторов частоты на основе ЛОВ, перекрывающих диапазон от 667 до 1100 ГГц. Кроме того, применение методов нестационарной микроволновой спектроскопии и компонентов твердотельной электроники позволило реализовать твердотельный спектрометр ТГц диапазона, работающий в режиме фазовой манипуляции частоты. Высокая чувствительность и спектральное разрешение дает возможность использовать разработанный спектрометр для многих приложений. В докладе представлены результаты применения прибора для задач медицины и биологии, hi-tech и систем безопасности.

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IMAGING, SPECTROSCOPY AND METROLOGY USING COHERENT MONOCHROMATIC RADIATION OF TERAHERTZ FREE ELECTRON LASER

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Terahertz Novosibirsk free electron laser (FEL) has been put into operation in the year of 2004. Since then, many original experiments on wave and statistical optics, spectroscopy and metrology have been performed using the high-power, coherent and monochromatic FEL radiation. This paper describes instrumentation development and experimental achievements in the field of terahertz imaging and its applications. The development of four techniques for real-time terahertz imaging was critically important for the performance of the above mentioned experiments. First imaging terahertz attenuated total reflection spectrometer has been designed and implemented for 2D spectroscopy of dynamic objects. Terahertz speckle patterns in the space domain have been first observed and used for speckle photography and speckle interferometry of static and moving objects, including screened by a non-transparent to visible light shade. Software developed enables the automatic detection of rough object movement. In-line and reference-beam terahertz holographic systems have been developed and tested. Talbot effect in the terahertz range was first demonstrated and used for recording in real-time sample distortion, distance measurement and laser wavelength measurement. Theoretical and experimental approaches to terahertz tomography are also in progress.

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DRUMMOND LIGHT OF CALCIUM OXIDE

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It is shown by optical spectroscopy and He–Ne laser backscattering that the so-called Drummond light of calcium oxide (dazzling bright white light) is quilibrium and caused by the transformation of this material a at certain threshold temperature (2000 K) from an analog of ideal white body (in the optical range) with an emissivity of about 0.1 into an almost ideal black body with an emissivity close to 1. Previously, it was believed that the intensity of this light approximately coincides with that of black body at temperatures above 900 K and exceeds the latter at lower temperatures due to luminescence.

[1] V.V. Kubarev, Optics and Spectroscopy, 106 (2009) 242.

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THREE-FREQUENCY INTERFERENCE AS A METHOD OF ABSORPTION MEASUREMENT IN THE TERAHERTZ RANGE

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At present, various methods based on nonlinear optical processes are among the most effective approaches for terahertz (THz) wave generation and detection. Efficiency of nonlinear-optical processes depends generally on the second-order optical nonlinearity and on the THz absorption coefficient of the nonlinear medium.

Near-forward Raman scattering (NFRS) spectroscopy is a very simple in implementation method for the measurement of optical properties of the medium in the THz range. But, as well as other methods that do not require external THz sources. NFRS is well-suited for the measurement of the dielectric constant real part and is not so appropriate for the measurement of the dielectric constant imaginary part. As a modification of the NFRS spectroscopy scheme, we report here the three-frequency interference method, which is designed for more sensitive dispersion measurement of the dielectric constant imaginary parts and absorption coefficients of the non-linear materials in the THz range.

Basically, the NFRS process can be interpreted as the decay of a pump photon in nonlinear medium into two photons: signal and idler. Non zero absorption of the medium at idler frequencies can be detected at signal frequencies since it results in the broadening of angular spectra of the signal radiation. But the same effect has a factor of limited interaction volume associated with the space-limited pump beam and the crystal length. This leads to considerable errors in the case of low absorption.

The three-frequency interference method was described for the first time in [1]. Three-frequency interference takes place in NFRS under specific boundary conditions: in our case there is a number of parallel pump beams separated by the same distance in a crystal. Signal fields generated by different pump beams interfere with each other. As a result, an interference pattern appears in the angular spectra of NFRS detected at any signal frequency, with a visibility that directly depends on the absorption of the crystal at the corresponding idler frequency (Fig.1). In this work we measure the THz dispersion of the absorption coefficient of crystals with different concentration of Mg dopants by measuring the visibility of the three-frequency NFRS interference in the visible frequency range.

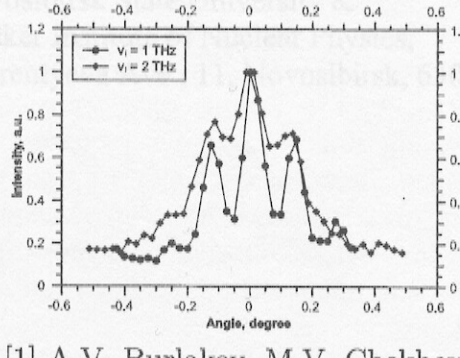

Fig.1 Angular line shape of the signal radiation, corresponding idler frequencies are 1 and 2 THz. Beam diameter $100\mu m$, separation distance $100\mu m$, pump wavelength 514.5 nm.

[1] A.V. Burlakov, M.V. Chekhova, D.N. Klyshko, S.P.Kulik, A.N. Penin, Y.H. Shih, D.V. Strekalov. Phys. Rev. A **56**, 3214 (1997).

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Detection of paramagnetic particles in flame by using terahertz radiation.

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A possibility of application of terahertz radiation (1 – 10 THz or 30 – 300 μm) for flame diagnostics seems to be promising for the following reason. This radiation range contains the lines of rotational transitions of many free radicals, which play a significant role in combustion processes. These include OH, CN, CH, CH_2 [1] and other radicals. Another attractive feature is a low scattering of long-wave radiation by micron-size particles. Unlike the existing optical techniques of radical detection that use visible-light and UV lasers, terahertz radiation method can be suitable for study of strongly scattering mediums, which are opaque for visible light. Examples of such objects are heavily sooting flames.

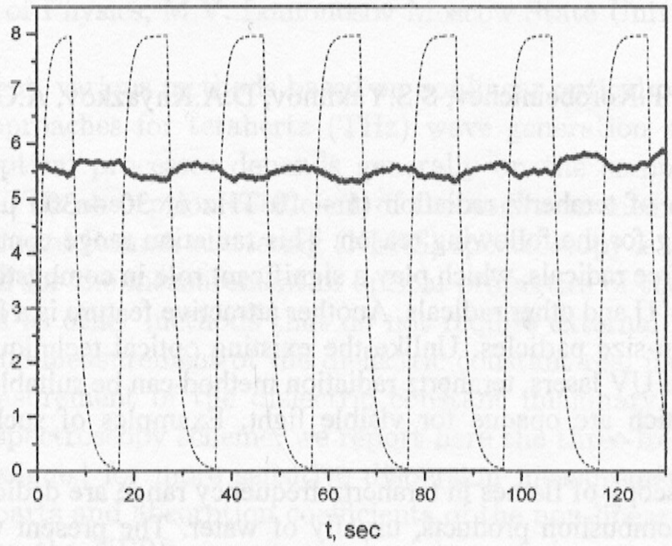
Available works on spectroscopy of flames in terahertz frequency range are dedicated to study of absorption spectra of stable combustion products, usually of water. The present work aims to study a possibility of using terahertz radiation for detection of paramagnetic particles in flame. To increase sensitivity we use Faraday rotation of polarization in magnetic field, which accrue at the frequencies coincident to absorption lines of paramagnetic particles. High sensitivity of Faraday method is provided by possibility of measurements of small angles of polarization rotation.

Free-electron laser NOVOSIBIRSK TERAHERTZ FEL was used as a source of radiation. The parameters of radiation were as following: tuning range, 1.3 – 2.5 THz; relative linewidth, 0.005; repetition rate, 5.6 MHz; pulse length, 0.12 ns; average power, 10 – 50 W.

The most convenient object for registration of Faraday rotation in flame is OH radical due to its high concentration in flame and intensive absorption lines in terahertz region. Two absorption lines of OH radical are within the tuning range of FEL: 1835 and 2512 GHz. These lines correspond to transitions from lower rotational states $^2\Pi_{1/2}$ (½ → 1½) and $^2\Pi_{3/2}$ (1½ → 2½).

Experimental setup consists of electromagnet with a burner between its poles, input polarizer, output polarizer (analyzer), pyroelectric radiation detector and required optical elements. FEL radiation has been directed along the magnetic field through the holes in magnet poles. Combination of convex and concave mirrors has been used for radiation focusing. In the burner area, laser beam has been approximately 1 mm in diameter. Radiation has been modulated at frequency of about 300 Hz by rotating disc with holes. Alternating signal from the radiation receiver has been detected with a phase-lock amplifier and entered into computer. To measure a spectrum of laser radiation, Bruker IFS-66V Fourier-spectrometer has been used. FEL radiation frequency has been tuned to absorption line before the experiment. Premixed flame $H_2/O_2/N_2$ (16.6%/7.4%/76.0%) was stabilized on the flat burner at pressure 1 atm.

Before working with the flame, operation of the setup was tested with NO absorption lines. NO molecules have permanent magnetic moment, and Faraday effect should be observed on the absorption lines of NO. The optical cell with polyethylene windows and filled with NO was placed in the electromagnet. The rotation of the polarization of terahertz FEL radiation induced by magnetic field was observed when laser radiation was tuned to NO absorption line. If the laser is tuned sideways from the NO absorption line the magnetic field doesn't influence on a terahertz radiation polarization.



Alteration of laser radiation due to switching of the magnetic field on the line of OH radical 2512 GHz. Dash line shows the dependence of the magnetic field on time.

The results of experiments on polarization rotation on radical OH $^2\Pi_{3/2}$ (1½ → 2½) line are shown on Figure 2. The burner described above was placed between the magnet poles. FEL has been tuned to the frequency of 2501 GHz. The signal is relatively small due to the small concentration of radicals. The angle of plane polarization rotation in this experiment was about $1*10^{-3}$ rad.

Theoretical analysis of the Faraday effect on the OH absorption line was performed. This analysis shows that the big spectral width of FEL radiation complicates the experiment and can reduce the observable signal. Therefore to improve signal to noise ratio we plan to make spectrum width of laser radiation smaller using monochromator. Also we plan to increase the frequency of modulation of magnetic field.

Thus, the magnitude of Faraday polarization rotate on for terahertz radiation tuned to the lines of OH radical absorption in atmospheric flame is available for measurement (~ 10^{-3} rad). We hope that on the basis of this effect, a sensitive method of detection of free radicals in flame in terahertz region can be developed. This result opens a prospect for detection and measurement of concentration of such compounds, which are important for combustion chemisty, as OH, CN, CH, CH_2, NO and others in sooty and dusty flames.

PROSPECTS OF ISOTOPE SEPARATION BY MEANS OF NOVOSIBIRSK FEL IRRADIATION (A REVIEW)

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Phenomenon of Infrared Multiple Photon Dissociation (IR-MPD) of molecules.

CO_2-laser and ability of selective IR-MPD.

Laser isotope separation (LIS).

First experiments on isotope separation by means of Free Electron Laser (FEL) irradiation.

Advantages of FEL and retrieval of perspective compounds for LIS.

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TYDEX: OPTICS FOR THZ PHOTONICS

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Nowadays interest to THz radiation is growing fast. Many different disciplines such as ultra fast spectroscopy, semiconductor device fabrication, and bio-medical imaging involve the recent development of THz technology. The THz research activities have mainly focused on generation and detection until lately, but the focal point has shifted to the practical applications such as high-speed communication, molecular spectroscopy, security imaging, and medical diagnosis, among many others [1].

Research and industrial applications require availability of good tool base. To satisfy needs of THz photonics TYDEX develops and produces a wide range of optics. Offered products can be divided into three groups:

- Passive components (lenses, windows, prisms, mirrors, splitters, and waveplates);
- Built up components (low pass and band pass filters, polarizers, and attenuators);
- Devices (Golay Detectors).

Crystalline materials (high-resistivity float zone silicon (HRFZ-Si), THz-grade crystal quartz and THz-grade sapphire) as well as polymer ones (polymethylpentene (TPX) and high-density polyethylene (HDPE)) are used for components manufacturing.

TYDEX offers lenses of different shapes: meniscus, hyper-/hypo-/hemispherical, bullet, and plano-cylindrical lenses made of HRFZ-Si as well as plano-convex and bi-convex lenses of TPX. Windows (plano-plano and wedged) are produced of any material mentioned above. TYDEX manufactures HRFZ-Si prisms of the following configurations: right angle and attenuated total reflectance ones. Also TYDEX produces splitters for applications where NIR or MIR radiation has to be reflected without transmission degradation in THz range. Mirrors for full reflection of THz beam are offered too. TYDEX supplies monochromatic $\lambda/2$ and $\lambda/4$ waveplates for different operating wavelengths.

Besides conventional polymers and crystalline optics TYDEX manufactures low pass and band pass filters, polarizers and attenuators. Low pass filters are intended to block radiation from 0.2 μm to 13-100 μm and to transmit at longer wavelengths and band pass ones – to pass radiation within a certain range only. To polarize radiation from 7 μm to MM waves TYDEX offers polyethylene polarizers. Variable wheel accessory is used for attenuation of high-power THz radiation. Set of attenuators allows obtaining different attenuation levels (transmission is varied from 30% to 0.001%).

Also TYDEX supplies one of the most efficient detecting devices - Golay Cell. Three models of Golay Cells are available:

- GC-1P - Golay Detector with HDPE window is intended for monitoring and control of MIR and THz radiation;
- GC-1T - Golay Detector with TPX window – for operating with UV-NIR and THz radiation;
- GC-1D - Golay Detector with Diamond window – for usage of VIS-THz radiation.

Other THz built up components and devices are in progress.

[1] Yun-Shik Lee, Principles of Terahertz Science and Technology (2008) 340.

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40 Years of the BWO-based THz Spectroscopy at the GPI

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Report overviews a four decade period of the technical mastering in the submillimeter wavelength range (is equivalent to the terahertz frequency range) for researches on the gas and condense matter physics and characterisation of devices. The terahertz frequency domain has for many years fallen behind compared to the neighbouring parts of the spectrum. It was attacked at 70-th from the low frequecy range (radiofrequencies) with help of miniaturized electrovacuum microwave generators called BWO (backward wave oscillator). BWOs have appeared to be highly efficient sources of the subterahertz radiation (to 1.2 THz): intensive, monochromatic, continuously tunable.

The effective BWO-based instruments (BWO-spectrometers) has been developed at GPI allowed to perform measurements on thousands of samples – single crystals and ceramics, glasses and polymers, composites, powders, liquids, ets., - and compile reference material on the dielectric properties of microwave and optical materials. Fundamental regularities have been studied of the frequency-temperature behaviour of the electrodynamic response function of dielectrics, ferroelectrics, ionic conductors, dipole glasses, incommesurate crystals, semiconductors, superconductors, antiferromagnets [1]. Additionally the materials have been investigated whose properties were mediated by cooperative electronic effects, such as systems with colossal magnetoresistance, heavy fermions, mixed-valence conductors, low-dimensional conductors with charge- and spin-density wave-type instabilities, spin ladder structures with magnetic and charge ordering and superconductivity, two-dimensional conducting layers with quantum Hall nanostructured conductors [2].

[1] G. Kozlov and A. Volkov, Coherent Source Submillimeter Wave Spectroscopy of Solids, in Millimeter and Submillimeter Wave Spectrocopy of Solids, Ed.: G. Gruner, Topics in Applied Physics, 1998, Vol. 74, pp 51-109.

[2]. B. P. Gorshunov, A. A. Volkov, A. S. Prokhorov, and I. E. Spektor, Methods of Terahertz-Subterahertz BWO Spectroscopy of Conducting Materials, Physics of the Solid State, 2008, Vol. 50, No. 11, pp. 2001–2012.

TALBOT EFFECT IN VISIBLE AND TERAHERTZ RANGES: EXAMINATION AND APPLICATION

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Talbot effect in the terahertz spectral range has been first observed and applied to metrology applications: measurement of distance, determination of radiation wavelength and detection in real-time of wavefront distortion.

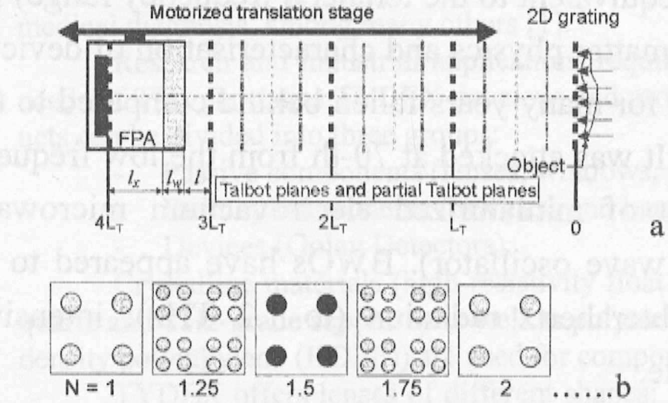

Fig. 1. Experimental schematic (a); images of an array of circular openings (d/p = 1:2) observing at main and partial Talbot planes (b).

