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## TERAHERTZ AND MICROWAVE RADIATION: GENERATION, DETECTION AND APPLICATIONS

27 February–2 March 2023, Moscow, Russia

# ABSTRACT BOOK

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**TERAHERTZ AND MICROWAVE RADIATION:**
**GENERATION, DETECTION AND APPLICATIONS (TERA-2023)**
**27 February — 2 March 2023, Moscow, Russia**

# ABSTRACT BOOK

# СБОРНИК ТЕЗИСОВ

**5-ой Конференции с международным участием**
**«Терагерцевое и микроволновое излучение:**
**генерация, детектирование и приложения»**
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Terahertz and microwave radiation: generation, detection and applications: Abstract Book of the 5-th International Conference. Moscow: Our Style, 2023. 162 с.

Сборник включает тезисы докладов 5-ой Конференции с международным участием «Терагерцевое и микроволновое излучение: генерация, детектирование и приложения» (ТЕРА-2023), посвященной обсуждению фундаментальных и прикладных проблем, связанных с генерацией и детектированием терагерцового и микроволнового излучения, а также его взаимодействия с веществом. Целью конференции является обсуждение актуальных теоретических и экспериментальных научных результатов в области технологий СВЧ и ТГц электромагнитных волн, организация экспертной площадки по обсуждению и формированию векторов развития в предметной области конференции.

The abstracts of reports of the 5th International Conference "Terahertz and Microwave Radiation: Generation, Detection and Applications" (TERA-2023). TERA-2023 conference is devoted to the discussion of fundamental and applied problems related to the generation and detection of terahertz and microwave radiation as well as its interaction with matter. The purpose of the conference is to discuss theoretical and experimental scientific results in the field of microwave and terahertz electromagnetic wave technologies, organize an expert platform for discussion and formation of development vectors in the subject area of the conference.

Аннотации докладов печатаются в редакции авторов, которые несут ответственность за содержание текста.

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# PROPERTIES OF MATERIALS

## OPTICAL PROPERTIES OF A GUHP CRYSTAL PROMISING AS A TERAHERTZ RADIATION SOURCE

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Despite the effective development of THz range, high spectral brightness radiation sources are still not readily available. One method of generating THz radiation is to use a crystal with a high nonlinear optical coefficient to convert an intense laser pulse into THz range. The creation of effective terahertz radiation generators depends heavily on the search for and research of new nonlinear optical crystals (or other materials).

In this regard, the paper presents studies of the optical properties of a new monoclinic semi-organic crystal of guanylurea hydrogen phosphate — GUHP, promising for efficient optical-terahertz conversion. [1].

An optical bench has been developed — a polarizing THz spectrometer, based on a continuous tunable source. Broadband polarizers built on an aluminum grating printed on a thin polypropylene substrate are utilized. The characteristics of the installation based on the Terahertz Frequency domain spectrometer (THz-FDS) Toptica Terascan were studied and its calibration was carried out. The angle of rotation of the main optical axes of the crystals relative to the crystallographic ones was measured. The dispersion of the refractive index and absorption coefficient from 0.2 to 2.2 THz was measured on a Terahertz Time domain spectrometer (THz-TDS). The optical properties are measured with great accuracy in the vicinity of 1.5 THz, in which effective generation of THz radiation under laser pumping is demonstrated, and the x axis absorption peaks in the vicinity of 1.45 and 1.85 THz (Fig. 1) are defined for the first time.

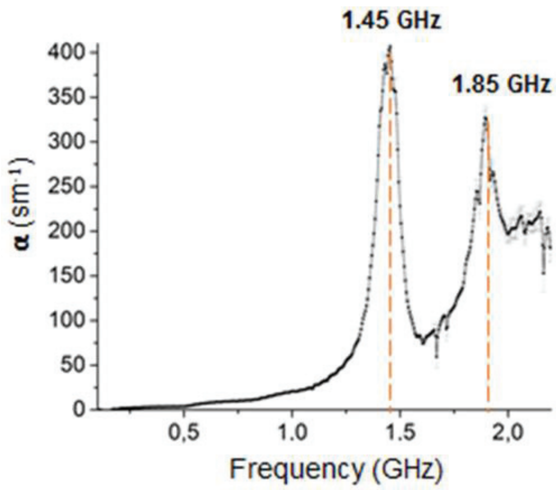


Fig. 1. Absorption coefficient, for the X axis of a GUHP crystal in the frequency range 0.1–2.2 THz.

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## SCATTERING OF THE FIELD OF FAST ELECTRONS ON COUPLED NANOPARTICLES

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2D slab photonic crystals are being actively studied not only for their interaction with electromagnetic waves, but also with charged particles. Interacting with electrons, they can produce THz radiation, with characteristics depending on the electron beam sizes. So, such targets can serve as a promising instrument for the electron beam diagnostics.

It was shown that in comparison with 1D materials there is a significant increase of radiation from 2D slab photonic crystals due to the generation of additional surface plasmon-polaritons [1]. Also, rich spectral and spatial distributions of radiation from such targets can occur due to the appearance of a band gap [2]. 2D slab photonic crystals can be organized, for example, as a massive of particles arranged in a plane [3].

Accounting for collective effects during the passage of an electron beam over such a structure is complicated problem. First, the interaction of the beam with the target leads to arising of coherent and incoherent form-factors that are difficult to calculate [4]. Second, the interaction between the particles can lead to significant effects, as was demonstrated in [5].

In this report we study the radiation, arising while the electrons interact with 2D slab photonic crystals. As a first approximation and to catch all the main effects we consider two electrons flying over two interacting nanoparticles. We show that the dipole-dipole interaction of the nanoparticles leads to a change in the orientation of their dipole moments, which significantly affects radiation patterns in the far zone. The frequency response of coupled particles to the incident field also changes: the resonant frequency shifts with respect to that for single particles.

This work was supported by the Russian Science Foundation, grant № 21-72-00113.

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## TERAHERTZ SPECTROSCOPY OF HIGH-ENTROPY HEXAFERRITE-BASED SOLID SOLUTIONS

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One of the promising directions in modern material science is associated with the creation and application of high-entropy systems. During last decades, the activity was focused mainly on metallic alloys. One of the rapidly growing new fields nowadays includes investigations of possibilities of creation of high-entropy crystalline solid solutions with magnetoplumbite structure. Most popular here are M-type hexaferrites that have been known for more than half a century due to their remarkable properties — chemical inertness, mechanical hardness, high values of the Curie temperature, coercive force and anisotropy field. With such properties, these compounds are widely used in various branches of science and technology. In recent decades, interest in hexaferrites has further increased due to the possibility of their use in high-frequency electronics. It has been shown that terahertz dielectric properties of these compounds can be smoothly "tuned" by changing their chemical composition (see, e.g. [1]). Creating high-entropy phases of hexaferrites will provide even broader opportunities for effective adjustment of their electrodynamic properties over a wide range due to a smooth quantitative change in composition. Recently, we managed to synthesize and stabilize high-entropy crystalline solid solutions of such systems (see, e.g., [2]). In this report, we present the first systematic study of terahertz spectra of complex dielectric permittivity ε*(ν)=ε›(ν)+iε»(ν) of a series of ceramic $BaFe_{12-x}(Ti,Mn,In,Ga)_xO_{19}$ compounds (x=1, 2, 3, 4, 5, 6, 7) at frequencies ν=0.2 THz — 1 THz and in the temperature interval from room down to liquid helium temperatures. Measurements were performed with use of pulsed time-domain spectrometer Menlo Tera K15. Fig.1 shows typical results, spectra of real ε› and imaginary ε» permittivity of a selected representative compound with x=7. Spectra indicate presence of higher-frequency infrared phonon resonance. During cooling, terahertz absorption ε»(ν) decreases, most probably due to narrowing of the infrared resonance. At high temperatures, low-frequency slope of the ε»(ν) spectra do not extrapolate to zero indicating presence of lower-frequency excitation that freezes out while cooling. We will discuss the dependences of terahertz dielectric properties of the $BaFe_{12-x}(Ti,Mn,In,Ga)_xO_{19}$ family on the temperature and the composition x, compare them with the spectra of low-entropy counterparts $BaFe_{12-x}Ti_xO_{19}$ and analyze the origin of discovered excitations.

The work was supported by the Ministry of Science and Higher Education of the Russian Federation (FSMG-2021-0005) and by the Russian Science Foundation (18-73-10049).

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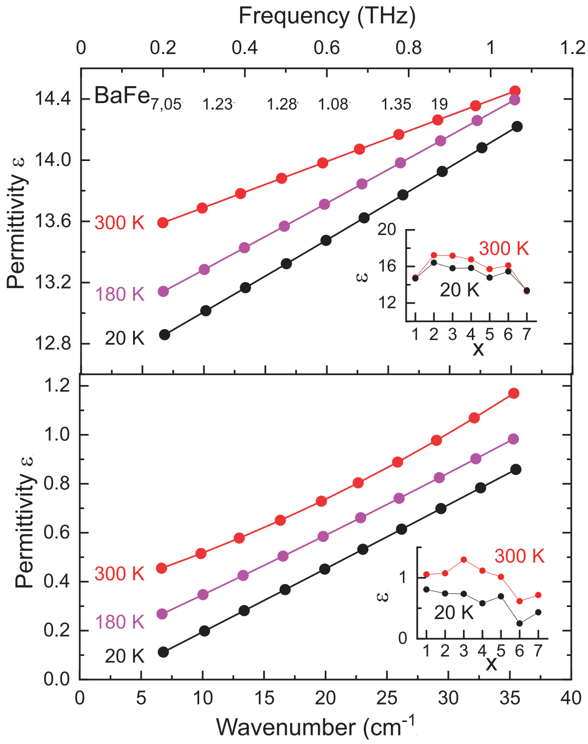


Fig.1. $(Ga)_xO_{19}$ with x=7.
Insets show dependence of ε› and ε»
on substitution degree x
at two temperatures

## TERAHERTZ FREQUENCY-SELECTIVE SURFACE BASED ON A SEMIMETAL-DIELECTRIC HYPERBOLIC MEDIUM

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Hyperbolic materials with different-sign axial and tangential dielectric permittivities are applied in many near-field applications like spontaneous emission control, sub-diffractional imaging, negative refraction, narrow optical angle filtering, and are widely proposed for microwave and visible/infrared frequency ranges [1-3].

The adaptation of such media to the terahertz frequency range and modifying their properties by imparting frequency selectivity through a periodic structuring of a semimetal film as a part of a layered hyperbolic medium is investigated both numerically and experimentally. The structuring is performed in a form of periodic cross-like cuts that preserve a polarization invariance [4]. This allows not only to reduce losses in the entire studied frequency range of 0.2-1.0 THz, but also to reach a dual-band or a multi-band hyperbolic/elliptic effective permittivity dispersion. The influence of the frequency-selective surface unit cell geometrical parameters onto amplitude and phase spectra of a THz wave interacting with this medium and onto its in-plane effective permittivity dispersion is studied. Results of the numerical simulation and the experiment agree well with each other and confirm the possibility of using such the tunable hyperbolic medium in various systems of THz signal modulation, imaging, etc.

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## MODIFIED TINKHAM'S EQUATION FOR EXACT THIN FILM COMPLEX CONDUCTIVITY MEASUREMENT BY THZ-TDS

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The field of terahertz (THz) photonics is being intensively developed at the present time due to possibilities opened in last few decades only with a creation of efficient and affordable sources and receivers of THz radiation. It is already being used in next-generation wireless communications, contactless diagnostics and imaging in medicine, security systems, pharmaceutics, food industry, etc. [1,2].

The progress in development of THz technologies is associated with application of new materials, including thin films with material parameters (e.g. complex effective permittivity and conductivity) differing noticeably from these of bulk media or being difficult to predict by using various models. As a rule, thin film is placed on a dielectric substrate transparent for THz waves, and complex amplitude spectra are measured for THz pulses transmitted through the air, bare substrate, and film-on-substrate structure by the method of THz time-domain spectroscopy (TDS). Then, thin film conductivity is calculated using an equation proposed by Tinkham in 1956 [3]. However, this equation does not take into account the imaginary part of a substrate refractive index and internal reflections in it, therefore, a separate filtering of THz waveforms is also required.

A modified equation is proposed in this work, which does not require preliminary waveform filtering and accounts for losses and internal reflections inside a substrate. It allows one to obtain an exact complex conductivity/permittivity dispersion of a thin film, which is confirmed by calculations based on the transfer matrix method.

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## SUPER-RESOLUTION THZ IMAGING OF BIOLOGICAL TISSUES: RECENT ACHIEVEMENTS AND CHALLENGES

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Unique effects of THz-wave–matter interaction push rapid progress in THz optoelectronics aimed at bridging the problematic THz gap [1]. However, majority of the THz technology applications still suffers from low spatial resolution of common lens- or mirror-based THz optics [2]. In fact, such optics cannot overcome the Abbe diffraction limit and provides the resolution larger than a free-space wavelength $\lambda$ — i.e., a few hundreds of micrometers or even a few millimetes [3,4]. Such a poor resolution particularly humpers the use of THz technology in vigorously-explored biomedical applications [5]: diagnosis of malignant and benign neoplasms [6–8], diabetes mellitus [9,10], therapy of inflammatory diseases and cancers [11], and others.

To mitigate this difficulty, supper-resolution THz imaging modalities were recently introduced. Among them, we particularly underline different methods of the THz scanning-probe near-field optical microscopy. They rely on strong light confinement on sub-wavelength probes and provide the advanced resolution as high as $\sim 10^{-1}$–$10^{-3}\lambda$ [12]. Meanwhile, they suffer from small energy efficiency (or presume an interplay among resolution, signal-to-noise ratio, and performance), while the scanning probe may interact with an imaged sample an even perturb its structure.

In our research, we developed a novel super-resolution THz imaging modality — so-called, THz solid immersion microscopy [2,13–20]. The essence of a solid immersion effect is a reduction in the electromagnetic beam caustic dimensions, when it is formed in free space, at small distance behind the high-refractive-index materials. We developed the THz solid immersion lens, that is based on a wide-aperture aspherical singlet [3] and a near-focal composite silicon hemisphere, operates in reflection mode, and provides the resolution as high as $0.15\lambda$ (beyond the Abbe diffraction limit) [14]. Our system possesses advanced energy efficiency thanks to the absence of any near-field probes in an optical scheme. It is adapted for imaging of soft objects and biological tissues, thanks to the composite construction of this hemisphere [14].

Al these modalities of super-resolution THz imaging were recently applied in biophotonics, where they allow for the highly-accurate delineation of the tumor margins, studying the tissue heterogeneity at the THz wavelengths scale and the related scattering effects [18–20]. In this talk, we discuss, recent achievements and challenging problems in super-resolution THz imaging of biological tissues.

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## IMPACT OF AIR ATMOSPHERE ON THE CONDITIONS FOR THE SYNTHESIS OF CERAMIC MATERIALS IN THE INTERACTION OF A MICROWAVE PULSE OF A GYROTRON WITH A MIXTURE OF $AL_2O_3$/AL POWDERS

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The increased demand for new methods for the synthesis of catalytic materials used in the chemical industry is increasing annually. At the same time, physical methods for obtaining complex powder and granular carriers for catalysts are of particular interest because they are more environmentally friendly and less resource-intensive compared to chemical synthesis methods.

The work being developed at the GPI RAS on the synthesis [1] of powder carriers and catalysts using a microwave beam of a gyrotron requires a detailed study of the air atmosphere in plasma-chemical processes. in the process of synthesis, two types of powders consist of metals (Pt, Pd, Al, Mg, Ti, etc.) and ceramic dielectrics ($Al_2O_3$, $SiO_2$, $TiO_2$, etc.). For rapidly oxidizing metals, such as Al during plasma-chemical synthesis in the atmospheric, it is necessary to observe the influence of the processes of oxidation, ignition, and combustion of the metal, since they significantly affect the conditions for the development of the discharge and synthesis products.

In this work, the main studies are carried out on the processes in a plasma-chemical reactor at of microwave radiation from a gyrotron (frequency 72.1 GHz, power 400 kW, duration pulse 8 ms) with a mixture of $Al_2O_3$/Al powders at a mass concentration of 20%. The described mechanism for the synthesis of ceramic carriers, taking into account the oxidation of the atmosphere in air normal conditions.

This work was carried under State Assignment GZ BV10-2021 “Study of Innovative Synthesis of Micro- and Nanoparticles with a Controllable Composition and Structure Based on Microwave Discharge in Gyrotron Radiation».

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## STUDYING SENSOR CAPABILITIES OF ARCHIMEDEAN SPIRAL METAMATERIALS WITH C-SHAPED RESONATOR USING THIN DIELECTRIC FILMS IN THE TERAHERTZ FREQUENCY RANGE

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Archimedean spiral metamaterials are periodically repeated subwavelength gratings which were compressed and rolled into a closed surface described as a topologically closed flat 2D metasurfaces [1]. They support excitation of spoof-localized surface plasmon polariton resonances (LSPPR) at the terahertz and microwave frequencies, whose properties are similar to classical LSPPR. Spoof LSPPs have several advantages over familiar LSPPs for creating highly-performance sensors in the terahertz range. Spoof LSPPRs depend on the geometry of the metaparticle, which provides flexibility in designing the electromagnetic properties of structures. Spoof LSPP metasurfaces can support high order resonances, high field confinement and large field enhancement. Moreover, ohmic losses that limit the sensitivity of sensors in the visible range can be neglected at low frequencies [2]. As a result, it is possible to achieve a higher sensitivity in the THz frequency range than in the optical range and realize sensors that are valuable for solving the problems of investigations of thin layers as well as spectroscopy of tiny biological objects at the terahertz frequencies [3].

In this work, we compared the frequency amplitude and phase spectra of spiral metamaterials with C-shaped resonator coated thin dielectric films numerically and experimentally. The sensitivity and figure of merit (FOM) were calculated. It was shown that phase measurements enable to increase the FOM of this type of sensors.

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## MUTUALLY CORRELATED OPTICAL AND TERAHERTZ PHOTONS: GENERATION AND APPLICATION

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Parametric generation of terahertz waves in nonlinear crystals has already been achieved by many groups aimed to construct the powerful sources of terahertz pulses at high gain [1]. But only few researches realize that the terahertz beam and the optical Stokes signal beam, if emitted at the same set-up in the absence of any external seeding, represent the so-called quantum "twin beams" and form together a kind of an entangled quantum state. The specific quantum properties of these beams are most clearly manifested in case of the low gain regime, when the unseeded parametric generation process transforms into spontaneous parametric down-conversion (SPDC) [2]. The pairs of mutually correlated photons ("biphotons") are generated under SPDC in a wide spectral range up to the pump frequency. The most famous are the all-optical biphotons emitted at comparable frequencies both in the optical range. Starting from pioneering works on SPDC-based spectroscopy and quantum photometry by D.N. Klyshko and A.N. Penin's group in Lomonosov MSU [3,4], now the optical biphotons are widely used in various quantum optical technologies, such as quantum communication, computing, metrology, imaging, and sensing [5]. The optical–terahertz biphotons, which consist from one optical photon, with close to laser pump frequency and one terahertz photon, with about two orders of magnitude lower frequency, also begin to attract a considerable interest. With the goal of expanding optical quantum technologies on the terahertz range, they have been tested in terahertz spectroscopy, sensing, and photometry [6].

We study optimal temperature, spectral and other experimental conditions for generation of optical–terahertz biphotons with the highest possible values of the correlation parameters, a second-order correlation function $g^{(2)}$ at low gain [7], and the photon noise reduction factor or covariance at high parametric gain [8]. The current absence of single-photon terahertz detectors makes it impossible to use typical quantum optical circuits for direct detection of the photon coincidences. The new approaches are developed for detection of the biphoton correlations, based on analysis of joint statistical distributions of analog readings of an optical detector in the signal channel and a terahertz detector in the idler channel of the SPDC set-up. Measurement of exact values of correlation parameters is of key importance in applications of the optical-terahertz biphotons in terahertz quantum ghost imaging with a single-pixel terahertz receiver, construction of single-photon terahertz sources, reference-free calibration of the spectral sensitivity of terahertz detectors, and other perspective tasks. Our current work is devoted to the study and absolute measurement of quantum efficiencies of the analog superconducting terahertz HEB bolometers. Experimental approaches based on the SPDC generation scheme with a nonlinear crystal placed in the He cryostat together with HEB and a single-photon detector in the optical detection channel are analyzed.

This work was supported by the Russian Science Foundation, project No. 22-12-00055.

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## ELECTRICALLY-TUNABLE REFLECTARRAYS FOR MILLIMETER WAVES BASED ON LIQUID-CRYSTAL-LOADED HIGH-IMPEDANCE SURFACES

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We present the results of experimental development of planar metamaterial structures operating in reflection in the range of 110-150 GHz and enabling spatially nonuniform electrical tuning of the reflection phase and amplitude. The devices have an optical diameter of 50-70 mm and are implemented as resonant high-impedance surfaces loaded with a thin liquid crystal (LC) layer. A unique nematic LC composition based on n-quaterphenyl and n-quinquiphenyl substances and distinguished by high optical anisotropy (0.39) and low dielectric losses (<0.002) at millimeter waves was developed for this work with the industrial implementation of the devices at the final stage. For 1D- and 2D-controlled meta-pixels of the reflectarrays we demonstrate two operation modes: 1) with phase tuning > 360 degrees, 2) with amplitude tuning > 30 dB. Possible applications of the developed devices as beam-steering/ beam-shaping antennas for 6G wireless communication systems, as well as spatial pattern generators in single-pixel subTHz imagers are discussed.

The work is partially supported by the Ministry of Science and Higher Education of the Russian Federation (grant FSUS-2020-0029). The authors acknowledge the Shared Equipment Center CKP "VTAN" (ATRC) of the NSU Physics Department for the instrumental and technological support.

## EXCITATION OF FUNDAMENTAL PLASMON MODES IN GRAPHENE RECTANGLE DEPENDING ON FINITE WIDTH

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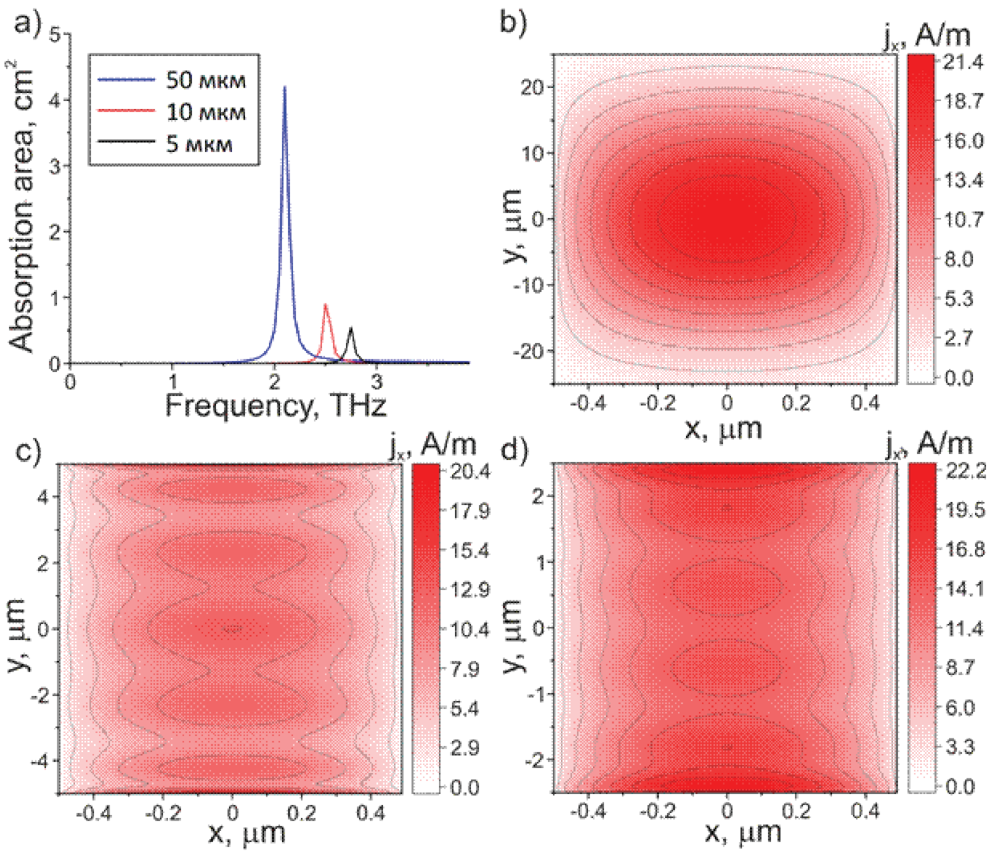
Two-dimensional (2D) plasmons can be used in terahertz (THz) devices for localization and gain of electromagnetic field [1]. One of the most useful materials for realization of 2D gas is graphene [2], which characterized by high mobility [3] and the relaxation time of the momentum of charge carriers, reaching 2 ps at room temperature [4].

We consider plasmon excitation in graphene rectangle separating two half-spaces with different dielectric constants. We solved the electrodynamic problem of incidence of electromagnetic wave polarized along the 0X on graphene plane X0Y. Calculated absorption area of incident wave upon excitation of plasmon in graphene rectangle demonstrates significant dependence of fundamental plasmon resonance frequency on transverse dimension along 0Y (Fig. 1a). Frequency increasing with decreasing transverse dimension along 0Y is connected with an increasing influence of edge effects is demonstrated in graphs 1b-d.

Financial support was provided by the Russian Science Foundation through the Grant No. 22-19-00611.




Pic. 1. (a) Absorption area dependence on plasmon wave frequency. (b)-(d) Rectified current density in graphene dependence on X0Y coordinates.

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## ON THE LIMITING POSSIBILITIES OF TWO-DIMENSIONAL PLASMONICS IN PHOTO-DETECTION APPLICATIONS

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In 1996 Dyakonov and Shur proposed a scheme for a potentially highly sensitive photodetector using plasmons in a two-dimensional electron system. The work generated many ideas for plasmonic detectors. However, in all currently known publications, only absorption oscillations associated with the presence of plasmon resonances were observed, without its enhancement [1].

We identify the reasons for their low sensitivity. We show that a large relaxation time of an electron pulse τ in the general case does not guarantee a large absorption cross section of light by a plasmonic resonator. A more important role is played by the matching of the ohmic and radiation resistances of the plasmonic system itself. Upon matching, the cross section reaches $\sigma_\lambda = \lambda_0^2/4\pi$, where $\lambda_0$ is the wavelength of light in vacuum. If matching is still achievable in the long-wavelength region of the spectrum, for IR it needs unrealistic τ. The addition of metal contacts of a simple rectangular shape to the system, which are in any case an integral part of the photodetector, makes it possible to achieve the limiting absorption at shorter values of τ. The key advantage of plasmonic detectors is their subwavelength dimensions, which, for example, makes it possible to place many detectors operating simultaneously at different wavelengths on an area $\sigma_\lambda$ without compromising the absorption cross section $\sigma_\lambda$ of an individual device. Simulation were made in CST Microwave Studio and supported by theoretical calculations [2].

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## MEASUREMENT OF TRANSMISSION AT TERAHERTZ FREQUENCIES FOR MATERIALS WITH A VERY HIGH TRANSPARENCY

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Complex terahertz systems utilize different materials with a high transparency, for example cryostat windows, infrared filters and others. These materials have to be in signal path and they should introduce as low as possible losses, about 1% or lower. The direct and precise measurement of the transparency level of such materials is the goal of our study.

Direct measurement of the transparency *T* (close to 1) of the target materials is strongly affected by the drifts in the system and by a beam steering introduced by the tested material. Basically, the difference in the signal level between the measurement with and without the material is so low that 1/f noise in the systems and the beam distortions are dominating. To minimize these effects, we propose to modulate terahertz signal using chopper made out of the material under study. In this case, the signal in the system will be (1-*T*)/*T* times lower compare to a nontransparent chopper. For 99% transparent material this gives almost 20 dB difference in the signal level, an example of a measurement is shown in the figure 1, making it a sensitive and a simple tool to estimate the transparency.

The study will examine various types of Teflon, Gore-Tex, Mylar and other films. To study them, a setup was assembled from a radiation generator, a signal chopper with blades made of the materials under study, a Lock-In Amplifier, and a detector based on a Golay cell. As a result, it is planned to obtain a graph of the transparency of the material depending on the frequency signal used in the installation.

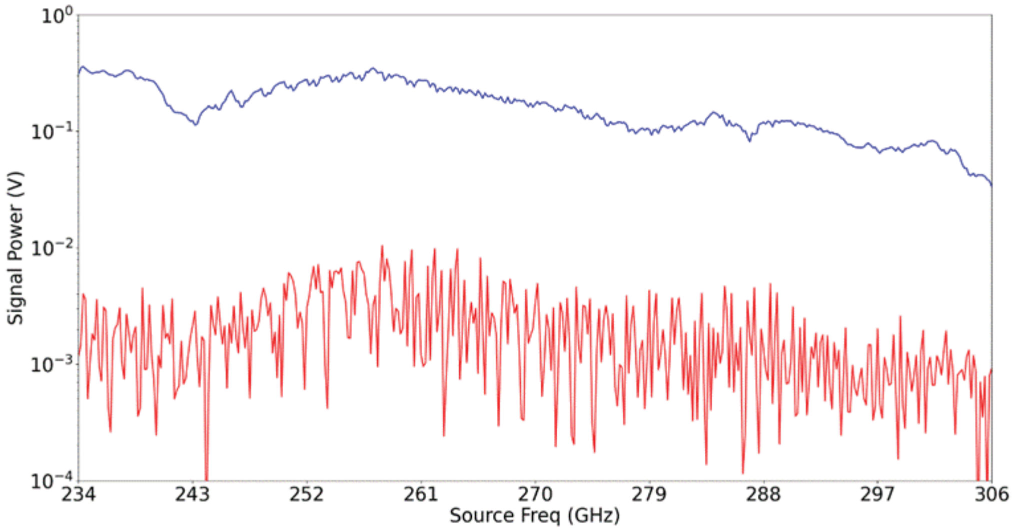


Fig. 1. Signal power with the metal blade (blue graph, material transparency close to 0%) and signal power with the blade made out of tested material (red graph, material transparency close to 99%).

## BORATE NONLINEAR-OPTICAL CRYSTALS AND THEIR APPLICATION AS SOURCES OF INTENSE TERAHERTZ RADIATION

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Nonlinear crystals of the borate family show high laser radiation conversion efficiency in the UV, visible, and near-IR ranges. They can be positioned as potentially effective optical-to-THz converters under near-IR pumping since they are generally transparent in the sub-THz frequencies. In this paper, we present a terahertz spectroscopy of the optical properties of LBO, β-BBO, and LB4 crystals and a detailed analysis of the optical-to-THz nonlinear conversion potential considering collinear phase matching. The results allow us to conclude that the β-BBO crystals can serve as reliable intense sub-THz sources. That was experimentally confirmed and the mechanisms of the THz radiation generation, which make the main contribution to the nonlinear conversion of laser frequencies, are being studied.