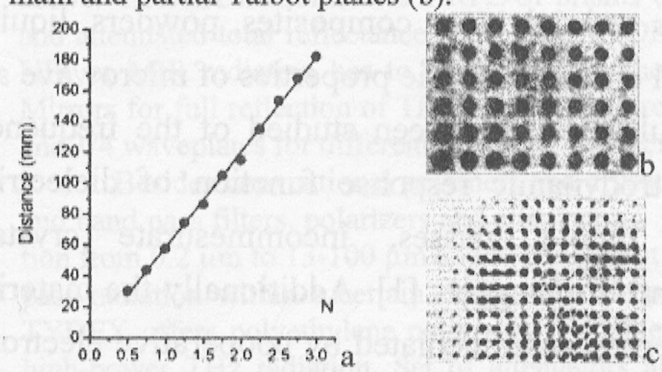

Fig. 2. Positions of Talbot planes vs. plane number (a); images at a main Talbot plane for undisturbed free electron laser beam (b) and with a f=150-mm TPX lens placed before the grating (c)

Measurements of radiation wavelength. "Tera-video" film of a length of 720 frames had been recorded while the FPA was moving by a 200-mm translation stage during 28 seconds. Plotting experimentally found positions of main and partial Talbot planes vs. number of the plane, one can easy calculate from Eq. (1) the radiation wavelength. Line slope in Fig. 2, a corresponds to λ=139±2 µm.

Measurements of distance. To measure distance between microbolometer array surface and silicon window (l_w = 2 mm, n = 3.41), which was unknown us, we used the equation $l_x = L_T - nl_w - l$ (2) where l was experimentally measured distance between closest main Talbot plane and the window. The result was l_x = 7.2 mm.

Measurements of wavefront non-uniformities. Perfect images of the grating in the main Talbot planes (Fig. 2, b) evidence high uniformity of the FEL wavefront. We have recorded many "tera-video" films for different dynamic and static objects placed close to the grating (see Fig. 1, a). Image in Fig. 2, c reveals both radius of converging spherical wave curvature and lens aberrations. Other examples will be given in the presentation.

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Image production with sub-diffraction resolution in radio vision devices of millimeter and terahertz range using receiving arrays and image scanning procedure

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The earlier proposed method of image reconstruction with sub-diffraction resolution in radio vision devices (RVD) of shortwave millimeter and terahertz frequency range is analyzed. The method is based on the image scanning using two-dimensional receiving element array of RVD when array and image move circularly in common plane relatively each other (rotating or not rotating) with small eccentricity between their centers. The results of scanning are signals read out by detectors of array receiving elements. Each signal is proportional to the integral of two functions product. One function is the perfect image field distribution of the observed object received by RVD at the assumption that there are no diffraction and other distortions. Another one is RVD optical (quasioptical) transfer function comprising beams delivering incident radiation to array detectors. The second function takes into account whole received radiation beam paths from RVD input to each detector including the effect of diffraction and reciprocal circular scanning of array and image. The image of observed object itself can be found solving inverse ill-posed problem determined by above mentioned integral relations. The estimation using computer simulation has shown that proposed method permits to increase resolution up to ten times in comparison with the case of diffraction restriction. The influence of receiving system noise to results of image reconstruction is analyzed as well. The method is aimed at radioastronomy telescopes and for the security, medical diagnostics and other RVD systems.

TERAHERTZ TOMOGRAPHY: ALGORITHMS AND EXPERIMENTAL SETUP

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At tomography implementation in a terahertz range strong diffraction effects do not allow using the methods well fulfilled for X-ray tomography. In this paper numerical simulations of tomography projections measurements are accomplished and diffraction tomography iterative algorithm is developed. Generalization of one of the most perspective algorithms of iterative type, - algorithm Gerchberg-Papoulis (G-P) [1], from X-ray on a diffraction tomography is performed. Experimental methods of tomography projections measurements in a terahertz range are developed.

At the heart of the G-P method iterative usage of Fourier-synthesis method lays. Here two spaces participate in iterations: Fourier-space and image space of the tomogram. Known relations between Fourier transform of the wave picture recorded on the flat detector and the Fourier transform of unknown complex refraction index distribution employing the Born or Rytov approximation [2], allows to fill out Fourier-space of the tomogram in iterations and then by inverse Fourier transform to receive the required tomogram. On each iterative step a priori information on an image in the given space is applied (see figure 1).

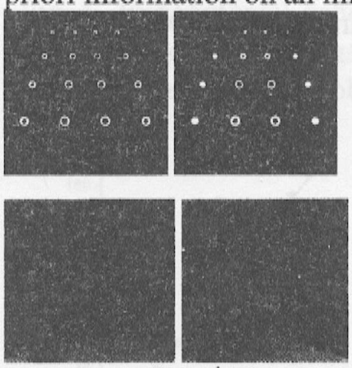

Figure 1. Example of reconstruction of the two-dimensional model tomogram by G-P algorithm. At the left from above – exact model, on the right – its reconstruction on 73 projections, 15 iterations, and RMS error - 33.7 %. Dimensions of the tomogram – 129x129. The bottom row: reconstruction of the three-dimensional model phantom by its two-dimensional projections. At the left – exact model, on the right – its reconstruction. Dimensions of the tomogram – 65x65x65.

Figure 2. Trial measurements of tomographical projections of several amplitude and phase objects have been accomplished at two wavelengths of FEL – 68 and 130 microns.

The greatest possible working field of the detector is 75x75 mm. This size allows to record projections of amplitude and phase objects without scanning. Example of the experimental projection for amplitude object is presented in figure 2, wavelength λ=130 μ.

In summary it is necessary to note high quality of model objects reconstruction by a few-view Gerchberg-Papoulis algorithm developed in this work, both in two-dimensional, and in three-dimensional diffraction tomography. This work was partially supported by the RFBR grant 09-02-12158.

[1] V.V.Pickalov, T.S.Melnikova. Plasma Tomography. Novosibirsk: Nauka (1995).
[2] F. Natterer, F. Wuebbeling, Mathematical Methods in Image Reconstruction. Philadelphia: SIAM (2001).

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Development of high frequency gyrotrons and application to high power THz technologies

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In this paper, we would introduce the development and applications of high frequency gyrotrons in FIR FU

The early gyrotrons developed in FIR FU are pulse gyrotrons operating in sub-THz region. Some of them have already applied for plasma scattering measurement, ESR spectroscopy, etc. However, continuous wave (CW) gyrotrons are sometime much more convenient for application to many high power THz technologies. For responding to such requirement, we have developed gyrotron FU CW series. Up to the present, nine CW gyrotrons were developed. Each gyrotron has its own objective and was optimized for respective application subject. Table 1 summarizes the status of Gyrotron FU CW series.

Table 1 The status of Gyrotron FU CW Series which consists of nine gyrotrons

Gyrotron	Freq. f range	Output power	Max. B	Applications
FU CW I	300 GHz	2.3kW, CW	12 T	Material processing, New medical technology
FU CW II, CW IIA	110–440 GHz	20–200 W, CW	8 T	DNP-NMR at 600 MHz for protein research at Osaka University, Heating of the Si substrate
FU CW III	130–1,080 GHz	10–220 W, CW	20 T	High power THz Technologies
FU CW IV	131–139 GHz	5–60 W, CW	10 T	DNP-NMR at 200 MHz for material science
FU CW V	203.4 GHz	100–200 W, CW	8 T	Accurate measurement on hyperfine structure of positronium, new medical technology
FU CW VI	393–396 GHz	50–100 W, CW	15 T	DNP-NMR at 600 MHz for protein research at Osaka □University
FU CW VII	203.7, 395.3 GHz	200W, 50W, CW	9.2 T	DNP-NMR at 300 MHz and 600 MHz at Warwick University
FU CW VIIA	131.5 GHz 395 GHz	200W, CW	8 T	ESR echo experiment in sub-THz region
FU CW VIII	100-350 GHz	100W, CW	8T	XDMR experiment with high power THz radiation at ESRF

These gyrotrons are being used for many high power THz technologies, such as material processing, new medical technology, DNP enhanced NMR spectroscopy, Accurate measurement on hyperfine structure of positronium, ESR echo experiment in sub-THz region, X-ray detected magnetic resonance (XDMR) measurement, etc. Gyrotrons are only radiation sources in order to develop high power THz technologies in future.

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SUBTERAHERTZ GENERATION BY STRONG LANGMUIR TURBULENCE AT TWO-STREAM INSTABILITY OF HIGH CURRENT 1-MeV REBs

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During past decade novel radiation sources for the range of subterahertz and terahertz frequencies were developed. In the paper [1] we proposed to use high current relativistic electron beams (REB) with particle energy about of 1MeV for two-stage generation of subterahertz radiation in the intercavity scattering scheme. As another way for production of electromagnetic waves in a subterahertz range we see the process of plasma wave transformation to electromagnetic radiation at strong Langmuir turbulence (LT) excited by such REB in plasma [2PhysScript]. In our recent experiments at GOL-3 facility on plasma heating by the high current REB we started to investigate this process as a base for future application to generate a pulse of high power subterahertz radiation.

A distinctive LT's feature is a possibility of electromagnetic radiation emission on plasma frequency (ν_p) as result of plasmon conversion on plasma density fluctuations and on double plasma frequency ($2\nu_p$) that is generated due to plasmon-plasmon merging. Taking into account these mechanisms one has to choose spectral interval of a registration system in accordance with the value of the plasma density at the REB heating experiment. In the experiments at the GOL-3 the plasma density is in the interval $2\div4\bullet10^{14}$ см$^{-3}$ so the developed multi-channel quasi-optical radiometric diagnostics is intended for spectral measurements in the range 100÷550GHz corresponding to aforementioned ν_p- and $2\nu_p$-emission. The diagnostics includes fast Shottky-diode-based receivers with internal preamplifiers for registering 1μW-10mW radiation at integration time < 5 ns, and a set of quasi-optical band-pass metal mesh filters for selecting spectral bands at typical FWHM 20÷60GHz and out-of-band rejection 20÷40dB (see e.g. [2]). Experimental studies are carried out at the long (12 м) plasma column in strong magnetic field (4 T). The electron beam with the current up to 30 kA and the particle energy up to 0.8 MeV is injected during 10 μs through the one end of the column. The level of the energy density of the Langmuir oscillations is estimated by measuring the beam electron distributed function and by registration of the laser radiation scattering in the turbulent plasma. The performed REB-plasma experiments revealed a significant level of subterahertz emission with duration 7-10 μs measured from the section of plasma in the distance 1 m from the beam injection place. It was observed a strong correlation of emission spectra with dynamics of plasma density, as well as spectra broadening and high-frequency shifting during REB-injection. Proceeding from the results of these experiments and similar experiments at INAR-device on heating plasma by REB at the plasma density about of $5\bullet10^{14}$ см$^{-3}$ [3] we propose to generate electromagnetic radiation with the frequency about one terahertz due to plasmon-plasmon merging. Theoretical estimations of the terahertz radiation power generated due to the pointed mechanism are also given.

[1]. A.V. Arzhannikov et al. " Intercavity Scattering Scheme for Two Stage Generation of Submillimeter Radiation on the Base Of Planar 2D Bragg FEM", Strong Microwave in Plasmas, Nizhny Novgorod, 2006 , Vol. 1, p. 228-232.

[2]. S. A. Kuznetsov et al. "Double Effective Band-Pass Submm-Filters Based on Anisotropic Resonant Meshes", Conf. Guide of Int. Conf. on Infrared, Millimeter, and Terahertz Waves

"IRMMW-THz 2008", Pasadena, California, USA, September 15-19th, 2008. Paper M3B4.1743.
[3]. A. Burdakov, A. Azhannikov, V. Astrelin et al. "Plasma heating and confinement in GOL-3 multimirror trap", Fusion Science and Technology, Vol.51, No.2T, 2007, p.106-111.

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SHORT-WAVE OROTRONS AND ORO-MULTIPLIERS

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Nowadays electron sources of coherent radiation such as backward-wave oscillators (BWOs) and gyrotrons can operate at the frequencies of up to 1.4 THz with milliwatt and kilowatt output power levels, respectively. However, THz sources with an intermediate power level of 0.1-10 W are much on demand in a number of spectroscopic applications. For these purposes, it would be attractive to replace the gyrotrons by cheaper slow-wave devices.

In recent years a collaboration of VNIIFTRI, Institute of Applied Physics, and Gycom Ltd. has developed pulsed orotrons — open-cavity oscillators based on stimulated Smith–Purcell radiation of rectilinear electron beams moving near periodic structures. The open cavity provides effective mode selection and allows a significant increase in transverse dimensions of both the interaction region and the electron beam in comparison with BWOs. Consequently, orotrons can provide higher output power. A series of developed orotrons overlap a frequency range of 90-410 GHz at a low operating voltage of up to 5 kV. In particular, a new orotron with a short-period structure (82 μm) has recently been manufactured and tested in the microsecond-pulse regime. A maximal frequency of 410 GHz, which is now the highest frequency for the low-voltage orotrons, was obtained in this device. The band of mechanical frequency tuning in this oscillator is close to 1.5 octaves. For a fixed distance between the cavity mirrors, the TEM_{00n} and TEM_{01n} open-cavity modes with high axial index $n = 25$-50 were observed. The higher frequency was limited by mode competition since for voltages higher than 3200 V parasitic surface modes with significantly low frequencies was excited. The output power (measured by comparing signals from a semiconductor detector powered with the studied orotron and the terahertz BWO with known power) at the frequencies of 300 to 350 GHz is 100-200 mW [1].

Orotron-like version of frequency multipliers (oro-multiplier) also seems an attractive device for frequency enhancement. This capability is based on excitation of a surface eigenwave of a periodic structure for bunching of the electron beam. Arising bunches can excite the open-cavity mode at the temporal harmonics of the surface wave frequency. Since the surface-mode starting current is fairly low, oro-multiplier can operate at high frequencies utilizing the moderate current when the direct orotron operation is complicated by the requirement of a very high current density. The possibility of the oro-multiplier operation has been experimentally demonstrated on a base of the device with multi-pin structure with period of 170 μm. The excitations of surface mode at the frequency of 95 GHz, as well as open-cavity mode at the double frequency of 190 GHz, were registered. An operating current (28-80 mA) was significantly lower than an orotron starting current (100 mA). The measured output power was about of 1 mW for a current of 40 mA and several mW for a current of 80 mA. Simulations show that at a frequency of 0.6 THz, an output power of 50 mW can be radiated by such a device with a voltage of 6 kV.

[1] V.L. Bratman, B.S. Dumesh, A.E. Fedotov, P.B. Makhalov, B.Z. Movshevich, F.S. Rusin, IEEE Trans. of Plasma Sci., 2009, v.39, No.6 (to be published).

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SECTIONED HIGH-HARMONIC GYROTRONS AND GYROMULTIPLIERS

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The use of the so-called Large Orbit Gyrotrons (LOGs) utilizing an axis-encircling electron beams is an attractive way to realize high-cyclotron-harmonic operation in THz gyrodevices. Recently, a unique third-harmonic 1THz/80kV/0.7A LOG has been realized in the IAP[1]. In the device, a long-length cavity with a high diffraction Q-factor has been used because of a weak electron-wave coupling at the high cyclotron harmonic and a low electron current. As a result, despite the essential electron efficiency (~10%) the output efficiency was only about 1% because of very high Ohmic losses (85%).

A possible way to combine a long-length interaction and a relatively low diffraction Q-factor is the use of a sectioned klystron-like system, in which particles interact with a near-cutoff wave only inside relatively short input and output cavities. These cavities are coupled through the drift region where the electron bunching occurs. Evidently, the Q-factor in such a scheme is determined mainly by the combined length of the short cavities, whereas the starting current is determined by the total length of the system. According to simulations for the third-harmonic THz LOG, the use of this approach results in the increase of the output efficiency up to 8%. Such an enhancement is caused by the increase of the total electron efficiency (up to 15%), as well as by a significant decrease of the Ohmic losses share (less than 50%).