The study was carried out within the framework of the State Assignment projects of IA&E SB RAS (No. 121032400052–6). The authors acknowledge Shared Equipment Center "Spectroscopy and Optics" of the IA&E SB RAS and core facilities "VTAN" (NSU) for the access to its experimental equipment.

## NUMERICAL ESTIMATE OF TEMPERATURE INFLUENCE ON NON-RECIPROCAL PROPAGATION OF TERAHERTZ RADIATION THROUGH INSB, INAS, GAAS

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This work presents the results of estimation of temperature influence on non-reciprocal propagation terahertz (THz) waves through magneto-optical semiconductors (InSb, InAs, GaAs). The studied materials have high carrier mobility and concentration and are transparent for the THz radiation which makes them suitable to perform as efficient non-reciprocal devices.

Changing the thermodynamic parameters of magneto-optical media is a little-studied and promising way to ensure the nonreciprocity of optical radiation propagation, which is extremely important for applications in waveguide structures and integrated circuits, in which a back-forward pulse from any optical device is undesirable and can lead to damage to other devices (in case of high-intensity radiation) or increased noise [1]. Temperature control makes it possible to directly control the mobility and concentration of charge carriers, and hence the magnitude of magneto-optical effects [2].

Thus, "turning on" and "off" one-way propagation can be achieved by changing the temperature of the medium. In this work the transmission of radiation up to 2 THz through samples of bulk InSb, InAs, and GaAs in a longitudinal magnetic field (Faraday geometry) was considered. Of all the materials studied, the most outstanding result showed InSb. The transition from 0 to 100 % isolation could be achieved by decreasing the temperature of 150 um bulk InSb from 293 to 240 K.

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## STUDY OF ELECTRON KINETICS IN GRAPHENE USING THZ AND OPTICAL PULSES

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The talk is devoted to the theoretical and experimental study of ultrafast dynamics of electrons in graphene excited by sub-cycle THz pulses and femtosecond optical pulses. It is well-known that linear (Dirac) dispersion law of graphene leads to high mobility of charge carriers and record nonlinear response; also, it causes unusual behavior of electron scattering probability, which is essentially important for understanding of the material response to the action of strong electromagnetic field. In this talk we overview our previous and recent results on nonlinear electrodynamics of graphene in optical and THz field, focusing of the role of electron-electron and electron-phonon scattering. First, we analyze graphene excitation by intense THz pulses and discuss the problem of the electronic distribution function isotropization in k-space.

According to our measurement of spontaneous photon emission and numerical calculations, the isotropization time dramatically decreases (compared to the expected value of several picoseconds) when graphene is excited by strong THz pulses of 100-300 kV/cm magnitude.

This is probably caused by the dominant role of electron scattering on optical phonons under the discussed conditions. Second, we revisit previous results on optical second harmonic generation in graphene in the presence of THz field, also analyzing the role of electron scattering and comparing estimated collision rate with ones obtained in other experiments.

Theoretical analysis and data interpretation were supported by the Russian Science Foundation (project #21-72-00076).

## DISPERSION OF Α–PINENE NONLINEAR REFRACTIVE INDEX COEFFICIENT IN THZ SPECTRAL RANGE

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Nowadays, terahertz (THz) photonics is one of the most developing and perspective technological areas. Recently discovered giant and low-inertia nonlinear refractive index coefficient for group of materials in the THz spectral range made it possible to design ultrafast THz devices such as THz transistors and memory cells [1]. According to the large amount of experimental and theoretical studies, α-pinene is expected to be nearly the most effective material to construct ultrafast THz devices [2]. However, there is still no data of nonlinear refractive index coefficient dispersion for α-pinene in the THz spectral region, while this information is crucially important to control the nonlinearity in ultrafast THz devices. Here we present experimentally obtained dispersion for linear refractive index and theoretically estimated dispersion for nonlinear refractive index coefficient of liquid α-pinene in the range from 0.1 up to 1.2 THz. It is shown that due to the low dispersion the value of α-pinene nonlinear refractive index coefficient lies within $10^{-10}$ W/cm$^2$ in the THz spectral range.

To calculate nonlinear refractive index coefficient the linear refractive index of α-pinene was measured using conventional THz Time-Domain Spectroscopy system [3]. Unlike most liquids, such as water, α-pinene is non-polar one, so its absorption coefficient in terahertz range is rather low. That allowed us to perform measurements in transmission mode by placing liquid α-pinene into 10 mm plastic cuvette. The obtained data showed a low dispersion of the refractive index near 1.47 in the range of 0.1-1.2 THz. The nonlinear refractive index coefficient of α-pinene has a predominantly vibrational nature [4], hence can be calculated using the formula

$$n_2 = \frac{3a_1^2 m^2 \omega_0^4 \alpha_T^2}{32 n_0 \pi^2 q^2 N^2 k_B^2}\left(n_{0,\nu}^2 - 1\right)^3 - \frac{9}{32}\frac{1}{\pi N}\frac{1}{n_0 \hbar \omega_0}\left(n_{0,\nu}^2 - 1\right)^2 \qquad (1)$$

where $n_0$ is the linear refractive index. Interpretation of other variables can be found in [4]. From a theoretical estimate, it is shown that $n_2$ has values of the order of $10^{-10}$ W/cm$^2$ and is not subject to pronounced dipsersion. This justifies the use of broadband pulsed radiation in the range of 0.1-1.2 THz to assess the nonlinearity of α-pinene.

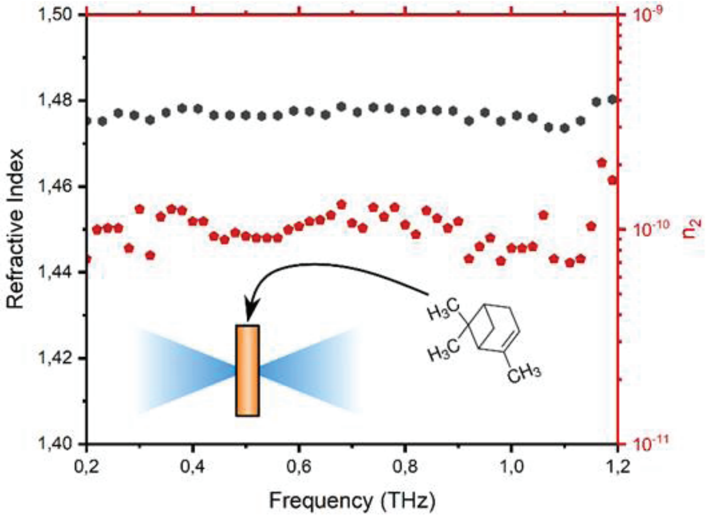


Fig. 1. Experimantal linear refractive index (gray dot) of α-pinene and its calculated nonlinear refractive index coefficient (red dot).

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## 3D PRINTED TERAHERTZ GRIN LENSES

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Usually such dielectrics have fixed permittivity and the entire operation of the optics relies on careful crafting of its shape. The undesired imaging aberration is particularly recognizable for the spherical lens, in which the imaging resolution of a single refractive lens becomes deteriorative due to the classical spherical aberration. Therefore, many modern imaging systems take advantage of stacking several lenses to deliver optimal imaging performance with lower aberrations, however, at the great expense of increased cost and complexity. A feasible solution is the use of GRIN materials, which possess a gradient in the refractive index and guide light rays to bend within the material. The rapid advancements in the fields of transformation optics (TO) and metamaterials have opened up possibilities for the realization of gradient-refractive index (GRIN) optical elements. Using the additive manufacturing technique, in this paper we demonstrate the successful implementation of a three-dimensional, TO terahertz GRIN lens. The spatially-distributed refractive index is achieved by designing and precisely fabricating a series of non-resonant metamaterials with varying dimensions using 3D printing process. The performance of 3D printed THz GRIN lenses was compared with THz refractive spherical lenses.

## THZ ELECTROMAGNETIC RESPONSE FROM CARBON-CONTAINING ELASTOMERS BASED ON A POLYETHYLENE MATRIX FOR USE IN ADDITIVE TECHNOLOGIES

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Elastomers are a class of polymers that allow changing their geometry up to 800% and withstand high loads without breaking down [1]. Now it is promising to use them in additive technologies, which allow the production of materials of any shape and size, in exchange for the old methods. Materials such as acrylonitrile butadiene styrene, polylactic acid, etc. have low elasticity, so there is interest in creating more elastic durable materials [2].

The material (1) is a polyethylene matrix with the addition of 20% ethylene-propylene rubber and 20% black carbon. Material marked (2) is a polyethylene matrix with the addition of 20% ethylene-propylene rubber, 20% black carbon, 20% C-1 grade colloidal graphite. The material (3) is a polyethylene matrix with the addition of 20% ethylene-propylene rubber, 10% black carbon and 10% C-1 grade colloidal graphite. The materials were obtained by the following method: polyethylene, rubber and filler were preliminarily mixed in a mixer. Next, the mixture was unloaded into a twin-screw extruder and the granules were produced. After the granules were placed in an extruder to form thin filaments and repeatedly passed through it. The extrusion temperature ranged from 175 to 210 °C. The resulting filament was run in a 3D printer at a nozzle temperature of 200 °C to obtain test samples. By TERAVIL T-Spec 1000 THz spectrometer the linear transmission coefficients α for three samples in the frequency range from 0.1 to 1.5 THz were obtained (Fig. 1.).

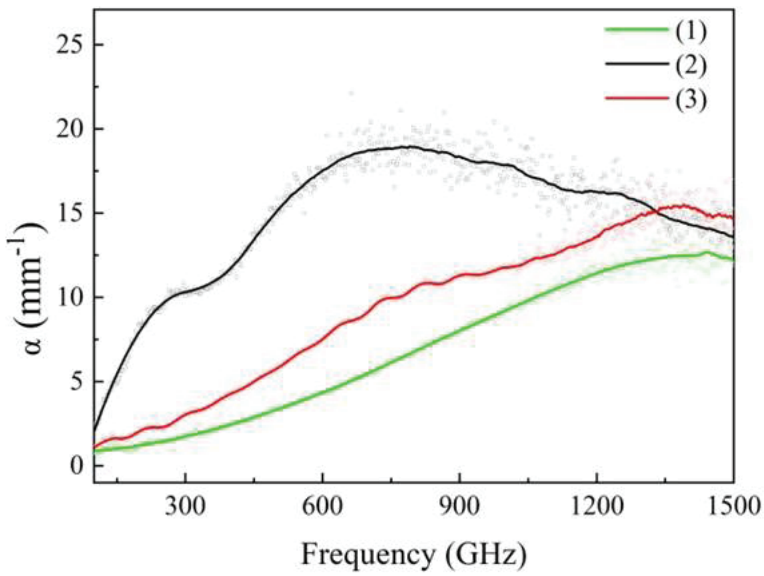


Fig. 1. Frequency dependence of linear absorption for a series of samples with different contents of carbon black and colloidal graphite.

The results show that the linear absorption of materials with the addition of graphite (samples 2 and 3) is higher. The greatest increase in absorption (4 times) is achieved with the addition of 20% carbon black and 20% graphite. Thus, these materials can be used for prototyping and production of structures when electromagnetic sealing of extremely high-frequency and hyper-high-frequency radiation is required.

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## MEASUREMENT OF RADIOPHYSICAL PROPERTIES OF MATERIALS AND COATINGS AT MICROWAVE FREQUENCIES IN A WIDE TEMPERATURE RANGE

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At present, in connection with the development of production technologies and the use of new heat-resistant composite and ceramic materials in many high-tech fields, including radioelectronic, aerospace, petrochemical, automotive, food, medical industries, high-precision methods for measuring radiophysical properties and electromagnetic parameters of materials in the microwave range are becoming essential. This is due to the fact that the practical use of existing, as well as the targeted synthesis of new materials and the construction of radio engineering structures based on them, cannot be carried out without referring to experimental studies of their electromagnetic properties in a wide frequency band, as well as in a wide range of operating temperatures. At the moment, there are many different approaches and methods for measuring radiophysical and electromagnetic material parameters at microwave frequencies [1]: using coaxial cells and probes, waveguide transmission lines, there are also various resonator, microstrip line techniques, etc. However, almost all of these techniques are used to study materials and coatings under normal conditions at room temperature without taking into account the influence of external factors on samples, which include, in particular, the effect of high and low temperatures. In addition, there is practically no information in the scientific literature regarding the study of the microwave properties of materials exposed to not only high (positive), but also low (negative) temperatures. In this connection, the measurement of radiophysical properties of materials and coatings at various temperatures corresponding to real operating conditions is of considerable interest both from the scientific and applied points of view.

This paper presents a non-contact method for measuring the radiophysical properties of samples of materials and coatings in free space (a quasi-optical method) in the near field of lens horn antennas. To form a diaphragmed wave beam and simplify the calibration procedure, measurements are carried out using a round metal diaphragm in combination with a shielding chamber [2, 3]. Important features of the method proposed are the possibility of both heating the test sample to high temperatures and cooling the sample to low temperatures when measuring its radiophysical characteristics in a wide microwave bandwidth from 3 to 24 GHz. The experimental bench, implemented on the basis of this method, makes it possible to measure the following characteristics: the frequency dependences of reflection coefficient in the temperature range from -70 to +1200 °C, as well as the frequency dependences of transmission coefficient and complex dielectric permittivity at positive temperatures in the range +20…+1200 °C.

To demonstrate the capabilities of the developed method, samples of various materials, including those with known dielectric properties, were measured in a wide microwave frequency band, and the temperature dependences of their radiophysical characteristics up to +1200 °C are given. The results of studies of the temperature dependences of the reflection coefficient of magnetodielectric coatings deposited on metal substrates are also presented in a wide temperature range from -70 to +180 ºC.

It should be noted that the proposed method can be used not only to develop new materials with the required microwave properties, but also to obtain temperature dependences of dielectric properties, which is necessary for designing radio engineering structures from already created materials.

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## DYNAMICS OF CHARGE CARRIERS IN THZ PHOTOCONDUCTIVE ANTENNAS BASED ON SI-DOPED GAAS (111)A

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The planar photoconductive dipole antennas (PCAs) with 20 μm gap were fabricated by photolithography on the following photoconductive materials: GaAs:Si layer 0.86 μm thick grown by molecular beam epitaxy on GaAs (111)A substrate at 380 °C (sample # 1000), *i*-GaAs layer 1.01 μm thick grown on GaAs (100) and (111)A substrates at 240 °C (LTG-GaAs, samples # 27V). Samples 27V were annealed at a temperature of 560 °C for 30′ in an $As_4$ flow, sample 1000 wasn't annealed.

The lifetimes of the photoexcited carriers in LTG-GaAs and GaAs:Si were determined by pump-probe experiment, and then the mobility of the photocarriers was deduced from a combination of the *U-I* curves measured under pulsed optical excitation and previously estimated carrier lifetimes. The temporal behavior of the THz field transmitting from the sample pumping by femtosecond optical radiation pulses was investigated, and the measured curves were approximated by the formula

$$\frac{\Delta E_{\mathrm{THz}}}{E_{\mathrm{THz}}{}^{0}} = A_1 e^{-\frac{t}{\tau_1}} + A_2 e^{-\frac{t}{\tau_2}} + A_3 e^{-\frac{t}{\tau_3}}$$

where the magnitudes $A_1$, $A_2$, $A_3$ are the same order, therefore, three relaxation processes with time constants $\tau_1$, $\tau_2$, $\tau_3$ make the similar contributions in the total decreasing of photocarriers concentration. We suppose that, among all time constants, $\tau_2$ is the time of capture of photoelectrons by the traps, therefore $\tau_2$ is the lifetime of free electrons.

The *U-I* curves of PCAs were measured under optical pump power of 20 mW, $\lambda = 800$ nm. The shape of these curves indicates the presence of a rectifying transition — a Schottky barrier between the metal contact and the semiconductor in the samples # 27V (111)A and # 1000, whereas the contacts of sample 27V (100) are almost ohmic. The resistance of PCAs $R = U/\langle I \rangle$ can be estimated from the near linear part of the curve in the region of high voltages, the estimated values are shown in Table 1.

The free carrier mobility μ of the photoconductors can be determined according to [1] from the measured average photocurrent $\langle I \rangle$ and carrier lifetime $\tau_2$ by the relationship

$$\mu\tau_{\mathrm{eff.}} = \frac{\hbar\omega}{e} \cdot \frac{l^2}{\eta\langle P \rangle} \cdot \frac{\langle I \rangle}{U},$$

where ħω is the optical photon energy, *e* is the elementary charge, *l* is the length of the gap, $\langle P \rangle$ is the average optical power incident on the gap, *U* is the applied bias voltage, and η is the illumination efficiency, accounting for the fraction of incident light absorbed in the photoconductor, which for our case is taken to be 0.80, as in [1]. The deduced values of μ are shown in Table 1. The carrier mobility is low in samples grown at 240 °C due to high concentration of antisite defects, whereas the carrier mobility in samples grown at 380 °C is sufficiently higher. As a result, sample # 1000 has the optimal combination of properties for THz applications.

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Table 1. Relaxation times of photoexcited charge carriers,
resistance of PCAs, mobility of photoexcited charge carriers.

| Sample # | $\tau_1$, ps | $\tau_2$, ps | $\tau_3$, ps | *R*, kOhm | Mobility, cm²/(V·s) |
|---|---|---|---|---|---|
| 27 V (100) | 0.30 ± 0.01 | 3.0 ± 0.3 | 177 ± 20 | 746 | 170 ± 20 |
| 27 V (111)A | 0.52 ± 0.06 | 5.8 ± 0.8 | 166 ± 15 | 943 | 70 ± 10 |
| 1000 (111)A | 0.25 ± 0.03 | 2.7 ± 0.2 | 140 ± 5 | 35 | 4020 ± 30 |

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## RADIATION FROM A METASURFACE AS AN INSTRUMENT FOR ELECTRON BUNCH DIAGNOSTICS

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Radiation from electron bunches is usually used for diagnostics of its transverse sizes in accelerators and colliders including FELs and synchrotron injectors [1,2]. However, the methods of diagnostics continue to improve. There are some ideas on single-short diagnostics, or non-destructive diagnostics, or using new types of targets, among which metamaterials and photonic crystals seem to be attractive. In this report we suggest using incoherent transition radiation from two-periodical targets in order to define transversal sizes of the bunch. Usually the diagnostics is reduced to comparison the measured data to the theoretical one, which take in account the coherent effects [3,4]. The generally accepted approach to take into account coherence from electron bunches consists in multiplying the radiation intensity from one particle by the bunch form-factor, which takes into account its size, shape, and distribution of electrons. We show that in polarization radiation for a wide class of structures, such as photonic crystals and metasurfaces, this approach is incorrect [5,6]. We construct a theory of coherent and incoherent Smith-Purcell radiation and transition radiation from such structures and discuss its applicability to relativistic electron bunch diagnostics.

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### SUB-TERAHERTZ/TERAHERTZ ELECTRON RESONANCES IN HARD FERRIMAGNETS

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Intensive development of ultrafast electronics requires materials with high-frequency spin dynamics [1]. In this light, the insulators that possess the magnetization precession phenomenon due to magnetic anisotropy are dark horses. On the one hand, modern hard magnetic materials reveal quite moderate resonance frequencies of the ferromagnetic mode (generally, dozens of GHz) [2,3], which are lower than the frequencies of the antiferromagnetic resonances [4,5]; on the other hand, the research in this area is quite scanty, which implies a room for a breakthrough. Here, an example of a hard ferrimagnetic insulator (cobalt ferrite $CoFe_2O_4$) was obtained in the form of nanoparticles and bulk ceramics via high-temperature methods. Due to high magnetic anisotropy fields, the samples in a single domain state show broad hysteresis loops. The materials also possess intensive resonance absorption at frequencies higher than 0.20 THz in zero external magnetic fields. For the first time, natural ferromagnetic resonance (NFMR) frequencies higher than 0.30 THz were registered. The ceramic sample demonstrates the highest-known NFMR frequency of 0.35 THz. The model based on the Landau-Lifshitz equation was developed to explain the demonstrated magnetodynamic properties and shed a light on those of hard ferrimagnets in general. The practical utilization of the electron resonances in hard magnetic insulators including cobalt ferrite, Al-doped M-type hexaferrite, and epsilon iron oxide is discussed. Our findings reveal that these materials should provide several orders of magnitude more powerful spin pumping at sub-terahertz/terahertz frequencies compared to insulating antiferromagnets even under unpolarized irradiation and even in the absence of external magnetic fields. This opens new horizons for the development of practical ultrafast electronics.

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## HEXAFERRITE-BASED HARD MAGNETIC INSULATORS REVEALING GIANT COERCIVITY AND SUB-TERAHERTZ NATURAL FERROMAGNETIC RESONANCE OVER 5 — 300 K

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M-type hexaferrites are solid oxides with the general formula $MFe_{12}O_{19}$ (M = Ba, Sr, Pb). They exhibit hard magnetic properties at room temperature and contain available and low-cost elements. They are already used as materials for magnetic recording and considered to be an alternative for expensive rare-earth alloys (Nd-Fe-B, SmCo) due to a number of important advantages. First, they are insulators, therefore can be applied as hard-magnetic probes for magnetic force microscopy. Second, they are chemically and thermally more stable than metal alloys. Third, they absorb the electromagnetic radiation at frequencies up to 100 GHz, which is not inherent in metal alloys [1]. The magnetic properties of hexaferrites can be tuned via partial substitution of $Fe^{3+}$ ions. Recently, it was shown that single-domain high-Al-substituted hexaferrites can demonstrate giant coercivities (20 — 36 kOe) and sub-terahertz natural ferromagnetic resonance frequencies (160 — 250 GHz) at room temperature [2]. Natural ferromagnetic resonance frequencies, huge coercive forces, and the possibility of large-scale fabrication of these materials opens opportunities for them to be used in industry. For example, sub-THz detectors and other spintronic devices operating *via* spin pumping mechanism even in the absence of an applied magnetic field can be created on the basis of the hexaferrites, which is extremely in demand today [3]. However, to understand the potential applications of a material, it is important to know the dynamics of its properties with temperature.

Herein, we demonstrate a study of the magnetostatic properties and natural ferromagnetic resonance of single-domain hexaferrites with the following compounds $Sr_{1-x/12}Ca_{x/12}Fe_{12-x}Al_xO_{19}$ ($x$ = 1.5 — 5.5) in temperature range of 5 — 300 K.

The hexaferrite samples were synthesized *via* a citrate-nitrate auto-combustion method. According to X-ray powder diffraction (XRD) all samples are singe-phase and consist of M-type hexaferrite. We have investigated the dependence of natural ferromagnetic resonance frequencies and magnetostatic properties of Al-substituted single-domain hexaferrites on the temperature. Throughout the range of the measured temperatures 5 — 300 K all samples keep their hard magnetic properties and possess hysteresis loops typical of an ensemble of randomly oriented Stoner-Wohlfarth particles. The saturation magnetization ($M_S$) monotonously increases with a decrease in a temperature. The maximum of $H_C(T)$ shifts to the low temperature region. The NFMR frequency raises with an aluminum concentration and the maximum of $f_r(T)$ also shifts to low temperatures. The highest both coercivity of 42 kOe and natural ferromagnetic resonance frequency of 297 GHz were observed for $Sr_{0.54}Ca_{0.46}Fe_{6.5}Fe_{5.5}O_{19}$ sample at 180 K. The sample possess the highest NFMR frequency among all materials so far and the highest coercivity value among non-textured ferrites.

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## THZ RADIATION BY FREE ELECTRONS FROM 2D PHOTONIC CRYSTALS AND METASURFACES

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Terahertz radiation sources based on the radiation of electrons in external fields attracts the attention of researches due to the huge energy stored in relativistic electron beams. Even a little part of this energy, being radiated, makes it possible to produce powerful radiation in various parts of spectrum, including terahertz one, which is exploited in gyrotrons, magnetrons, orotrons etc. Besides its customary applications in powerful radiation sources and in non-destructive diagnostics of relativistic electron beams, the last decade SPR is intensively investigated for more exotic structures, like plasmonic crystals [1-3], graphene nanoscale gratings [4, 5], metasurfaces [6, 7]. These novel structures are widely investigated today due to their tunability, opportunity to tailor the properties of the surfaces, which results in developing novel modulators [8] and filters [9] — the key elements in applications of modern optics.

In this report we review briefly state of the art in this field of research, and present new results concerning radiation of relativistic electrons and their beams generated from arrays of small particles arranged into 2D flat structures [10-14]. We show that for such surfaces spatial distribution of radiation and its polarization differ drastically from those for conventional targets, and explore the way of focusing the radiation at arbitrary distances from the surface.

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## TERAHERTZ BIOPHOTONICS

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Over the past decade, biophotonics methods have found many clinical applications [1]. Various effects of the light–matter interactions in the UV, VIS, and IR ranges make it possible to solve complex problems of medical diagnostics, therapy, and surgery [2–5]. More recently, the capabilities of THz radiation in biomedicine have been discovered, which are mainly due to the strong sensitivity of THz waves to the content and state (free or bound) of tissue water [6]. This has been demonstrated in pilot applications of THz technology in the medical diagnosis of malignant and benign neoplasms [7] (e.g., basal cell and squamous cell carcinomas, dysplastic nevi and melanomas of the skin [8,9], tumors of the breast [10] and brain [11]), colon cancer [12], etc.), diabetes mellitus

[13,14] and obesity [15], traumatic injury and tissue viability [16,17], viral infections [18], as well as therapy for inflammatory diseases and cancers [19]. However, THz biophotonics is still an emerging field of research, with a number of problems preventing the translation of THz technologies into clinical practice, which are discussed in this talk and should be resolved in the future.

- The existing THz instruments remain rare, expensive, low-ergonomic for the clinical use [7], and it will take considerable time, research and engineering effort to mitigate this difficulty.
- As compared to the VIS–IR ranges, quite small amount of data is accumulated on the THz-wave interactions with healthy and pathologically-altered tissues. This problem should be addressed to objectively-uncover strength and weaknesses of THz methods.
- Resolution of common THz optical systems obeys the Abbe diffraction limit and usually as low as a few hundreds of microns or even a few millimeters [20]. Overcoming this limit is of crucial importance in THz medical spectroscopy and imaging.
- In contrast to the VIS and IR ranges, there is a luck of commercially-available THz waveguides, fibers, and endoscopes for spectroscopy and imaging of remote hard-to-access tissues [21–23]
- In fact, the depth of THz-wave penetration in tissues is limited by only a few hundreds (or even a few tens) of microns [7]. Improving the tissue probing depth by immersion or compression optical clearing techniques [1,2,24] seems to be very promising research topic.

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## TUNABLE TERAHERTZ AND INFRARED DEVICES BASED ON SN-DOPED $VO_2$

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Vanadium dioxide ($VO_2$) is considered one of the most promising smart thermal control materials due to its a unique multi-stimulus responsive Metal–Insulator temperature reversible phase Transition (MIT) accompanied by a structural phase transition (SPT) with striking changes of physical properties including optical, electrical and thermal properties, etc., making it ideal for smart windows, micro-bolometers, actuators, modulators, etc. Since the attractive performances of $VO_2$ are rooted in MIT behavior (coupled with SPT), element doping becomes a powerful tool in tailoring $VO_2$ performance. Oriented on the practical requirements, element-doped $VO_2$ is more promising and competitive in terms of performance, prospect, and cost. Here we focus specifically on Sn-doped $VO_2$, the recent progress and potential challenges of which are discussed. We devote attention to the crucial roles of Sn doping in modulating the properties and driving the practicality of $VO_2$ fims in terahertz and infrared band.

# STRONG THZ FIELDS AND NONLINEAR PHOTONICS

## FREQUENCY UPSHIFTING OF CHERENKOV-TYPE TERAHERTZ RADIATION BY FREE-CARRIER GENERATION IN LITHIUM NIOBATE

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We demonstrate experimentally that free carrier photogeneration can provide substantial spectral broadening to higher frequencies of the terahertz Cherenkov radiation produced by optical rectification of intense femtosecond laser pulses in electro-optic crystals. The effect is produced by electromagnetic emission from the carriers, accelerated by the rectified optical field, which interferes with the radiation generated by the nonlinear polarization.

The emission of Cherenkov radiation from femtosecond laser pulses propagating in nonlinear crystals, such as lithium niobate, has become an established way of terahertz generation [1]. Cherenkov optical-to-terahertz converters provide record-high conversion efficiencies (~1% [2]) with sub-mJ pump laser pulses. To generate strong terahertz fields, high pump intensities are required. Highly intense pump laser pulses experience multiphoton absorption which is accompanied by the generation of free carriers, which is commonly accepted to be detrimental to the conversion efficiency due to absorption of terahertz radiation by carriers. Recently, it was shown, however, that free carrier generation can lead to the appearance of low-frequency precursors ahead of the laser pulses in the collinear geometry of terahertz generation [3]. Here we demonstrate that free carrier generation can broaden the spectrum of the Cherenkov-type terahertz radiation to the higher frequencies.

In the experiment, a sandwich-like structure consisting of a Si prism and 0.5-mm-thick layer of $LiNbO_3$ was pumped by an amplified Ti: sapphire laser (800-nm wavelength, 300-fs pulse duration, up to 5-mJ pulse energy, and 1-kHz repetition rate). The laser beam was focused by a cylindrical lens to a 25-μm-wide line on the entrance face of the $LiNbO_3$ layer. Terahertz radiation emitted from the structure was measured by electro-optic sampling in a 1-mm-thick ZnTe crystal. Figure 1 shows the measured terahertz waveforms and their Fourier-transform spectra for the optical pump energies of 6, 12, and 18 μJ. The effect of spectral broadening is clearly visible.

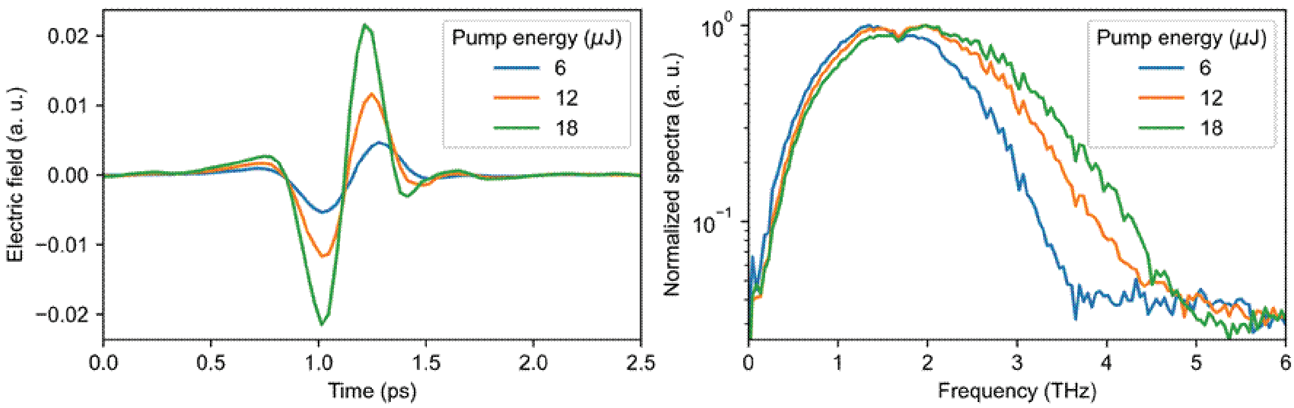


Fig. 1. Experimental waveforms and spectra for different pump energies.

This work was supported by the Russian Science Foundation (22-19-00371).

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# CORRELATION OF SELF-PHASE MODULATION AND TRIPLE FREQUENCIES GENERATION OF FEW-CYCLE THZ PULSES IN CUBIC NONLINEAR MEDIA

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High-intensity single-cycle terahertz (THz) pulses demonstrate unusual effects while propagating through cubic nonlinear media. In was experimentally [1] and theoretically demonstrated [2] that the interference of self-phase modulated radiation and radiation of third harmonics generation caused the appearing of new spectra maximum in the area of quadruple frequencies. Fig. 1 demonstrates the initial spectrum (green curve) at the medium input and spectral contribution of the phenomena of self-phase modulation (blue curve) and generation of triple frequencies (red curve) in the cubic nonlinear medium. The propagation distances of the order of the nonlinearity length which It was assumed smaller than the dispersion length and the diffraction length.

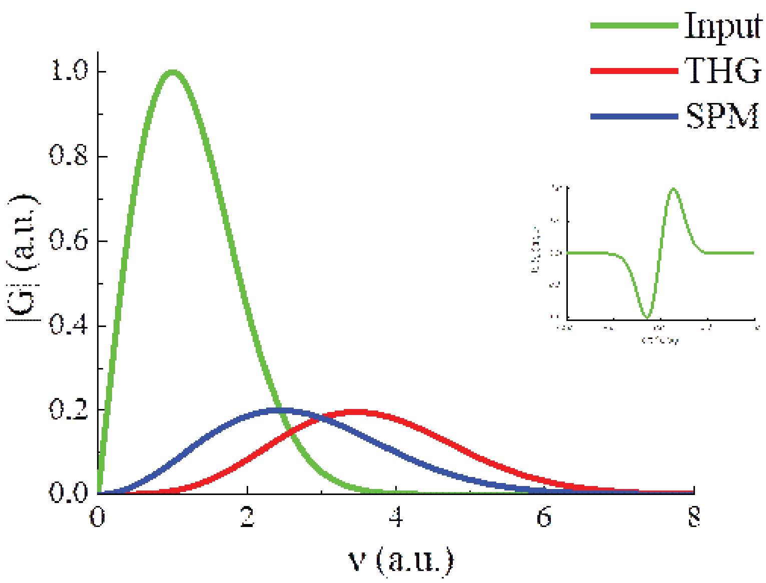


Fig. 1 — The spectrum of initial pulse and two components of cubic nonlinear response (self-phase modulation and generated third-harmonics radiation). Insert demonstrates the temporal representation of single-cycle pulse.

The correlation of self-phase modulation and triple frequencies generation can be described with the complex coherence coefficient:

$$\gamma = \frac{\int_{-\infty}^{\infty} G_1(\omega)\cdot G_2^*(\omega)d\omega}{\sqrt{\int_{-\infty}^{\infty} G_1(\omega)\cdot G_1^*(\omega)d\omega \cdot \int_{-\infty}^{\infty} G_2(\omega)\cdot G_2^*(\omega)d\omega}}$$

where $G_1(\omega)$ and $G_2(\omega)$ are spectral contributions of self-phase modulation and third harmonics radiation . The calculated result is a real value since both components have similar complex phase, and coefficient depends on both spectra and their complex conjugate form. The values of complex coherence coefficients were calculated for pulses with different duration. The modulus of this values equals to 0.85 for single-cycle pulse, 0.61 for 1.5-cycle pulse and 0.11 for 2-cycle pulse.

Finally, it is demontsrated that increase in the number of oscillations leads to the decrease of complex coherence coefficient. The pulse with one full oscillation experiences unusual effects in a process of propagation through cubic nonlinear media and the increase in number of oscillations causes fast disappearance of these phenomena.

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# INVESTIGATION OF THZ WAVES GENERATION FROM NANO- AND MICROSCALE TARGETS IRRADIATED WITH FEMTOSECOND LASER PULSES

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Past years, a huge number of researches has been provided in the way of study of high intensity laser radiation to matter interaction aimed on elaborate multi-spectral pulsed radiation source on the base of laser induced plasma. In particularly, clustered gas jets with inherent high local and relatively low average density of matter, and single micro-size droplets have been applied as laser target for generation of radiation in a wide spectral range from X-ray through deep-UV to THz, as well as for generation of flow of fast charged particles [1-3].

Here we present and discuss a recent results on investigation of THz waves generation from nano- and microscale targets irradiated with femtosecond laser pulses, which is a continuation of our experiments on studies of interaction of high intensive short laser pulses with nano-cluster gas jet and free-falling single microdroplets started a few years ago [4,5]. Both types of laser targets have been examined to generate THz and X-ray radiation under the same optical excitation with sub-TW laser systems. We compare and discuss results of studies on THz generation from Ar gas-cluster jet and from single free-falling microdroplet made of liquid metal. For instance, in Figs. 1 and 2 one may notice a significant difference in the THz radiation patterns measured for these two cases. We believe that observed behavior of the THz radiation patterns could be attributed to an interference of contributions from the dipole and quadrupole currents, and for the second case the presence of opaque "thick" droplet which could lead to effective decreasing of forwardly directed contribution into the THz signal should be taken into account as well.

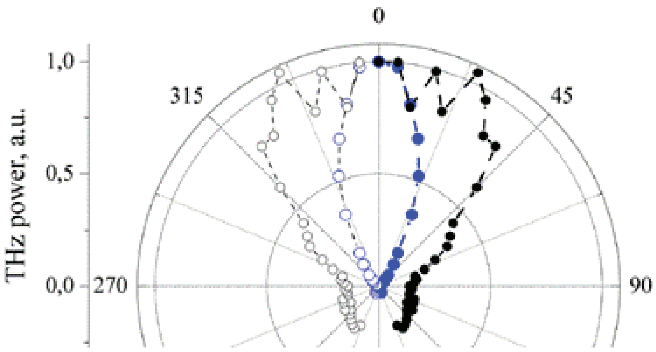


Fig. 1. Dependence of the THz signal from clustered Ar plasma on the detection angle relative to laser beam propagation direction (0 degrees). Black/blue symbols correspond to laser focusing at a distance of 1.5/13.5 mm below the nozzle outlet.

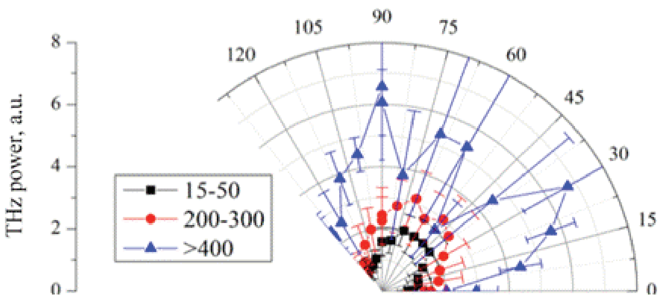


Fig. 2. Dependence of the THz signal from 50 μm diameter microdroplet on the detection angle relative to laser beam propagation direction (0 degrees) and the energy ranges of X-ray photons (15-50, 200-300 and >400 in arbitrary units).

This work was funded partly by RFBR and ROSATOM according to the research project № 20-21-00143, partly by the Ministry of Science and Higher Education within the State assignment FSRC "Crystallography and Photonics" RAS and in part by the Ministry of Science and Higher Education of the Russian Federation in framework of Agreement № 075-15-2022-830 from 27 May 2022.

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# MULTI-CYCLE COHERENT TERAHERTZ EMISSION PRODUCED DUE TO LINEAR CONVERSION OF LASER WAKEFIELDS ON A HARMONIC MODULATION OF PLASMA DENSITY

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Sources of tunable coherent terahertz (THz) radiation capable of producing pulses with high electric fields (~1 MV/cm) and high energies (> 1 mJ) are presently demanded in a number of scientific and practical applications. High-power THz radiation opens new possibilities in control and manipulation of different nonequilibrium states of matter, in wakefield acceleration, as well as in location and security systems. Plasma based radiation sources are able to produce electromagnetic emission of high intensity with amplitudes significantly exceeding typical destruction threshold of solid matters. Nonlinear properties of plasma allow one to realize down-conversion of high-frequency laser radiation to low-frequency terahertz radiation near the plasma frequency $\omega_p = (4\pi n_0 e^2/m_e)^{1/2}$, where $n_0$ is the unperturbed plasma density, e and $m_e$ — the charge and mass of an electron. A long-lived plasma wake can be linearly converted on a small-amplitude periodic ion density perturbation at the appropriate period into a superluminal satellite capable of matching in phase with vacuum electromagnetic waves. Due to the dependence on plasma density, varying a value of $n_0$ allows one to easily change the radiation frequency in a wide range, thereby covering most of the THz band.

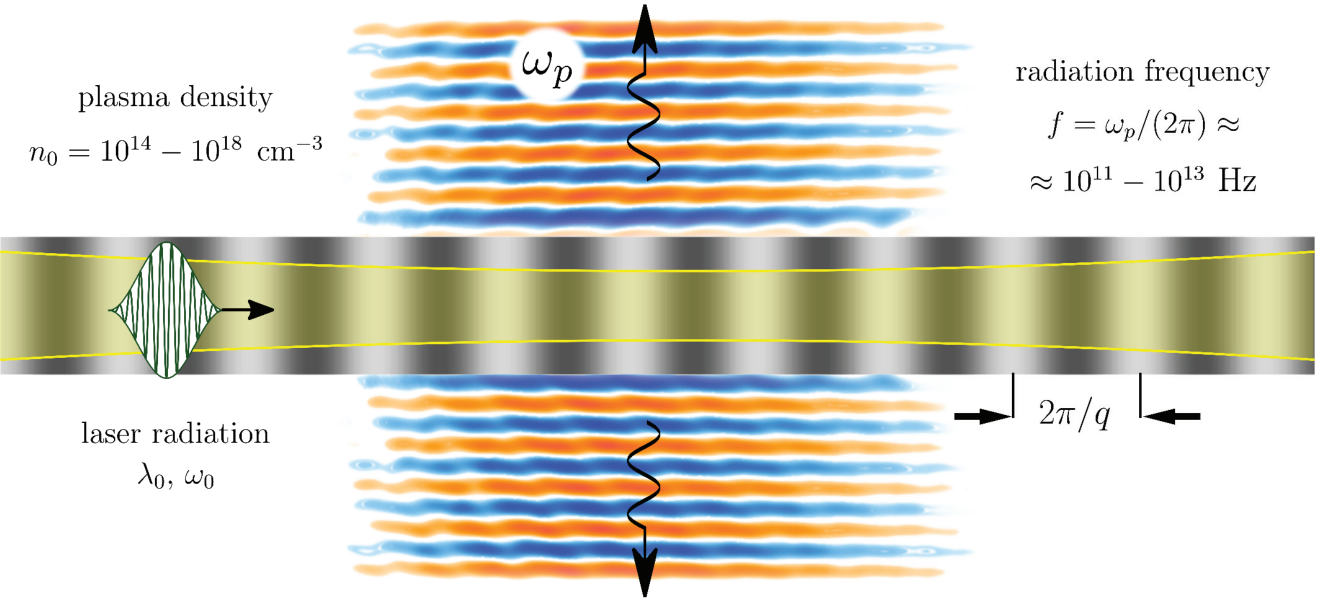


Fig. 1. The problem statement illustration.

It has been shown [1] theoretically that coherent THz radiation with a narrow line-width can be efficiently generated in a finite-size plasma channel that is uniform in the transverse direction and has a longitudinal density modulation with the period being equal to the wavelength of excited plasma wave. In such a scheme, there is no need in laser guiding, since the diffracting laser driver generates equally intensive electromagnetic radiation along the distance comparable with 5-10 Rayleigh lengths.

Moreover, electromagnetic waves produced at the cut-off frequency can almost freely escape from a relatively thick plasma (~ 20 $c/\omega_p$) due to electromagnetic diffusion which, in the presence of long-time pumping, amplifies the radiation amplitude. These effects are reproduced in simulations using particle-in-cell method with well agreement with an analytical theory**.** According to theoretical estimations, the total efficiency of narrow-band electromagnetic radiation at the plasma frequency lying in the THz range enables to exceed 0.3 %.

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## THZ RADIATION GENERATION IN THE INTERACTION OF RELATIVISTIC LASER PULSE WITH TW TO PW PEAK POWER WITH DENSE PLASMA

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The generation of THz radiation during the interaction of laser pulses of relativistic intensity with matter is currently under active investigation [1]. Despite the large number of THz radiation sources, and, in particular, laser-plasma sources [2], the relativistic laser-plasma interaction is uniquely positioned due to the fundamental absence of the saturation effect. This, in theory, opens up the possibility of obtaining THz radiation pulses with extremely high energies. The maximum experimentally achieved efficiency of conversion of laser radiation to THz was achieved in [3] and amounted to ~1%. At the moment, a large number of mechanisms for generating THz radiation in relativistic laser-plasma interaction [1] are considered, the most discussed mechanism being coherent transition radiation (CTR). When using a beam with the number of particles N for wavelengths λ>>L, where L is the characteristic spatial size of the beam, the coherence condition will be satisfied and the radiation power in a selected solid angle will increase as $\sim N^2$. A similar dependence is also observed by another mechanism — sheath radiation (i.e. radiation of an accelerated dipole with charge Q formed by accelerated electrons and ions moving behind them) where the radiation power is $\sim Q^2$ [3]. Therefore, to increase the energy of THz radiation generated in the relativistic laser-plasma interaction, it is necessary to accelerate a large number of particles, i.e. increase the beam charge.

In this work we used a tape solid target (preionized by an additional prepulse) and a 1 TW laser system to experimentally generate an electron beam with relatively high charge (up to 0.1 nC for energies >1 MeV) and a good collimation (~0.1 rad). The main acceleration mechanism was found to be direct laser acceleration (DLA) and the conversion efficiency reached 1–2 nC/J [4]. The properties of THz radiation generated in this interaction were studied and the main mechanism of its generation was shown to be CTR [5]. Experimentally observed THz radiation properties are in agreement with ones calculated analytically using measured beam parameters. A series of numerical particle-in-cell simulations were also made to expand the observed type of interaction to more powerful laser systems (up to 15 PW peak power). The estimated field strength of the THz source could reach is $\sim 1a_0$ THz, and the energy is up to units of J, which, when focusing, will make it possible to achieve relativistic intensities in the THz range.

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## MATERIALS FOR ULTRAFAST TERAHERTZ PHOTONICS: VIBRATIONAL NONLINEARITY PREDOMINANCE

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Recent investigations have predicted and proved the existence of giant and low-inertia nonlinearity specific to a number of materials in the terahertz (THz) spectral range.

That discovery has made possible the design of ultrafast THz photonics devices. To gain the highest efficiency such devices require the biggest nonlinear refractive index coefficient $n_2$ and the lowest settling time of the nonlinear response τ in the THz range. In this research, we analytically show that the ratio $n_2/\tau$ is determined by the square of the medium thermal expansion coefficient and the fifth power of its dominative stretching vibrational mode frequency. $n_2/\tau$ evaluation indicates that for some liquids and crystals in the THz range the efficiency of the vibrational nonlinearity tends to predominate over almost all nonlinearity mechanisms in the various spectral ranges. We demonstrate that alpha–pinene has the record value of the $n_2/\tau$ to be about $10^6$ cm$^2$/J.

For the vibrational nonlinearity mechanism, we derived the ratio of the nonlinear refractive index coefficient $n_2$ to the inertial (or settling) time of nonlinear response τ using the analytical model describing the vibrational polarization response dynamics of the isotropic dielectric media to incident THz radiation, which is shown in [1, 2]. Then we determined the values of $n_2/\tau$ for the respective liquid water and α-pinene; $LiNbO_3$, NaCl, and KCl crystals using the following expression:

$$\frac{n_2}{\tau} = 10.46 \cdot 10^{26} \frac{m^2 a_l^2}{q^2 N^2 n_0^2} \frac{\alpha_T^2 \omega_0^6}{\sqrt{\omega_0^2 - 4\gamma^2}} \left(n_{0,\nu}^2 - 1\right)^3 \qquad (1)$$

where $m$ is the effective mass of the vibrational unit; $a_l$ is the molecular diameter (for liquids) or lattice constant (for solid media), $\alpha_T$ is the thermal expansion coefficient, $\omega_0$ is the central frequency of the dominative stretching vibrational bond, $n_{0,v}$ is the vibrational contribution to the low-frequency refractive index, $q$ is the effective charge of the vibrational bond, $N$ is the number density of vibrational units, $n_0$ is the linear low-frequency refractive index, and γ is the dumping coefficient.

Fig. 1 shows the comparison of $n_2$ and τ values for different nonlinearity mechanisms in various spectral ranges. It is clearly seen that the vibrational nonlinearity in the THz range is almost the most effective one. Analyzing our calculations for the aforementioned materials we deduced that α-pinene has the biggest $n_2/\tau$ value compared with all studied materials in the THz range, namely $5\times10^6$ cm$^2$/J.

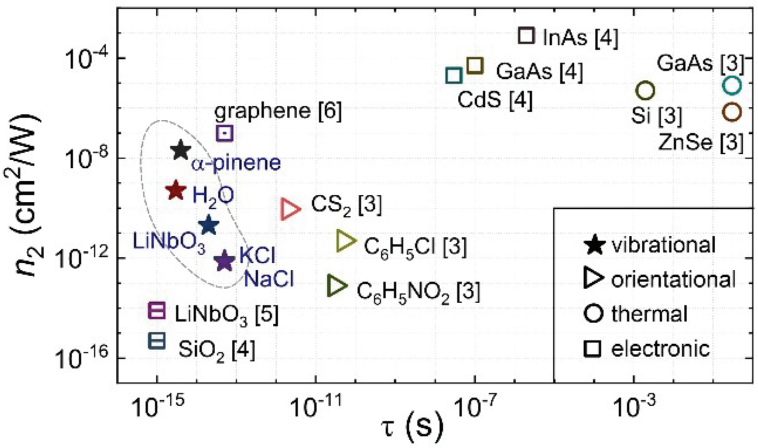


Fig. 1. The comparison of the nonlinear refractive index coefficient $n_2$ and the settling time of nonlinear response τ values for different nonlinearity mechanisms in various spectral ranges of several media. The results of this work for the vibrational nonlinearity case in the THz range are represented by the star symbols.

This work was supported by the Ministry of Science and Education of the Russian Federation (2019-0903).

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# DOMINATION OF CUBIC NONLINEAR EFFECTS OVER QUADRATIC ONES IN THE THZ SPECTRAL RANGE

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Large amount of recent experimental studies has reported about giant and low-inertia refractive index for group of materials in the THz spectral range. This phenomenon was earlier predicted and described by the theory of vibrational nature polarization nonlinear response to incident THz radiation. In the current study, using the same theory we deduced appearance of cubic nonlinear effects domination over quadratic ones for some materials in THz electric field during increase of radiation intensity. Considering this theoretical prediction, we conducted an experiment, where we propagated THz single–cycle pulse of intensity near $10^8$ W/cm$^2$ through MgO:LiNbO$_3$ crystal. The experiment revealed disappearing of quadratic nonlinear effects while cubic ones were still observed. Hence, we claim that in materials with giant vibrational nonlinearity in the THz spectral range cubic nonlinear effects can be superior to quadratic ones during medium interaction with the field of pulse THz radiation.

According to the theory of vibrational nonlinearity [1,2], the ratio of cubic and quadratic non-resonant nonlinear responses at the frequencies 3ω and 2ω, respectively, for an isotropic dielectric media in the THz radiation field can be represented as

$$P_{3\omega}^{(3)} / P_{2\omega}^{(2)} = \chi^{(3)} E_\omega / 4\chi^{(2)}, \quad (1)$$

where $E_\omega$ is the amplitude of THz pulse at the frequency ω, $\chi^{(3)} = qN\alpha^3(2a^2/\omega_0^2 - b)/\omega_0^8$ and $\chi^{(2)} = - qNa\alpha^2/2\omega_0^6$ are cubic and quadratic non-resonant nonlinear susceptibilities, respectively. Here $q$ is the effective charge of the chemical bond, $N$ is the number density of vibrational units, α is the polarizability, $a$ and $b$ are the coefficients characterizing quadratic and cubic anharmonicity of local molecular oscillations, respectively, $\omega_0$ is the dominational stretching bond central frequency.

Numerical evaluations of equation (1) for LiNbO$_3$ showed that cubic nonlinear effects become dominant to the quadratic ones at the intensities over $10^7$ W/cm$^2$. To check this statement our group conducted the experiment: we propagated THz single-cycle pulse with central frequency at 0.75 THz and intensity near $10^8$ W/cm$^2$ through 1 mm MgO:LiNbO$_3$ crystal. Fig. 1 illustrates obtained experimental results. Besides the effect radiation shift from triple to quadruple frequency, which was described in [3], we observe disappearance of the twice frequencies in the experiment, while triple ones are detected. That result matches well with our theoretical prediction.

This work was supported by the Ministry of Science and Education of the Russian Federation (2019-0903).

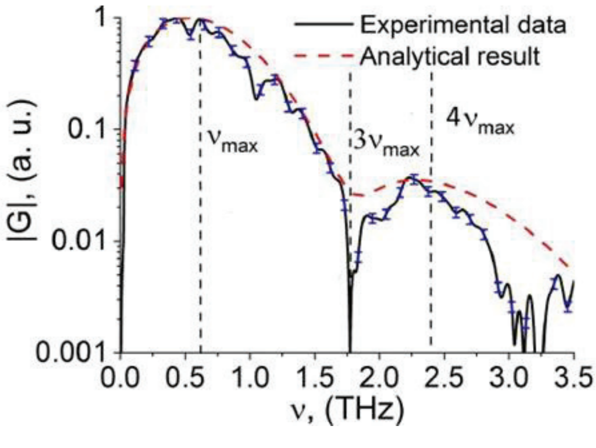


Fig. 1 Frequency spectrum for the THz single-pulse electric field of intensity near $10^8$ W/cm$^2$ obtained after propagating through 1 mm MgO: LiNbO3 crystal. Black solid curve illustrates experimental data, red dash curve represents theoretical estimations. [3].

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# TERAHERTZ LASING IN THE CAVITY WITH GRAPHENE HYPERBOLIC MEDIUM

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Complex resonator with thin hyperbolic media inside is investigated in the way of developing theory of THz laser. We studied in detail the processes of wave propagation in a complex cavity with thin hyperbolic media (HM) inside. We employ asymmetrical hyperbolic medium (AHM) based on graphene-semiconductor multilayer structure with optics axis tilted with respect to outer boundary as an active media Fig.1 (a) [1].

The transverse permittivity of the AHM with saturation is given as follow

$$\varepsilon_{\perp} = \varepsilon_{\parallel} + \frac{i}{d\omega\varepsilon_0}\left[\sigma'(\omega, E_0) + i\sigma''(\omega, E_0)\right]$$

where $\omega$ is the angular frequency, $d$ is the period of the AHMM, $E_0$ is a component of the external electric strength vector transverse to the graphene plane, $\varepsilon_0$ is the vacuum permittivity, and $\sigma(\omega, E_0)$ is the surface conductivity of graphene. THz wave emission in the cavity was investigated numerically using transfer matrix method [1,2]. Total transfer matrix of one period of the structure $P_t = P_0(l)P(h)$, where $l$ is total length of air gap in resonator; $h$ is thickness of AHMM. Due to the linearity of the eigenvalues problem at a given $E_0$ the eigenvalues of the entire transfer matrix $P_t$ are $\Lambda_i = e^{(i\varkappa i L)}$, where $\varkappa_i = \ln \Lambda_i$ characterizes the phase delay at one pass ($L = l + h$). The frequency of oscillation and field intensity proportional to $E_0$ are the solutions of the equations Re($\varkappa_i(k_z,E)$)=0, Im($\varkappa_i(k_z,E)$)=0. These equations may be solved numerically to find $k_{z0}$ and $E_0$. The eigen waves of the cavity have been calculated for different values of the period AHM $d$ and have shown on the Fig.1 (b). We have shown the existence of amplification of the THz waves in such structure [1]. We estimated the gain saturation effect and have shown that the gain saturation arises at the electric field strength about $2.7 \cdot 10^{12}$ V/m. The intensity of THz radiation and the frequencies of oscillations have been calculated using recursive procedure.

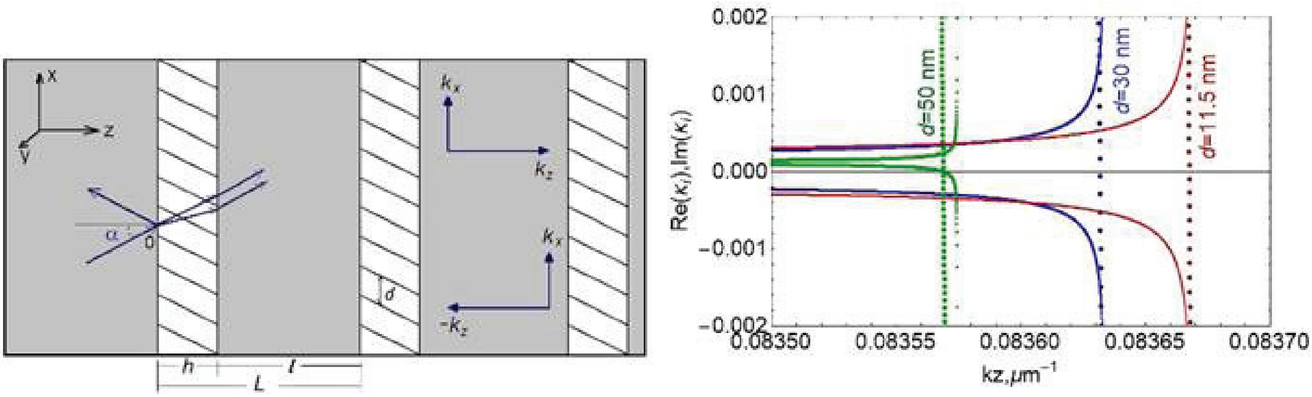


Fig.1 (a) A cavity partially filled with AHMM slab (white rectangle, planes symbolized graphene sheets). (b) Real (dotted curve) and imaginary (solid curve) parts of eigenvalues of the extraordinary wave $\kappa_i$ vs $k_z$ for one of extraordinary wave. $L$=1320μm, $h$=5μm. Euler angles j=p/2, θ= 55°, incidence angle a=15°; EF = 25 meV,t = 10-12 c, T = 300º K.

The optimal conditions for efficient THz lasing were clarified. The parameters of AHM were carefully analyzed to find ones providing the maximal gain of the THz radiation. The radiation incidence angle on processes taking place in the resonator containing AHM taken into account and was defined similarly to the Brewster angle for an active medium of a laser cavity to reduce the reflection from AHM. Selection of the incidence angle has been done simultaneously with choosing of other parameters of the complex resonator. The region of frequencies where considered AHM possess hyperbolic properties and amplification properties simultaneously was determined for different values of the AHM period. The emission band width was estimated based on numerical simulation and is $\Delta f \approx 0.00455$ THz.

This work was carried out at IREE RAS within the framework of the state task.

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# TERAHERTZ RADIATION FROM FEMTOSECOND PLASMA CHANNELS IN DUAL-COLOR, DC-BIASED AND TRANSITION REGIMES

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Conical directional diagram of terahertz radiation from a single-color filament becomes on-axis as the electrostatic field increases above 3.2kV/cm and frequency is upto 1THz. Without biasing, transition from dipole to quadrupole radiation source is investigated.

Over the past years, research and development of THz science and technology have demonstrated its broad application prospects in non-invasive imaging [1], medical diagnosis [2], spectroscopy applications [3] etc. Such applications increase the demand for highly efficient THz sources and detection systems. The most efficient way to generate broadband THz radiation in air is a two-color (ω–2ω) filamentation [4, 5]. To optimize conversion efficiency from such a two-color source with a conical directional diagram [6], one should take care of the collection aperture as well as ω–2ω phase adjustment [7]. At the same time, the THz radiation source based on the plasma channel biased by external electrostatic field (i.e. a single-color DC-biased filament) is free of the tedious ω–2ω pulse delay adjustment [8]. Besides, the directional diagram of THz radiation from the DC-biased plasma channel is characterized by the on-axis maximum [9]. The decrease of the conversion efficiency in a single-color filament as compared with the two-color one is compensated by the unlimited energy scalability when using terawatt peak power femtosecond laser sources producing multiple plasma channels [10].

In this work, we study THz generation during filamentation in the external electrostatic field (DC-biased single-color filamentation) [11, 12]. Directional diagram, frequency content, threshold of the external electrostatic field, providing for the transition from the conical to the on-axis THz emission, are studied experimentally using 744 nm single-color plasma channel and simulated based on the unidirectional pulse propagation equation ensuring frequency content from 0.01 THz to 3 PHz and angular divergence till 60°. Special consideration is given to the transition from the light pressure dipole radiation source at sub-THz frequencies to quadrupole source at higher frequencies in the unbiased plasma channel (filament) regime. This transition is observed in the measured 2D frequency-resolved far-field distributions of THz emission, which evolves from the conical one at 0.1–0.5 THz to the two-lobe one at higher frequencies [13].

In the experiment [11] with the DC field of $E_{DC}$ = 10 kV/cm we focused the laser pulse (744 nm, 0.5 mJ, 90 fs) into the air gap between the plane electrodes. At the selected by the THz narrowband filters frequencies $v$ below 1 THz, a wide flat-top angular distribution was measured by a bolometer (Fig. 1). The simulations showed the transition of THz directional diagram from the flat-top to the conical one for $v$ > 8 THz due to the destructive interference of THz waves from the ionization front propagating with the superluminal velocity. At lower DC fields, the transition from conical to on-axis emission was observed (Fig. 2) [12]. The balance of DC source term, which provides the on-axis maximum, and quadrupole source term, which appears due to plasma oscillations in unbiased filament, is attained at (3.2 ± 0.8) kV/cm. This follows from the fits of the measured data by the interference model with transverse quadrupole and external electrostatic field induced dipole sources, with geometry of the filament taken into account.