Another way of realization of high-harmonic gyrodevices may be connected with developing of the gyromultipliers. In these devices, the high-frequency (HF) radiation from the high cyclotron harmonic is a result of nonlinear interaction of the electron beam with a relatively low-frequency (LF) wave, which helps to increase the selectivity and decrease the starting current of the HF generation. At THz frequencies, the self-exciting gyromultipliers, in which both the LF and HF waves are emitted from the same electron beam, are preferable, since no external LF source is needed. An important peculiarity of the electron-wave interaction is that the HF harmonic of the electron current saturates at a shorter distance as compared to the LF one. Therefore, the optimal position of the "HF generator" is inside the LF one[2]. This can be realized by the use of a sectioned klystron-like scheme of the LF oscillator, so that the drift region of this "klystron" operates as a HF oscillator.

Since the drift region should be open to provide output of the HF-wave power, we slightly complicate the described above sectioned klystron-like scheme. Namely, we use the idea of a gyrotron cavity with mode transformation. In the input cavity of the sectioned microwave system, electrons interact with a near-cutoff LF mode $TE_{m,p}$. After the drift region, this mode is transformed into a higher mode $TE_{m,q}$, which is a near-cutoff mode of the output cavity. The drift region of this LF "klystron" is used to generate the HF mode $TE_{(nm),r}$ at a multiplied frequency. Preliminary simulations for such a gyromultiplier with a 80kV/0.7A axis-encircling electron beam predict a possibility to achieve a power of ~100 W at the 4th cyclotron harmonic and at the frequency of 1.3 THz.

[1] V. L. Bratman, Yu.K. Kalynov, and V.N. Manuilov. "Large-Orbit Gyrotron Operation in the Terahertz Frequency Range." Phys. Rev. Lett. Vol. 102, p. 245101 (2009).
[2] I.V. Bandurkin, V.L. Bratman, G.G. Denisov et al. "Single-Cavity Gyromultipliers." Terahertz Science and Technology, Vol. 1, No. 3, pp. 169-189 (2008).

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TERAHERTZ FLUX-FLOW OSCILLATOR PHASE-LOCKED BY HARMONIC MIXER BASED ON SIS JUNCTION

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We propose a new approach for phase-locking of a Flux Flow Oscillator (FFO) [1] in a superconducting integrated receiver [2, 3]. According to this concept a superconductor-insulator-superconductor (SIS) junction is implemented both for down-conversion of the FFO frequency and for producing the signal to phase-lock the FFO to the external reference by applying the Harmonic Mixer (HM) output directly to the FFO control line. In other words we introduce a new element of superconductive electronics, which is based on the SIS junction and works as a cryogenic harmonic phase detector (CHPD).

For efficient FFO phase-locking the HM output signal is maximized. Value of this signal depends in a complicated way on the HM bias voltage, frequencies and powers of the local oscillator and the FFO signals. We have studied the HM theoretically and compared results of the calculations with experimental measurements. Good qualitative and quantitative correspondence has been achieved.

For demonstration of the FFO phase-locking by the CHPD we have realized a special feedback loop (Fig.1). Such a loop was also integrated on the same chip together with the FFO and the CHPD. The FFO frequency is equal to a harmonic of the local oscillator signal applied to the CHPD. Such a PLL system is expected to be extra wideband due to considerable reduce of the loop length.

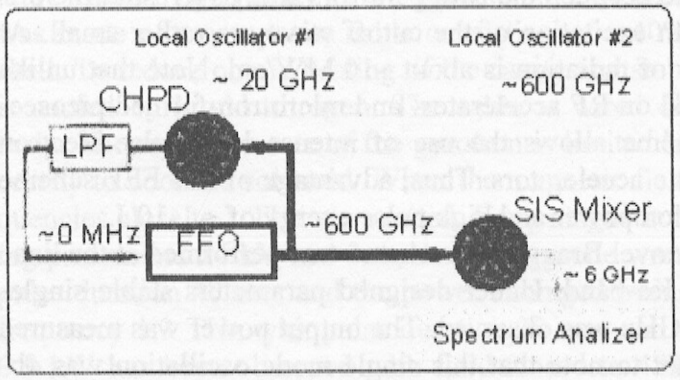

Fig.1. Block diagram. CHPD is used for FFO phase-locking. The SIS Mixer is used for visualization of the FFO radiation line and observed of the synchronization effect.

Presented concept is very promising for building of the multi-pixel SIR array.

[1] T. Nagatsuma, K. Enpuku, F. Irie, and K. Yoshida *J. Appl. Phys* **54** 3302 (1983)
[2] V. P. Koshelets and S. V. Shitov, "Integrated Superconducting Receivers," *Superconductor Science and Technology*, vol. 13, pp. R53-R69 (2000).
[3] V.P. Koshelets, A.B. Ermakov, L.V. Filippenko, A.V. Khudchenko, O.S. Kiselev, A.S. Sobolev, M.Yu. Torgashin, P.A. Yagoubov, R.W.M. Hoogeveen, and W. Wild, "*IEEE Trans. on Appl. Supercond.*", vol. 17, pp 336-342 (2007).

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POWERFUL THz FELs WITH ADVANCED BRAGG RESONATORS

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The use of Bragg resonators in the form of shallow-corrugated waveguides [1] is sufficient for narrow-frequency operation of FEM at Ka-band. However traditional Bragg resonators (based on coupling of two counter-propagating waves having high group velocities) lose their selectivity with increase of the oversize factor that is necessary to advance of the FEM into short wavelengths. This problem can be solved using advanced Bragg structures based on coupling of propagating and quasi-cutoff waves [2]. In this scheme a beam of wiggling electrons interacts with a propagating wave, which is coupled at the Bragg corrugation with a quasi cut-off mode. Similar to gyrotrons implication of the cutoff wave into the feedback loop results in mode spectrum purification because distance between the cut-off waveguide modes is much higher than between paraxial waves. Under the optimal parameters oscillation frequency in such Bragg FEL is close to the frequency of the cutoff wave. Simulations demonstrate that advanced Bragg structures are able to provide selectivity up to transverse size ~ 10 - 20 wavelengths [3].

In this paper we simulated planar Bragg FEL operating at the frequency of 1 THz and driven by sheet electron beam with energy of 6.5 MэB and current density of 120 A/cm. Operating transverse velocity in the beam would be pumped in the undulator of the period of 4.5 cm and the magnetic field of ~ 0.3 T. A two-mirror planar resonator with the regular section of 160 cm long and advanced Bragg reflectors of the lengths of 30 cm (up-stream) and 12.5 cm (down-stream) having corrugation of the period of 0.3 mm and depth of 7.5 μm was considered. Simulations demonstrate establishment of a steady-state oscillation regime (the transient time of ~ 300 ns) with formation of coherent structures with correlated phases. The main amplification of the wave takes place between the Bragg mirrors and, as a result, the diffraction and Ohmic losses associated with excitation of the cutoff wave are rather small. At the efficiency of ~ 2% the power density of radiation is about ~10 MW/cm. Note that unlike the realized FELs in THz waveband based on RF accelerator- and microtron-formed picosecond electron bunches, the proposed scheme allows the use of intense long-pulse electron beams formed by the linacs or electrostatic accelerators. Thus, advantage of this FEL scheme is possibility to achieve multi-MW radiation power and high pulse energy of ~ 1-10 J.

Prove-of-principle experiment of novel Bragg FEM scheme was performed at the linac LIU-3000 (0.8 MeV / 200 A / 200 ns) at Ka-band. Under designed parameters stable single-mode operation at the frequency of 30.2 GHz was observed. The output power was measured at the level of 10 -15 MW. It is important to note that this single-mode oscillation was obtained at any wiggler fields from the zone of self-excitation that demonstrates high stability of the FEM to the change in beam parameters. Experimental study of 60-GHz FEM operating at second harmonic of the bounce-frequency is in progress currently where the advanced Bragg structure should provide stable selective single-mode excitation in the cavity with diameter of about 4 wavelengths.

[1] V.L.Bratman, e.a., IEEE J. Quant. Electr. 19 (1983) 282.
[2] N.S.Ginzburg, e.a., Phys. Rev. ST–AB 8 (2005) 040705.
[3] N.S.Ginzburg, e.a., Appl. Phys. Lett. 95 (2009) 043504.
[4] N.S.Ginzburg, e.a., JETP Lett. 91 (2010) 286.

GENERATION OF 5-KW 1-THZ COHERENT RADIATION FROM A GYROTRON WITH A PULSED SOLENOID

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Gyrotrons are capable of producing high-power coherent electromagnetic radiation in the millimeter and submillimeter wavelength ranges. The important and promising direction of gyrotron development now is investigations in the sub-terahertz (sub-THz) and terahertz (THz) frequency bands. Development of compact, simple and reliable sources of coherent sub-THz and THz radiation is important for numerous applications, which include plasma physics, spectroscopy, detection and imaging of explosives and weapons, new medical technology, etc. Gyrotrons are much more compact than powerful free electron lasers because they do not require large accelerators or high-voltage modulators. From the other hand the gyrotrons can realized essentially higher output power comparing with solid state devices.

However, to provide cyclotron resonance between gyrating electrons and fast waves excited in smooth waveguides at THz frequencies near cutoff, high magnetic fields are necessary: in the range of 40 T for the fundamental harmonic interaction at the radiation frequency of 1 THz; at higher harmonics magnetic field decreases inversely proportional to the cyclotron harmonic number. The frequency rise needs operating at high order modes to store the reasonable scale of interaction region. The progress in frequency increasing delay by problem of mode competition at high order harmonic modes operation and impossibility realized nonvolatile pulsed coils with strong enough magnetic fields and effective cooling for fundamental harmonic operation. It should be taken into account that typically magnetic field, which can be produced in cryomagnets with a large enough inner bore, do not exceed 20 T. Higher magnetic fields can be realized only with the use of pulsed or hybrid solenoids.

In the recent two years terahertz gyrotrons get remarkable achievements in experimental research. High power THz demountable tube was developed at IAP RAS [1]. A 50 T coil was made of a composite cable consisting of a 40%Nb-60%Ti alloy put in an outer copper shell. To reduce ohmic heating of the cavity and stabilize the gyrotron operation, the solenoid is cooled by liquid nitrogen. The cable is wired directly on a thin stainless steel gyrotron body. The repetition rate of the gyrotron is limited by one shot per minute because of the necessity to cool the solenoid. When the magnetic field is varied, a number of modes with frequencies close to 1 THz are excited. For a magnetic field of 38.5 T and an electron beam having parameters 24 kV and 3 A, the $TE_{17,4}$ mode was excited at a frequency of 1.02 THz with pulse duration 40 mcs and the power averaged over the pulse being up to 5 kW. The highest frequency 1.3 THz with pulse duration 30 mcs and the power averaged over the pulse about 0.5 kW has been observed with field closed to 48T. Powerful gyrotron with frequency 0.3 THz and power 1 MW has been developed at IAP RAS based on water cooled coil. Some technical problems of pulsed tubes are illustrated by cavity design and test. The coil successfully tested and tube experimental test started soon.

[1] M.Yu. Glyavin, A.G. Luchinin, and G. Yu. Golubiatnikov. Phys.Rev.Lett, 100, 1, (2008), 015101

[2] M.Yu.Glyavin, A.G.Luchinin Int. J. Terahertz Science and Technology, 2, 4, (2009), 150

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GENERATION OF THZ RADIATION IN A LASER SPARK

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In a recent years a laser spark produced by fs optical radiation as a source of coherent broad-band THz radiation became a subject of enhanced interest due to interesting and important fundamental physics and a number of possible applications. In the present communication we give a brief review of experimental activity and small sketch theoretical achievements.

The main part of experimental investigations was performed using SPITFIRE laser system capable to deliver 50 fs pulses at 780 nm wavelength with the averaged power 3-5 W with the repetition rate 1 kHz (pulse energy about 3 mJ). Discharge in the ambient air was initiated by focusing of fs laser pulses either by axicon lens or by traditional spherical lenses with different focal distances. There was also the possibility to apply a dc electric field (up to 15 kV/cm) to the discharge region transverse to the axis of a discharge and to add the admixture of the optical radiation at the second harmonics using nonlinear BBO crystal for its generation. The specialized detection system for the investigation the radiation patterns of THz pulses and the distribution of their polarization was used. It included the InSb bolometer at cryogenic temperature, opaque screen with small hole in it movable in the plane orthogonal to the beam axis and greed polarizer (for more details see [1]).

The results already obtained by world scientific community have been confirmed such as essential increase of THz radiation generation efficiency with applying dc electric field to the region of the discharge produced by focusing fs radiation with spherical lenses, more significant increase in the efficiency with addition of second harmonics to fs radiation, dependence of generation efficiency on phasing between optical fields at the first and at the second harmonics etc.

A number of new results were obtained in our group, such as:

- Quite different reaction to the applied external dc electric field in the case of axicon discharge and for the discharge produced by focusing optical radiation with spherical lenses – there is practically no reaction in the first case and essential increase in THz generation efficiency in the latter case.

- Quadrupole radiation pattern for THz radiation from the laser spark, produced by focusing the optical radiation with the spherical lenses.

- The existence of optimal orientation angle of type I BBO crystal which provides maximum efficiency of THz radiation generation efficiency.

- Possibility to control polarization of generated THz radiation by longitudinal shift of BBO crystal.

- Absolute measurements of conversion efficiency of optical radiation into THz one.

- A simple theoretical model for the source of low-frequency current, generated in a laser spark has been proposed basing on peculiarities of tunnel ionization in bi-chromatic optical field, which allows good qualitative explanation of main part of obtained experimental results.

[1] R.A.Akhmedzhanov *e.a.*, *Radiophysics and Quantum Electronics*, 2009, v.52, p. 482.

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Generation of Terahertz Radiation from a Low-Density Plasma Slab Irradiated by a Laser Pulse

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Abstract. The generation of terahertz electromagnetic radiation when a laser pulse propagates through a low-density plasma slab is considered. It is shown that terahertz waves are excited because of the growth of a weakly damped, antisymmetric leaking mode of the plasma slab. The spectral, angular, and energy parameters of the terahertz radiation are investigated, as well as the spatiotemporal structure of the emitted waves. It is demonstrated that terahertz electromagnetic wave fields are generated most efficiently when the pulse length is comparable to the slab thickness.

The present paper gives a detailed analytic study of the excitation of terahertz electromagnetic radiation when a short laser pulse is incident from vacuum on a low-density plasma slab. A new mechanism for generating terahertz radiation is considered that is associated with the growth of an antisymmetric leaking mode of the slab under the action of the ponderomotive forces of the pulse. The spatiotemporal distribution of terahertz waves is investigated and it is shown that they propagate into vacuum in the form of electromagnetic field pulses with a frequency close to the plasma frequency and a duration equal to the reciprocal of the damping rate of the antisymmetric leaking mode of the plasma slab (fig. 1).

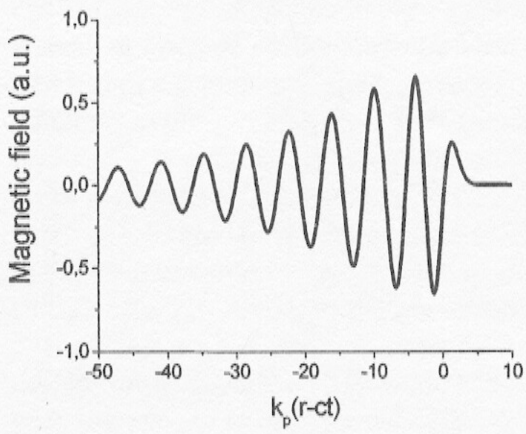

Fig. 1. Distribution of the magnetic field in a terahertz pulse in vacuum, generated by a laser pulse with the parameters $\omega_p\tau=\sqrt{2}$, $k_pR=2\sqrt{2}$ and emitted at the angle $\pi/6$ to a plasma slab with the thickness $k_pd=1/3$. Where ω_p is the plasma frequency, $k_p=\omega_p/c$, τ is the duration of the laser pulse, R is the radius of the pulse focal spot, 2d is the plasma slab thickness.

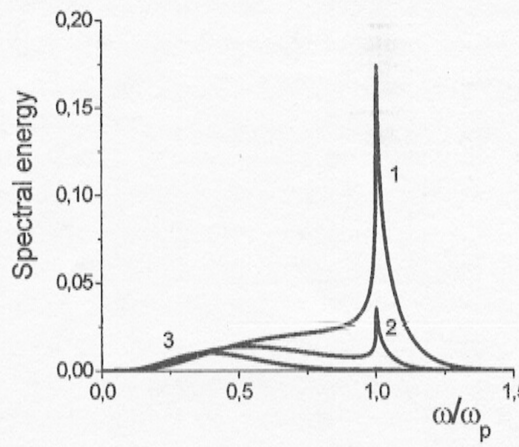

Fig. 2. Spectrum of terahertz radiation in vacuum for the parameters $k_pR=\sqrt{2}$ and $k_pd=1$. Curves 1-3 are for the laser pulse durations $\omega_p\tau=\sqrt{8}$, $\sqrt{12}$, and $\sqrt{20}$, respectively. Where ω_p is the plasma frequency, $k_p=\omega_p/c$, τ is the duration of the laser pulse, R is the radius of the pulse focal spot, 2d is the plasma slab thickness.