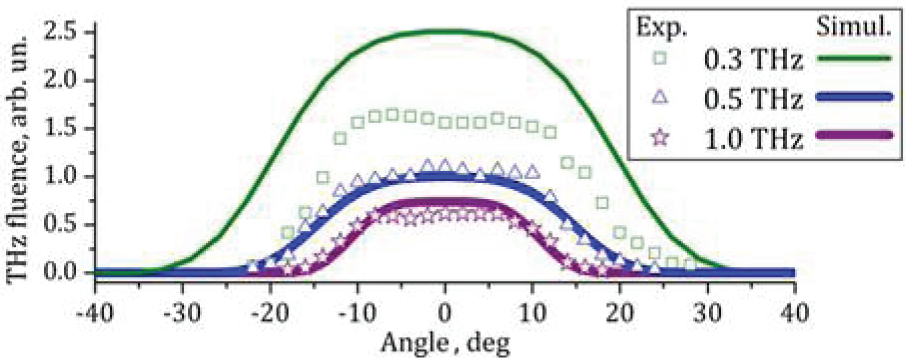


**Fig. 1.** Angular distributions of THz fluence obtained for three frequencies in the experiment (symbols) and simulations based on unidirectional pulse propagation equation (UPPE) [14] (lines).

Without a DC field, our measurements of spectrally resolved 2D directional diagrams of THz emission from a single-color filament reveal that they evolve from conical shape in the sub-THz range to the two-lobe pattern at 1 THz and higher frequencies. Such variation of THz angular distributions with frequency cannot be described by a unique THz source such as the light pressure force, which induces the longitudinal dipole momentum, or the ponderomotive force, which initiates the transverse quadrupole one. We developed a model taking into account both these forces acting on the electron. The dipole- and quadrupole-induced THz fields are proportional to the squared and the cubed electromagnetic radiation frequency, respectively. This difference in scaling laws for dipole and quadrupole THz sources explains the transition from the conical axially symmetrical distribution at 0.1–0.5 THz to the two-lobe one at higher frequencies.

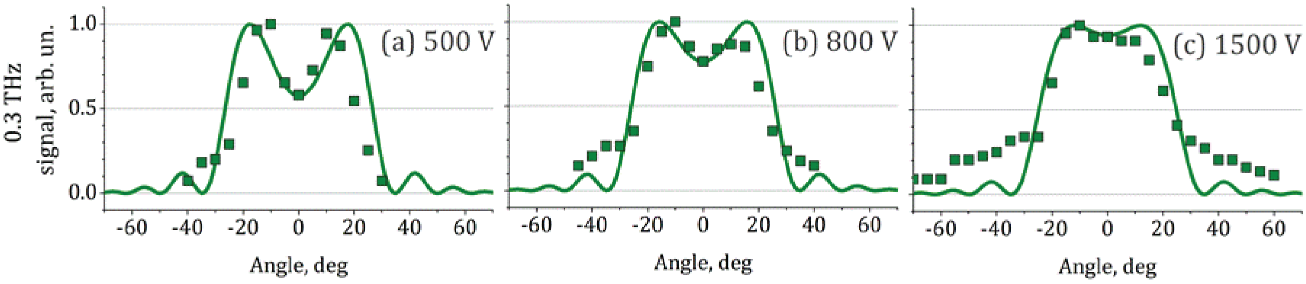


**Fig. 2.** Angular distributions of THz fluence at 0.3 THz obtained for three voltages of external electrostatic field in the experiment (symbols). Their respective fits by the interference model (lines).

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## POINT-LIKE PLASMA-LIMITED HIGH-TEMPERATURE THZ LASER DISCHARGE

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A continuous equilibrium point laser discharge in the form of a ball 1mm in diameter with a plasma density of $4.5{\cdot}10^{17}$ cm$^{-3}$ and a temperature inside the ball of 4.0-4.5 eV (46000-52000 °K) was obtained at the Novosibirsk Free Electron Laser (NovoFEL). The ways of increasing the plasma parameters and its potential application as a source of VUV radiation are considered.

The terahertz radiation range is optimal for obtaining a high-temperature discharge in gases at pressures close to atmospheric. Such a thermodynamically equilibrium discharge, upon reaching a temperature ~ 10-12 eV, can be an alternative to non-equilibrium pulsed systems for obtaining VUV radiation. Its main advantages are the continuity and stability of the VUV radiation. The NovoFEL is now the only terahertz source in the world capable of maintaining such quasi-continuous laser discharge. However, in addition to the appropriate power, to obtain a high-temperature discharge, special methods are required to reduce the plasma volume and correspondingly increase the power density input into the plasma. To conduct such studies, a special user station was created at the NovoFEL [1,2].

Without special measures, a terahertz laser discharge in inert gases (Ar, Kr, Xe) on the NovoFEL at average power of 200-300 W has the form of a dazzlingly bright ball about 1 cm in diameter. Moreover, the plasma temperature is quite low (~1 eV) and practically does not depend on the laser power (only the size of the plasma ball changes).

To reduce the plasma volume and increase its temperature, three methods were tested: a discharge in a stagnant inert gas (Ar, Kr) with the addition of $N_2$, a discharge in a gas jet (Ar+$N_2$, Kr+$N_2$) near the radiation focus into the atmosphere of the gases, and a discharge in a jet of pure inert gas into forevacuum atmosphere.

To obtain VUV radiation, the third method is optimal. But due to the problems of directed gas injection in the case of a highly rarefied atmosphere, the best plasma parameters listed above were obtained now in the second method.

At present, special methods of gas injection in the form of two-component jets are being developed, and work is also underway to increase the average NovoFEL power by operating at double and quadruple frequency of its output terahertz pulses.

The study was supported by a grant of the Russian Science Foundation (project No 19-72-20166).

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## INVESTIGATION OF TEMPERATURE DEPENDENT WATER NONLINEAR INDEX IN THZ FREQUENCY RANGE

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In recent years the nonlinear terahertz (THz) photonics applications have significantly grown due to investigation of high-intensity THz radiation sources and elaboration of THz radiation propagation theory: spectroscopy, communications, non-destructive evaluation, light-control devices etc. Basing on theory of vibrational nonlinearity in THz range it was shown that nonlinear refractive index for various materials in the THz frequency range exceeds the ones in both visible and NIR ranges by several orders of magnitude [1] — these results were proven experimentally by various groups [2, 3].

In this study, we demonstrate the direct measurement of the water nonlinear refractive index for broadband pulsed THz radiation with the conventional z-scan method at different temperature varying from 14°C to 21°C. We show that obtained experimental data matches well with analytical dependence of nonlinear refractive index on temperature (Figure 1). These results are new and significant confirmation of the vibrational nature of the refractive index giant low-inertia nonlinearity of liquids in the THz range. A distinctive feature of the experiment was the use of a liquid jet rather than a cell, which makes it possible to avoid the cumulative thermal effect that can affect the nonlinearity. Since the measurements of the nonlinear characteristic of water were carried out using the jet, each subsequent THz pulse interact with a new region of the water jet, therefore, the inertia of the nonlinearity mechanism did not exceed 1 ps. This work is of great importance for future development of the self-controlled radiation photonics systems, nonlinear switches, modulators, and systems requiring control of different materials nonlinear properties in the terahertz frequency range.

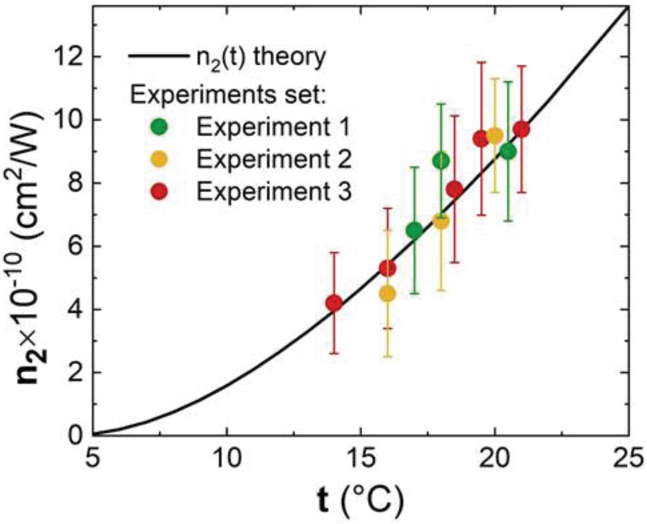


Fig. 1. Nonlinear refractive index $n_2$ dependence on water temperature (theoretical dependance [1] shown with black curve and experimental z-scan measurements shown with colored dots).

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## CONTROLLING THE POLARIZATION OF THZ RADIATION IN SPINTRONIC EMITTERS

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Analogously to common (near-visible) optics, THz optics requires a set of THz optical elements to generate, manipulate, and detect THz radiation. Spintronic THz emitters prove to be indispensable in their characteristics due to the width of the generated spectrum (0.5–10 THz) and compactness [1]. A very important task in operating THz radiation is to control its polarization. At present, for this task, THz quartz wave plates are used. However, the absorption of quartz is quite strong in the THz range, particularly for frequencies higher than 3 THz In addition to unwanted losses, this means that the THz radiation transmitted through the half-wave plate intrinsically has an irreducible elliptical polarization component. An efficient way to control polarization is provided by spintronic emitters. They allow for control of the polarization directly during THz generation: switch the phase, rotate the polarization, or even adjust the polarization in a more sophisticated way. Since the polarization of the terahertz wave is perpendicular to the magnetization of the spintronic emitter, the magnetization should be rotated to rotate the polarization. Initially, the idea of mechanical rotation of a magnet around the emitter was proposed.

We suggested the THz emitter, which rotated the polarization by simply increasing-decreasing the current in the electromagnet [2]; the operation is based on a spin-reorientation phase transition in magnetic nanostructures. The current trend, driven by the requirements for energy efficiency and compactness of devices, is to replace current-controlled systems with voltage-controlled ones. The use of a composite multiferroic is a way to combine the advantages of spintronic THz emission and voltage control.

Here we report on electric field control over the magnetization direction and, therefore, on the control over the THz-wave polarization without changing the THz-pulse amplitude. We propose a technique for the experimental determination of the strain-induced parameter, VS, which is responsible for magnetoelectric control of THz polarization. We establish a fundamental relationship between the applied electric voltage and the angle of reorientation of the magnetic anisotropy axis caused by the magnetoelectric effect. It allows us to directly measure (without any fitting or use of unknown material characteristics) the magnetoelectric parameter of THz polarization and to control the magnetization with an electric field. For the studied $TbCo_2$/FeCo/PMNPT structure, the measured value of the magnetoelectric parameter is equal to VS =0.07 for an electric field of 0.2 MV/m.

At present, the main problem of controlled spintronic emitters is their efficiency, The most efficient structure for THz generation so far is reported is based on Co/Pt structures (three-layered is more efficient than two-layerd), but no control over them is reported so far. In contrast, $TbCo_2$/FeCo reveals very efficient control, but lower efficiency. The ways of inproving the situation will be discussed here as well.

The work was supported by, Ministry of Science and Education (Project No. 075-15-2022-1131).

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## OBSERVATION OF CONICAL EMISSION FROM DC-BIASED FILAMENT AT 10 THZ

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Femtosecond filament in the external electrostatic field (DC-biased filament) is a prominent source of terahertz (THz) radiation [1]. As the external field grows above ~3 kV/cm [2], the directional diagram of the THz emission from a DC-biased filament in air is unimodal with the maximum on the laser beam axis. This was confirmed by numerous experiments and numerous registration techniques, either narrowband detection [2], wideband detection [3, 4], or spectrally resolved [5, 6]. The excellent directionality of THz emission from DC-biased filament makes this THz source a promising tool for the measurements of low ($10^{13}$–$10^{15}$ $cm^{-3}$) densities of free electrons [7]. The measurements of THz directional diagrams [2–6] were done in the low-frequency range below 2–3 THz. However, 3*D* + time simulations of THz generation in DC-biased filament performed in our recent work [6] predicted the appearance of THz conical emission in high-frequency THz range (for our 90-fs pulse at ~10 THz). In this work, we confirm this prediction experimentally.

In our experiment, we focused the 740-nm, 90-fs, 1.8-mJ pulse into the air gap between the electrodes biased by 15-kV/cm static electric field. The plasma filament between the electrodes was a source of THz radiation detected by a superconducting MoRe bolometer Scontel RS-CCR-1-12T-1+0.3-3T-0.1 sensitive in the spectral range of 0.3–10 THz. T

he bolometer with the bandpass filters (centered at the frequencies $v$=0.5, 1, 3 and 10 THz) was fixed on the 40-cm-long horizontal board and rotated at the horizontal angle $\alpha$ around the vertical axis. The spherical mirror was fixed on the vertical 40-cm post. To vary the vertical angle $\beta$, we moved the focusing mirror along the post. So, the variation of the angles $\alpha$ and $\beta$ allowed us to reconstruct the 2*D* distributions of the THz fluence $F(\alpha, \beta)$ at the frequency $v$ determined by the bandpass filter. We traced experimentally the transit from the on-axis unimodal angular distribution at 0.5–1 THz to the conical one at 10 THz, see Fig. 1.

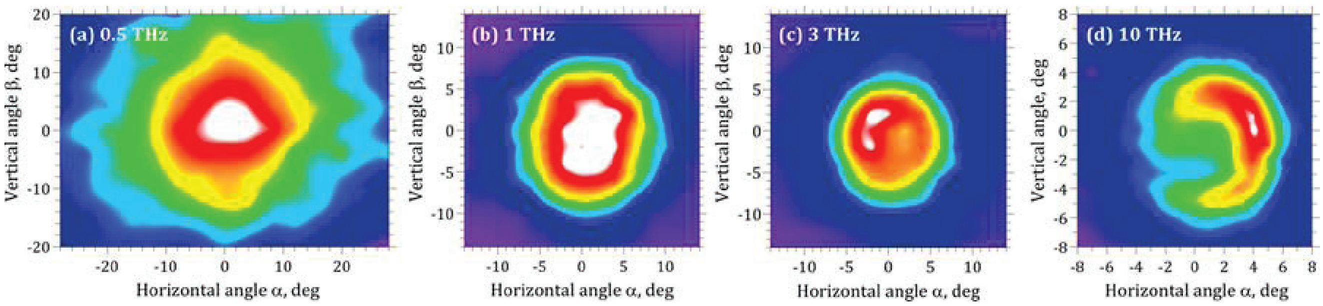


Fig. 1. 2D distributions of the fluence F(α, β) measured at frequencies (a) $v$= 0.5 THz, (b) 1 THz, (c) 3 THz, (d) 10 THz.

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## DEPENDENCE OF THE PROPAGATION ANGLE OF TERAHERTZ EMISSION FROM A SINGLE-COLOR FILAMENT ON THE PLASMA CHANNEL LENGTH

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Plasma formed during single-color filamentation of laser pulses is known as one of the terahertz radiation sources [1]. In paper [2] a model is proposed, according to which the direction of terahertz radiation is determined by the formula $\theta \sim (\lambda_{THz}/L)^{1/2}$, where $\lambda_{THz}$ is the wavelength of terahertz emission and $L$ is the filament length. However, this dependence has not been experimentally confirmed. Moreover, the data given in the works [3,4] do not consist with it. Therefore, the aim of this work is to experimentally study the directivity of individual spectral components of terahertz radiation generated during single-color filamentation, depending on the plasma channel length.

The experiments were carried out with laser pulses having a central wavelength of 740 nm and duration of about 90 fs. By changing the laser pulse energy within the range of 0.5 — 6 mJ and the beam focusing conditions, it was possible to vary the length of the plasma channel from 0.5 to 100 mm. The angular distribution of terahertz radiation was measured by a bolometer rotating around the beam geometric focus. To measure individual spectral components, narrow-band terahertz filters were placed in front of the bolometer window.

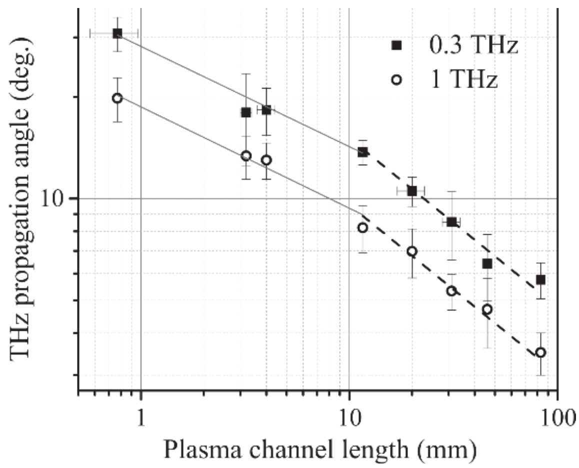


Fig. 1. Dependence of the propagation angle of 0.1 THz radiation on the filament length. Dashed line depicts to the trend $\theta \sim L^{-1/2}$, where $\theta$ is the propagation angle relative to the beam axis, $L$ is the filament length.

Fig. 1 shows the obtained dependence of the propagation angle of terahertz radiation with frequencies of 0.3 and 1 THz on the filament length. For long plasma channels (longer than 10 mm), which correspond to the non-linear focusing mode [5], the experimental data are well described by the inverse root dependence of the angle on the length, as predicted in [2]. In the case of shorter channels observed in the linear focusing mode, the plasma density in the filament begins to increase sharply, and the growth of the angle for both terahertz frequencies slows down with plasma channel length decreasing.

The research is supported by The Russian Science Foundation (grant 21-49-00023) and the National Natural Science Foundation of China (grant 12061131010).

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## X-Y DISTRIBUTION OF TERAHERTZ EMISSION FROM A SINGLE-COLOR LASER FILAMENT

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Terahertz (THz) radiation attracts wide attention due to various possible applications. Femtosecond filaments are one of the sources of THz emission. Usually, an axisymmetric distribution of THz emission is assumed in the works, and only one (as a rule) horizontal cross section of such radiation is measured. In our work, we measured the X-Y distribution of THz emission from a single-color filament plasma.

We use pulses of a titanium-sapphire laser with a central wavelength of 750 nm, a duration of 90 fs, and an energy of 1.5 mJ, which are focused by a mirror with a focus of 50 cm. THz emission is recorded by a hot-electron bolometer with a frequency range of 0.1–6 THz using bandpass filters. In experiments, the optical axis at a fixed position of the geometric focus is rotated at a certain angle from the horizontal, and by rotating the bolometer around the geometric focus, we obtain a horizontal distribution of THz emission. Next, the optical axis is rotated to another certain angle from the horizontal, and the procedure is repeated. Thus, the X-Y distribution of THz radiation is obtained.

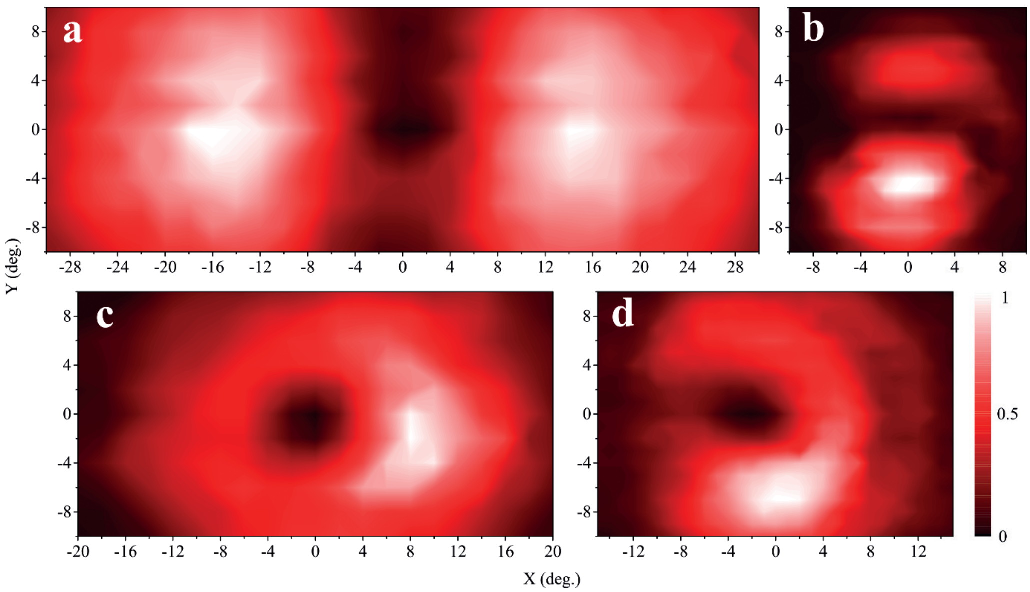


Fig. 1. X-Y distributions for terahertz radiation of different frequencies: (a) 0.1 THz, (b) 1 THz, (c) 0.3 THz, (d) 0.5 THz.

We show that at some frequencies the pattern of conical emission is asymmetric (Fig.1). The asymmetry has a different origin at various frequency.

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## GENERATION OF MULTICOLOR AND SUPERCONTINUUM RADIATION IN TERAHERTZ AND MID-INFRARED RANGES DUE TO GAS IONIZATION BY TWO-COLOR CHIRPED LASER PULSES

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One of the directions for generating short mid-IR pulses utilizes nonlinear multiwave mixing of two-color laser pulses in gases, including ambient air [1-8]. In particular, mid-IR generation can be realized using two-color laser pulses with angular frequency ratio $\omega_1/\omega_0 \approx 2$. In this case, the generation occurs at the detuning frequency of the higher frequency from the doubled lower one, $\omega_1 - 2\omega_0$. The underlying physical mechanism can be the hyperpolarizability of neutral atoms or molecules or the ionization-induced response of free electrons in a symmetry-broken electric field [1-8]. Recently we proposed a method for creating and controlling the frequency detuning in two-color laser pulses, which consists of using a stretched-in-time fundamental field and its second-harmonic field, which is assumed to be created by frequency-doubling crystal [8]. The fields have linear chirps and a group time delay, which corresponds to the instantaneous component frequencies $\Omega_0(t)=\omega_0+\beta t$ and $\Omega_1(t) = 2\Omega_0(t-\tau_d)$, where $\omega_0$ is the fundamental central frequency, $\beta$ is the chirp of the fundamental field, and $\tau_d$ is the time delay. The resulting detuning frequency is $\Omega_1-2\Omega_0=-2\beta\tau_d$ and is constant throughout the laser–gas interaction.

This paper generalizes the proposed method to generate multicolor low-frequency pulses. To do this, we propose to use several second-harmonic components with different group time delays relative to the fundamental field. We show analytically and numerically that for high intensity of the laser pulse, the current density resulting from isotropic gas ionization contains several components: the detuning frequencies and triple combination detuning frequencies. Intensities of the triple combination frequencies can be compared with that of the main detuning frequencies, which significantly enriches the generation spectrum. Moreover, the presence of a large number of generated components and the ability to control their spectra opens up the possibility of generating a broadband supercontinuum covering the THz and mid-IR ranges [9].

This work was supported by the Russian Science Foundation (Grant No. 22-72-10133).

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## THE USE OF BRUNEL HARMONICS GENERATION BY ELLIPTICALLY POLARIZED LASER PULSES FOR HIGH-RESOLVED DETECTION OF LOWER-FREQUENCY RADIATION

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One of the methods for measuring the time profiles of terahertz (THz) pulses generated by optical methods is based on the generation of the second harmonic of the gating laser pulse due to the third-order nonlinear response of neutral atoms and molecules [1-3]. The second harmonic intensity is served to measure the instantaneous value of THz field strength, and an entire THz field waveform is obtained by varying the arrival time of the gating pulse. The absence of phonon resonances, better phase matching, and continuous renewability makes gases more attractive for detecting broadband and high-power THz pulses than crystals and photoconductive antennas. However, the temporal resolution of detection is limited by the second harmonic duration $\tau_p/\sqrt{2}$, where $\tau_p$ is the gating pulse duration [3].

In this work, we propose to use the generation of even Brunel harmonics by optical laser pulses for high-resolved sampling detection of THz and mid-infrared pulses. Brunel harmonics originate from the acceleration of free electrons produced during tunneling ionization, and Brunel harmonics pulses durations are much shorter than the laser pulse duration [4-6]. The latter makes it possible to significantly increase the temporal resolution of detection compared to second harmonic generation due to the cubic nonlinear response of bound electrons. However, as we show by solving the time-dependent Schrödinger equation for the helium atom, for linearly-polarized intense laser pulse, the atomic response contains a broadband noise signal that interferes with Brunel harmonics. The latter allows one to measure only very strong fields, reducing this detection method's capabilities. We show that the nature of this noise is related to the population of the Rydberg states of the atom, which can be effectively suppressed by using elliptical polarization of the gating pulse [7].

This work was supported by the Russian Science Foundation (Grant No. 22-72-10133).

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## TERAHERTZ RADIATION GENERATION BY ATOMIC SYSTEMS INTERACTED WITH TWO-COLOR LASER FIELDS

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The source of terahertz radiation (THz) can be a variety of processes: from the mechanical detachment of an ordinary adhesive tape (the generation of THz radiation occurs due to its tribocharge during detachment followed by a discharge) [1] to the movement of relativistic electrons in an undulator in "megascience" devices [2]. Among the variety of methods for generating THz radiation, laser ones stand out due to the compactness ("table-top") of the resulting THz source, while maintaining the possibility of generating large-amplitude fields [3] and controlling the parameters of the generated radiation. During the interaction of femtosecond laser radiation, the generation of THz radiation can occur due to the movement of free charges obtained during the ionization of matter due to the laser field (photocurrent model) and due to intra-atomic nonlinearities [4].

In this paper, we present the results of studying of the THz radiation generation due to intra-atomic nonlinearities in two-color laser fields formed by linearly polarized first and second harmonics of a laser source interacting with atomic media.

The studies were carried out using a non-perturbative theoretical approach [5] and interference model [6]. The results of generation of THz radiation both by a single atom and by an extended medium, including a set of gas jets, are presented. The influence of two-color laser field parameters on the THZ radiation characteristics (efficiency, ellipticity, spectrum) is demonstrated. The influence of phase and quasi-phase matching on the angular-frequency spectra of the generated radiation is discussed [7].

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## TERAHERTZ WAVES EMISSION FROM LASER-INDUCED MAGNETIZED PLASMA

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Optical-to-terahertz conversion of ultrashort laser pulses in magnetized plasma is a proven way to generate high-power terahertz radiation [1]. The laser driver propagates transversely to an external dc magnetic field and excites large-amplitude plasma wakes with frequencies lying in the interval between the plasma and upper hybrid frequencies via the Cherenkov radiation mechanism. Due to partially electromagnetic nature of the magnetized wake, it has a nonzero group velocity and, therefore, is able to propagate to the plasma boundary and couple to free-space electromagnetic radiation.

There are two drawbacks for applying the phenomenon of magnetized wakes for the efficient generation of powerful terahertz radiation. First one is the angularly dispersed emission, i.e., wakes with different frequencies are emitted by the laser driver at different angles [2]. Second, in the case of a weakly magnetized plasma [1,2], with the electron cyclotron frequency ($\omega_c$) smaller than the electron plasma frequency ($\omega_p$), there is an evanescent region for the magnetized wakes in the descending plasma density ramp at the plasma boundary.

Here we propose a way to overcome the limitations above. We revisit the concept by Yoshii et al. [1] and extend the 2D theory developed in Ref. [2] to the regime of a strongly magnetized plasma, with $\omega_c > \omega_p$. In this regime, a part of the wake spectrum with the frequencies $\omega_p < \omega < \omega_c$ does not encounter any evanescent region in the boundary layer and couple efficiently to free-space radiation.

We numerically investigated the strongly magnetized regime and obtained the spectral and angular distributions of the radiated energy for different widths of the laser beam and different ratios $\omega_c/\omega_p$. It is shown that the peak value of the angular distribution decreases with $\omega_c/\omega_p$ and the peak position shifts to the larger angles. Increasing the laser beam width reduces the peak hight and shifts the peak to the smaller angles. It is also demonstrated that the waves with $\omega < \omega_c$, which can be efficiently couple to free-space radiation at the plasma boundary, propagate at angles $|\theta| < 40°$. As a result, this reduces the efficiency of the radiation coupling to the free space, especially for large $\omega_c/\omega_p$. The transmission of the magnetized wake through the inhomogeneous boundary layer also were studied (see Fig. 1). In the strongly magnetized regime ($\omega_c > \omega_p$), the power transmission coefficient is close to unity and weakly depends on $\omega_c/\omega_p$. In the weakly magnetized regime ($\omega_c < \omega_p$), it has a minimum at $\omega_c/\omega_p \approx 0.6$.

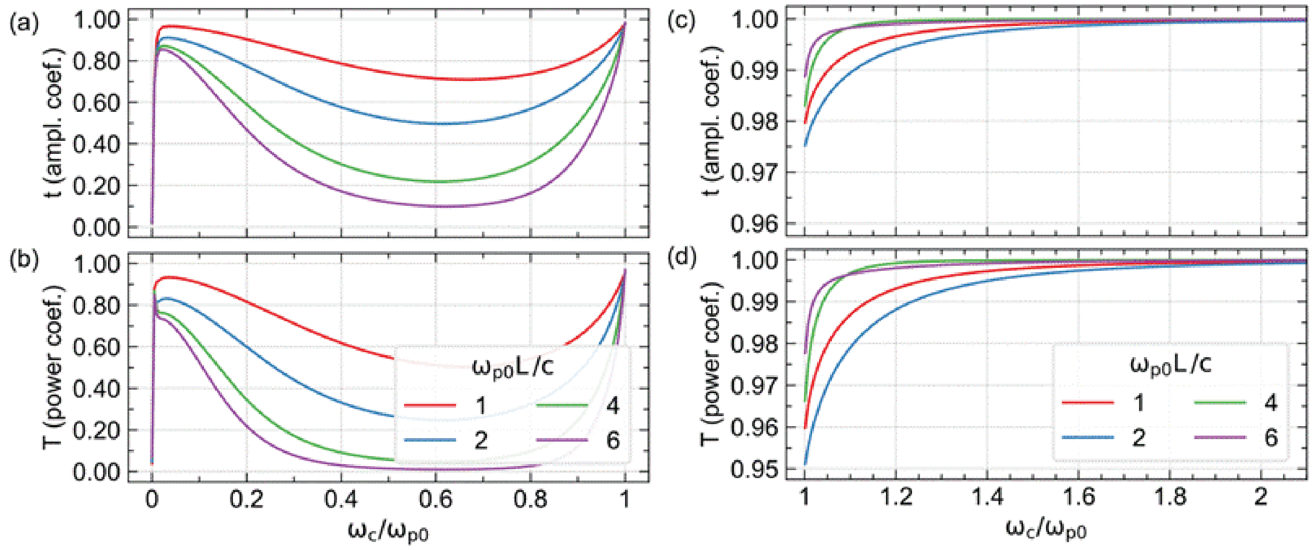


Fig. 1. (a, c) The amplitude and (b, d) power transmission coefficients of the wave with $\omega = \omega_{p0}$ as functions of $\omega_c/\omega_{p0}$ for different $\omega_{p0}L/c$ (L is the length of a linear plasma density ramp) in the case (a, b) $\omega_c > \omega_{p0}$ and (c, d) $\omega_c < \omega_{p0}$.