The angular, spectral, and energy parameters of the terahertz radiation are investigated. It is shown that the radiation energy is emitted predominantly along the normal to the slab boundary into a cone the angle of which decreases as the size of the focal spot of the laser pulse increases. It is demonstrated that, for a short laser pulse, the terahertz radiation spectrum has a sharp peak at the plasma frequency and that this peak narrows substantially with increasing the pulse spot size. As the

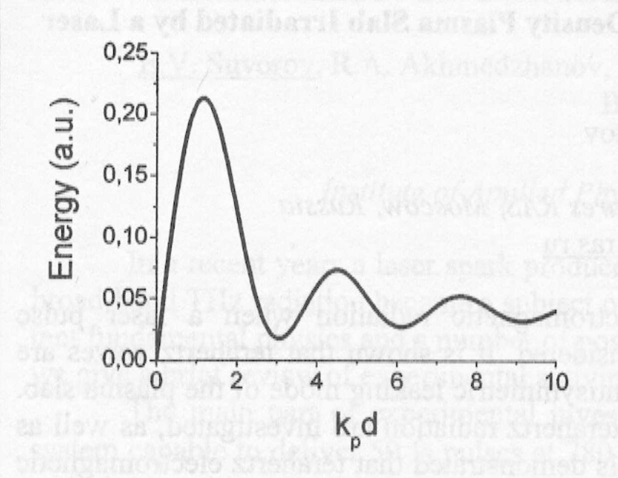

Fig.3 Dependence of the total dimensionless energy of the terahertz radiation in vacuum on the plasma slab thickness for the laser pulse parameters: $\omega_p\tau=\sqrt{2}$, $k_pR=\sqrt{20}$.

laser pulse duration increases, the spectral line at the plasma frequency disappears and a broad peak arises at a frequency comparable to the reciprocal of the pulse duration (fig. 2).

The total energy of the terahertz radiation is calculated and its dependence on the size of the focal spot of the laser pulse and on the thickness of the plasma slab (see fig. 3) is examined. It is shown that terahertz waves are excited most efficiently when the pulse length is comparable to the slab thickness.

A comparison with earlier results [1, 2] shows that, for a laser pulse with large transverse sizes, the radiation energy from the slab is much higher than the energy emitted by a plasma half-space. According to the estimates presented here, the interaction of a femtosecond laser pulse with gas jets can generate megawatt-level terahertz radiation power.

1. L. M. Gorbunov, A. A. Frolov, JETP 102 (2006) 894.
2. L. M. Gorbunov and A. A. Frolov, Plasma Phys. Rep. 32 (2006) 850.

Nonlinear optical phenomena and the THz pulse generation in the plasma filament

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We present integral view on interaction of essential radiation parameters of ultrashort laser pulses and gas medium itself leading to pulsed THz wave generation with different properties.

Nonlinear optical phenomena and the THz pulse generation in the plasma filament

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The atomic gas at the focal spot of a femtosecond laser, is a source of radiation at THz frequency. The emitted THz power increases manifold if a bicolor scheme is used where a fundamental optical wave is mixed with its second harmonics satellite at doubled frequency. The characteristics of emitted THz wave are influenced by several parameters of the radiations at pump frequencies such as, relative time delays between pulses, orientation of polarization vectors and intensities of pulses. The formation of a plasma channel in the process of optical breakdown has the significance in the analysis of the process generation of THz radiation. We should differentiate two formation regimes of the medium: ionization-free and multiphoton ionization of gas. The imaginary time method is used to describe the multiphoton ionization of atoms of gases under the bicolor femtosecond laser irradiation. The obtained formulas are applied for the qualitative explanation of experiments in the generation of THz radiation from an optical breakdown in a focus spot of a femtosecond laser in gas. We also discuss a new mechanism of the THz radiation generation in an atomic gas caused by the response of the atom itself to the presence of the bicolor femtosecond laser field. In the model and in the experiments we suppose that the laser field strength is lower than the atom ionization. In spite of this, the efficient generation of the THz radiation takes place. However in the presence of the multiphoton ionization this mechanism may also be observed.

SOME ASPECTS OF NUMERICAL SIMULATIONS OF THZ RADIATION GENERATION IN A LASER INDUCED PLASMAS

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In the last few decades intense terahertz (THz) wave generation during the optical discharge induced by femtosecond laser pulses is attracting more attention. The most effective transformation of laser radiation into THz band is obtained when a superposition of the fundamental and the second harmonic optical fields is used for the ionization process [1]. One more successfull way in THz generation utilizes application of static electric field in the optical discharge region. As a result a 2-3 orders grouth of THz intensity was obtained [2] in the experiments with dc bias of some kV/cm.

It is noteworthy that some experimental results, namely the polarization characteristics of THz radiation generated by photoionization of air with laser pulses having linear polarization, have not explained yet. In a recent work [3], a quadrupoletype angular pattern of THz emission has been reported. As opposed to the earlier works [2], which showed conical shape of the THz emission independent of laser field polarization, the physical mechanism behind this effect cannot be attributed to ponderomotive force. Moreover, angular pattern measured in [4] has counterintuitive features. Suppose that the laser pulse propagates in z-direction and laser electric field has only x-component. Then THz radiation displays two-peak shape of angular pattern and the main THz E-field is directed along the y-axis.

The underlying mechanism can be explained by anisotropic heating of plasma during the process of tunnel ionization of the air. Thermal expansion of plasma in the laser wake induces DC current responsible for THz radiation. The axial symmetry of the laser pulse intensity allows us to reduce the number of dimensions of the initial equation set and consider the temporal evolution of J, E, H in r, z-space only. In linear case the azimuthal dependence separates, and according to boundary conditions (particularly, to laser field polarization), zero-order (symmetric), first (dipole, proportional to $\cos(\phi)$) or second (quadrupole, proportional to $\cos(2\phi)$) azimuthal mode, or even their combination is excited. Our computations show that in the case considered, zero- and second-order modes are excited simultaneously, and the resulting effect is similar to the experimental observation [3].

The numerical code used for the simulations calculates the evolution of every azimuthal mode separately. This code actually is a sort of FDTD code in cylindrical coordinates with the certain azimuthal dependence imposed. The reduction of dimensions enables to use the calculation resources more effectively and the mode approach simplifies the analysis of the results. Moreover, our mode approach can be applied for description of THz generation when a static electric field is applied to the ionized region along direction x (perpendicular to the filament axis z) and also for the analysis of the problem of ionization of the air by two-color laser field. In these both cases, first-order ($m = 1$) azimuthal modes are excited. This situation allows us to compare the two most successful generation schemes directly and explain distinct difference in their THz radiation spectra.

[1] K. Y. Kim, J. H. Glownia, et.al., Opt. Express 15, (2007) 4577.
[2] C.D. Amico, A. Houard, et.al., New Journal of Physics 10 (2008) 013015.
[3] R. A. Akhmedzhanov, I. E. Ilyakov, V. A. Mironov, et. al., JETP Lett. 88, (2008) 569; Radiophysics and Quantum Electronics, 52, (2009) 482

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MULTIPHOTON IONIZATION BY A TWO-COLOR LASER PULSE

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A method of imaginary time [1] is used to calculate the probability of multiphoton ionization of atoms in the field of a femtosecond laser, which contains a small admixture of the second harmonic. The conditions for the second harmonic to dominate over the first harmonic in the course of ionization of atoms are found. It is shown that the average momentum of the photoelectrons ejected from an atom depends on the phase shift between the first and second harmonics, as well as on their mutual polarization. Asymptotic formulas for the ionization probability and the average momentum are obtained. They are used for qualitative explanation of recent experiments on the generation of terahertz radiation from an optical breakdown in a focus spot of a femtosecond laser in a gas [2].

[1] V.S. Popov. JETP, 93 (2001) 278.
[2] A.V. Balakin, A.V. Borodin, I.A. Kotelnikov, and A.P. Shkurinov. J. Opt. Soc. Am. B 27 (2010) 16.

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Production of Electromagnetic Wave in THz Range by Beating of Two Short Laser Pulses

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The potential applications of THz radiation in the fields like time domain spectroscopy, remote sensing, biological spectroscopy, communication etc. has made the subject of THz generation an interesting field of research [1, 2]. The use of collective properties of laser-produced plasma underlies a number of methods of THz generation that include mechanisms based on the phenomenon of nonlinear ponderomotive force induced excitation of plasma wake oscillations. However, conversion efficiency of these schemes is very poor [3, 4].

We present a theoretical and numerical study for the THz generation, in which two Gaussian lasers with different frequencies and wave numbers but with the same amplitudes of the electric field beat in a rippled density plasma. Spatial variation in the resultant intensity of the two lasers produces a ponderomotive force transverse to the direction of propagation of the lasers. Consequently an oscillatory transverse current is obtained, which leads to the electromagnetic radiation in the THz range. We investigate the effects of laser frequencies, shape of ripples in the plasma density and the density of the plasma on the emitted THz radiation.

References:

1 G. Segschneider, F. Jacob, T. Loffler, H. G. Roskos, S. Tautz, P. Kiesel, and Go. Dohler,Phys. Rev. B **65**, 125205 (2002)

2 P. Gaal, K. Reimann, M. Woerner, T. Elsaesser, R. Hey, and K. H. Ploog, Phys. Rev. Lett. **96**, 187402 (2006).

3 H. Hamster, A. Sullivan, S. Gordon and R. W. Falcone, Phys. Rev. E **49**, 671 (1994); Z.-M. Sheng, K. Mima, J. Zhang, and H. Sanuki, Phys. Rev. Lett. **94**, 095003 (2005).

4 W. P. Leemans, J. van Tilborg, J. Faure, C. G. R. Geddes, Cs. Toth, *C. B. Schroeder, E. Esarey, and G. Fubianif, Phys. Plasmas 11, 2899 (2004).*

E.coli proteom expression under terahertz irradiation

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An influence of terahertz radiation on biologic systems is studied rather weakly. As the subjects influenced by terahertz radiation we have selected the following biologic systems : (1) artificial gene-sensors based on the stress sensitive promotors of the E.coli genes and (2) proteomes of the strain 17 *E.coli* cells. These subjects are convenient and thoroughly studied models in the experimental biology.

Genosensors *E. coli/pDps-gfp and E. coli/pKatG-gfp* were irradiated by terahertz radiation with the wavelength of 130 micron and power density of 1.4 W/cm^2. As shown experimentally, both the influence of terahertz radiation and 5 mM hydrogen peroxide resulted in induction of the fluorescent protein in *E.coli/pDps-gfp* genosensor cells.

An analysis of the *E.coli* proteome was performed by a combination of the proteome analysis including the 2D-electrophoresis followed by identification of proteins with the technique of the MALDI-TOF mass-spectrometry (UltraFlex III, Bruker). The high resolution of the used methods and techniques in studying proteome enabled us for the first time to identify the terahertz influence on the *E.coli* cells and proteins whose synthesis was induced by the terahertz radiation. *E.coli* genes corresponding to these proteins were identified.

The identified genes are functionally different and take part in various metabolic pathways: anaerobe breathing, metabolism of carbohydrates (*gltA*), transport of carbohydrates (*rbsA, manX*), electron transport (*cydA, appC*), apoptosis induction, cytolysis (*hlyE*), metabolism of nucleotides (*upp, purA*), transcription (*rpoD*), translation (*rplY*), transport of ions (*tsx*), aspartate biosynthesis, glutamine (*aspC, glnA, respectively*), protein recycling (*degP*). A comparative analysis was performed for the regulatory regions of these genes (promoter regions) and promoter regions of the gene-sensors *dps* and *katG* for the presence of the potential binding sites of the stress transcription factors (STF). With use of the computer technique SITECON, it was shown the presence of the potential binding sites of STF OxyR, MarA, PurR, LexA in the promoter regions of genes induced by influence of terahertz radiation. When studying the regulatory regions of genes induced by terahertz radiation it was shown that for TF OxyR, MarA, PurR, LexA the density and frequency of the potential binding sites in their promoters are higher than that in the control ones. The presence of binding sites with TF OxyR, MarA both in the promoters of genes *dps* and *katG,* and in the promoters of the identified *E.coli* genes evidences in favor of the development of the cell responses to terahertz radiation according the mechanisms similar to the stress response mechanisms.

Transient surface photoconductivity of GaAs emitter studied by terahertz pump-emission spectroscopy

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The ultrafast carrier dynamics and surface photoconductivity of unbiased semi-insulating GaAs have been investigated in detail by using terahertz pump-emission technique. Based on theoretical modeling, it is found that transient photoconductivity plays a very important role in the temporal waveform of terahertz radiation pulse. Anomalous enhancement in both terahertz radiation and transient photoconductivity is observed subsequent to the excitation of pump pulse, and we attribute these phenomena to carrier capture in the EL2 centers. Moreover, the pump power- and temperature-dependent measurements are also performed to verify this trapping model.

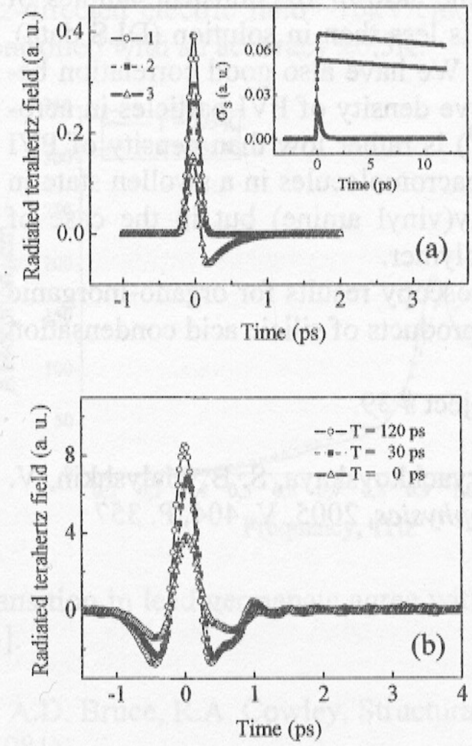

Figure 1. (a) Theoretic waveforms of radiated terahertz pulses emitted from SI- and LT-GaAs calculated from Eq. (2), (3), and (5). Since the relaxation from satellite valleys will not happen, so it is reasonable to let $\mu_f = \mu_i$. Because of the very low excitation fluence used in the experiment, we assume $B = 0$. Curves 1 and 2 are for SI-GaAs (τ_{car}=100 ps) with $\mu_f = 4000\,\mathrm{cm^2/V \cdot s}$ and $\mu_f = 3000\,\mathrm{cm^2/V \cdot s}$, respectively; curve 3 is for LT-GaAs ($\tau_{car} = 1\,ps$) with $\mu_f = 2000\,\mathrm{cm^2/V \cdot s}$. The inset shows the corresponding calculated time-varying surface photoconductivity of the emitter. (b) Waveforms of terahertz radiation observed at different pump-generation delay times.

[1] Yulei Shi, Qing-li Zhou, and Cunlin Zhang, Transient surface photoconductivity of GaAs emitter studied by terahertz pump-emission spectroscopy, Chin. Phys. B, Vol 18 No 10, 4515 (2009).

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STUDY OF NANOPARTICLES IN WATER SOLUTION BY TERAHERTZ LASER ABLATION / AEROSOL SPECTROMETRY

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First experiments [1] have shown that under the action of submillimetric radiation from free electron laser, nanoparticles can be softly transformed from solution to the gaseous phase and their size and quantity can be measured with modern aerosol equipment.

Our aim was to estimate how terahertz laser ablation (TLA) data correspond to results of classical methods with some simple nanoparticles. We have chosen two types of objects: inorganic nanoparticles which have rigid 3D-structure, and water-soluble polymers with flexible linear chains. The main difference between these particles is in swelling ability – linear macromolecules can change size of the coil with a change of solvent in contrast to inorganic particles.

The obtained results show a good agreement between TLA and dynamic light scattering (DLS) for inorganic particles (silica and aluminium hydroxide nanoparticles). This confirm dispersion of inorganic materials down to individual particles during the sampling and retention of the particle structure in ablation experiment. In the case of fractionated samples of poly(1-vinylimidazole), diameter of the ablated particles is less than in solution (DLS data), but there are a fine linear correlation between these data. We have also good correlation between radius and $(MM)^{1/3}$ which allow to estimate effective density of PVI particles in aerosol, after ablation. The corresponding value (0.058 g/cm^3) is rather low than density of PVI (1.3 g/cm^3). This is an evidence of the presence of PVI macromolecules in a swollen state in the aerosol. Similar results have been obtained for poly(vinyl amine) but in the case of poly(acrylic acid) the ablated particles are close to solid polymer.

TLA data comparing with DLS and electron microscopy results for organo-inorganic composite nanoparticles will be discussed by example of products of silicic acid condensation in the presence of poly(vinyl amine).

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[1] A. K. Petrov, A. S. Kozlov, M. B. Taraban, T. N. Goryachkovskaya, S. B. Malyshkin, V. M. Popik, and S. E. Peltek, *Doklady Biochemistry and Biophysics*, 2005, V. 404, P. 357

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FERROELECTRIC PHASE TRANSITION IN LEAD GERMANATE STUDIED BY TERAHERTZ SPECTROSCOPY

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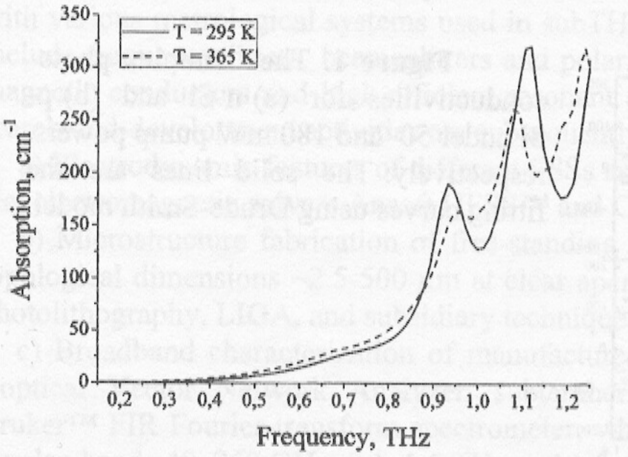
Lead germanate $Pb_5Ge_3O_{11}$ is an uniaxial ferroelectric with a transition temperature T_c≈450K, at which the crystal changes from high-temperature paraelectric phase of C_{3h} symmetry to a ferroelectric phase of symmetry C_3. This structural phase transition is associated with instability of the crystal against a particular normal mode of vibration A_{1g}, which is known as a 'soft mode'. In spite of the fact that several experimental studies of the temperature dependence of this mode have been made using Raman scattering and neutron scattering techniques at temperatures 200K÷500K the results show a number of unexpected and unsatisfactory features especially close to T_c [1].

In this paper we report on measurements of the phase transition in lead germanate (LG) using terahertz spectroscopy techniques. The measurements of terahertz spectra were performed using the table-top spectrometer based on two-channel erbium-doped fiber laser [2]. Before the measurements the LG samples were poled to a single domain by application of a z-directed electric field ~16kV/cm.The temperature of the LG sample in the furnace was controlled with an accuracy ±0,5K.



Two typical THz absorption spectra at different temperatures are shown on the figure. The analysis of experimental data shows that phase transition in LG has soft mode character, that is $\omega^2 \sim (T-T_c)$ for $(T-T_c)>60K$, and $\omega^2/\gamma \sim (T-T_c)$ for $60K>(T-T_c)>10K$ (ω – soft mode frequency, γ – damping constant). The damping constant (full width at half maximum peak) increases rapidly and the soft mode becomes overdamped above ~ 380K. For $(T-T_c)\leq 10K$ the soft mode is purely relaxational. The theoretical implications of our experimental observations of phase transition in lead germanate agree with the modern conceptions of structure phase transitions [3].

1. A.D. Bruce, R.A. Cowley, Structural Phase Trasitions, Taylor&Francis Ltd., London (1981).
2. V.D. Antsygin, A.A. Mamrashev, N.A. Nikolaev, O.I. Potaturkin, Optoelectronics, Instrumentation and Data Processing, N4 (2010).
3. V.K. Malinovsky, A.M. Pugachev, N.V. Surovtsev, Physics of Solid State, V. 51 (2009)1390.

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Carrier dynamics and terahertz photoconductivity of doped silicon measured by femtosecond pump-terahertz probe spectroscopy

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The carrier dynamics and terahertz photoconductivity in the n-type silicon (n-Si) as well as in the p-type silicon (p-Si) have been investigated by using femtosecond pump-terahertz probe technique. The measurements show that the relative change of terahertz transmission of p-Si at low pump power is slightly smaller than that of n-Si, due to the lower carrier density induced by the recombination of original holes in the p-type material and the photogenerated electrons. At high pump power, the bigger change of terahertz transmission of p-Si originates from the greater mobility of the carriers compared to n-Si. The transient photoconductivities are calculated and fit well with the Drude-Smith model, showing that the mobility of the photogenerated carriers decreases with the increasing pump power. The obtained results indicate that femtosecond pump-terahertz probe technique is a promising method to investigate the carrier dynamics of semiconductors.

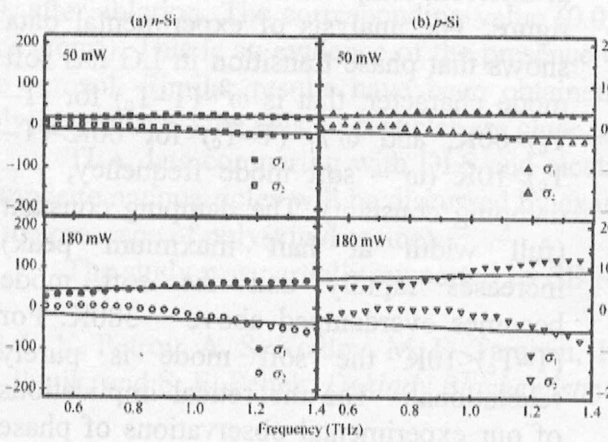

Figure 1. The complex photoconductivities for (a) n-Si and (b) p-Si under 50 and 180 mW pump powers, respectively. The solid lines are the fitting curves using Drude-Smith model.

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MICROSTRUCTURED QUASIOPTICAL SELECTIVE COMPONENTS FOR SUBTERAHERTZ AND TERAHERTZ APPLICATIONS

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On the frequency scale of the electromagnetic spectrum the region of subterahertz and terahertz frequencies, extensively explored during the last decade, occupies a unique position due to its huge and still non-depleted potential for novel applications in physics, chemistry, biology, medicine, security etc. In many cases a successful realization of (sub)THz-experiments demands adequate quasioptical selective devices or components to control the properties of radiation beams. Such components implemented on basis of planar regularly-patterned metalized microstructures of subwavelength topology, commonly referred to in literature as frequency selective surfaces (FSSs), serve as the best solution since their amplitude, phase and polarization response can be properly tailored via FSS topology, as well as the number of FSS layers used.

In this communication we overview the development results for different types of single- and multi-layered FSSs designed both for stand-alone applications and for integration with various metrological systems used in subTHz and THz measurements. The components include frequency filters, beamsplitters and polarization converters, metastructures, artificial magnetic conductors and high-efficient resonant absorbers etc. The following aspects of research-and-development activities are subsequently considered in our presentation:

a) Electrodynamic features of different FSSs and their accurate simulations using commercial electromagnetic solvers Ansoft HFSS™ and CST Microwave Studio™;

b) Microstructure fabrication of free-standing and polymeric-substrate-backed FSSs with topological dimensions ~2.5-500 µm at clear aperture diameter up to ~80 mm by employing photolithography, LIGA, and subsidiary techniques;

c) Broadband characterization of manufactured prototypes using AB Millimetre™ Quasioptical Vector Network Analyzer, subteraherz Mach-Zehnder BWO-spectrometer and Bruker™ FIR Fourier-transform spectrometer, which measurement frequencies subsequently overlap bands 40–260 GHz, 0.1–1.5 THz and 1.5–21 THz respectively.

d) Application of the developed prototypes to different (sub)THz experiments, such as harmonics filtering at the Novosibirsk terahertz free electron laser, multiband radiometry of turbulent plasma at the nuclear fusion plasma facility GOL-3, realization of left-handed electromagnetic metamaterials, implementation of a novel type of spectrally- and polarization-selective bolometric detectors and imaging systems, and some other tasks.

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Materials consisting of nanostructured oxyhydroxides of aluminum (NOA) and its applications for Terahertz range

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This work was aimed on design of new functional nanomaterials for terahertz range by the structural and chemical modifications of NOA. Row NOA materials were synthesized by the selective oxidation of the surface of liquid alloys in humid atmosphere at the temperatures from 20 up to 30 °C [1]; this original method provides production of NOA monolith samples possessing the following properties: small density (0,02 – 0,04 g/cm^3), high porosity (~ 99 %), and large specific surface (250 – 350 m^2/g). The sample's structure can be described as three-dimensional network formed by the amorphous nanofibrils with diameter ~5 nm, having a composition $Al_2O_3 \cdot nH_2O$, were n values are between 1 and 3.6, depending on the conditions of synthesis. An annealing at 900 – 1700 °C does not destroy solidity and porous structure of NOA monolith, but the composition of fibril's is changing and the size of samples scales proportionally and isotropically. Using different temperatures of annealing allows to vary physical properties of porous alumina monolith in a wide range: the density from 0,04 up to 3 g/cm^3, the porosity from 99,3 down to 25 %, and specific surface from 350 down to 1 m^2/g.

The row and annealed NOA samples were studied by XRD. Diffraction patterns obtained from row NOA samples corresponding to a weakly ordered supramolecular structure. Annealing at the temperature ~100 °C destroys this structure and it replaced by the amorphous state, which persists up to 650 – 900 °C. Further increasing of annealing temperature leads to crystallization and γ- alumina phase is formed; this transformation completes at the temperatures of 900 – 1000 °C. An effect of influence of surface modification on phase transition in NOA based materials has been observed. Modification of NOA surface was achieved by the sample exposition in trimethylmethoxysilane vapor. Isochronous annealing of exposed samples revealed increasing of phase transition temperatures by 200 – 300 °C due to kinetic limitation for surface diffusion and phase stabilization by residual water content.

To describe the properties of the NOA as a porous multiphase medium in terahertz range was used the effective medium model of Maxwell-Garnett. It relates the dielectric properties of the components of NOA system with the properties of whole sample. The permittivity of the principal substance – the fibers of NOA was determined.

Experimental study of NOA materials combined with theoretical estimations allowed to create a device prototype, such as a waveguide with high transparency in terahertz range. Development of NOA technology, improving of the waveguide structure, as well as design of new devices for terahertz range, are the promising directions for further work.

Literature

[1] P.N. Martynov, R.S. Ashadullin, A.N. Khodan, P.A. Yudintsev New industrial technologies, №4, p.48 – 52, 2008.

[2] A.F. Skryshevsky " Structural analysis of liquids and amorphous solids " M.: Higher School, 1980.

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TEMPERATURE DYNAMICS AND THE SPECTYRAL LINE ASSIGNMENT FOR THZ ABSORPTION SPECTRA OF PROGESTERONE, 17α-HYDROXYPROGESTERONE AND CORTISONE

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Progesterone (P), 17α-hydroxyprogesterone (17 OP) and cortisone (E) are cyclopentaphenanthrene derivatives that are belong to corticosteroid hormones. These hormones have similar basic structure and differ only on the position of OH-group in steroid nuclear. The molecules in our sample under study is aggregated into the molecular crystals that are related to the orthorhombic space group ($P2_12_12_1$) with four molecules in a cell. The molecules in the crystal are linked with intramolecular and intermolecular hydrogen bonds. The presence of four rings in corticosteroid molecule provides a specific structure with conformational flexibility that is expected to be resulted in a number of low-frequency vibrational modes.

In the work we present the studies of THz-TD Spectra of P, 17 OP and E and compare their absorption spectra with Raman ones. The Raman and THz-TD spectra were measured in temperature range from 83 K to 297 K. Based on quantum chemical calculations of frequencies we can assign the vibrational bands in both, the THz-absorption and Raman spectra.

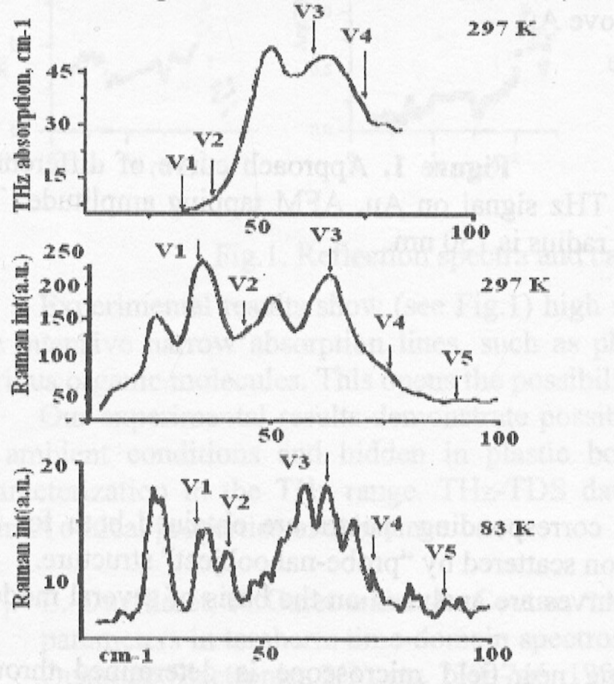

Figure 1. THz absorption and Raman spectra of 17 OP at 297, 83K and the V_1-V_5 - DFT calculation.

We show that studied substances have several intensive and specific absorption features in THz frequency region. If the sample is cooled down to 83 K, the temperature dymanics of the THz absorption and the Raman bands are observed. The positions of bands shift to the higher frequencies. We present THz and Raman spectra of 17 OP as example (fig. 1). The THz absorption spectrum of 17 OP has intensive absorption at 52 и 67 cm^{-1}. The DFT calculation assigns five vibrational modes in this region -V_1 – V_5, which include deformations of whole steroid nuclear.

We observed specific temperature dynamics of Raman spectra of all studied hormones also at 153 K. We interpret this temperature behavior as fully solid-phase transitions in molecular crystals of hormones.

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TERAHERTZ SCANNING PROBE MICROSCOPE

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We present a terahertz (THz) scanning probe microscope which combines THz coherent spectrometer and scanning probe microscope. It detects forward-scattering and employs harmonic signal demodulation to choose the signal of near-field scattering.

Experimental dependencies of specular reflected THz electric field amplitude on probe height are obtained both in full reflected and differential signal registration cases. Fundamental and second harmonics of differential signal are extracted from the full reflected THz signal. Real position of the probe above the sample is determined via synchronous registration of field-distance experimental dependences and AFM approach curves.

In our experiments we use GaAs with Au stripes deposited on it as a sample. Geometric parameters of the sample are controlled independently via scanning electron microscope and scanning probe microscope. Experimental dependencies of differential THz signal conditioned by "probe-nanoobject" structure's scattering and absorption on probe height are obtained both when probe is under metal or semiconductor. Probes with different tip radii are used in measurements. It is noticed that approach curves of differential THz signal's character (typical distance at which differential signal grows) varies according both to material underneath the probe and to tip radius. Figure 1 shows the approach curve of differential THz signal for 150 nm probe above Au.

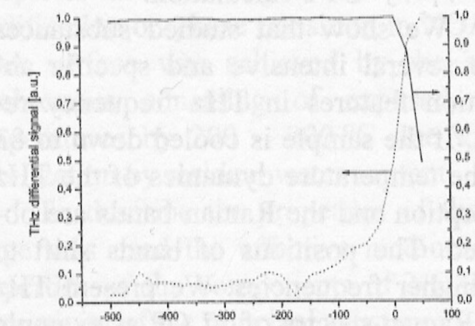

Figure 1. Approach curve of differential THz signal on Au. AFM tapping amplitude. Tip radius is 150 nm.

Experimental THz waveforms and corresponding spectra are obtained both for full reflected THz emission and for THz emission scattered by "probe-nanoobject" structure.

Experimental THz field approach curves are analyzed on the basis of several models: Mie theory and simple antenna model.

Spatial resolution of THz scanning near-field microscope is determined through simultaneous THz-AFM analysis of several topographic samples. We demonstrate that THz field amplitude maps' resolution is identical to that of the AFM and, in common case, is dependent on the tip radius.

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REFLECTION SPECTROSCOPY OF RESONANT MATERIALS FOR STAND-OFF TERAHERTZ PROBING

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Terahertz time-domain spectroscopy (THz-TDS) provides non-destructive capabilities for probing samples. In many applications the reflection spectroscopy is the only method to characterize object compound. This method is very useful for distant measurements, for instance for industry control and security. We present reflection THz-TDS results of organic samples possessive resonant absorption in THz region.