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## FORWARD THZ EMISSION FROM THE LONG DC-BIASED FEMTOSECOND FILAMENT

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In this paper we discuss percularities of the THz generation from a filament created by the loosely focused TW laser pulse if transverse electrostatic field is applied along its full length. In the experiments filaments were formed in air by a plano-convex lens with a focal length in a wide range of lengths (from 50cm to 10m) by a laser pulse from the 10 Hz terawatt Ti:Sa femtosecond laser system (805 nm, 55 fs, 1-50 mJ, beam diameter 10 mm or 5mm FWHM). Transverse electron current caused by the DC-biasing of the filament plasma channel by the 5.5 cm–47 cm long electrodes with field strength of 10 kV/cm generate THz radiation. We have measured THz pulse energy, its angular pattern, autocorrelation function and spectrum. A wide band acoustic technique has been used additionally to estimate the volumetric and linear absorbed power density and diameter of the filament plasma channel.

Efficient summation of the THz emission along the biased plasma channel greatly enhances the THz yield almost proportionally to the electrodes length. The THz radiation is emitted into the full cone with open angle which decreases with an increase of the electrostatic field application length. The THz spectrum measured by the Michelson interferometer lies in the 0.05 — 0.3 THz range. It is also shown that the laser beam numerical aperture has a significant effect on the efficiency of THz radiation generation and its spectrum. In the case of small numerical apertures the self-focusing leads to early (before the focus point) splitting of the beam into multiple filaments and limits the electron density in individual plasma channels and THz pulse energy due to intensity clamping.

In the case of large numerical apertures the efficient generation of THz radiation is limited by the small length of the filament, as well as the THz radiation refraction on the plasma. Numerical simulations within the framework of UPPE explain the experimental findings.

## EXCITATION OF HIGH-INTENSITY TERAHERTZ SURFACE MODES AT THE PLASMA BOUNDARY UNDER ACTION OF TWO-FREQUENCY LASER RADIATION

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The excitation of a terahertz (THz) surface wave (SW) was studied under the ponderomotive action of two-frequency laser radiation on a semi-bounded plasma [1]. The oblique incidence of the two laser fields with close frequencies at their counter propagation along the plasma boundary is considered. The space-time distribution of SW electromagnetic fields in plasma and in vacuum is calculated, and it is found that the SW field is determined by the magnitude of the ponderomotive potential of laser radiation at the difference frequency at the plasma boundary. It is shown that the noticeable amplification of the SW fields occurs when the resonance condition is satisfied and the frequency difference of the laser fields coincides with the surface eigenmode frequency.

The SW energy flux density is calculated under this resonance conditions and it is shown that in vacuum the energy is carried in the direction of propagation of the surface mode, and in plasma the energy transfer occurs in the opposite direction. The boundary value problem for *s*- and *p*-polarized two-frequency laser radiation is solved and the ponderomotive potential for both polarizations at the plasma boundary is calculated. The energy characteristics of the SW are investigated as the function of the incidence angle and the polarization of laser radiation, as well as the plasma electron density. It is shown that the SW energy flux density is maximum, when both *s*- and *p*-polarized laser radiation is incident on the plasma boundary at the angle of total reflection. If, for the *s*-polarization of the laser field, the maximum of the SW energy flux density occurs at the grazing incidence of laser radiation on a rarefied plasma, then in the case of *p*-polarization, the SW energy flux density is maximum when the laser radiation is incident at small angles to the boundary of the plasma with a near-critical electron concentration. The estimations for the characteristics of THz surface wave for the typical parameters of modern laser-plasma experiments are given. It is shown that when *p*-polarized two-frequency laser radiation is incident at the angle of the total reflection on plasma with the near-critical density of electrons, the SW of the THz frequency range with the energy flux density exceeding the laser radiation intensity is excited. The possibility of the experimental realization of the considered mechanism of SW excitation is discussed.

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## MICRO STRUCTURED MATERIALS FOR BROADBAND THZ FIELD MANIPULATION

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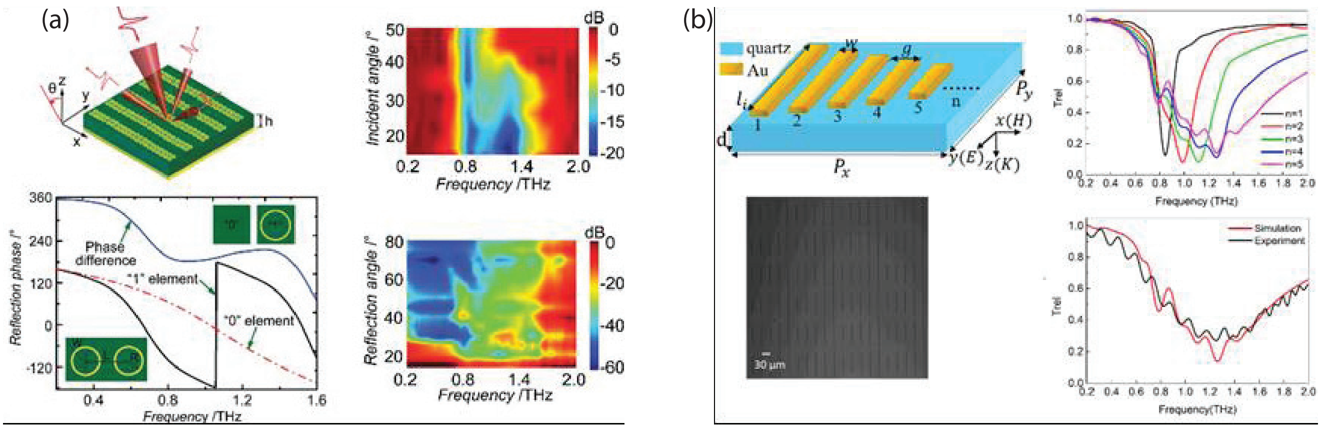
Terahertz (THz) waves have played an important role in both fundamental research and practical applications. However, in order to take full advantage of THz waves, there is an urgent need in developing functional THz devices and components with high performance. Micro structured materials have emerged that provide new opportunities due to the realization of tailored interactions with THz waves, which are often unavailable or very difficult to obtain from natural materials.



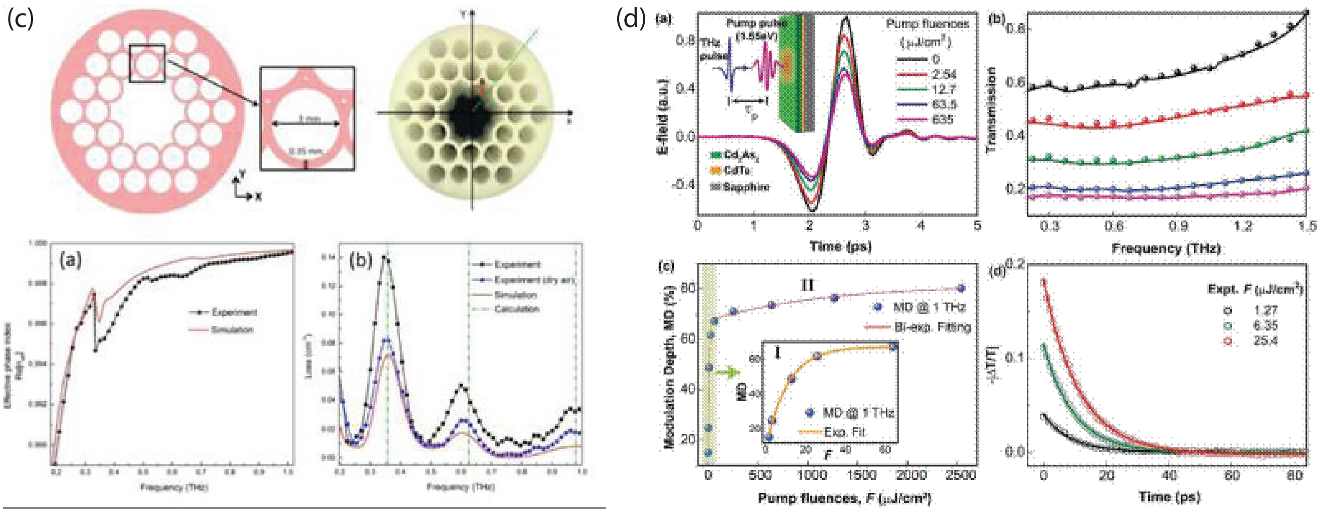



Fig.1 (a) Conformal coding metamaterials, (b) Multiplexed metallic bar resonators, (c) Kagome fiber, (d) ultrathin Cd3As2 film modulator.

In this work, several micro structured materials for broadband THz field manipulation THz devices are demonstrated, including digital coding metamaterials, chirped metamaterials, Kagome fiber and 3D Dirac semimetal film. Based on these newly design micro-structures, various THz components have been developed. For examples: (1) a wideband THz thin film metamaterial with extremely low specular reflection by optimizing the coding sequences [1], (2) an ultrabroad and angle tunable terahertz filter based on multiplexed metallic bar resonators [2], (3) 3D printed low-loss THz waveguide based on Kagome photonic crystal structure [3] and (4) all-optical, low-power, ultrafast broadband modulation of terahertz waves using an ultrathin film (100 nm, λ/3000) of Cd3As2 through active tailoring of the photoconductivity [4].

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## ANALYZING LIQUID-BASED THZ EMISSION MECHANISM VIA PLASMA EXPERIMENTAL STUDIES

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The laser-induced plasma is an important object of research in modern fundamental and applied physics. Special attention is paid to the sources of generation of THz radiation during filamentation in jets of various liquids [1].

Usually, the generation of THz radiation by a laser-induced plasma is described through the quasi-free electron density dynamics [2]. It is important to analyze the plasma density in the case of different experimental scheme geometry since the THz waves generation exhibits various features in this case [3]. A technique for estimating plasma based on reflected radiation in the case of double-pulse excitation of a liquid jet is presented in [4].

In this work, the optical properties of plasma formed during filamentation in various liquid jets in case of double-pulse excitation are analyzed. The dependences of the electron density dynamics and the efficiency of THz radiation at the same experimental conditions are revealed. Dynamics of changes in the induced reflection of the third harmonic from laser-induced plasma is recorded by changing the time delay between pulses. The experimental scheme is assembled in such a way that the liquid jet plane is located in the filament formation area and can be moved along the pump radiation axis. Additionally, the possibility of jet rotation relative to the laser pulse propagation direction allows measuring angular dependence of third-harmonic reflection.

The generation of the third harmonic occurs as a result of the plasma formation during filamentation in the air before the liquid jet plane. The dependence of third harmonic reflection intensity on the time delay between two pulses and the angle incidence of pump radiation with respect to the normal of the thin water jet are shown on the Fig.1. The obtained data correlates with the results of the THz radiation generation efficiency presented in [3].

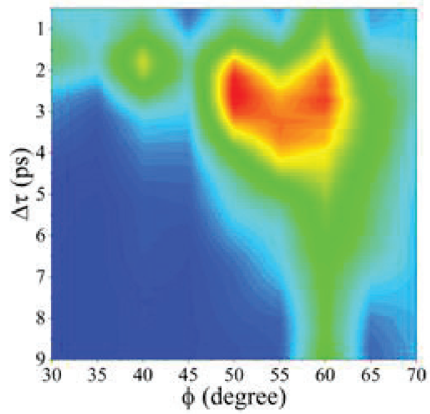


Fig. 1. Dependence of the third harmonic reflection dynamics on the angle of incidence of pump radiation with respect to the normal of the thin water jet.

The obtained experimental data revealed peculiar correlation between third harmonic reflection and the THz radiation generation during filamentation in a liquid jet. These results shed light on the previously reported data on the plasma-based THz radiation sources [3,5].

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# MEGASCIENCE

## STUDY OF THE PHASE LOCKING OF HIGH-POWER GYROTRON OSCILLATORS COUPLED WITH DELAY

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Ultra-high power levels can be attained by power combining of high-power microwave oscillators [1]. It has been demonstrated that relativistic magnetrons, vircators, and backward-wave oscillators can aggregate their powers coherently up to multi-gigawatt power levels. Since arrays of high-power gyrotrons are crucial for applications like the electron-cyclotron-resonance plasma heating, power combining of gyrotrons has recently gained a lot of attention [2-3]. Phase and frequency locking is a significant problem for coherent power summation. Peer-to-peer locking approaches as well as injection locking have both been extensively researched.

The complexity of the system is dramatically increased by the need to account for the signal propagation delay between connected oscillators since at microwave frequencies this distance significantly exceeds the operating wavelength [4]. The paper is devoted to the study of mutual synchronization (peer-to-peer locking) of two gyrotrons coupled with delay. A theoretical study of synchronization of gyrotrons and other microwave oscillators is usually carried out by numerical simulations using certain well-established models of microwave electronics. Using this approach, it is difficult to provide a fairly complete synchronization pattern. Simplifed models are required, which would allow bifurcation analysis using methods and ideas of nonlinear dynamics.

The study is based on a bifurcation analysis of the modified quasilinear model of two coupled gyrotrons proposed in [5]. A comparison is also made with numerical simulation using the non-stationary theory of a gyrotron with a fixed high-frequency field profile. Using the proposed model, we plot the synchronization domains on the coupling coefficient — frequency mismatch plane of parameters for various synchronous modes, the number of which increases with the delay time. The model also makes it possible to compute the most important output parameters, such as power, efficiency, and oscillation frequency.

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## PROJECT OF A BEAM-PLASMA GENERATOR OF THZ RADIATION BASED ON 1-MEV INDUCTION ACCELERATOR

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The necessity of generating submillimeter (submm) radiation fluxes ($\lambda \sim 0.3$ — 1.5 mm) with a megawatt level of pulsed power is associated with a wide range of their possible applications. First, such fluxes make it possible to solve a number of engineering and technical problems. These tasks include analysis and structure modification of composite materials and complex metal-dielectric objects; visualization of objects hidden under non-metallic shelters; study of material local areas with high resolution; suppressing the operation state of radio-electronic devices in order to ensure safety, etc. On the other hand, submm radiation fluxes open up new opportunities in fundamental research of physical, chemical, biomedical objects and substances. The absence of devices that provide the necessary powerful submm radiation fluxes stimulates research on the creation of appropriate generators. In this report, we will present the results of the development of a submm radiation generator based on the intense beam-plasma interaction [1]. This generator utilizes a relativistic electron beam formed by an accelerator diode at a voltage of 1 MV generated by magnetic inductors [2].

The generator of submm radiation developed by our team, includes the source of a high-current e-beam, a system for its magnetic tracking and its subsequent compression before injection into a plasma column, a high-voltage discharge system for creating a thin plasma column, a unit for separating the generated radiation from e-beam. The initial beam with a current up to 2 kA is generated in an axially symmetric diode that was previously developed as an injector for the LIA (see [2]). The beam is generated in the absence of an external magnetic field in a vacuum gap by a voltage pulse ~ 1 MV with a duration ~ 0.1 — 0.2 μs. Further, a beam with a diameter of 4 cm propagates in a vacuum tube to a distance of 2 meters and then is compressed to a diameter of 4 mm by the increasing magnetic field up to 1.5 T. This value is equal to the field in the plasma column. The plasma column with the required density n ~ (2-5)·$10^{15}$ $cm^{-3}$ and about 30 cm long is created by a high-voltage (~ 20 kV) discharge in a gas cloud formed due to a pulsed gas puffing. The current density ~ 10 kA/$cm^2$ of the compressed beam is quite acceptable to pump upper-hybrid plasma oscillations in the column resulting in radiation flux with a maximum spectral power density at a frequency of 0.6 -0.8 THz generation. On the other hand, the low beam current density during its propagation outside of the plasma column makes it possible to separate these areas from the plasma by thin foils. In the report, the status of the project on the generator development will be described in details.

Part of this work, related to creation of the plasma column is supported by the Russian Science Foundation (project no. 19-12-00250).

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## GAS DISCHARGE BREAKDOWN THRESHOLD SUSTAINED BY POWERFUL RADIATION OF 1THZ GYROTRON

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In this work, the thresholds for the breakdown of noble gases by high-power radiation from a gyrotron with a frequency of 1 THz are studied. Interest in this topic is because using powerful radiation in the terahertz frequency range it is possible to create a point-like discharge [1-3] in an inhomogeneous gas flow with characteristic dimensions of less than 1 mm, which can act as a bright source of vacuum and extreme ultraviolet radiation.

It is shown that, at the currently existing powers of terahertz gyrotrons (0.4 kW at a frequency of 1 THz [4]), breakdown in their focused beams is possible only in the case of preliminary ionization of the gas. The presence of a pre-plasma created, for example, with the help of a high-voltage spark, makes it possible to reduce the loss of charged particles by changing the diffusion mechanism. In this case, however, with a decrease in losses, a more significant role is played by the fact of the finite duration of the pulse of heating electromagnetic radiation. It is shown that for a pulse duration of 8 microseconds, which is typical for existing gyrotrons with a radiation frequency of 1 THz, the power required for breakdown increases by a factor of 2.5 (1.5 in case field strength) compared to a stationary breakdown.

The work is supported by the Russian Science Foundation, Project # 19-19-00599.

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## ACCELERATION OF A RELATIVISTIC ELECTRON IN A UNIPOLAR PULSE

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Unipolar pulses of electromagnetic radiation — the waves with practically constant electric field — were suggested by Bessonov in 1981 [1], and called "strange waves" even by the author. These are the cut-off parts of a sine wave of radiation, when $\int dt \cdot E(t) \neq 0$. Today the formation of unipolar pulses [2, 3] and their possible applications for acceleration of charged particles [4] are being intensively investigated.

In this report, we consider the laser pulse pursuing an escaping electron: in that case the interaction time of the electron with the radiation increases in $\gamma^2$ times, with $\gamma$ being the Lorentz factor. The numerical estimation on the base of the theory developed shows that the acceleration rate for a pulse duration $T_L = 10^{-14}\,s$ and strength $E_L = 5 \cdot 10^8\,V/cm$ is $58.7\,MeV/cm$, which is very large: say, it exceeds a hundred times the acceleration rate at the most modern classical accelerators/colliders. We also calculate the characteristics of radiation of a relativistic electron in the field of a unipolar pulse and show that the radiation is narrowly directional with a characteristic set of frequencies determined by the pulse duration.

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## REVIEW OF THE TERAHERTZ EXPERIMENTS ON THE NOVOSIBIRSK FREE-ELECTRON LASER FACILITY

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For almost 20 years, users from various fields of science have been conducting fundamental research at the unique facility Novosibirsk Free Electron Laser (NovoFEL) of the Siberian synchrotron and terahertz radiation research center.

The combination of unique characteristics of NovoFEL radiation [1], as high spectral power, monochromaticity, wavelength tunability in a wide wavelength range (8–400 µm), spatial and temporal coherence, enable to solve the scientific problems that are inaccessible when using conventional terahertz sources [2].

Among the ongoing work at the NovoFEL, several main streams of research can be stand out (Fig. 1): THz photonics and plasmonics, materials science, THz acousto-optics, ultrafast time-resolved spectroscopy of molecules, optical discharge in gases, THz EPR spectroscopy of molecular magnets and paramagnetic compounds, studies the affect of THz radiation on biological objects.

The most significant results of researches achieved at the Novosibirsk radiation source in recent years will be presented.

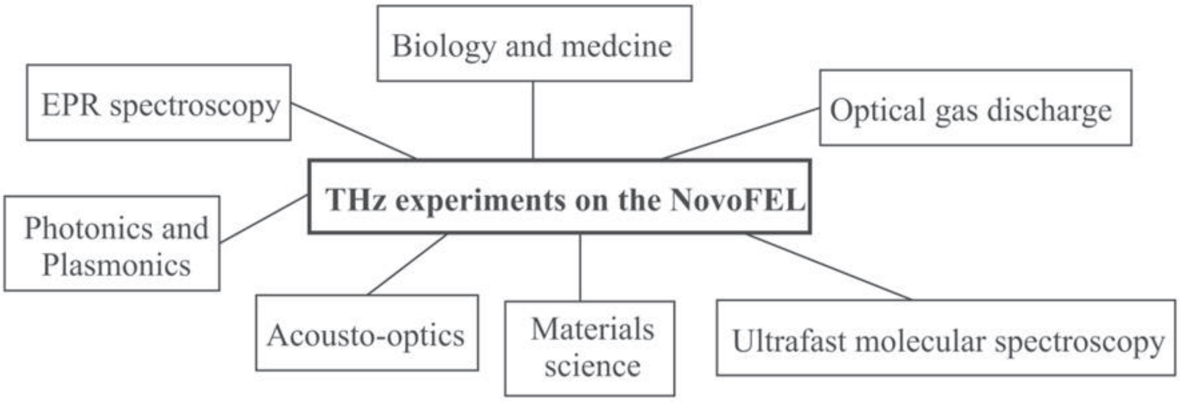


Fig. 1. Main streams of THz research performed on the NovoFEL facility.

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## THE NOVOSIBIRSK FREE ELECTRON LASER FACILITY: CURRENT STATUS AND PLANS

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The Novosibirsk Free Electron Laser (FEL) facility [1] includes three FELs [2] operating in the terahertz, far-, and mid- infrared spectral ranges. It has rather long history, but its potential has not been fully revealed so far.

The first FEL of this facility has been operating for users of terahertz radiation since 2004. It remains the world's most powerful source of coherent narrow-band radiation in its wavelength range (90 — 400 μm). The second FEL was commissioned in 2009. Now it operates in the range of 15 — 120 μm. This wide tunability range was achieved by recent replacement of the old electromagnetic undulator by new variable-period one [3], and its short wavelength boundary was shifted down to 15 μm. The average radiation power of the first and second FELs is up to 0.5 kW and the peak power is about 1 MW. The third FEL was commissioned in 2015 to cover the wavelength range of 5 — 20 μm. Its undulator comprises three separate sections. Such lattice is suited very well to demonstrate the new off-mirror way of radiation outcoupling in an FEL oscillator (so called electron outcoupling [4]), which we also plan for near future. We also intend to improve the accelerator injection system. As a result, the average electron beam current and consequently the radiation power of all the three FELs will increase.

Undulators of the FELs are installed on the first, second, and fourths orbits of the multi-turn energy recovery linac (ERL). The Novosibirsk ERL is the first multi-turn ERL in the world. Its peculiar features include the normal-conductive 180 MHz accelerating system, the DC electron gun with the grid thermionic cathode, three operation modes of the magnetic system, and rather compact (6×40 $m^2$) design.

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## HIGH-POWER SUB-THZ BAND SPATIALLY-EXTENDED SURFACE-WAVE OSCILLATORS WITH 2D-PERIODICAL SLOW-WAVE STRUCTURES

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Relativistic oscillators of Cherenkov type based on high-current electron beams provide record level of pulsed power in cm — wavelength band. However, further increase in the output power and transition to shorter radiation wavelength bands leads inevitably to the necessity of increasing interaction space oversize, and, correspondingly, to the problem of provision of mode selection with respect to the transverse index. Projects of spatially-extended Cherenkov masers based on 2D-periodical slow-wave structures operating up to sub-THz frequencies are under development currently at the IAP RAS (N. Novgorod). In these projects, the 2D slow-wave structures combine the properties of a slow-wave system realizing conditions for an effective Cherenkov interaction with a high-current rectilinear electron beam, and a high-Q resonator utilizing the 2D distributed feedback mechanism and providing selective excitation of the operating mode in the strongly oversized system. Using of a 2D distributed feedback is universal method to generate powerful spatially-coherent radiation from the oversized active mediums which can be applied in both classical and quantum electronics.

Spatially-extended Cherenkov Surface-Wave Oscillator (SWO) operating at the W-band (operating frequency is about 74 GHz) was constructed based on the high-current explosive-emission accelerator "Sinus-6" 0.5 MeV / 5 kA / 25 ns (IAP RAS) forming wide tubular electron beam with a diameter of about 40 mm. Oscillators of such type are preferable among the relativistic Cherenkov masers due to the larger values of the electron-wave coupling impedance. For this SWO, the 2D slow-wave structure of cylindrical geometry was designed with oversize parameter Ø/λ ~ 10 (perimeter of the system ~ 30 wavelengths), a corrugation period of 3.59 mm, an azimuthal number of variations (corrugation turns) of 32, a corrugation depth of ~ 1 mm, and a total length of about 10 cm.

Simulations of the W-band 2D SWO for parameters close to the experimental conditions were carried out using PIC code CST Studio Suite. Results of simulations demonstrated establishment of narrow-band oscillation regime with the output power of 0.25 — 0.3 GW and the electron efficiency of up to 15% under the design parameters. Mode pattern of the synchronous slow wave demonstrates azimuthally symmetric distribution and contains the $TM_{0,n}$ type waveguide modes.

In the proof-of-principal experiments, powerful narrow-band radiation was detected under the design parameters. Output radiation directional diagram was analyzed by means of the neon bulb panel set at various distances from the oscillator and demonstrated a pronounced minimum at the axis, which corresponds to excitation of designed pattern of $TM_{0,n}$ type modes. At the operating frequency of about 74 GHz, output power was measured at the level of ~ 0.15 — 0.2 GW. Experimental studies of this SWO are in progress.

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## GYROTRONS: NOVEL OPTIMIZATION

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There is a number of topical scientific problems that require the creation of powerful sources of microwave electromagnetic radiation in the frequency range 0.1-1 THz. Gyrotrons are the most powerful radiation sources in the sub-THz and THz wavelength ranges. Despite the difficulties with the generation of high-intensity magnetic fields required for resonant conditions of electron-wave interaction in volumes sufficient to accommodate electron-optical and electrodynamic systems of gyro devices, the problem of shaping high-power electron fluxes with a high fraction of rotational energy and low velocity spread, and the problem of selective excitation of high-order operating modes, harmonic excitation, etc., the gyrotrons continue to be the object of intense research and show a significant potential for improving the characteristics of the generated radiation [1].

Gyrotrons are in demand for the ECR of plasmas in controlled-fusion installations, the creation of systems for high-gradient acceleration of electrons by terahertz waves, energy transfer using narrow beams of microwave radiation, spectroscopy, and diagnostics of various media.

The years 2021-2022 were marked by an increase in the number of requests for megawatt (MW) gyrotrons both from representatives of large thermonuclear facilities well known to the gyrotron community (ITER, KSTAR, EAST) and from a number of new projects (F4E, MAST-U). An explosive growth in the number of commercial companies that focus on obtaining thermonuclear energy by 2025-2030 should be mentioned [2]. The use of complexes consisting of a large number (from tens to thousands) of synchronized powerful sources of electromagnetic radiation is also under discussion. Since 2021, the development of Russian gyrotrons for controlled-fusion installations has been supported by the comprehensive program "Development of equipment, technologies and scientific research in the field of using atomic energy in the Russian Federation for the period up to 2024" [4].

The purpose of this paper is to present a number of the most striking achievements of the IAP RAS and GYCOM in the development of gyro devices, which include i) testing a prototype gyrotron with a frequency of 230-250 GHz in a pulsed generation mode, ii) creating a cryomagnetic system with a hot bore diameter 150 mm and a field of 10 T for a megawatt power level gyrotron, iii) completion of the driver gyrotron tests and the fulfillment of experiments on frequency locking of a megawatt gyrotron by an external signal, iv) development of a pulse compressor circuit for a high-power gyrotron and preliminary analysis of its key elements for provision of microwave radiation with a power level of about 100 MW and a pulse duration of about 10 ns, and v) analysis of new schemes for broadband frequency tuning and excitation of higher harmonics.

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## SUPER-POWER FREE-ELECTRON MASERS WITH 3D DISTRIBUTED FEEDBACK

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Original conception of super-power pulsed spatially-extended microwave generators has been developing during a number of years in collaboration between IAP RAS (N. Novgorod) and BINP RAS (Novosibirsk). This concept is based on the use of high-current sheet relativistic electron beam (REB) and planar geometry of the interaction space, which allows enhancing the total output power by increasing the generator transverse size. Spatial coherence of the radiation under the conditions of substantial oversize is achieved by using two-dimensional distributed feedback (DFB) [1]. Operability of the novel feedback mechanism was demonstrated experimentally in the W-band FEM which was realized based on the accelerating complex ELMI 1 MeV / 5 — 7 kA / 3 μs (BINP RAS) forming "model" sheet REB with a transverse size of up to 0.3 cm × 18 cm. As a result, at the transverse size of the system of about 2.5λ × 50λ, the output power at the level of ~ 100 MW was acheived [2], which is a record for this class of generators.

Further increase in the radiation power can be obtained by using a "full-scale" sheet REB formed by the U-2 accelerator 1 MeV / 140 kA / 5 μs, the transverse size of which reaches 1 cm × 140 cm. However, when designing a generator based on such beam, the problem arises of ensuring the mode selection along a "narrow" transverse coordinate (i.e. the coordinate directed along the gap of the planar system). To solve this problem in two-mirror resonator scheme, the so-called advanced Bragg resonators were previously studied, the distinctive feature of which is the presence of a quasi-cutoff wave in the feedback loop [3].

Combination of the selection mechanisms implemented in the described Bragg structures allows development of the size of relativistic masers in both transverse directions. "Three-dimensional" Bragg structures of planar geometry have been proposed, with the corrugation, which is the sum of corrugations of the 2D and advanced Bragg structures [4]. Such structures realize a feedback mechanism through wave-beams propagating in the three mutually-perpendicular directions and provide mode selection over all three (longitudinal and both transverse) mode indexes. High selective properties of proposed resonators under substantial oversize conditions were corroborated by the results of 3D simulations based on the CST Microwave Studio software.

Simulations of FEM with 3D DFB was carried out within the framework of the developed original averaged model of the coupled waves approach (quasi-optical approximation). The possibility of implementation of a super-power sub-THz band oscillator based on the U-2 accelerator was evaluated, the simulation parameters were assumed to be close to the conditions of the planned experiments. The resonator forming the 3D DFB mechanism was designed with the transverse size of 10λ × 350λ. Simulations demonstrated the onset of a stable narrow-band oscillation regime under the design parameters. Oscillation frequency and spatial structure of the RF-field in the stationary regime corresponded to the establishment of the fundamental highest-Q mode found in the frame of analysis of the "cold" resonator. With a length of the interaction space (resonator) of about 50 — 70 cm, the electron efficiency reaches ~ 10-15%, which corresponds to the output radiation power of up to 10-20 GW.