A reliable algorithm for estimating the T-ray characteristics of dielectrics was proposed in 1996 [1]. This method uses a model based on simple Fresnel equations and an iterative fit algorithm. Complex refractive index of the medium can be denoted as $\tilde{n} = n - ik$. The values n and k can be obtained from real and imaginary parts of reflection spectra [2], and absorption coefficient as $\alpha = 2\pi k / \lambda$.

All measurements are carried out in ordinary atmospheric conditions with water vapour presence in optical trace up to 4 meters. Reflection spectra are presented at Fig.1. for L-Cystine sample with resonance near 2 THz.

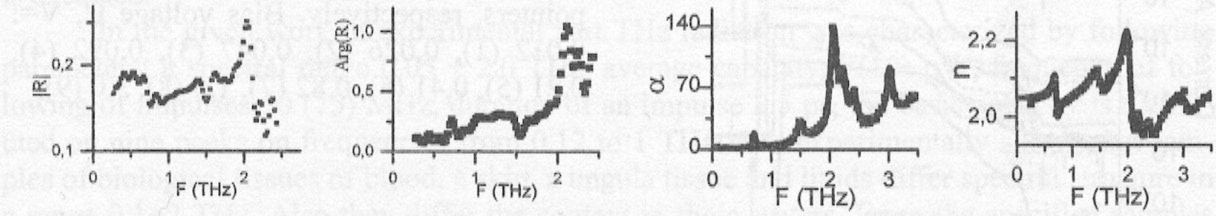

Fig.1. Reflection spectra and calculated optical indices

Experimental results show (see Fig.1) high sensitivity of the reflection spectroscopy to the intensive narrow absorption lines, such as phonon and collective vibrational modes of various organic molecules. This opens the possibility of explosive substances detection.

Our experimental results demonstrate possibility of resonant substances detection even in ambient conditions and hidden in plastic box. This simple technique enables distant characterization in the THz range. THz-TDS data is processed by numerical algorithm to extract optical properties of substance.

[1]. L. Duvillaret, F. Garet and J.-L. Coutaz, "A reliable method for extraction of material parameters in terahertz time-domain spectroscopy", IEEE Journal of Selected Topics in Quantum Electronics 2(3), pp. 739–746, 1996.

[2]. M.M. Nazarov, A.P. Shkurinov, E.A. Kuleshov, V.V. Tuchin, "Terahertz time-domain spectroscopy of biological tissues", Quantum Electronics 38, No.7, pp.647- 654, 2008

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PHOTOCURRENT DYNAMICS IN PbSnTe:In FILMS IN THE SUBMILLIMETER SPECTRAL RANGE

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The photocurrent dynamics in the narrow-gap semiconductor PbSnTe:In epitaxial films, grown using MBE technique on (111) BaF_2 substrates, has been studied experimentally on Novosibirsk free electron laser installation in the wavelength range λ=70÷208 micron. Series of time functions of current for λ=123 micron at various specimen bias voltages are shown in Fig.1.

The obtained results are considered on a basis of theory of predominant injection currents from contacts limited by a space charge in the presence of electron traps distributed over the band gap [1].

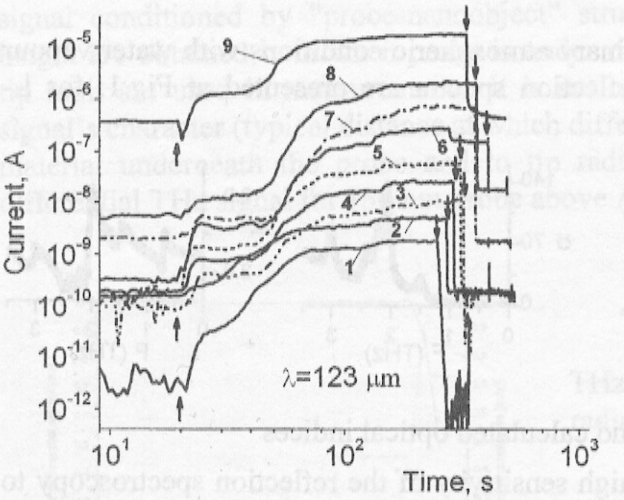

Figure 1. Current time functions. T=4.2 K. The moments at which the illumination (λ=123 micron) was swithed on and off are shown with upward and downward pointers, respectively. Bias voltage U, V=: 0,012 (1), 0,026 (2), 0,047 (3), 0,092 (4), 0,21 (5), 0,41 (6), 0,82 (7), 1,5 (8), 3,0 (9).

[1] A.E. Klimov, V.N. Shumsky, Physica B **404** (2009) 5028.

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TERAHERTZ DIAGNOSTICS AND THERAPY OF HUMAN AND ANIMALS HARD AND SOFT TISSUES

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Creation of biotissues diagnostics by terahertz (THz) radiation is an actual problem for the medical physics and engineering applications. During past twenty years considerable success has been achieved in development of devices and systems for pulse terahertz (THz) coherent radiation (0.1 - 10 THz) generation and detection with femtosecond laser systems and optoelectronic devices. It has evoked a great number of works on the analysis of application possibility of this radiation for scientific research and development of new perspective technologies, including nondestructive control of atherosclerotic plaques, dermatitis and teeth. At all stages of formation of atherosclerotic plaques, and also healing dermatitis and skin traumas, it is necessary to carry out test diagnostics of the amazed area, to distinguish with the big accuracy healthy sites of tissue from damaged and to check efficiency of therapeutic procedures and preparations.

The modelling spent in given work, has shown that THz radiation of a range 0.3÷2 THz does not lose collimating at passage through the sample of fat in the thickness of 0.5 mm. The model of an atherosclerotic plaque in a blood vessel, and also models of an adipose and ungula tissue is created. In model the radiating aerial is optimized and visualization of objects is executed.

In the given work in experimental part THz radiation was characterized by following parameters: a spectral range 0.05 ÷ 2.0 THz, average capacity 5 (10) μW, frequency of following of impulses 50 (75) MHz, duration of an impulse 2.5 ps, the basic capacity is distributed on nine peaks on frequencies from 0.12 to 1 THz. It is experimentally shown that samples of biological tissues of blood, a skin, a ungula tissue and lipids differ spectral structure in a range 0.1÷2 THz. Also they differ the content in them waters. From the specified samples the best advancing the adipose biotissue possesses. Schedules of absorption of a nail of the person and a skin of a turkey have an appearance similar each other, with peaks of absorption a little displaced on frequency. Such feature can be caused the general elements of a chemical compound of the specified samples. At increase in a thickness of a dressing from 0.1 to 0.3 mm (three layers of a gauze) THz radiations advancing decreases for 60 %. The spectrum of "the dried up blood" has characteristic peaks of absorption, unlike a spectrum of "fresh blood". In the dried up blood sharp peaks which correspond to blood components, such as leukocytes, erythrocytes and hemoglobin are visible.

Depending on a task in view of diagnostics of dermatological diseases are required various sources monochromatic THz radiation. So, for detection of it is degrees of hydration of a biotissue use better sources on lengths of waves: 1,09; 1,16; 1,41; 1,69; 1,73; 1.81;1.88 and 1,94 THz. For diagnostics in which water is the negative factor for diagnostics more preferably to use THz radiation in ranges: 0,1 ÷ 1,09; 1,16 ÷ 1,41; 1,41 ÷ 1,69 THz.

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REAL-TIME IMAGING ATR SPECTROMETER WITH TUNABLE TERAHERTZ FREE ELECTRON LASER AS A RADIATION SOURCE

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In this paper we describe implementation of first imaging attenuated total reflection (ATR) spectrometer using the Novosibirsk terahertz free electron laser (NovoFEL) as a source of radiation and a microbolometer focal plane array (MB FPA) as an image recorder [1].

Existing ATR spectrometers for the visible and MIR spectral ranges [2] consist of a Fourier spectrometer coupled with a FPA module. Tunability of FELs in a wide spectral range, as well as a very low beam divergence, enables realization of another kind of imaging ATR spectrometer. The input and output optical systems of the spectrometer are shown in Fig. 1. Scanning the laser wavelength and using a microbolometer camera to record images of the terahertz beam reflected from the ATR element–sample interface, one can retrieve the spatial distribution of spectral characteristics of the sample.

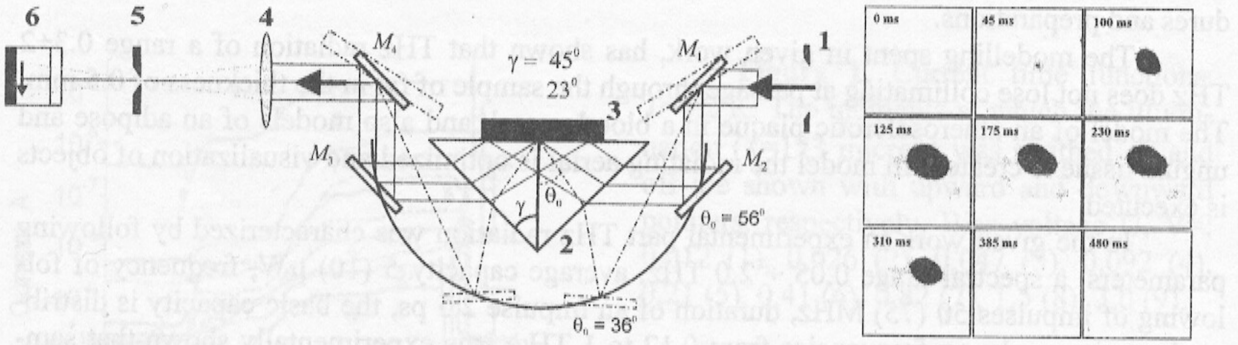

Figure 1. Schematic of imaging ATR spectrometer with two interchangeable prisms; the incidence angle is changed with the help of the movable mirror (left): 1, 5 – diaphragm, 2 – silicon prism, 3 – sample, 4 – lens, 6 – MB FPA.
Frames selected from the "terahertz video" recorded with the microbolometer FPA during injection of ethanol into water (right).

In another operation mode, the ATR spectrometer can be used to study transient processes at the interface at a fixed laser wavelength. Fig. 2 demonstrates real-time images of the terahertz beam reflected from the interface during injection of ethanol into a water pool (the incidence angle was 57 degrees and the laser wavelength was 0.13 mm). Since absorption of ethanol is very low in comparison with absorption of water, the reflection coefficient for areas with the silicon-ethanol interface is close to unity. The pictures show clearly the ethanol drop dynamics, appearance of "jets", and some "trace" at the interface after dissolution of the drop.

[1] M.A. Dem'yanenko, D.G. Esaev, B.A. Knyazev, G.N. Kulipanov and N.A. Vinokurov. Appl. Phys. Lett. 2008, **92** (13), 131116, 3 p.
[2] S.G. Kazarian, J. Van der Weerd. Pharmaceutical Research, 2008, **25**(4), 853-860.

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Transparent power diffractive lenses for FEL radiation

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Abstract

Unique FEL was developed and built up by Siberian Photochemical Research Centre SB RAS [1]. But development and producing of transparent optical elements, applicable for high intensive radiation, is very urgent task. The reason of this lays in the fact that most of optical materials (glasses and crystals) have a high absorption factor for radiation in the terahertz wavelength band. So TDI SIE was challenged for creating specialized terahertz band DOE, applicable for the high-intensive radiation [2].The development of the vacuum hot-pressing technology for creating the polypropylene terahertz band power diffractive optical elements (DOE) with low fabrication costs is the goal of this paper.

Technology for creating transparent diffractive lenses (DL) with high diffractive efficiency for Free Electron Laser (FEL) radiation, developed in TDI SIE SB RAS, are based on using sheet polypropylene State Standard Specification (SSS) 21996-86 and specialized bimetallic nickel-steel plates for stamping DOE with hot-pressing method. A set of DL has been developed. The set includes DL for fixed wavelengths from 120-235 micrometer band and high-quality short-focus DL, external zone size of which is comparable with terahertz wavelength.

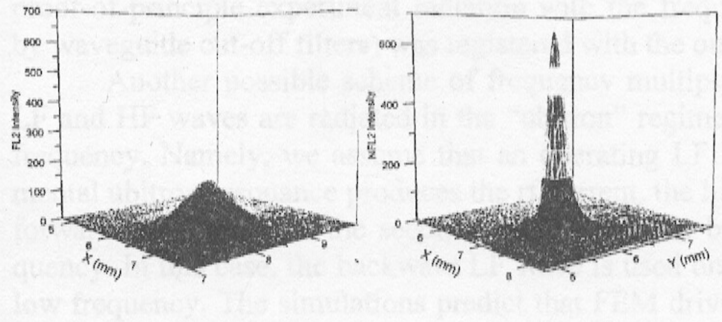

Fig. 1. Focal spots recorded by a microbolometer focal plane array for a long-focus and a short-focus Fresnel lenses.

Fig. 1 displays the intensity distribution in the focal spots for Fresnel lenses with f = 180 mm and f = 80 mm at the wavelength of 0.13 mm, recorded with a microbolometer FPA [3]. The lenses were illuminated with the diverging Gaussian beam of the FEL In the focal spot FWHM was equal to 0.70 mm for the left distribution and 0.23 mm for the right one. The assembly average value of diffractive efficiency is equal to 89%. The assembly average value of the point spread function width is 6% wider than the diffraction limit for DL from the set. During permanent functioning DL has been heated up to temperature of 40 ^{o}C in the radiation beam with power of 30 – 50 watt. It agrees with the result of our mathematical simulation of heating process. DL can be run in beams with power up to 100 watt.

References

1. B A Knyazev, G N Kulipanov, N A Vinokurov. Novosibirsk terahertz free electron laser: instrumentation development and experimental achievements. *Measurement Science and Technology*, V. 21, 054017, 13p. 2010.
2. Vedernikov V.M., Dutov P.M., Knyasev B.A., Palchikova I.G. e.a. Transmissive Diffractive Elements For The Terahertz Spectral Range// Proc. of Int. Symposium on Measurement Technology and Intelligent Instruments, Saint-Petersburg, D.S.Rozhdestvensky Optical Society, 2009, Vol. 2 p. 2-366 –2-370.
3. Dem'yanenko M.A., Esaev D.G, Knyazev B.A., Kulipanov G.N., Vinokurov N.A. Imaging with a 90 frames/s microbolometer focal plane array and high-power terahertz free electron laser. *Appl. Phys.Lett.*, V. 92, 131116, 2008.

COMPACT SUBMILLIMETER FEL PROJECT

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A compact submillimeter FEL project is being developed now at Budker INP. The machine is based on a dedicated 10 MeV L-band linac. All the aspects of the feasibility study of the project are discussed. The expected parameters of the machine are listed.

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MILDLY-RELATIVISTIC FEM WITH FREQUENCY MULTIPLYING

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An attractive solution to realize powerful generator of a THz frequency band is a FEM-scattron using a GHz pumping wave and driven by a mildly relativistic electron beam. We propose to realize an inter-cavity scattering regime in Bragg FEM operating in two-wave (ubitron and scattron) resonance conditions[1]. In the "ubitron" regime electrons interact with the forward GHz wave, whereas the backward GHz wave is used for the feedback and, simultaneously, operates a secondary wiggler to provide stimulated scattering into a THz forward wave. To increase efficiency of the THz generation we proposed operation at a multiple frequency. In this case no feedback (resonator) is needed for THz wave.

Experimental realization of this FEM scheme was started in collaboration between JINR and IAP RAS using 0.8 MeV / 150 A / 250 ns electron beam at the linac LIU-3000 (JINR). This project is based on 30 GHz JINR-IAP FEM which currently generates 20-MW pulses with the frequency spectrum width of up to 6 MHz (close to the theoretical limit) and stability demonstrated during ~ 10^5 pulses[2]. The electron beam quality and quality of pumping wave, which is realized in these experiments, seem to be acceptable for THz generation.

The project of sub-mm FEM was developed for operation at the 12th harmonic. Simulations demonstrated possibility to achieve 100-kW level of output radiation at 360 GHz when using 30-GHz backward wave in a two-wave FEM operating regime described above. In the proof-of-principle experiment radiation with the frequency higher than 300 GHz (measured by waveguide cut-off filters) was registered with the output power estimated at 10-kW level.

Another possible scheme of frequency multiplying in a FEM supposes that both the LF and HF waves are radiated in the "ubitron" regime at different harmonics of the bounce-frequency. Namely, we assume that an operating LF $TE_{1,1}$ mode self-exciting at the fundamental ubitron resonance produces the rf current, the higher harmonic of which radiates to the forward $TE_{2,1}$ mode at the second harmonic of the bounce oscillations at a multiplied frequency. In this case, the backward LF wave is used only for providing a feedback loop at the low frequency. The simulations predict that FEM driven by LIU-3000 is able to produce the power of up to 6 MW when operating at 60 GHz at the second harmonic and up to 1.5 MW when operating at 90 GHz at the third harmonic.