This work is partially supported by the Russian Scientific Foundation (grant # 19-12-00212).

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## TERAHERTZ AND OTHER TYPES OF RADIATION DURING TERAWATT EXPOSURE TO METAL FOIL

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With sub petawatt Ti:Sa laser system we develop THz short pulse sources for time-resolved studies in strong fields. We use oblique incidence of P-polarized laser radiation and varied laser intensity from $10^{14}$ to $10^{18}$ W/cm$^2$ either by pulse duration (30-2000 fs) or by energy (1-200 mJ). Simultaneous measurements of THz, bremsstrahlung and characteristic X-rays, optical harmonics 2ϖ and 3/2ϖ — provides additional information about spatial-temporal plasma properties. Changing the intensity and duration we switch between several known processes of laser-plasma energy transfer. All secondary radiation signals demonstrated similar dependency on laser pulse energy and duration. We believe that the main intermediate process is hot electrons formation, for witch two-plasmon decay instability [1] make a considerable contribution.

Almost twofold increase in secondary radiation (in THz, visible and X-ray ranges) reflected from Cu foil was discovered when foil thickness decreases from 100 to 10 µm. We attribute this to the recirculation of hot electrons, known process for X-ray yield increase [2, 3], but not for THz or optical harmonics.

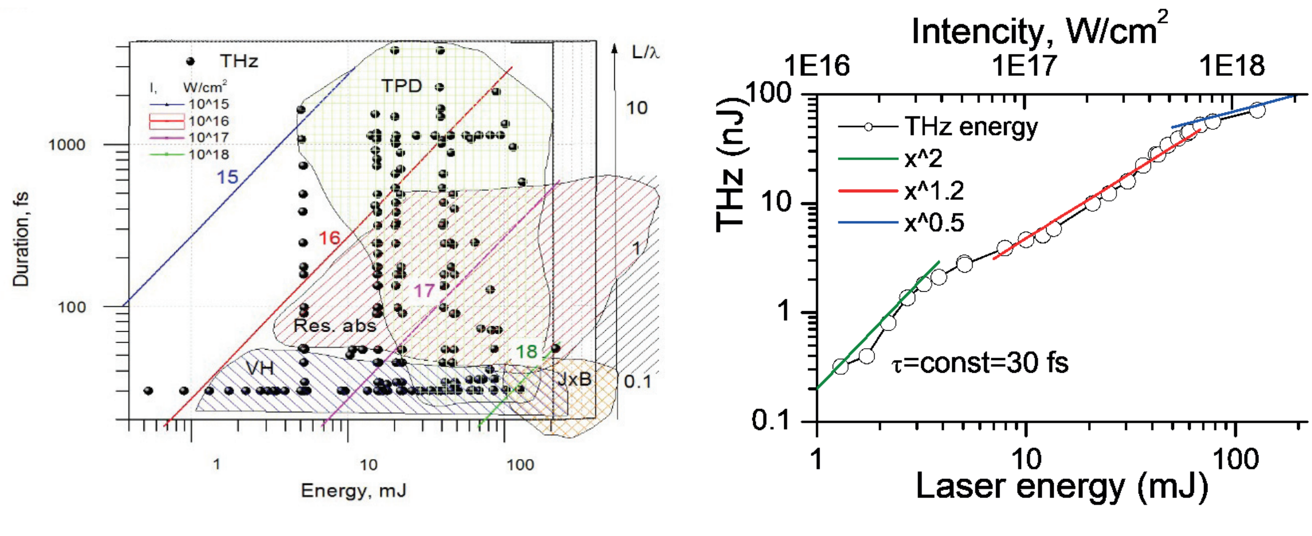


Fig.1 The map of the used intensity, energy, duration — left. THz vs laser energy — right.

As a result of the optimization we obtained 120 nJ THz pulse and $5\cdot10^8$ ph./pulse·2π X-ray flux[4], that is enough for efficient Bragg X-ray diffraction of CuKa on Si(111) crystal, required for THz_pump-X_ray_probe studies. Long fs pulses provided better efficacy for secondary radiation generation. The main advantage of suggested scheme is the absence of saturation above TW power level, the presence of optimal X-ray pulses brightness for time-resolved studies. This work is supported by Ministry of Science and Higher Education of the Russian Federation in framework of Agreement No.075-15-2022-830 from 27 May 2022 and by RFBR grant 20-21-00140.

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## QUASI-ANALYTICAL THEORY OF GYRO-BWO WITH A ZIGZAG QUASI-OPTICAL ELECTRODYNAMIC SYSTEM

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Recently, a microwave system in the form of a quasi-optical transmission line is proposed as an interaction circuit of an oscillator based on the cyclotron resonance maser (CRM) instability [1]. The circuit consists of focusing mirrors, which are periodically spaced along the longitudinal z-axis and provide transport of the Gaussian wave beam along a zigzag path (Fig. 1 a). A beam of electrons is guided by a static magnetic field along the z -axis so that the e-beam periodically crosses the wave beam. In this work, we develop the quasi-analitical small-signal theory of the zigzag-type gyro-BWO. A simple 2-D model describes a large number of effects specific to this device, including (i) a discrete piecewise character of the dependence "frequency versus magnetic field" $f(B_0)$ (Fig. 1 b), (ii) establishment of stationary generation modes in the process of competition of different modes of the system located at different sites different branches of the discrete dependence $f(B_0)$ (Fig. 1 c), (iii) estimations for values of basic characteristics of the BWO (efficiency, optimal length of the system), (iv) switching to auto-modulation regimes when the operating current (the normalized length of the system) increases (Fig. 1 c), (v) the possibility of implementing the super-radiant regimes of formation of short powerful wave pulses in this device, and (vi) complication of the nature of the dependence of the generation power on the magnetic field in a situation where different sections of the system are slightly different.

The work was supported by the Russian Science Foundation under grant No. 21-19-00443, https://rscf.ru/project/21-19-00443/.

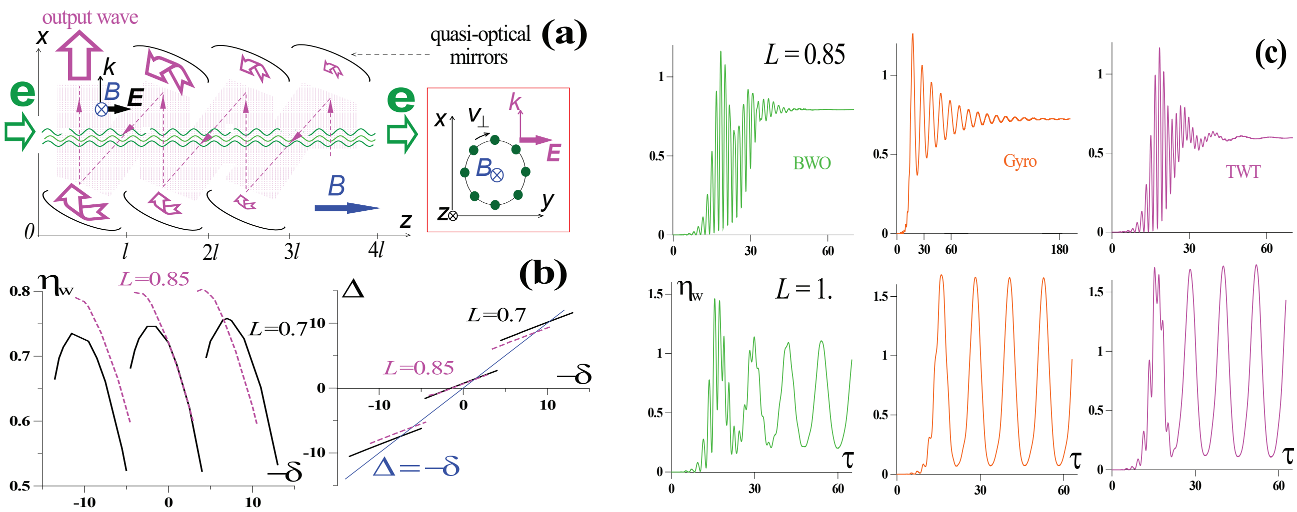


Fig.1. (a) 2-D model of a Gyro-BWO with the zigzag quasi-optical microwave system consisting of four sections of electron-wave interaction. (b) Results of numerical simulations: normalized output wave power $\eta_w$ and the normalized frequency of the generated wave Δ in the stationary steady-state regime versus the normalized operating magnetic field $-\delta\sim B_0$. (c) Dynamic of excitation of the zigzag BWO in the cases of different normalized magnetic fields and different normalized lengths.

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# PROJECT OF POWERFUL LONG-PULSE SUB-THZ / THZ BAND FEL: DEVELOPMENT OF SELECTIVE OVERSIZED ELECTRODYNAMIC SYSTEM

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Project of free-electron laser (FEL) is under development in collaboration between BINP RAS (Novosibirsk) and IAP RAS (N.Novgorod) based on a new generation of induction linac LIU

5 — 20 MeV / 2 kA / 200 ns implemented in recent years at BINP RAS. The use of such beam makes it possible to realize ultra-high power long-pulse FEL operating from sub-THz to THz band with energy content at the level of ~ 10 — 100 J [1]. Initial proof-of-principle experiments are planned to start at the 0.3 THz and 0.7 THz ranges with prospects of transition to higher frequencies after positive results would be demonstrated.

To transport this intense electron beam through the FEL interaction space, the cavity diameter would be Ø ≥ 20 mm [2] that in orders exceeds the radiation wavelength at the specified frequencies. Thus, one of the "key" problems in implementation of this generator is elaboration of electrodynamic system that can provide stable narrow-band oscillation regime in such strongly oversized interaction space.

To solve this problem, we proposed two types of the cavity: (1) advanced Bragg resonators based on coupling of quasi-cutoff and propagating waves and (2) quasi-optical Talbot-type resonators.

For realization of coupling of the propagating and quasi-cutoff waves in advanced Bragg structures, the corrugation period should be approximately twice as long as in "conventional" structures. Involvement of a quasi-cutoff wave in the feedback loop, similarly to gyrotrons or orotrons, results in significant purification of transverse mode spectrum of the substantially oversized resonator and improvement of its selective properties in comparison with the Bragg structures of "conventional" type [3].

Advanced Bragg resonators with the specified diameter (acceptable for the beam transportation) were designed for the FEL operation in the ranges of 0.3 THz (Ø/λ ~ 20) and 0.7 THz (Ø/λ ~ 45). Results of the 3D CST-simulations demonstrate that novel Bragg structures provide selective power reflection for the operating mode with ~ 80 — 90% efficiency even at such large transverse dimensions.

Results of "cold" electrodynamic tests coincide with the simulations and confirm the existence of effective narrow-band reflection in the designed frequency ranges.

The idea for the Talbot-type resonator is based on relinquish of fixed transverse mode excitation in favor of the excitation of a supermode formed by a fixed spectrum of several transverse modes of an oversized waveguide having the same frequency [4]. Such a high-Q supermode can be formed inside a simple waveguide cavity ended by two mirrors as a result of Talbot's effect namely, periodic reproduction of the transverse structure of a multi-mode wave field in a quasi-optical waveguide. For "cold" tests, a prototype of the Talbo-type resonator was manufactured in 0.3 THz range with an oversize factor of Ø/λ ~ 40.

Excitation of the resonator was carried out from the input side, the output signal detection was carried out through a coupling hole made on the output mirror.

In accordance with the simulations, in the conducted "cold" tests, a well-distinguishable peak of the detected output power was observed at a frequency corresponding to the excitation of the operating mode (supermode) of the resonator, which thus confirmed its operability.

This work is partially supported by the Russian Science Foundation (grant # 19-12-00212).

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# PROGRESS IN DEVELOPMENT OF PHOTOINJECTOR COMPLEX IN IAP RAS

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At the Institute of Applied Physics, a photoinjection electron accelerator is being developed, in which a step-by-step acceleration of particles up to an energy of about 20 MeV should be provided. The first 3.5 MeV section of the accelerator can be used to experimentally study promising regimes of terahertz radiation of short electron bunches. The low emittance bunches additionally accelerated in the second section are planned to be used for injection into the plasma accelerator system for the subsequent increase of the energy to a GeV level. In addition, work is underway to study new promising options for photocathodes.

The first section of the accelerator is a classic version of a photoinjector with one-and-half-cell accelerating structure based on the symmetric TM π-mode. Powering the cavity from a 5 MW klystron at a frequency of 2.45 GHz provides an amplitude of the accelerating field at the cathode of about 70 MV/m and particle acceleration to an average energy of ~ 3.6 MeV. The design of the magnetic electron-optical system of the photoinjector includes a focusing system of the accelerating section consisting of a main solenoid with a field of about 0.25 T and a counter-cathode coil providing a zero magnetic field on the cathode surface. Such a system provides a regime of compensation for the space charge-related emittance [1] and focusing of the electron beam over a length of about 1 m.

For the second stage, a system of accelerating sections and focusing solenoids has been designed. Each accelerating section is a sequence of 6 coupled cells powered by a single microwave signal source at a frequency of 2.45 GHz. This frequency coincides with the operating frequency of the first stage of the photoinjector, which makes it possible to synchronize all final microwave amplifiers in both stages, feeding them through controlled phase shifters from one stable low-power continuous microwave signal source. The operating TM mode of the accelerating structure is a π-mode with antiphase field oscillations in neighboring cells. With a power supply signal of 5 MW, the amplitude of the accelerating field in the cavities is about 35 MV/m, which, according to calculations, provides an increase in the energy of relativistic particles of about 6.5 MeV over a length of one section of about 40 cm.

In parallel with the design of the accelerator, a study of photocathodes based on CVD diamond films is under way. Such cathodes can combine high quantum efficiency and insensitivity to vacuum quality [2, 3]. Investigations are carried out using a specially designed vacuum chamber, which makes it possible to register the electric charge emitted from the cathode surface under the action of laser radiation. Nanocrystalline diamond films were deposited in a CVD plasma microwave reactor on n-type silicon substrates with a size of 20×20×0.5 $mm^3$. The thickness of the deposited film was about 0.5 μm. The films were grown in a mixture of hydrogen and methane, to which a gas containing a dopant, phosphine PH3, was added in a small amount. Several samples of photocathodes were grown, the growth conditions of which differed in the content of methane, phosphine in the gas mixture, and the substrate temperature. As a result, the diamond films had different ratios of the diamond and non-diamond phases and phosphorus content. The quantum efficiency of the studied cathodes varied in the range (4 — 9)·10-6.

The work is supported by the Russian Science Foundation (grant #20-12-00378 for development of 3.5 MeV stage and photocathode studies and grant #21-72-30027 for development of 20 MeV stage).

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# MICRO-UNDULATOR FOR THE X-RAY FEL BASED ON PLASMA ACCELERATOR

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Free electron lasers (FELs) are capable of generating coherent radiation at wavelengths of up to hundredths of an angstrom [1, 2]. Existing and currently being designed X-ray FELs require, as a rule, large and expensive electron accelerators [3, 4], which makes it an important problem to realize a more compact design [5, 6]. One of promising possibilities is the use of a plasma electron accelerator [7, 8], which, due to a much larger acceleration gradient than in classical systems, makes it possible to provide the electron bunch energy necessary for generation in the X-ray range over a much shorter distance. The principle of operation of such systems is based on the acceleration of particles by a superstrong electric field of a wake wave following a powerful short laser pulse or a dense driver electron bunch propagating in the plasma. At the same time, the implementation of efficient X-ray FELs based on plasma accelerators is still hampered by the low quality of accelerated electron

beams — along with a high average energy (from hundreds MeV to few GeV), they have a significant (a few percent) energy spread and a noticeable (fraction of a degree) angular divergence. Nevertheless, examples of the implementation of such systems already exist [9, 10]. In addition, the possibilities of improving the quality of bunches at the output of a plasma accelerator are considered. For example, this may be achieved by injecting into a plasma wave of a cold electron bunch from a preliminary accelerator of relatively low (tens of MeV) energy.

The operation of an FEL is based on the interaction of an electron beam pumped in a transverse periodic magnetic field of an undulator with an electromagnetic wave. Since it is practically impossible to create a mirror resonator for an oscillator scheme or to provide an external coherent seed in the X-ray frequency range, FELs of this range are designed to operate in the so-called SASE (self-amplification of spontaneous emission) regime, when powerful coherent induced radiation arises from electron beam noise over a long interaction length. Due to the significant angular divergence of the electron beam from the plasma accelerator and the accompanying rapid decrease in beam brightness along the distance, it seems promising to reduce the interaction length to several centimeters by shortening the undulator period from typical values f a few centimeter to millimeters and simultaneous increasing the FEL growth increment to the level of a unit per mm. One of the main problems in this case is to ensure a sufficient pumping of electrons in the undulator field (large enough undulator parameter), since the required transverse magnetic field increases inversely with the undulator period, and, moreover, quickly decreases with the distance from the magnetic system.

In this paper, we propose and study a variant of a current micro-undulator based on thin conducting plates with cuts. According to the simulations, the proposed design possesses sufficient mechanical strength and resistance to overheating. In the report, the parameters of the micro-undulator necessary for the generation of X-rays are discussed, and the design, analytical description and numerical simulation of the proposed system are considered.

The work is supported by the Russian Science Foundation (grant #20-12-00378).

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# EXPERIMENTAL TEST OF NEW GENERATION TECHNOLOGICAL GYROTRON SETUP WITH HIGH POWER AND EFFICIENCY

**M. Proyavin, M. Morozkin, V. Manuilov, E. Soluyanova, E. Tai, M. Kamenskiy, A. Orlovskiy and M. Glyavin**

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Based on previously performed theoretical work, a new generation of technological gyrotrons on the first cyclotron harmonic with a radiation frequency of 28 GHz and a power of up to 25 kW has been developed. The generation efficiency of gyrotron reaches 55% (without a system of recovery of residual electron energy) and efficiency of the entire system is about 35% (considering oil-cooled solenoid, equipped with ferromagnetic shields) in the case of maximum radiation power. The correct operation of the developed electron-optical system under conditions of a quasi–adiabatic magnetic field in magnetron-injection gun area and a non-adiabatic field in the collector region is confirmed. The obtained experimental results are consistent with numerical simulations. This allows us to further count on the implementation of generators up to the W frequency band using the existing magnetic system and high-voltage power sources.

A new generation of technological gyrotron has been successfully manufactured and experimentally tested using a magnetically-shielded system (MSS) [1-2]. Due to advantages of this magnetic source (low power consumption and possibility to achieve induction up to 1.8 T), the gyrotron was able to operate at the fundamental cyclotron resonance at frequencies 28, 35, 45 GHz and at the second harmonic at 95 GHz. According to specific profile of magnetic field in MSS, which has a sharp drop in fronts near the homogeneous region, the optimization of the magnetron-injection gun was thoroughly carried out. Based on previous numerical simulations, described in works [3], an experimental study of the main generation regime at a frequency of 28 GHz was carried out. Here we obtained (without a system of energy recovery) efficiency of the gyrotron up to 55%, driven by accelerating voltage of $U_a$ = 23 kV and electron beam current of Ib = 0.5 A and total complex efficiency about 35% at microwave power level of 23 kW at Ib = 2.4 A / $U_a$ = 23 kV. Generation modes at frequencies of 35.4 GHz (TE22,1.3 T), 45 GHz (TE-13, 1.65 T) and 95 GHz (TE16, 1.75 T, second harmonic) can be implemented in the same magnetic system with the corresponding currents of the coils. However, these frequencies require modification of the output vacuum window and will be presented later.

This work was supported by the Russian State Assignment Program, IAP RAS project 0030-2019-0027.

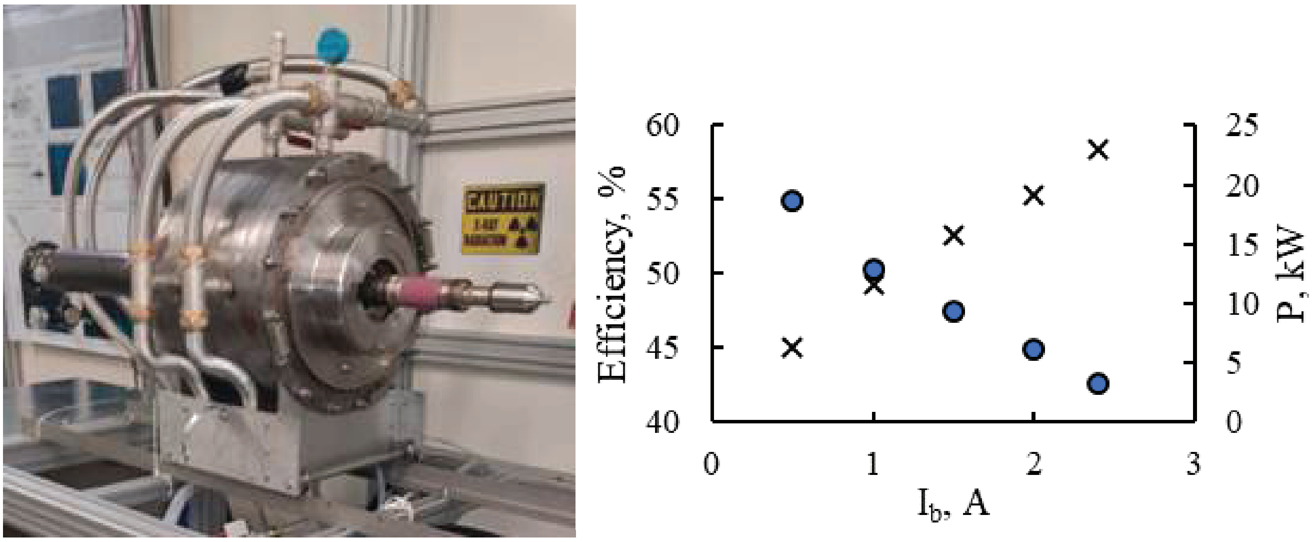


Fig. 1. Photo of the gyrotron setup with MSS (left), efficiency and power vs. beam current (right).

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# SUB-TERAHERTZ GYROTRONS WITH COMPLICATED CAVITIES

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We describe our works aimed to development of sub-THz gyrotrons with complicated cavities. In particular, recently [1] an azimuthally-nonsymmetrical cavity with azimuthal resonant irregularities (Fig. 1 a) was proposed to provide selective third-cyclotron-harmonic generation in the pulsed 100kV/1.2A/1THz large-orbit gyrotron. In this paper, we describe results of detailed "hot" 3D SCT simulations of this gyrotron, which demonstrate the selective excitation of the operating third-harmonic wave with an output power at a level of 3-4 kW. In addition, we discuss a possibility to use such systems as a way to realize a selective frequency-tunable cavity based on operation at an azimuthally-symmetrical transverse mode.

As a continuation of our works under gyrotron cavities with non-symmetrical azimuthal cross-sections, we propose a cavity based on the use of resonant photonic structures (two parallel corrugated Bragg-type mirrors) shown in Fig. 1 b. Such a cavity supports high-Q standing waves only in a narrow (several %) frequency band. These operating waves are formed by backward reflection from the corrugated mirrors based on the (-1)st order diffraction mechanism. Thus, high-cyclotron-harmonic gyrotron excitation of such waves can be provided without the danger of their competition with parasitic waves excited at lower harmonics. In addition, mechanical variation of the distance between the two parallel gratings can ensure tuning of the eigenfrequency band of this system in a wide (~20%) frequency band. Simulations for a sub-THz gyrotron system together with description of the wave output system are presented in this work.

In addition, in this review presentation we will mention our project of a frequency-tunable sub-THz gyrotron based on the use of an irregular cavity and a frequency-tunable narrow-band mirror, which is located outside the gyrotron window (that is, outside the vacuum zone) (Fig. 1 c). More detailed description of this work will be given in [2].

The work was supported by the Russian Science Foundation, Projects # 19-19-00599 and # 20-72-10116.

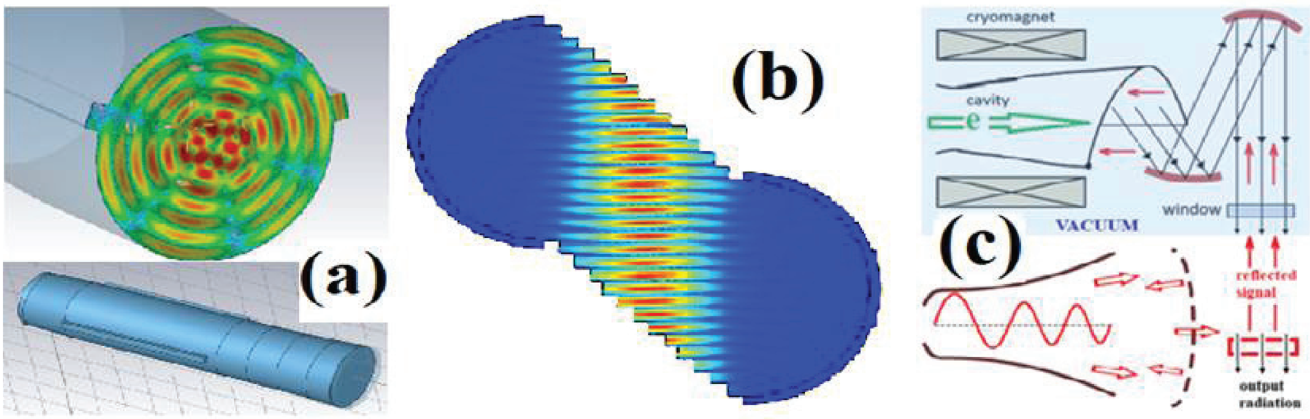


Fig.1. (a) A gyrotron cavity with azimuthal resonant irregularities. (b) Cross-section of a cavity formed by two parallel photonic structures, as well as the transverse structure of an eigenmode. (c) Frequency-tunable gyrotron based on the use of an irregular cavity and a frequency-tunable external mirror.

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## SUB-TERAHERTZ FREQUENCY-TUNABLE GYROTRON WITH EXTERNAL MIRROR: DESING AND SIMULATIONS

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For spectroscopic applications, compact sources of continuous coherent radiation of the sub-terahertz frequency range with relatively high (tens of Watts and higher) power are required. Important requirements for such sources are a narrow-band spectrum of the output radiation and, simultaneously, the possibility of smooth broadband frequency tuning, which would make it possible to obtain a spectral picture in a frequency band of at least a few percent. We describe a project of a frequency-tunable sub-THz gyrotron. To ensure smooth broadband frequency tuning, we propose to implement a scheme based on excitation of different far-from-the-cutoff axial modes of an irregular cavity. The change of the operating mode provides the change of the operating frequency. The selective excitation of each of the modes is provided by reflecting part of the output signal from a narrow-band mirror, which is located outside the gyrotron window (that is, outside the vacuum zone) and "tuned" to the frequency of the excited mode (Fig. 1 a). The absence in an irregular cavity of high-Q modes that could be excited without external reflection is principally important. In this situation, the frequency of the excited mode is easily changed by mechanical change of the frequency of the external mirror (or even replacing one mirror with another). According to simulations, the use of an irregular cavity with an optimized profile provides the possibility of highly efficient excitation of a wide range of different axial modes of the system.

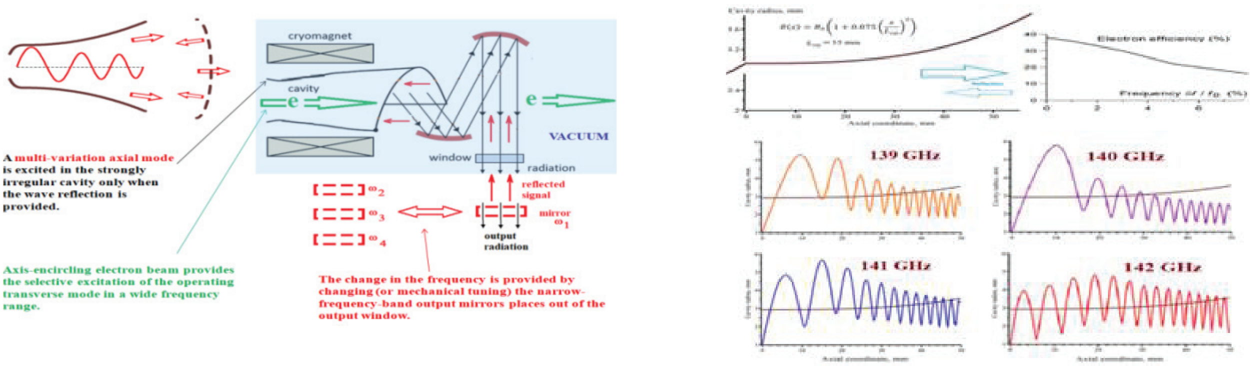


Fig.1. (a) Schematic of the gyrotron with the external frequency-tunable mirror. (b) Simulations of the frequency-tunable gyrotron. The resonator profile, calculated axial structures of waves excited at different frequencies, as well as the dependence of the efficiency on the frequency.

We present a design and results of preliminary simulations of large-orbit gyrotrons at the fundamental (the frequency is close to 140 GHz) and the second (~280 GHz) cyclotron harmonics. Simulations predict selective excitation of different axial modes in a wide (~10%) frequency band with a relatively high (20-35%) efficiency of the electron-wave interaction (Fig. 1 b). In addition, we discuss possible designs of of the external mirrors, which should have the following properties: operation in the sub-terahertz frequency range, smooth adjustment of the reflection frequency in the band of the order of 10%, and a narrow (less than 1%) frequency band when operating at a given frequency (this is needed to provide single-mode operation).

The work was supported by the Russian Science Foundation, Project # 22-19-00490.