[1] A.V. Savilov, N.Yu.Peskov, A.K.Kaminsky, Nucl. Instr. Meth. in Phys. Res. A507 (2003) 162.
[2] A.K.Kaminsky, e.a., Tech. Phys. Lett., 36 (2010) 37.

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ON TERAHERTZ NON-DESTRUCTIVE DETECTION OF ENERGETIC MATERIALS

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The need for remote non-destructive detection of explosives and other energetic materials (EM) arises in various situations: beginning from their manufacturing at chemical factories, subsequent warehousing, storage, transportation, and final application. The problem urgency has sharply increased last decade in connection with the increased terrorist threat, including illegal transportation and application of EM. Special importance of the remote detection of EM has got for passenger transport. Application of THz-radiation is considered as prominent way to resolve this problem.

The purpose of this work is study of mechanism and regularities of interaction of THz-radiation with typical examples of EM with sensitizing additives. The single-walled carbon nanotubes (SWCNT) have been chosen as such additives. According to recent theoretical publications SWCNT are able to resonant interact with electromagnetic irradiation in THz-range. At the same time SWCNT can generate THz-radiation under exciting electromagnetic waves.

It is revealed, that small additives of SWCNT can change notably the pattern of the basic EM interaction with THz-radiation. Therefore SWCNT-additives can serve as markers for EM-manufacturer to control the EM use. The specified effect as well as high thermal and chemical stability of SWCNT are the scientific base for an advanced method of remote detecting of EM using THz or ultra-short waves that is developed by authors of this paper.

Technological base for production of EM (individual and composite), containing up to 1% of SWCNT distributed uniformly in the material volume are developed. At the technology development we used SWCNT synthesized by CO2-laser ablation of graphite targets [1], and also SWCNT synthesized in electric arc (technology of Prokhorov GPI RAS). Samples of TNT (2,4,6-Trinitrotoluene) and nitrocellulose (with various containing of nitrogen) have been used as individual EM. In the case of composite EM we developed technology of SWCNT uniform addition in the binding components. We used PP (polypropylene), PMMA (polymethylmethacrylate), and also NC (nitrocellulose compositions) for modeling of passive and active binders.

The absorption spectra of samples of PP, TNT, and NC with the SWCNT-additives have been compared with spectra of pure samples (without SWCNT) using a standard Bruker VECTOR 22 Fourier-spectrometer in the MID-IR. The measurements have been carried out in the transmission mode and in the mode of attenuated total reflection (ATR) using a single-reflecting 45-degree silicon prism.

The results obtained in this work prove principal of feasibility using of SWCNT as sensibilizers of EM for their non-destructive detection.

This work was partially supported by the Program of basic researches of the Russian Academy of Sciences No P-05-2008, Section “Electromagnetic waves of THz range”, Russian Foundation for Basic Research 09-02-12158, integration grant from SB RAS №89, and RF State contract № 02.740.11.0556.

1. I.G. Assovskiy, G.I. Kozlov et al. Method to produce single-walled carbon nanotubes, installation for its realization, and a way of manufacturing of composite carbon targets. The patent of the Russian Federation for the invention № 2302371, ROSPATENT, 2007, reg. № 2005130740 from 05.10.2005.

DEVELOPMENT OF CONFOCAL 3D SURFACE SENSOR BASED ON THE DIFFRACTION - CHROMATIC CODING METHOD FOR THE PURPOSE OF SPECTROSCOPIC MEASUREMENTS

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Near-field terahertz photonics is one of the promising directions in the terahertz science. One of the near-field techniques is the scanning near-field microscopy with small subwavelength metal or cored dielectric tips. Such the technique can be, probably, used for micro- and nanoobject study in the terahertz imaging attenuated total reflection spectroscopy [1]. This article presents description and features of confocal 3D surface sensor which is based on the principle of diffraction-chromatic coding with subsequent RGB image processing for the purpose of terahertz spectroscopy applications. The main part of the sensor is a specially designed hybrid refractive-diffraction objective lens. RGB color image decomposition processing was done by regular color video camera.

The goal of this work is development of the optical surface sensor, which can be utilized for precision surface distance measurement for precision positioning of the micromanipulator stage. High precision position control of the micromanipulator stage is required for the positioning of a sub-wavelength conductive needle (probe) into the working field of attenuated total reflection imaging spectrometer based on free-electron terahertz laser. This would allow overcoming the diffraction limits due to the relatively long wavelength of the terahertz radiation (30 - 300 micrometers) and investigation of the complex samples without special pretreatment required otherwise.

Currently optical confocal method is utilized in microscopy for acquisition of volumetric (3D) images of samples with high spatial resolution [2]. In confocal microscopy a special confocal diaphragm is applied for suppression of image component which is out of the microscope focal plane in the object field. Therefore this approach provides the optical image/signal which is located only in vicinity of the focal plane and rejecting everything else.

In the method of chromatic coding [3] a white light source is illuminating the object via special objective lens. The object is illuminated in such a way that different spectral components are focused at different focal distances from the objective. Therefore, only certain short range of wavelengths is focused on the object. The reflected light is collected back through the same objective lens and passes confocal diaphragm, so only specific wavelength corresponding the focal distance close to the object distance is received back as an image.

Measuring the dominating wavelength of received image allows estimation the corresponding object distance with a high precision.

References

1. V. V. Gerasimov, B. A. Knyazev and V. S. Cherkassky. Obtaining spectrally selective images of objects in attenuated total reflection regime in real time in visible and terahertz ranges. Optics and Spectroscopy, 108 (2010) 859-865
2. Robert H. Webb "Confocal optical microscopy" Rep. Prog. Phys. 59 (1996) 427-471.
3. Aleksander V. Ginzhul, Marina A. Zavjalova, Yuri V. Obidin RGB image processing method for color classifying diamonds [Текст] // Proceedings of ISMTII-2009 (The 9th International Symposium on Measurement Technology and Intelligent Instruments). Published by D.S. Rozhdestvensky Optical Society, Russia. Saint-Petersburg, Russia, 29 June – 2 July 2009. Vol. 4. – P. 4-167 – 4-171

Influence of ionization regime on THz emission from femtosecond air breakdown plasma filament

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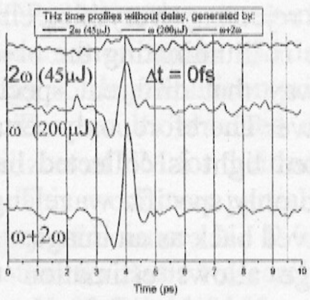
Over 15 years it is known that a gas breakdown plasma filament induced by an ultrashort high-intensity ($10^{12}\div10^{15}$ W/cm^2) femtosecond pulse is a source of a broadband coherent pulsed THz radiation. Recently, it has been noted that emitted THz power increases manifold if a two-color scheme is used where a fundamental optical wave with the frequency ω is mixed with its second harmonics satellite at the doubled frequency 2 ω [1].

The process of two-color field ionization is crucial for generation of strong THz radiation. In our experimental setup as well as in the most of the works published by now, the magnitude of optical field corresponds to the multiphoton ionization mode for both w and 2w beams. The role of the 2ω beam in the ionization process and in the build-up of a free-electron photocurrent is of particular interest in our work.

The experimental setup we use is fed by 2.5 mJ 120 fs 800 nm pulses from Ti:Sa regenerative amplifier. For studying the role of second harmonics, we designed a setup with separation of the ω and 2 ω beams which allows independent adjustment of power, polarization and time delay of each beam. Optical beams are recombined with a dichroic mirror and then focused with a 8 cm lens in air and argon at atmospheric pressure.

We observe the generation of THz waveforms from both ω and 2 ω beams. When the two beams arrive in the focus with time delays larger than the pulse duration, the THz waveforms from each beam add independently to the resulting THz signal. In contrast, when the two beams arrive simultaneously, we observe a nonlinear sum of the two THz waveforms in the resulting signal (see Figure 1). Moreover, the brightness of the plasma filament for two-color optical beam also depends on the time delay between ω and 2 ω beams. The fluorescence patterns of each optical beam add nonlinearly only if the two beams are matched in time. This shows that the influence of second harmonics on ionization of gas medium substantially increases when the two beams are matched in time.



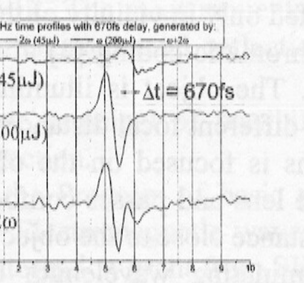


Figure 1 represents temporal waveform of THz signal from ω, 2ω beams separately and together in case when beams arrive simultaneously (left) and when 2ω beam is delayed for 670fs.

[1] D. J. Cook and R. M. Hochstrasser, Optics Letters **25**, 1210–1212 (2000).

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APPROACHING TERAHERTZ HOLOGRAPHY USING THE FREE ELECTRON LASER

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Many experiments in the terahertz region have been performed using low-power shot-pulse wideband sources. Appearance of more intense monochromatic terahertz sources (quantum cascade lasers, free electron lasers) and terahertz image sensors enables the implementation of classical variants of optical techniques in the terahertz range.

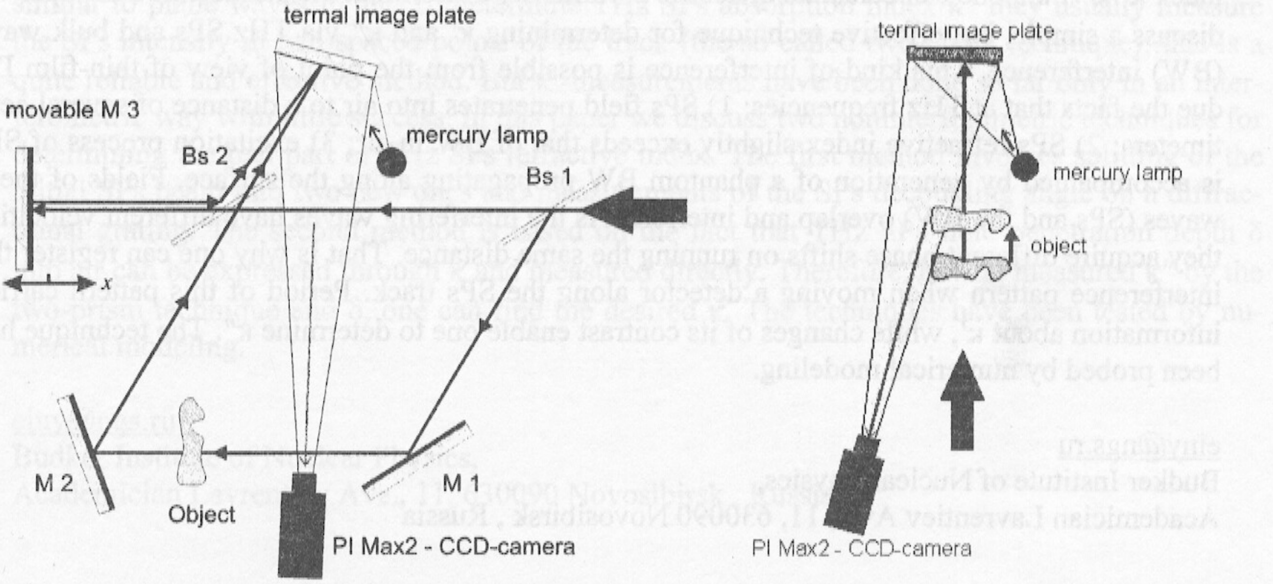

Fig 1. Schematics for recording in-line holograms (right) and reference-beam holograms (left)

In this paper experiments on recording in-line and reference-beam holograms were performed using tunable terahertz Novosibirsk free electron laser. All measurements were carried out using real-time image sensors: a microbolometer focal plane array and a luminescence-quenching thermal image plate with PI Max2 intensified CCD camera. A modified Mach-Zender interferometer employed for recording reference-beam holograms and the setup schematic used for recording in-line holograms are shown in Fig.1. Methods for reconstruction of holograms in the terahertz range were examined.

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TERAHERTZ DISPERSIVE SPECTROSCOPY FOR THIN-FILM STUDY VIA SURFACE-PLASMON – BULK WAVE INTERFERENCE

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Dispersive spectroscopy (DS) establishes the dielectric properties of a medium as a function of frequency. In case of bulk samples DS can be performed by Fourier spectroscopy, ellipsometry, and others. But if the sample represents itself a thin film with thickness much smaller than the wavelength, the named techniques may fail, especially in the far infrared or the terahertz (THz) region. For such samples study a method based on generation of surface plasmons (SPs), a kind of surface electromagnetic waves, was developed. Having determined the SPs complex refractive index $\kappa=\kappa'+i\cdot\kappa''$, one can calculate dielectric permittivity of a film at the surface. In this paper we discuss a simple, but effective technique for determining κ' and κ'' via THz SPs and bulk wave (BW) interference. This kind of interference is possible from the point of view of thin-film DS due the facts that at THz frequencies: 1) SPs field penetrates into air to a distance of several centimeters; 2) SPs refractive index slightly exceeds that of BW in air; 3) excitation process of SPs is accompanied by generation of a phantom BW propagating along the surface. Fields of these waves (SPs and the BW) overlap and interfere. As the interfering waves have different velocities they acquire different phase shifts on running the same distance. That is why one can register the interference pattern when moving a detector along the SPs track. Period of this pattern carries information about κ', while changes of its contrast enable one to determine κ''. The technique has been probed by numerical modeling.

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NONINTERFEROMETRIC TECHNIQUES TO DETERMINE TERAHERTZ SURFACE-PLASMON COPLEX REFRACTIVE INDEX

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Surface plasmons (SPs) are a kind of surface electromagnetic waves existing on an interface "conductor - dielectric". Having determined the SPs complex refractive index $\kappa=\kappa'+i\cdot\kappa''$, one can calculate two parameters of the wave guiding structure: whether the optical constants of the metal or thickness and refractive index of the layer on the surface. This method of surface study was named SP-spectroscopy and is widely used in the visible and middle infrared. As for the terahertz (THz) range, determination of κ is a problem, because at these frequencies SPs are very similar to plane waves in air. To determine THz SPs absorption index κ'' they usually measure the SPs intensity in two spaced points of the track (the so called two-prism technique); this is a quite reliable and effective method. But κ'-measurements have been done so far only in an interferometric way with little success. In this paper we discuss two noninterferometric techniques for determining the real part of THz SPs refractive index. The first method involves splitting of the initial SPs beam into two new ones and measurements of the SPs decoupling angle on a diffractional grating. The second method is based on the fact that THz SPs field penetration depth δ into air can be expressed through κ and measured directly. Therefore, having measured κ'' by the two-prism technique and δ, one can find the desired κ. The techniques have been tested by numerical modeling.

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Sideband Separating Mixer for 600-720 GHz

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Abstract:

The ALMA band 9 (600-720 GHz) receiver cartridge based on two single-ended (dual sideband) SIS mixers in orthogonal polarizations has been produced. In the case of spectral line observations in the presence of atmospheric backgound, the integration time to reach a certain desired signal to noise level can be reduced by about a factor of two by rejecting the unused sideband. The goal is to upgrade the current ALMA band 9 cartridge to a full dual-polarisation sideband separating capability, with minimal impact on the overall structure of the cartridge, providing a minimal-cost upgrade path.

Design features of the sideband separating mixer will be presented. Here we also will demonstrate the first experimental results of the sideband separation performance and noise temperature measurements.

The ALMA requirements are 335K SSB noise temperature over 80% of the band, and 500K over the entire band; the sideband separation should be better than 10dB.

Categories:

SIS Mixers, Poster Session

THEORETICAL AND EXPERIMENTAL INVESTIGATION OF THE EFFECT OF THE TERAHERTZ RADIATION ON THE CONFORMATION DYNAMICS OF BOVINE SERUM ALBUMIN IN WATER BY MEANS OF SPIN PROBE IN SITU

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Theoretical consideration of the conformation dynamics of bovine serum albumin (BSA) in water and in thin film was carried out using the approach based on molecular mechanics (MM2) for the purpose of attributing these changes to vibrational-rotational motions associated with hydrogen bonding. The verify the assumptions, experimental investigation of conformation dynamics in BSA under the action of the terahertz radiation (81.5, 120 mkm) was performed with the help of electron spin resonance spectroscopy with *in situ* spin probing. The compound used as the precursor of spin probe was dihydropyrazine dioxide (DPDO) shown in Fig. 1.