## SUB-TERAHERTZ QUASI-OPTICAL GYRO-BWO WITH ONE-OCTAVE FREQUENCY TUNING BAND

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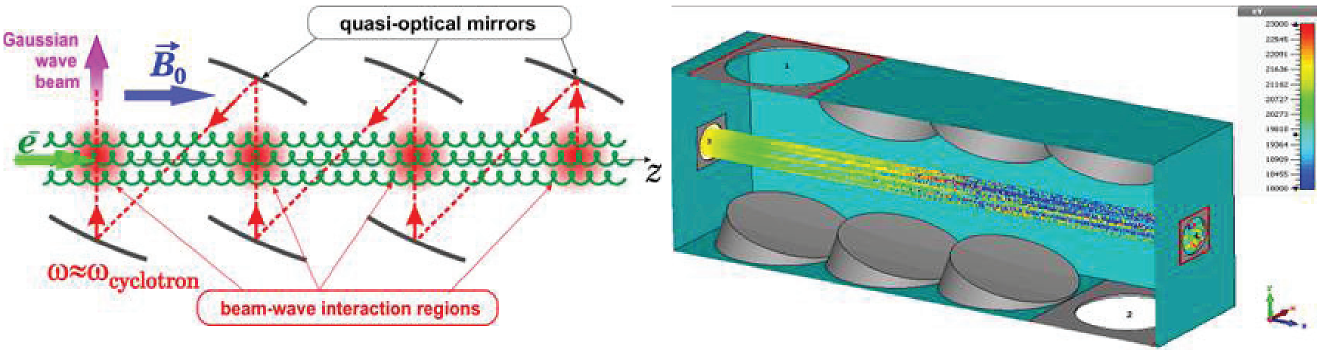
A gyrotron backward-wave oscillator (gyro-BWO) is a variety of cyclotron resonance maser (CRM), which differs from a gyrotron (the most developed version of CRM) by the capability of much wider and smoother oscillation frequency tuning band (see e.g. [1], [2]). However, in conventional smooth-waveguide gyro-BWOs, the frequency tuning is, as a rule, piecewise with strong variations in the power and spatial structure of the output radiation [3]. In [4], we proposed a concept of a CRM, based on the use of an open quasi-optical (QO) mirror transmission line as a microwave circuit, in which a Gaussian wave beam is directed by mirrors along a zigzag path, so that its periodic intersections with the electron beam occur at right angles (Fig. 1). 3D Particle-In-Cell (PIC) simulations show that such a configuration is prospective for implementation of relatively high-power short-millimeter-wave amplifiers and oscillators with extremely wide frequency tunability.




a) b)

Fig. 1. Schematic layout (a) and CST model (b) of a gyro-BWO with 3-period zigzag QO transmission line.

At the Conference, design of a proof-of-principle experiment on realizing of such a broadband frequency-tunable gyro-BWO will be presented. A general layout and results of computer modeling of major experimental components (interaction circuit, electron gun, output microwave system etc.) will be discussed for a CW device using a cryomagnet with the B-field of 4-8 T. According to CST simulations and the simplified theory [5], the designed gyro-BWO ensures output of nearly Gaussian wave beam of kilowatt power level at any predefined frequency within 107-215 GHz range. A feasibility of the higher-frequency (up to nearly 600 GHz) device operating with the use of a 20-T magnet will be also discussed.

The work was supported by the Russian Science Foundation under grant No. 21-19-00443, https://rscf.ru/project/21-19-00443/.

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## CHANGING THE SPECTRAL COMPOSITION OF TERAHERTZ RADIATION FLUX GENERATED DUE TO BEAM-PLASMA INTERACTION IN CASE CONDITIONS OF BEAM INJECTION ARE VARIED

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Some of collective processes in plasma result in the conversion of plasma Eigen oscillations into electromagnetic waves (EM), which can escape into free space. The frequency of the escaped radiation is located in area of the plasma frequency and for the plasma density above $10^{14}$ cm$^{-3}$ its value is belong to the terahertz (THz) range. Pumping the plasma oscillations by a relativistic electron beam (REB) with kiloampere current gives opportunity to obtain escaped radiation fluxes with multi-megawatt power level [1]. Studies on radiation generation in a beam-plasma system are carried out at the GOL-PET facility in the Budker Institute of Nuclear Physics [2]. The pumped waves are transformed into EM ones due to the mechanisms described in [3].

The facility operation process is realized in two stages. At the first stage, a column of preliminary plasma with the diameter 6 cm is created in open multi-mirror magnetic trap with the mean induction 4 T. The column cross section may has significant radial gradients at the mean density value (0.5-1.5)*$10^{15}$ cm$^{-3}$. At the second stage, to pump the upper hybrid waves in the plasma, the relativistic (0.6 MeV) electron beam with the current about 10 kA and the pulse duration 6 μs is injected into the plasma column. To date, the experiment results have demonstrated ability of this system to create the directed radiation flux with the peak power about 10 MW in the (0.2-0.3) THz range [4, 5].

Recently, a series of experiments aimed at studying the process of the radiation generation in the beam-plasma system in depends on the compression degree of the REB cross section before its injection into the plasma column was started [6]. The necessary degree of the beam compression was achieved by varying the induction magnetic field in different parts of the GOL-PET facility (it means coils in areas of the accelerator diode, of the beam compression and of the plasma column). In varying of the magnetic field configurations, the plasma density profile is also changed. To check these changes from pulse to pulse and during the time of the beam injection, we measured the plasma density by two laser methods: the interferometry (10 μm) and the Thomson scattering (1 μm). Spectral composition of the escaped radiation flux was measured in frequency interval 0.1 -0.6 THz by an eight-channel polychromator. Results of these measurements will be presented in the correlation with the plasma density measurements.

Part of this work related to measurements of the plasma density and radiation spectra was supported by the Russian Science Foundation (project no. 19-12-00250).

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## APPLICATION OF A HIGH-CURRENT RELATIVISTIC ELECTRON BEAM GENERATED IN A LINEAR INDUCTION ACCELERATOR AS A DRIVER FOR A TERAHERTZ FEL

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Project of submillimeter free-electron laser (FEL) based on the relativistic electron beam ($E_e$ up to 10 MeV, $I_b$ up to 1 kA, with normalized emittance ~1100 π·mm·mrad) was suggested at BINP SB RAS in collaboration with IAP RAS [1]. In accordance to our theoretical analysis [1], the e-beam produced in the linear induction accelerator (LIA) [2, 3] with specified parameters is a suitable driver for generating pulses of coherent EM-radiation in the range of 0.3-1 THz with sub-gigawatt power level and the energy content up to ~100 J. Electrodynamic system of the FEL could be realized on the base of the oversized (⌀~40$\lambda$) highly selective advanced Bragg reflectors or oversized (⌀~50$\lambda$) Talbot structures [4, 5]. The application of such structures will provide a narrow band generation with $\Delta\omega/\omega$ ~ $10^{-4}$ at a high electron efficiency of few percent for the specified frequency range. To apply the beam for pumping the radiation in the electrodynamic system with the Bragg reflectors it is necessary to realize the magnetic compression of the beam cross-section from its initial diameter of 4 cm at the LIA exit to the size less than 20$\lambda$ (that means 20 mm for 0.3 THz and 6 mm for 1 THz).

The article presents the general design of the FEL-generator, as well as its base units: electrodynamic and magnetic systems. In order to select a technical solution for their design, 3D simulation of the beam passage in regions with a converging magnetic field inside the compression system and a helical undulator field inside the FEL electrodynamic system was performed. The main goal of this simulation was to find the necessary conditions for beam compression while maintaining its small emittance, which is necessary for highly efficient energy transfer from the beam to radiation in the FEL. In addition, other factors affecting the growth of the beam emittance are discussed [7,8].

This work was funded in part by the Russian Science Foundation, project №19-12-00212.

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## NON-EQUILIBRIUM PLASMA TORCH MAINTAINED BY CONTINUOUS RADIATION FROM A GYROTRON WITH A FREQUENCY OF 263 GHZ AT ATMOSPHERIC PRESSURE

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Sub-terahertz and terahertz frequency ranges still remain the least studied from the point of view of gas discharge physics. Investigation of terahertz gas discharge, sustained by the powerful focused beams of the electromagnetic radiation, has become possible recently due to the development of the powerful sources in this range and is of interest both from a fundamental research and from possible applications.

This work presents the results of an experimental study of the parameters of the discharge maintained by continuous focused 263 GHz gyrotron radiation in a gas flow at atmospheric pressure. The power density in the beam waist region is up to 20 kW/cm$^2$. Using the methods of optical emission spectroscopy, a significantly nonequilibrium distribution of the temperature characteristics of the discharge was demonstrated. The electron temperature is 3 eV, which is above 15 times the gas temperature. Based on the broadening of hydrogen emission lines of Balmer series due to the Stark effect, it was shown that the electron density in the plasma jet is close to the cut off value for the heating wave frequency and is about $3 \cdot 10^{15}$ cm$^{-3}$.

The studied subterahertz discharge is a promising nonequilibrium medium for modern industrial plasma chemistry. On the example of the model problem of the destruction of carbon dioxide molecules, a high degree of conversion at the level of 15% was achieved.

This study was supported by a grant from the Russian Science Foundation (Project No.22-72-00073).

# EXPERIMENTAL TESTING OF 0.7 THZ MODIFIED CYLINDRICAL BRAGG STRUCTURES BASED ON THE COUPLING OF PROPAGATING AND CUT-OFF MODES

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A new high-power terahertz-range long-pulse free-electron laser (FEL) is being developed on a base of a linear induction accelerator (5 — 20 MeV / 2kA / 200 ns) at the Budker Institute of Nuclear Physics (Novosibirsk, Russia) [1]. One of the key problems in the implementation of FEL is the development of an electrodynamic system capable of providing a stable single mode regime of narrow-band generation under conditions of significant transverse sizes. To date, the Bragg resonators proposed in [2] in the form of waveguide segments with shallow corrugation of the side walls have been widely used as electrodynamic systems of relativistic masers. However, an increase in the transverse dimensions of conventional Bragg resonators (based on the coupling of two counter propagating paraxial waves) is associated with a loss of selectivity in the transverse directions. At the same time, the advancement of powerful FEL — oscillators into the submillimeter range inevitably requires an increase in the size of the interaction space to wavelength ratio.

This is necessary, on the one hand, to form a channel for transporting an intense electron beam, and on the other hand, to reduce ohmic losses. A promising approach to solving this problem can be considered the use of the so-called modified Bragg structures, the distinguishing feature of which is the coupling between propagating and quasi-cutoff waves [3].

To implement the indicated feedback mechanism, the corrugation period should be approximately twice as long as in conventional structures. Using of cut-off waves in the modified Bragg structures leads to a significant rarefaction of the eigenmodes spectrum and, thus, to an improvement in their selective properties compared to conventional analogs. According to the modeling performed both on the basis of averaged models and FDTD method, the modified cylindrical Bragg structures make it possible to provide selective excitation of the operating mode at diameter Ø ~ 50 λ up to the THz frequency range, which seems to be sufficient for the formation of a channel for transporting intense relativistic electron beams.

The proposed Bragg structure designed and implemented by 3D printing technology to operate at a frequency of 0.7 THz has diameter 20 mm, length 50 mm, corrugation period 0.43 mm and depth 0.15 mm. These parameters provide effective coupling of $TE_{1,1}$ and $TE_{1,45}$ modes.

According to full-wave 3D simulations, the structure can selectively reflect back the operating mode with 90% power efficiency. For measurements the structure's properties at low power level, symmetrical quasi-optical converters were developed and manufactured. The single-mode waveguide output of the vector network analyzer is connected to the diagonal square horn which produces the Gaussian-like diverging wave beam. The plano-convex hyperbolic lens cuts the center part of the wave beam and flattens its phase front, the rest of the beam is absorbed by a low-reflection plastic case.

The beam structure after the lens has more than 85% of power in $TE_{1,1}$ mode of the 20 mm waveguide. After the Bragg structure, the output electromagnetic field is directed into the input single-mode waveguide of the vector network analyzer by the reversed quasi-optical converter. The transmission coefficient measurements are in good agreement with the theoretical predictions.

This work was supported by RSF grant #19-12-00212.

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## FIELD EMITTERS OF A NEW TYPE FOR SUB-TERAHERTZ GYROTRONS

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Recently, attempts have been made to create subterahertz spectroscopic gyrotrons with field emitters. Replacing thermionic cathodes with cold field emitters can significantly simplify operation and provide inertialess starting and shutdown of these miniature, but high-voltage devices. The authors continue to conduct research aimed at the creation and improvement of field emitters resistant to intense ion bombardment in gyrotrons, as well as on the development of methods for forming annular in cross section electron flows with the help of such emitters for this type devices [1–3]. The report presents results of experimental study and calculation of characteristics of new developed by the authors multitip and multilayer cathodes and electron flows formed by the electron-optical systems (EOS) with such cathodes.

The emission characteristics of cathodes, structure, and velocity spectrum of electrons in flows with magnetic confinement formed by EOS with such cathodes were experimentally studied. Electron trajectories, the distribution of the current density in the cross section of the electron flow, spectra of longitudinal (along magnetic lines) and transverse velocities were calculated for different EOS regions. Multitip silicon emitters with two-layer metal-fullerene coatings and multilayer field emitters made of brought into contact nanolayers with different work functions were studied. The metal-fullerene coating protected the tips from the destructive action of ion bombardment. Multilayer cathodes operated quite stably in technical vacuum without any protective coatings. The ion sputtering of their surface in the studied regimes slightly changed the geometric dimensions of the structures. Multitip cathodes with an optimized structure made it possible to obtain stable emission currents up to approximately 100–120 mA at current densities from the cathode up to approximately 0.5 A/cm$^2$. The optimized multilayer cathodes ensured lower emission currents in the studied regimes (no more than 30–40 mA), but the current densities from their surface reached extremely high values, approximately up to 200–300 A/cm$^2$. Obtained data indicate the possibility of using the created cathodes to ensure the operation of subterahertz spectroscopic gyrotrons of moderate power on the order of several tens of watts.

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## SINGLE-PULSE MODE CONTENT ANALYSIS OF WAVE BEAM FROM A SHORT-PULSE HIGH-POWER GYROTRON WITH PULSED MAGNETIC FIELD

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The quality of the output beam of a high-power microwave source is an important characteristic of the device. The methods of beam profile measurement and mode content analysis for continuous wave devices are well developed. Most of them record microwave-induced temperature variation in a dielectric sheet [1], [2]. However, these methods are not applicable for imaging of wave beam from short-pulse sources with low repetition rate. In this work for imaging of a beam from short-pulse sub-THz sources we applied a technique based on the visible light emission from the plasma of a microwave-induced gas breakdown, which was initiated by a metal-dielectric screen (MIGBIS plasma) [3]. That method allows to visualize the beam in a single pulse, which is beneficial for the analysis of mode content of the beam from a sub-THZ gyrotron with pulsed magnetic field [4]. This gyrotron with operating frequency of 530 GHz was used in experiments on sub-THZ gas discharge in gas flow [5]. In the experiment, several quasi-parallel beams were observed, which complicated the positioning of the gas nozzle and measurements of gas discharge parameters. To determine the cause of the wave beam nonuniformity we carried out a study, which combined the single-pulse beam imaging with the numerical simulation of gyrotron beam transformation and propagation. The radiation output system of the gyrotron consists of the profiled electron beam collector, the output window made from a 2 mm thick Teflon sheet and the external quasi-optical mode converter. The profile of the collector was optimized to minimize transformation of the operating mode $TE_{23,7}$. The output Teflon window had the significant curvature, caused by pressure difference between atmosphere and the vacuum in the tube. The calculations of mode transformation in curved Teflon window revealed, that at least 3 spurious modes with different radial index and content of 0.15 were formed at gyrotron output. The 3D modeling of electromagnetic field in the mode converter was based on a combination of EFIE integral equation solution, physical optics analysis and MLFMA algorithm. Calculated beam pattern after the mode converter is in good agreement with the experimental results (see Fig. 1(a) and Fig. 1(b)). The replacement of the Teflon window by the quartz one improved the wave beam quality (see Fig. 1(c)).

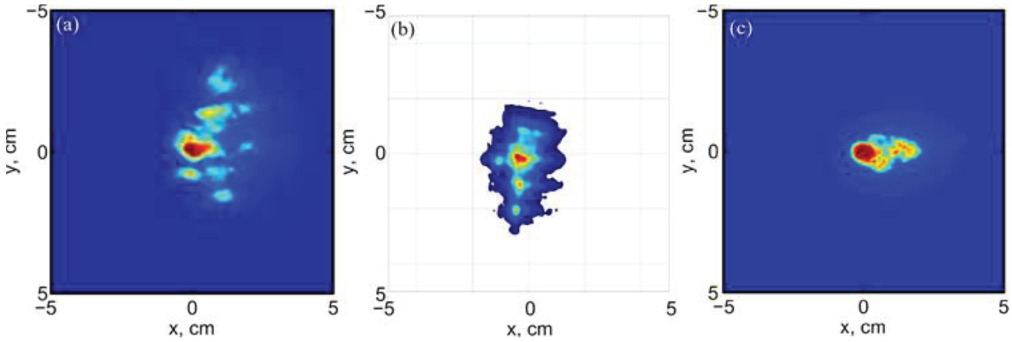


Fig.1. Measured intensity of light emission from MIGBIS plasma (gyrotron window from Teflon (a) and from quartz (c)) and calculated beam pattern (b) at the distance of 200 mm from the gyrotron.

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## PROSPECTS OF WIDEBAND FREQUENCY TUNING IN MULTI-BEAM SUB-THZ GYROTRONS

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The progress of sub-THz and THz sources in not limited to the increase of the output power and operating frequency, but also to the increase of the occupied frequency band. The frequency tunability is important both for low power devices for spectroscopy as well as the high-power systems for ECRH and current drive. In gyrotrons, the frequency tuning can be performed either step-wise, by switching of the operating modes [1, 2], or smoothly, by excitation of a series of high-order axial modes [3]. The former one can provide the frequency band close to the octave in high-power gyrotrons operating at the first cyclotron harmonic [4]. In this work we consider the prospects of the step-wise frequency tuning in multibeam gyrotrons.

We considered the addition of the active and absorbing beams to two gyrotrons. The first case is the effect of an additional active electron beam in a high-power gyrotron with operating frequency of 250 GHz [5]. The additional modes excited with the second beam allow to increase the "fill factor" — relation between the frequency band occupied by gyrotron radiation and the total tuning band. The second setup is the gyrotron operating at the second harmonic of the cyclotron frequency. With the addition of the absorbing electron beam, it opens the possibility of excitation of modes both at the fundamental harmonic and at the second harmonic, increasing the total tuning band twofold. On the basis of the 527 GHz gyrotron [6] we investigate the limitations of the electron optics, starting currents and the influence of the absorbing electron beam on the mode competition.

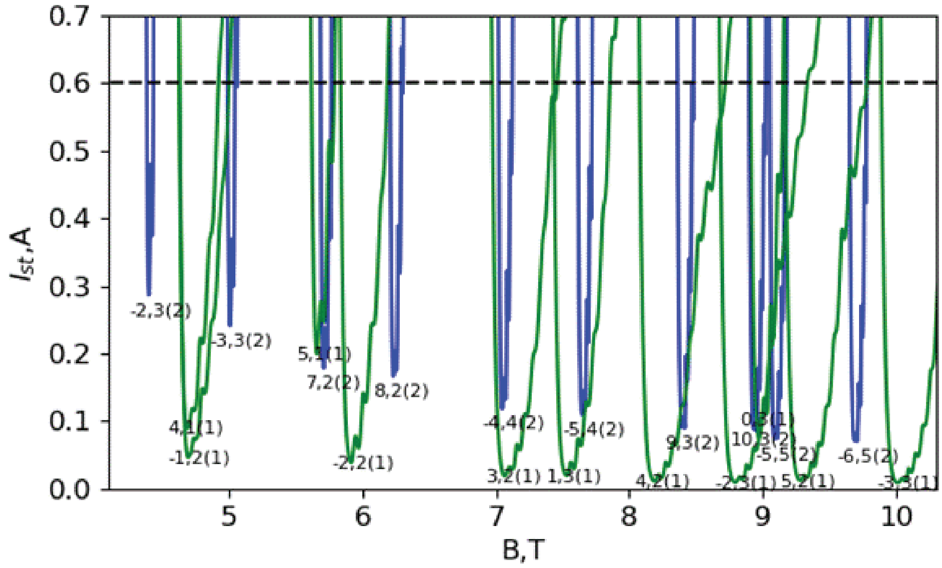


Fig. 1. Starting currents of modes at the fundamental (green) and second cyclotron harmonic (blue) in the 527 GHz gyrotron.

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## THE TECHNOLOGICAL REQUIREMENTS FOR THE MANUFACTURING OF MODERN GYROTRON RESONATORS

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The progress of sub-THz and THz gyrotrons is fueled by the development of new electron-optics systems, mode selection methods and methods of manufacturing of resonators. The resonator, being the main component of the gyrotron, has a number of requirements to the quality and precision of manufacturing. In our work we consider different requirements arising from a number of modern projects involving gyrotrons. The first requirement is on the precision of the gyrotron radius, arising from the experiments on gyrotron synchronization, mutual influence and frequency locking by external signal. In this work we present the measurements of output frequency of gyrotrons at 28 GHz (a series of gyrotrons for technological applications) [1], 170 GHz (MW-class gyrotrons for ECRH and current drive) [2] and sub-THz gyrotrons for spectroscopy [3]. Using the obtained data, we determine the maximal error in the means of $\Delta f/f$ and $\Delta r/r$ for each considered experiment. For high-frequency systems the uniformity of the gyrotron profile also becomes an issue, with even small (less than 1 μm) cone having a significant effect on the gyrotron efficiency and output power.

The electrodynamic mode selection methods impose new requirements on the profile of the resonator. The addition of resonant scattering elements [4], phase correctors [5] or sectioned cavities [6] has new limitations on the frequency matching of different elements.

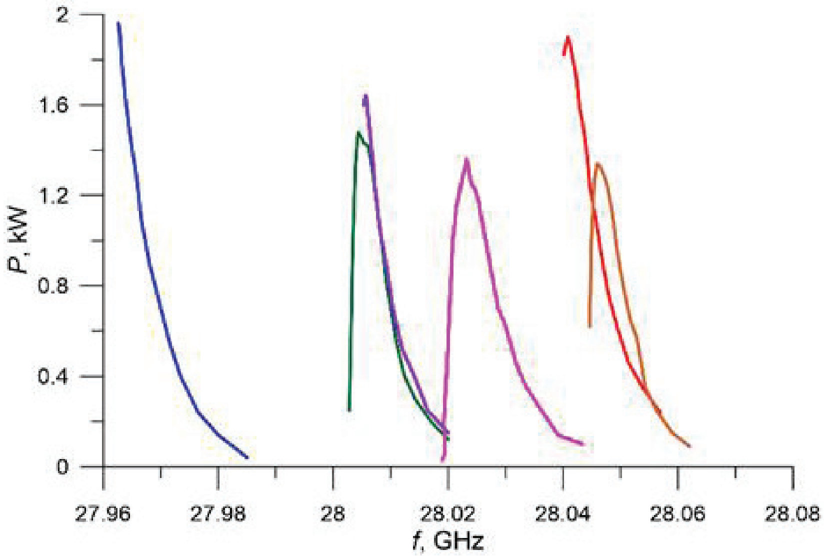


Fig. 1. Experimental dependence of output power vs. frequency for a series of 28 GHz gyrotrons for technological applications, operating at accelerating voltage of 16 kV and beam current 0.5 A.

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## GENERATION OF TRAIN OF THZ SUPERRADIANT PULSES IN THE PROCESS OF STIMULATED BACKSCATTERING OF LASER PULSE CIRCULATING IN FABRY-PEROT RESONATOR

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Generation of powerful terahertz pulses are of interest for some applications. In [1] it has been shown that such pulses can be generated in the process of superradiace (SR) by scattering of the laser pulse on a high-current relativistic electron beam. Under the resonance conditions $\omega_i - k_i V_{\parallel} = \omega_s + k_s V_{\parallel}$, laser pulse (index 'i') propagates in the forward direction while scattered radiation (index 's') has the opposite (backward) direction with respect to an electron bunch (Fig.1). In such configuration frequency of SR pulse is much less than pumping pules and belongs to terahertz band.

As an alternative to [1], where electron beam considered as quasi-continuous, in this paper we investigate scheme exploiting a periodic sequence of short electron bunches formed at photocathodes. Due to the low depletion of the pump pulse and the preservation of its shape, each act of scattering of laser radiation by the next electron bunch can be considered independent of the results of the previous interaction. In this case, it

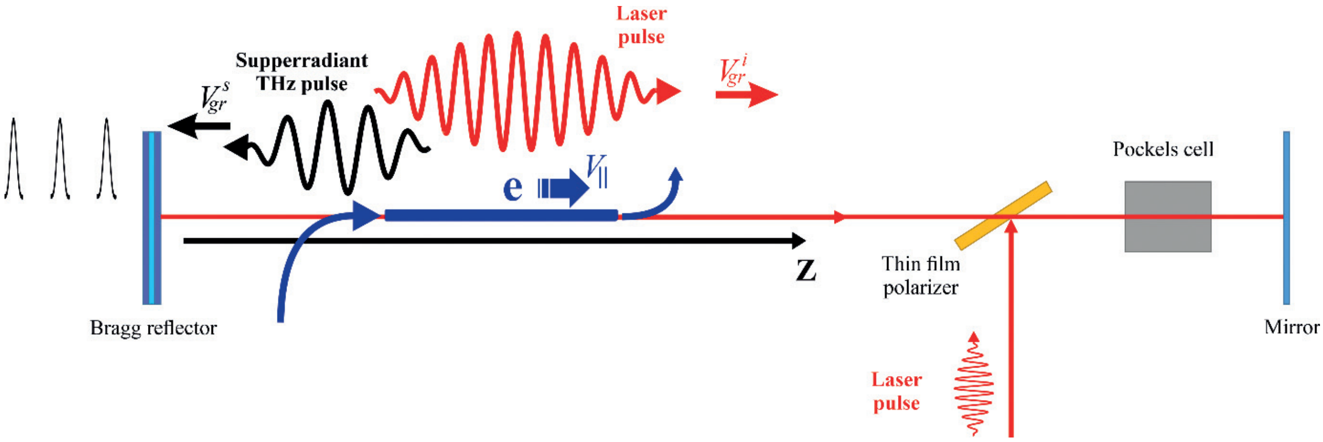


Fig.1. Scheme of generation of a terahertz SR pulses in the process of stimulated scattering of a laser pulse by a periodic sequence of electron bunches from photoinjector. Bragg reflector for laser puse is transperent for THz radcation.

is advantageous to propose a system in which a laser pulse is fed into the resonator using a Pockels cell and circulates between the mirrors of the Fabry-Perot resonator. The period of circulations should match the period of e-bunch injection. In such a scheme, generation of a periodic sequence of terahertz radiation pulses can be realized (Fig.1).

Simulations were performed for parameters of several existing experimental setups. As a pump, we take the laser pulse with a total energy of 3 kJ and a wavelength of $\lambda_i = 1.053$ µm, generated by one of the channels of the Luch/Iskra-5 laser facility [2]. As the source of the electron bunches we consider the photo-injector with the parameters of Argonne Wakefield Accelerator (AWA) [3]: current of 3.3 kA, particle energy of 2 MeV, and duration of 30 ps (the charge is up to 100 nC). Simulations show that at the interaction length of 15 mm, it is possible to generate the train of SR pulses at the central frequency of 3 THz with power of 220 kW, energy of 4 µJ and repetition period of 0.6 ns

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# BIOPHOTONICS BIOMEDICINE

## APPLICATION OF THZ HIGH RESOLUTION SPECTROSCOPY FOR INVESTIGATION OF BIOFILMS SPECIFIED FOR ENT PATHOLOGIES

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Biofilm is a community of microorganisms located on any surface, the cells of which are attached to each other or to the substrate and are covered with an exopolysaccharide matrix (glycocalix) produced by the microbes themselves to protect bacteria inside the biofilm. The physiological processes, including the production of metabolites and biologically active substances in a biofilm pass in a different way, in comparison with pure planktonic cultures of bacteria. The response of microorganisms to changing environmental conditions in a biofilm is significantly different from the response of each individual species in a monoculture. Biofilms can also be very dangerous, as they are often formed in various infectious pathologies. Biofilms appear also at ear-nose-throat (ENT) pathologies. It is known that chronic pathology of the pharynx is formed in 54-60% of children. The problem of revelation of forming the pathobiofilms at various pathologies at earlier stages is current of great importance.

The biofilms are investigated now by various methods: the XTT reductase test (where XTT is 2,3-bis-(2-methoxy-4-nitro-5-sulfophenyl)-2H-tetrazolium-5-carboxanilide), scanning electron microscopy, spectrophotometry, using thedyes etc. All these methods allow investigating the film culture microorganisms at the level of cells or macromolecules (proteins and polysaccharides).

The THz gas spectroscopy method allows to detect volatile compounds in a multicomponent gas mixture, including ones of biological origin. Therefore, it is promising to study the volatile compounds (products of thermal decomposition of macromolecules) as secondary metabolites of films, that appear when the sample is heated. The study of the main pathobionts and their ability to biofilm formation in chronic adenoiditis and hypertrophy of lymphadenoid tissue of 2-3 stages with the identification of tissue metabolites and a comparative analysis confirming the action of the pathogen were carried out with using the THz high resolution gas spectroscopy methods. The spectrometers with phase switching or with fast frequency sweeping developed by the authors, operating in the range of 118-178 GHz, were used. The sensitivity of the recorded absorption coefficient for these spectrometers at a cell length of 1 m is from $10^{-7}$cm$^{-1}$ to $5*10^{-8}$cm$^{-1}$.

The biofilms formed by Staphylococcus aureus, Streptococcus pyogenes, Klebsiella and Enterobacter were investigated. Besides the various types of agars were investigated for excepting their thermal decomposition products and revealing the set specified for the pathogens. The sets of thermal decomposition products of biofilms samples demonstrate the difference in their compositions. The results obtained will further be used to detect infection of tissues of ENT organs with specific bacteria, as well as to determine the presence of biofilms in the microflora of ENT organs.

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## COMPARATIVE ANALYSIS OF OPTICAL PROPERTIES OF SOLUTIONS OF TABLET FORMS OF LACTOSE SAMPLES BY THZ SPECTROSCOPY

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THz spectroscopy in the time domain as a way to visualize the processes of hydration and dehydration of lactose is caused by the sensitivity of the range to the presence of OH-bonds in the substance. The study of changes in the molecular structure of organic crystals by THz spectroscopy shows that this method is sensitive enough to detect the transformation of the vibrational spectrum [1]. Changes in the optical properties of tablet forms of drugs during dissolution can also be used to assess solubility [2].

The aim of the work was to study the transformation of the optical properties of lactose in the composition of tablet samples during their dissolution. The following samples were studied: lactose saturated with high dilution (HD) of antibodies (AB) to IFNg; lactose saturated with HD of purified water; intact lactose. For a more complete dissolution, the samples were ground into powder. HD refers to the sequential dilution of the original solution with intensive mechanical action on the solution at each step (≥12 steps). Solvents were used: aqueous solutions of HD AB to IFNg; HD water; purified water. The transformation of the spectral characteristics of the samples was studied using a THz spectrometer T-Spec (EXPLA, Lithuania) in the frequency range from 0.2 to 1.2 THz.

When analyzing experimental data, it was found that the use of HD AB to IFNg as a solvent to a greater extent widens the peak of lactose at a frequency of 0.53, which is most likely due to the increased activity of this solvent than purified water and HD water. Thus, it is shown that an aqueous solution of HD AB to IFNg is a more effective solvent for all tested lactose samples.