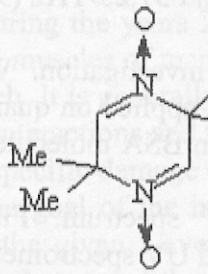

Figure 1. Compound used as precursor of in-sity spin probe:dihydropyrazine dioxide (DPDO).

In BSA solution, this compound gets transformed into the nitroxide radical. The parameters of its ESR spectrum are strongly dependent on the conformation status of the polymer surrounding the spin probe in solution. Changes arising in the ESR spectrum observed after preliminary THz irradiation of BSA as thin film were followed. The irradiated BSA sample was dissolved in water, then DPDO solution was added, and the sample was placed in a flat quartz ampoule for ESR measurements. ESR spectra were recorded in the X-band in the real time mode. The dynamics of the spin probe was observed to change under the action of preliminary THz irradiation. In particular, the width and intensities of ESR lines were critical parameters subject to the influence of preliminary irradiation. Combining the observed changes with simulation results achieved by means of MM2, we propose a possible explanation of conformation changes in the system and a mechanism responsible for spine probe alternation. An attempt is also made to link the effect of preliminary terahertz radiation on the UV absorption spectrum of BSA [1] and conformation changes revealed by the spin probing experiment.

[1] O. P. Cherkasova, V. I. Fedorov, E. F. Nemova, A. S. Pogodin, Optics and Spectroscopy, 107 (4), 2009, 536–539.

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INFLUENCE OF TERAHERTZ RADIATION OF VARIOUS RANGES ON MOLECULE'S CONFORMATION OF BOVINE SERUM ALBUMIN

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The present work is experimental research of THz laser radiation influence on conformation changes in biopolymers molecules of bovine serum albumin (BSA). It's fundamental transport protein of blood serum. BSA has complex globular structure, consists of 607 amino-acid residues.

In our researches we used submillimeter NH3 – laser with an optical pumping and waveguide CO_2 – laser with microwave pumping as generators of THz radiation. These lasers radiate on next frequencies: 1,15 THz (261 mcm); 3,68 THz (81,5 mcm) and 31,25 THz (9,6 mcm). Radiation power was about 10 mW.

Bovine serum albumin (BSA Sigma) was used as subject of investigation. We researched prepared powder (lyophilized) BSA and BSA film preparations applied on quartz supports. We used UV spectroscopy for appreciation of THz laser effect on BSA molecule's conformation.

Powder preparations were dissolved for registration of UV spectrum. Film preparations were researched directly. For registration of spectrums we used UV spectrometer SHIMADZU UV-3101PC.

Ability of BSA to bind steroid hormone (progesterone) was appreciated in size of constant Stern – Folmer. This constant was estimated by intensity of fluorescence suppression.

Series of experiments led as to the next conclusions.

THz laser radiation causes spectral changes of irradiated powder and film preparations of BSA. Optical density of dissolved powder and film samples BSA increase on its typical absorption bands (200 – 220 nm for amid groups and 280 nm for tryptophan residues).

Native binding ability of BSA received by fluorometric measurements testify to conformation changes of protein molecule. All our data indicates that THz laser radiation causes molecule's modification, but doesn't break transport ability of BSA molecules.

Finally results of this work testify to evident influence of THz laser radiation on conformation of protein molecules. This influence doesn't break structure and functions of protein. And, apparently, received changes not caused by direct thermal influence of low intensity THz radiation on protein.

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INTERACTION OF THE TERAHERTZ LASER IRRADIATION WITH A MAMMAL SKELETAL MUSCLE

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Investigations involving the electromagnetic radiation of the terahertz frequency range are increasingly developing during the recent decade all over the world. The most powerful source of this radiation in the world has been developed at G. I. Budker Institute of Nuclear Physics SB RAS. It is the Free Electron Laser (FEL) on the recuperating accelerator that generates the radiation with smooth retuning of wavelengths within 100-200 μm, in the form of 50-picosecond pulses with the repetition frequency of 5.6 MHz, with the average power up to 400 W and peak power of 0.6 MW. The FEL allows carrying out unique investigations in physics, chemistry, biology and other research areas.

During the years 2006- 2009, investigation of the interaction of the THz laser radiation with the skeletal muscles of mammals (rat, cow) have been carried out at the Siberian Center for Photochemical Research. It is generally known that the wavelengths of the laser radiation are characteristic of Van der Waals interactions and the interactions of biological molecules (proteins, DNA etc.), so we expected to detect specific damage of muscle tissue which would be typical for this wavelength range.

The goal of the investigation was to study the consequences of the interaction of the radiation within the given wavelength range with strongly structured biological tissue, to study wavelength-specific damage of the muscle tissue, to evaluate the interaction of the radiation with a large massif of the tissue. In addition, as a reference, we investigated the interaction of CO_2 and Nd lasers with the muscle tissue. Histological examination of the samples was also carried out using the standard procedures for all the kinds of microscopy. Investigations performed with the help of the THz laser, as well as those carried out with CO_2 and Nd lasers, revealed the substantial differences in their action on the muscular and conjunctive tissues.

A detailed description of the consequences of the action of the THz radiation on the tissues is presented. It is shown that the morphology is radically different from that of thermal injury. It is demonstrated that the consequences of the action of the THz radiation differ substantially from those of the shorter-wavelength action (CO_2 and Nd). Possible reasons of the observed situation are discussed.

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EFFECT OF THE TERAHERTZ LASER RADIATION ON AGGREGATION OF THE ERYTHROCYTES IN HEALTHY BLOOD

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Investigations involving the electromagnetic radiation of the terahertz frequency range are broadening in the world during the recent decade. The most powerful source of this radiation in the world has been developed at G. I. Budker Institute of Nuclear Physics SB RAS. It is the Free Electron Laser (FEL) on the recuperating accelerator that generates the radiation with smooth retuning of wavelengths within 100-200 μm, in the form of 50-picosecond pulses with the repetition frequency of 5.6 MHz, with the average power up to 400 W and peak power of 0.6 MW. The free electron lasers (FEL) (1) allow obtaining monochromatic radiation at any required wavelength. During the years 2007- 2009, investigation of the interaction of terahertz FEL radiation (of the laser developed and G. I. Budker Institute of Nuclear Physics) with human blood was carried out.

It is generally known that the wavelengths of the laser radiation are characteristic of Van der Waals interactions and the interactions of biological molecules (proteins, DNA etc.), so we expected to detect sound biomolecular effects.

Distortions of microcirculation and rheology of blood are the major leading factors of pathogenesis of atherosclerosis and ischemia. In some cases, acute disturbances of cerebral circulation, sudden coronary death, myocardial infarction develop in persons with unaffected cerebral and coronary arteries. These states are most frequent in young persons and in women in menopause. An increase in blood viscosity in combination with the spasm of cerebral, coronary arteries is the reason of vascular catastrophes in the patients of this kind.

The goal of the investigation was to evaluate the effect of the radiation of aggregated erythrocytes of healthy volunteers.

Peripheral blood was taken from healthy volunteers, then the blood was mixed with sodium citrate in equal amounts. Then irradiation with non-focused beam was carried out in different versions: at different wavelengths, with different exposures, at different time of blood exposure prior to irradiation (10 minutes to 1 hour), and at different times of blood exposure before histological examination. In addition, 2 reference samples were used: non-irradiated blood and blood exposed for 1 hour after irradiation – to evaluate the state of erythrocytes after the action. All the samples were studied histologically with the help of optical microscopy with the magnification of 300- 600 times, under standard coloring and in the native form.

At different radiation exposures, optimal times for the given laser power were determined to be 10- 15 s. At the exposure shorter than 5- 7 seconds, no significant disaggregation of erythrocytes was detected; at the exposure longer than 20- 25 seconds, the destruction of cell membranes was observed; it was evident during the investigation of the samples 1 hour after the action.

After having obtained the images, their processing was carried out for the purpose of obtaining statistically reliable data on the number of sole erythrocytes and their aggregates. It was also noted that the results of the statistical treatment did not differ for colored and native samples. The degree of disaggregation of the erythrocyte subjected to irradiation was 30 to 90%, so, the action of the THz radiation on whole blood has a clear anti-cohesion effect.

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BIOLOGIC EFFECTS OF TERAHERTZ RADIATION

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Radiation of low-frequency part (0.3…6 THz) of terahertz range corresponds to submillimeter region (50…1000 mcm) of spectrum (SMM THz). SMM THz radiation does not disrupt chemical bonds and does not lead to chemical transformations. Many of macromolecule vibration and rotary transitions are in this frequency range. Modes of intermolecular interaction are located also in this gap. Biological effects of this range were the "blank spot" in our knowledge on electromagnetic wave influence on living systems long time. Now we can do the first systematization of character reactions of living systems on SMM THz radiation.

SMM THz radiation induces change of polar macromolecule conformation (DNA, proteins), influences a binding activity of proteins and specific enzyme activity, braking up hem–globin bond, induces oscillations of protein molecule.

SMM THz radiation generates varied direction of cell reaction on membranous and genetic levels: from a fall of cell viability till a rise of spontaneous and mitogen-induced proliferous activity. SMM THz radiation influences intercellular relationship and DNA synthesis. Various functional states of cells determine different cell reactions on SMM THz radiation. Radiation decreases normal membrane resistance but increases reduced membrane resistance of red blood cells. Radiation induces an acceleration of migration of rat spleen cells at reduced initial level of migration and inhibition of migration at expressed initial level. SMM THz radiation induces an alteration of neuron membrane and forming of interneuron connection. Stromal and cancerous cells do not reaction on SMM THz radiation.

SMM THz radiation influences polymorphysm of bacteria and induces various reactions of bacteria: from an inhibition of mitosis till an appearance of polynuclear cells. SMM THz radiation influences gene activity of bacterial cell. SMM THz radiation induces change of morphologic, physiologic and biochemical parameters of plant growth and development. SMM THz radiation induces shortening of wheat grain imbibition period and increase of stem and panicle length, panicle mass, grain number in panicle and grain protein content. SMM THz radiation induces mutagenic effects in offspring (F2-F5) of irradiated rice seeds. Phenotypic variations induced by SMM THz radiation have different direction in insects and plants: from fertility increasing till induction of sterility and emergence of recessive mutations. SMM THz radiation causes a decrease in a number of spontaneous and gamma-induced somatic mutations in fruit fly adults after irradiation of larvae.

Effect of SMM THz irradiation of mammals depends on a stage of biological process. SMM THz radiation influences endocrime and immune activity of laboratory rats. SMM THz irradiation of mice causes a feeling of uneasiness and prolonged alarm reaction.

Thus, SMM THz radiation influences molecular, cellular and organism levels of microorganisms, plants, invertebrata and mammals. This influence is declared on membranous and genetic levels. SMM THz radiation induces conformation transitions of biopolymers, alterations of membrane permeability and genetic activity, phenotypic variations, influences physiologic regulatory system state and behavioral reactions.

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Tunable THz Generation by Short Laser Pulses

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A theoretical and simulation study has been done for THz generation by direct conversion of an ultra short laser pulse into terahertz radiations. In our mechanism we use two very short laser pulses (one is circularly polarized and other is linearly polarized with same frequency while different amplitude and phases) focused on a gas which tunnel ionizes the gas. The conversion is due to ionization induced excitation in presence of static magnetic field and subsequent transverse transient current because of the presence of residual momentum after passing the laser pulse. Due to this oscillatory current THz radiation is emitted. The directionality of the emitted THz radiation is observed to be controlled by the phase difference of incident fs laser pulses. This mechanism is observed to be very efficient and is able to provide THz radiation with high power level of the order of GW.

Analysis of dual frequency interaction in the filament with the purpose of efficiency and polarization control of THz pulse generation

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Abstract: We show that in the Kerr–induced birefringent filament the dual frequency (800_nm (ω) and 400_nm (2ω)) interaction between high intensity ultrashort laser pulses may lead to the generation of terahertz (THz) radiation with various state of polarization. We show also that the THz field strength can be controlled through ω-2ω delay and their relative polarization orientation.

Analysis of dual frequency interaction in the filament with the purpose of efficiency and polarization control of THz pulse generation

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The co-propagation of 800 nm pump pulse on the fundamental frequency (ω) together with its second harmonic (SH, 2ω) in air or noble gases (such as argon, krypton, xenon etc) in the plasma filament zone is shown as one of the methods to produce pulsed terahertz radiation [1]. Possible physical interpretation of the phenomenon involve four-wave mixing (FWM) [2,3], based on the neutral response of the molecules. Alternatively, the laser-produced plasma is considered as a source of THz radiation [4,5]. Assuming FWM explanation, one can attribute the x and y components of THz radiation of electromagnetic field vector in the laboratory coordinate system to various components of the field on the fundamental and the SH frequencies through the expression

$$E^{i}_{THz} \sim \exp i(k_{2\omega} - 2k_{\omega}) \sum_{jkl} \chi^{(3)}_{ijkl} E^{j}_{2\omega} E^{k}_{\omega} E^{l}_{\omega} \qquad (1),$$

where $E^{j}_{2\omega}, E^{k}_{\omega}, E^{l}_{\omega}$ are the projections of the second and the fundamental light field vectors, respectively, on the corresponding coordinate axes (x or y), and $\chi^{(3)}_{ijkl}(0;2\omega,\omega,\omega)$ is the third-order susceptibility tensor. The authors of [2] revealed significant contribution of the cross term $\chi^{(3)}_{xyxy} + \chi^{(3)}_{xyyx}$ to the THz yield in the case of co-propagation of the ω and 2ω waves. In [3] it is shown that the polarization of electric field of the THz radiation is perpendicular to the orientation of the $\mathbf{E}_{2\omega}$ vector. Thus, the importance of the $\chi^{(3)}_{xyxy}$ tensor component was confirmed.

In this paper we vary the initial polarization orientation and delay of the 800 nm Ti:Sapphire pump (ω) relative to the polarization of the independently produced SH (2ω) pulse (a BBO crystal is not in the pump path). The optimum ω–2ω delay and angle between the initial polarization directions are studied and the values producing the maximum THz pulse energy are numerically justified. The direction of THz polarization vector is found both locally in each particular position of the pump-produced filament and as the result of the integration over the filament longitudinal extension.

In the experiment a single filament was created by 800 nm pump pulse in noble gas or in the air with the energy up to 3 mJ, linearly polarized (at 0°), generated by two Ti:sapphire based laser systems with either 50 or 120 fs pulse duration. The fundamental beam was split into two beams: beam 1 to form a filament and beam 2 to produce the SH pulse (100 fs, 1 μJ) in a BBO crystal. The pump (beam 2) transmitted through the BBO was blocked, while the SH was combined together with the beam 1 to co-propagate in the filament. Polarization direction and ellipticity of THz pulse generated in the filament was studied as it is suggested in [3], while the polarization of the SH pulse was analyzed by a cube polarizer placed after the 800 nm mirror.

In the simulations the light field complex amplitudes E of both the pump and the SH waves are represented by two components E_x and E_y in the plane perpendicular to the propagation direction z. For each of the four light field components we take into account diffraction effects, material dispersion, the group velocity walk-off, self-Kerr nonlinearity and Kerr nonlinearity cross-phase-modulation at the frequencies ω and 2ω (i.e. the Kerr-induced birefringence [6,7]), plasma generation and ionization-induced energy loss. Generation of THz radiation is modeled locally according to Eq.(1) and then the obtained electromagnetic field is integrated along the pump-produced filament.

We found that the Kerr–induced birefringence and isotropy breaking in gases [6,7] leads to the appearance of the elliptically polarized THz field, following the filament-induced polarization ellipticity of the SH pulse. The dependence of the efficiency of such THz field generation is analyzed for different longitudinal extension of the filament.

1. D.J. Cook et al, Opt. Lett. 25, 1210(2000).
2. A. Houard et al, Opt. Lett. 33 1195(2008).
3. Y.Zhang et al, Opt. Lett. 34 2841(2009)
4. K.Y.Kim et al, Nat. Photonics 2, 605(2008).
5. A.V. Balakin et al, JOSA B 27 16(2010).
6. P. Béjot et al, Opt. Express 16, 7564 (2008).
7. Y. Chen et al, Opt. Lett. 33, 2731 (2008).

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INTERNATIONAL SYMPOSIUM «TERAHERTZ RADIATION: GENERATION AND APPLICATION»

July 26 – 28, 2010

DIGEST REPORTS

МЕЖДУНАРОДНЫЙ СИМПОЗИУМ ПО ГЕНЕРАЦИИ И ПРИМЕНЕНИЮ ТЕРАГЕРЦОВОГО ИЗЛУЧЕНИЯ

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