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## ANALYSIS OF BLOOD SERUM THZ-TDS SPECTRA BY UNSUPERVISED MACHINE LEARNING

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U87 glioblastoma blood serum samples were studied by terahertz (THz) time-domain spectroscopy and unsupervised machine learning methods. Spectra of tumor and control groups were collected after first, second, and third week of experiment, 6 groups in summary [1]. The measurements were taken in a special cuvette. Each sample was tested at 6 different points of cuvette producing 6 spectra. Data pre-processing was made by Savitsky-Golay filter. Considering individual tumor growth rate, we focused on cluster analysis of samples by the THz spectra similarity in the feature space and verified it by the volume of the tumor data. Following unsupervised machine learning techniques were applied: k-means, c-means, DBSCAN, agglomerative clustering [2]. We also tested Sustain algorithm [3], known to be able to cluster data according to the disease progression. The visualization of multinomial spectral data was made by principal component analysis and t-sne dimensionality reduction methods. Adjusted Rand index, Jaccard coefficient, and Fowlkes Mallows Score were chosen as performance evaluation metrics for the unsupervised learning algorithms [4]. Proposed processing pipeline presented in figure 1.

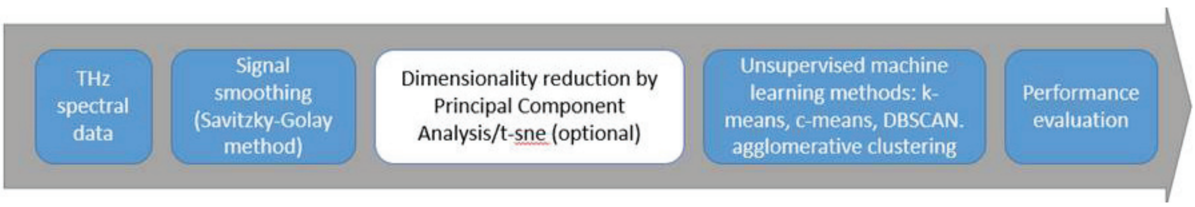


Fig. 1. Proposed processing pipeline.

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## EXPERIMENTAL STUDY OF THE VASCULAR BED OF TUMORS OF DIFFERENT MORPHOGENESIS

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In this paper, a combination of methods of diffuse optical spectroscopy (DOS) and optoacoustic (OA) microscopy was proposed to assess the structure of the vascular bed and the level of oxygenation of experimental neoplasms. The aim of the work was to compare the structure of vascular network and the level of oxygenation of experimental tumors of various morphogenesis by OA and DOS methods. To verify the DOS data, an immunohistochemical study of tumor tissues with the hypoxia marker pimonidazole was performed.

The study was conducted on female Balb/c-nude mice with subcutaneously grafted tumors based on cell lines SN-12C (human kidney cancer, n = 4), HCT116 (human colon cancer, n = 4), Colo320 (human colon cancer, n = 4). The study was carried out when average tumor volume reached 700 mm3 on the 29th day of growth of HCT116 and Colo320 tumors, and on the 125th day of growth of SN-12C.

For OA and DOS studies, animals under isoflurane anesthesia were fixed in a position on their side on a portable support plate with an opening for the study area above the OA sensor of the microscope. Two facilities (IAP RAS) were used for such experiments. The first one, for OA, based on the laser with a wavelength of 532 nm and a repetition frequency and pulse duration of 2 kHz and 1 ns was used [1].

Another one, for DOS method, use an optical probe made of four fibers using an LED with a wavelength of 400-700 nm as a source and a spectrometer as a detector [2].

For immunohistochemistry, pimonidazole was injected intraperitoneally and after 45 minutes tumors were extracted. After the tumors were removed, they were subjected to deep freezing and several cryosections were made.

The sections were stained using mouse monoclonal antibodies to pimonidazole conjugated with fluorescinisothiocyanate. The relative hypoxic fraction was calculated as a percentage of the area of PM-positive zones from the total area of the sample.

Finally, it was shown that SN-12C tumors are characterized by a low growth rate compared to Colo320 and HCT116. By the DOS method, Colo320 showed an increased hemoglobin content and a reduced level of blood oxygen saturation compared to SN-12C and HCT116. The reason for the reduced oxygenation is the high content of deoxyhemoglobin, which characterizes the oxygen consumption of tissues.

With the help of OA visualization, the absence of a regular structure of the vascular network of all experimental neoplasms is shown. The Colo320 tumor is characterized by the presence of extensive hemoglobin-containing structures presumably hemorrhages.

The immunohistochemical method revealed higher values of the relative hypoxic fraction in Colo320 compared to SN-12C and HCT116, which confirms the results of the DOS.

The work was supported by the grant of the Russian Science Foundation No. 21-15-00032.

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# THE EFFECT OF TERAHERTZ RADIATION ON THE BLOOD ANTIOXIDANT STATUS IN EXPERIMENTAL THERMAL INJURY

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The therapeutic effect of terahertz (THz) waves on biological tissues is a promising non-invasive treatment technique that promotes accelerated regeneration of damaged tissues, activation of vascular trophism and oxygen saturation of the blood, which is especially important in the treatment of thermal injuries [1,2]. The aim of work: to evaluate the effect of THz radiation on the blood antioxidant status in experimental thermal injury (TI).

The studies were carried out on 30 Wistar rats weighing 300 g. with accordance with ethical standards and rules of good laboratory practice (GLP).

The animals were divided into 3 groups: 1 — intact animals, 2 — control, 3 — experimental. Animals of the control and experimental groups under anesthesia simulated a contact-thermal burn. For physiotherapy of rats of group 3, an experimentally developed device (155 GHz) was used (IPF RAS, N. Novgorod). Animals of groups 2 and 3 were withdrawal from the experiment on the 7$^{th}$ day. Blood were stabilized with sodium citrate (1:4). The activity of oxidoreductases (superoxide dismutase (SOD), glutathione reductase (GR), glucose-6-phosphate dehydrogenase (G6PD) was evaluated in the twice-washed erythrocytes hemolysate by spectrophotometry [3]. The level of triene conjugates (TC) and Schiff bases (SB) was determined in blood plasma on a spectrophotometer SF PE-5400 (Russia) [3]. Statistical data processing was carried out using the program Statistica, version 6.0, using the nonparametric criteria.

An increase in the activity of antioxidant enzymes of the experimental group was found: SOD by 20,215% (p=0,0007), GR by 174,723% (p=0,0006) compared control. The data obtained indicate that THz radiation of 155 GHz contributes to inactivation of free radical production and reduces oxidative stress that occurs during TT. GR performs an important function in protecting the structure of erythrocytes from emerging peroxide compounds, therefore, the activation of the enzyme at the influence of THz lead to an increase in the erythrocyte resistance at the TI.

There was a statistically significant increase in the activity of G6PD by 175.672% (p=0,0007) in the experimental group compared with control, indicating an intensification of the pentose phosphate. Probably, THz radiation contributed to an increase in the NADPH coenzyme in the blood, generated by G6PD, necessary for the work of GR, thereby reducing the processes of free radical oxidation (FRO) and hypoxia in general[4]. To assess the pro-oxidant status of blood at TI, the level of LP products were evaluated. It was found that under the influence of THz waves the level of TC significantly decreased by 9,039% (p=0,031), SB by 16,867% (p=0,012) compared with the control group.

The decrease of the LP products level in the blood of the 3$^{d}$ group rats may be associated with an increase of antioxidant enzymes activity under the influence of THz radiation, as well as the activation of respiration processes, due to the acceleration of the pentose phosphate pathway.

It was revealed that THz radiation of 155 GHz range has a corrective effect on the blood antioxidant status in experimental thermal injury, aimed at normalizing the specific activity of antioxidant enzymes, as well as reducing the level of FRO destructed proteins and lipids.

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## BREATH AIR SAMPLES ANALYSIS USING IR AND THZ LASER SPECTROSCOPY AND MACHINE LEARNING

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The report is devoted to implementations of machine learning pipeline for IR and THz laser spectroscopy data to create prediction model suitable for medical diagnostics. This problem is connected with a decomposition of a complex gas mixture samples using its absorption spectrum, informative features extraction and effective classification methods selection. The informative features can be extracted from breath air samples absorption spectra profiles or volatile molecular compounds contained in a breath concentration profiles. The latter approach requires special methods of spectral inverse problem solution because the breath air content is not a priori known. A choice of acceptable classification methods is mostly defined by the ability to work well with small-volume datasets.

We will discuss the ways and demonstrate examples of above mentioned problems' solution.

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## ANALYSIS OF SPECTRAL CHARACTERISTICS OF COLLAGEN SOLUTIONS IN THZ SPECTRUM REGION

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In the region of terahertz (THz) frequencies, there are strong absorption lines of many substances, as well as the vibration frequencies of many biopolymers, which are sensitive to the geometric shape of the molecule, its environment and play an important role in biochemical reactions. The advantage of terahertz spectroscopic approaches is that they allow the measurement of amplitude and phase information, which are directly related to the absorption coefficient and refractive index of proteins. Morphological studies of dehydrated tissues (paraffin blocks) in the THz region of the spectrum show a good correlation with histological analysis. However, the use of fixation reagents when creating a histological preparation affects the structure and chemical properties of proteins. When examining biological samples, it is important to understand how formalin fixation can affect THz absorption spectra. The aim of this work is to analyze the spectral characteristics of collagen type 1 solutions in the THz spectral region in the frequency range 0.2-1.1 THz.

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## BIOMEDICAL APPLICATIONS OF NEAR-FIELD MICROWAVE TOMOGRAPHY: STATE-OF-ART AND FUTURE PERSPECTIVES

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The study of the dielectric properties of biological objects has been carried out for more than half a century, but during this period both the methodological support of the technology and the physiological and pathological standards for various conditions remain controversial. Active microwave sensing methods based on various physical principles of signal reading and processing have become the most widespread in biomedical research.

One of the options for the implementation of the diagnostic technology under study is the near-field sensing principle, which allows an integral assessment of the dielectric characteristics of subsurface structures at a depth corresponding to the distance between the generating and receiving parts of the applicator. Modification of this parameter allows not only to obtain data on the integral dielectric properties of a biological object, but also, in the presence of a full-fledged primary information processing apparatus, to carry out its tomographic examination.

Currently, most experimental and clinical work in the field under consideration is focused on the analysis of the structures of a biological object by integral indicators — dielectric permittivity and conductivity. It should be noted that the vast majority of publications on this topic were made without the use of a tomographic approach. The authors also use a wide range of microwave antennas operating at frequencies in the range of 10 MHz-30 THz.

At the same time, it was found that for different types of tissues, it is necessary to use specific frequencies within the specified range. In addition, visualization of individual structures or pathological formations in some cases determines the choice of special probing frequencies. At the same time, it is fundamentally possible to isolate a universal frequency range at which it is permissible to evaluate the dielectric properties of various organs and tissues, as well as real biological objects that are a combination of heterogeneous permeability and conductivity components.

The data we have obtained allow us to speak about the informativeness of such an approach. Based on many years of own research and analysis of literature data, the diagnostic value of near-field resonant microwave sensing of biological tissues in solving diverse biomedical and veterinary tasks is shown.

## MICROWAVE MONITORING OF ORGAN VIABILITY DURING TRANSPLANTATION

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In world practice, there are no express methods for diagnosing the viability of organs during transplantation. The evaluation of viability during transplantation is carried out on the basis of subjective conclusions. The organoleptic properties of the organ are taken into account: color, consistency, appearance.

The processes of tissue ischemia and reperfusion complications can be recognized only by biopsy followed by electron microscopy, which takes a long time. When transplanting an organ, the loss of several hours is unacceptable.

As is known, pathological processes in the human body are accompanied by changes in the electrodynamic characteristics of tissues (dielectric permittivity and conductivity). This physiological fact is the basis for the method of assessing the viability of organs during transplantation.

The method of measuring the electrodynamic parameters of organ tissues is as follows. The area of the medium located in the near field of the probing electrically small antenna affects its impedance. If the antenna is included as a load in the resonant system, then by shifting the resonant frequency and changing the Q-factor, it is possible to judge the electromagnetic parameters of the medium near the antenna and evaluate the properties of the object under study by them. A high-quality microwave resonator on a piece of coaxial cable or a two-wire line was used as a resonant system. Spatial resolution and sensitivity were determined by the design and dimensions of an electrically small antenna.

Preliminary experiments were conducted on laboratory animals (rabbits) and organs removed during surgery in humans. The process of multi-organ sampling for transplantation was completely simulated. The studied organs were washed through the arteries with a preservative solution of "custodiol" until the blood was completely washed out. The dynamics of changes in the electrodynamic characteristics of the parenchyma was studied at room temperature and at a temperature of 5°C.

Comparison of the obtained data with histomorphological changes in tissues (for this purpose, a biopsy was used) made it possible to create a scale of correspondence of electrodynamic parameters with the degree of viability of the transplant organ.

## THE IMPACT OF TERAHERTZ RADIATION ON STRESS RESPONSE SYSTEMS OF PROKARYOTES

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This story began with acquaintance with a group of physicists who in 2003 were completing the creation of the Novosibirsk free electron laser. Nowadays terahertz (THz) frequency range is widely used, especially in the fields of security inspection and medical diagnostics.

We have shown absence of direct mutagenic and genotoxic effects for pro- and eukaryotic cells of THz radiation. It was found that the oxidative stress system and homeostasis of transition metal ions system are sensitive to the presence the THz irradiation impact on E.coli cells, while antibiotic response was not affected.

Under THz irradiation of E. coli cells, cell aggregation controlled by the genes tdcABCDEFGR and matA–F was launched, whereas cell motility was suppressed (gene yjjQ), as well as the process of cell division (genes dicABCF, FtsZ, and minCDE).

We observed synthesis of adhesins (genes sfmACDHF) and stabilization of cell envelope (genes yjbEFGH and gfcA). Cell aggregation and biofilm formation are known to increase resistance of cultured E. coli to all stressors including THz radiation. Fine structure of type 1 pili was studied by electron microscopy after the exposure of E. coli cells to THz radiation, and the results reveal that this treatment causes extensive bundling of pili and gives rise to bundle-like structures (filaments) consisting of two, three, or four docked pili as well as it disturbs cell envelope morphology and inhibits cell division.

We are currently continuing experiments with thermotolerant bacteria in the hope of understanding the difference in the response of their genome to THz radiation. Specific feature of the thermophilic bacterium G. icigianus response to THz irradiation is impaired activities of the electron transport chain, cellular metabolism, and of some components of translation. This observation is confirmed by the rapid and sustained activation of the cellular systems that compensate for the inhibition of the respiratory and glycolytic systems, namely, upregulation of ATP synthase and a wide range of enzymes generating NADH.

On the other hand, G. icigianus cells proved to be sufficiently resistant to stress. They demonstrate a rapid recovery (to baseline) of systems having chaperone, protease, nuclease, and antioxidant activities together with partial restoration of the accuracy and efficiency of the translation system in 10 min after THz irradiation.

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## FEATURES OF THE USE OF TERAHERTZ RADIATION IN BIOLOGICAL AND MEDICAL RESEARCH

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THz radiation has been widely used in scientific research in recent decades. The use of THz radiation in biomedical research and applications has features that must be taken into account when organizing experiments and interpreting the results of research. These features are:

Due to the absorption of THz radiation by the atmosphere in the process of evolution, living organisms have not developed a natural defense against it. The lack of natural protection requires experiments to study the effect of THz radiation on living systems, study the toxicity of THz radiation and develop standards for its safe use. The experiments performed show a significant change in the proteomic profile of irradiated bacteria and the activation of bacterial defense mechanisms. THz radiation is also convenient to use as a stressful effect on living systems and the study of defense mechanisms that have not been developed in the course of evolution. In contrast to chemical stress factors, THz radiation can be dosed over a wide range and instantly terminated.

THz radiation is non-ionizing. The frequencies of conformational vibrations of biomolecules, bonds responsible for higher orders of organization of biopolymers, and intermolecular bonds lie in the THz region. Experiments show no direct genotoxic effect of THz radiation on living systems, but there is a significant change in the proteomic profile. THz radiation can affect both the translation of RNA and proteins, and the operation of the DNA repair system. Based on the determination of the frequencies of conformational vibrations of successive parts of DNA, direct DNA sequencing is possible.

The concept of "water" should be understood as a solution, while nano and picomolar additives can significantly change the properties of "water", the same applies to saline solutions. This is especially important in the application of THz radiation in medical diagnostics based on spectroscopic methods and absorption of THz radiation by tissues.

The characteristic thickness of THz radiation absorption by saline solutions is tens of microns. A good organization of experiments on the effect of THz radiation on living systems is given in the article [1]. THz radiation passes through a double-disk obturator with an adjustable aperture. The adjustable hole allows you to adjust the average irradiation intensity and set the required sample temperature. Changing the average power of periodic laser radiation and an adjustable aperture allow you to change the peak intensity of irradiation. The sample is placed in a special cuvette — the sample thickness of 40 microns is selected for uniform irradiation throughout the volume. When biosamples are irradiated with THz radiation, it is heated. To control the temperature of the paragraphs, a thermal imager with an accuracy of 0.03 degrees was used.

Examples of experiments using THz radiation are given: soft non-destructive ablation for a new method of mass spectroscopy and obtaining ultrapure biopolymers, ablation of living tissues in surgery and diagnostic methods.

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## SENSITIVITY OF THE HUMAN NEURONAL-STEM-LIKE CELLS TO THZ RADIATION

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Recent progress in developing high-power sources of THz radiation have resulted in an exponential increase of the number of studies of induced biological effects in cells (see the reviews [1,2]). In this report a system for long-term cell irradiation [3] was used for exposure of human neural progenitor cells (drNPCs) and neuroblastoma cells (SK-N-BE (2)) to high-power pulses of THz radiation.

OH1 organic nonlinear crystal with high coefficient of second-order nonlinearity pumped by near-infrared femtosecond laser pulses was applied to generate THz radiation. Broadband (0.1-3 THz) sub-picosecond (0.5 ps) pulses of THz radiation were focused to a spot of about 0.5 mm with intensity of 20 GW/cm$^2$ and electric field strength of 2.8 MV/cm. High peak power of THz pulses helped to overcome strong THz absorption of water, penetrate the culture medium, and reach the cell culture.

Phosphorylation of histone H2AX at serine 139 has first been found in cells exposed to ionizing radiation and is considered to be one of the most sensitive biomarkers for assessing genotoxicity [4]. Immunofluorescent analysis (Fig. 1) with subsequent estimation of foci number per cell in both experimental and parallel control groups was performed. The number of histones per cell (1.97±1.60) in neuroblastoma (SK-N-BE (2)) after irradiation for 30 min exceeded that (1.36±1.44) in control group by ~1.5 times. These differences however were not statistically significant. Zero foci were found in drNPC groups. The conducted experiments demonstrated that exposure of healthy and tumor cells to THz pulses did not cause genotoxic effect nor did they lead to a statistically significant change in proliferative activity.

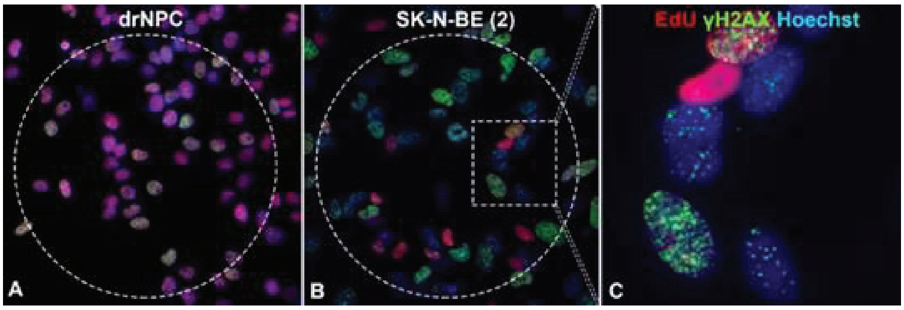


Fig. 1. Immunofluorescent analysis of γH2AX foci in (A) SK-N-BE (2) and (B) drNPCs. (C) Enlarged area of (B).

The reported study was supported by the Ministry of Science and Higher Education of the Russian Federation (State Assignment No. 075-01056-22-00). The experiments were performed using the unique scientific facility "Terawatt Femtosecond Laser Complex" in the "Femtosecond Laser Complex" Center of the Joint Institute for High Temperatures of the Russian Academy of Sciences.

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## STUDY OF THE EFFECT OF TERAHERTZ RADIATION ON THE PROCESSES OF TISSUE ISCHEMIA IN AN EXPERIMENT

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The aim is to investigate the effect of THz–band EMR on the functional and biochemical parameters of rats in the process of reparative regeneration. Animals (n=15) were divided into 3 groups: 1st — intact, 2nd — operated (skin flap), 3rd — operated with THz EMR irradiation at a dose of 0.12 MJ. The duration of the experiment is 7 days . The concentration of glucose, lactate, activity of lactate dehydrogenase (LDH), superoxide dismutase (SOD) and catalase were determined in the blood. Microcirculation was assessed by the LDF method. In the erythrocytes of animals of the 2nd group, a decrease in the activity of SOD by 16% was noted. In group 3, the activity of SOD and catalase increased by 30% and 12%, reaching intact indicators. EMR irradiation contributed to a decrease in the concentration of lactate in plasma and erythrocytes by 34% and 51%, respectively. EMI THc caused an increase in LDH activity. Irreversible vascular changes in the flap of animals of the 3rd group were less pronounced compared to the 2nd. It has been shown that the EMI of THz 110-170 GHz in ischemia led to an increase in the antioxidant status and energy metabolism of the blood, as well as an improvement in microcirculation.

## THE INFLUENCE OF ARGON COLD PLASMA ON DIELECTRIC PROPERTIES OF THE RATS' SKIN

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Currently, plasma medicine is one of the most dynamically developing areas of biomedical science, due to the wide range of biological effects of cold plasma and its diverse clinical applications. On the other hand, achieving a full-fledged effect of cold plasma therapy is possible only if its molecular-cellular and systemic mechanisms are disclosed. In particular, an important aspect is the assessment of the functional state of tissues at the site of exposure to cold plasma, however, the range of methods of lifetime and associated with the need for biopsy monitoring of the structural and functional response to the physical factor in question. One of the informative methods suitable for solving this problem is subsurface microwave sounding, but such studies are not presented in the literature. In this regard, the aim of the work was to study the modification of the dielectric properties of rat skin when treated with argon cold plasma in various modes.

The study was performed on 40 adult male Wistar rats (body weight — 250-300 g), randomized into 4 equal groups. No manipulations were performed with animals of the first group (n=10), except for a single microwave study. The rats of the second, third and fourth groups (n=10 in each) were treated with a pre-epilated section of the back (2x2 $cm^2$) with a gas stream for 10 consecutive days. This stream contained non–ionized argon for animals of the second group, or argon cold plasma (processing time — 1 and 2 minutes for the third and fourth groups, respectively). The dielectric properties of the skin and underlying tissues of rats were studied by the method of near-field resonant microwave sensing using a specialized hardware and software complex. The main parameter to be evaluated was the dielectric constant.

It was found that the treatment of animals with argon flow reduces the level of dielectric permeability of the skin at probing depths of 3 and 5 mm by 14.9 and 11.0% relative to intact animals, whereas the use of argon cold plasma for 1 minute practically does not change this indicator, and an increase in the exposure time of the factor to 2 minutes causes its increase by 9.3 and 8.6% accordingly.

## THE POTENTIAL OF TERAHERTZ SPECTROSCOPY FOR CANCER DIAGNOSIS

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Early diagnosis of oncology can be achieved by analyzing blood plasma [1, 2]. Terahertz (THz) time-domain spectroscopy and machine learning were used to study liquid and lyophilized blood plasma of healthy individuals and those with malignant tumors. We examined samples with c cholangiocarcinoma [3], glioblastoma [4] and malignant thyroid nodules [5]. The oncology molecular marker levels were correlated with the sample's absorption at 1 THz. Machine learning methods were used to separate groups of samples from patients and healthy individuals, as well as to differentiate the stage of oncology. Achieved prediction accuracy, sensitivity, specificity were over 90%. A relation was established between tumor size and the THz spectral profile of blood plasma samples. Thereby, the possibility of early detecting of oncology using blood plasma spectral patterns in the terahertz range was demonstrated.

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# DETECTION OF GLIOMA MOLECULAR MARKERS BY TERAHERTZ NANOANTENNA SENSOR

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Gliomas are invasive brain tumors with high rates of recurrence and mortality [1]. It has been shown that specific markers for glioma's differential diagnostics are enantiomers of 2-hydroxyglutarate (L-2HG and D-2HG) in brain tissues and blood [2]. These isomers have unique absorption peaks originating from vibrational and rotational transitions in their molecules. In particular, the peaks centered at 1.337 THz and 1.695 THz correspond to L-2HG and D-2HG isomers, respectively [3].

The goal of this work is to develop highly efficient frequency-selective sensors for L-2HG and D-2HG isomers using the effect of nanoantenna-assisted plasmonic enhancement of THz absorption. Such an approach provides a noticeable increase in detection sensitivity versus direct non-resonant methods. We present the numerical results of the design optimization for L-2HG and D-2HG sensors based on Si/SiO2-wafer-backed arrays of golden nanoantennas of linear geometry.

The optimal structural parameters of the arrays found through integral averaging of the square of the surface electric field over an array unit cell are recommended for further nanolithographic fabrication of this kind of THz sensor. In this work, we present description of the experimental implementation for this sensor using E-beam lithography and its characterization with a THz-TDS system [4].

Nanoantenna sensor designed for L-2HG with the resonant frequency of 1.337 THz was tested with different amount (0-11 ng) of L-2HG. No noticeable resonance frequency shifts compared to the bare Nanoantenna sensor were revealed. On the other hand, we see a decrease in the resonant transmission minimum when changing the L-2HG quantity.

Then the NA sensor was cleaned and tested on the same amounts of D-2HG. The mechanisms of the THz spectral response and possibility of selective determination of L-2HG are discussed.

The work was supported by the Russian Foundation for Basic Research, project 19-52-55004, by the Ministry of Science and Higher Education of the Russian Federation within the State assignment FSRC "Crystallography and Photonics" RAS, by the Interdisciplinary Scientific and Educational School of Lomonosov Moscow State University "Photonic and Quantum Technologies: Digital Medicine". The authors acknowledge the Equipment of the Center CKP "VTAN" (ATRC) of the NSU Physics Department.

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# SUPER-RESOLUTION THZ IMAGING OF HETEROGENEOUS BIOLOGICAL TISSUES: FINGERPRINTS OF THZ-WAVE SCATTERING IN TISSUES

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Methods of THz spectroscopy and imaging have been widely used in various fields of science and technology in recent decades. Biomedical applications of THz technology are of particular importance [1–7]. Due to the relatively low spatial resolution of traditional THz optical systems, the effective medium approach is commonly used to describe the interaction between THz waves and tissues, while the tissue is considered to be homogeneous and isotropic at the THz-wavelength scale, and various relaxation models are used to define the tissue dielectric response at THz frequencies. At the same time, it is known that biological tissues consist of many structural elements (cells, microfibrils, organelles, etc.), some of which have mesoscale dimensions ~$\lambda$, where $\lambda$ is a THz wavelength. Such tissue elements and heterogeneities can lead to the Mie scattering in the THz range. In addition, there is a structural anisotropy of tissues (inhomogeneity in the size and arrangement of scatterers, fiber stacking direction), which is not taken into account when describing the THz-wave — tissue interactions. Thus, the mainstream approach based on the effective medium theory significantly limits capabilities of THz spectroscopy and imaging in biophotonics, may lead to a noticeable dispersion in the measured effective THz optical properties of tissue and, thus, reduce the THz diagnosis efficiency.

Thereby, novel approaches to describe the THz-wave — tissue interactions are required, that take into account both absorption and scattering effects. In order to mitigate this challenge, in our work, we use the polarization-sensitive super-resolution quantitative THz solid immersion microscopy [8–13] to study heterogeneous tissues, such as the rat brain [13]. We observed, for the first time the structural optical anisotropy of *corpus callosum* caused by directed stacking of neural cells. We also reveal structural tissue heterogeneities that can cause Mie scattering of THz waves, such as fat cells embedded into fibrous connective tissues of the human breast. Then, we perform theoretical studies of THz-wave scattering in such tissues using analytical methods of the Mie scattering theory and the radiation transfer theory, while the observed results are verified by the THz pulsed spectroscopy of tissue mimicking phantoms. Information about the tissue structural anisotropy and the scattering effects is useful for further developments of THz biophotonics and medical imaging.

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# COMPONENTS OF MICROWAVE AND THZ SYSTEMS

## MONOATOMIC LAYER TRANSITION METAL DICHALCOGENIDES AS A WAY TO IMPROVE THE CONVERSION OF SPIN-POLARIZED CURRENT

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The efficiency of THz radiation generation by hybrid spintronic emitters Co/$WSe_2$ and Co/$MoSe_2$ has been experimentally investigated. The effect of a transition metal dichalcogenides (TMDs) monolayer on the generation of THz by the studied structures is described. The effect of the wavelength of exciting laser radiation on the efficiency of THz generation is estimated.

The terahertz (THz) frequency range (0.1-30 THz) is currently the most studied and promising for use in many areas of human activity [1]. Studies of the last decade have demonstrated such a type of THz emitters as spintronic emitters [2-4]. The principle of their operation is based on spin effects (reverse spin Hall effect, ultrafast demagnetization, etc.), which allows using magnetic influence to control the properties of THz radiation generated by them [5].

In the article [6], an increase in the efficiency of hybrid spintronic emitters based on the ferromagnetic metal (FM)/transition metal dichalcogenides (TMDs) structure was demonstrated. In our work, we continue to study such structures and consider the influence of the TMDs type on the efficiency of THz radiation generation.

In this paper, hybrid spintronic Co/$WSe_2$($MoSe_2$) emitters were studied. Monolayer TMDs films were grown by gas phase deposition on $Al_2O_3$ substrates. A cobalt film with a thickness of 3 nm was applied to the surface of the TMDs films by magnetron sputtering.

To form a strongly pronounced magnetic anisotropy in the Co layer, an antiferromagnetic IrMn film with a thickness of 5 nm, coated with a protective layer of $SiO_2$, was applied on top of it. The study was carried out by the method of terahertz time-domain spectroscopy (THz-TDS) in geometry for passage, the technique of which is described in detail in [5].

During the experiment, time profiles of THz signals were obtained, on the basis of which frequency spectra were obtained using the Fourier transform. From the time profiles, a weak influence of a specific type of TMD (~3-5%) on the magnitude of the induced THz signal was established.

The efficiency of THz generation was also investigated when the wavelength of the exciting radiation was changed to 400 nm. As a result, the efficiency of THz radiation generation decreased by ~30%, due to a strong decrease in the absorption of optical pumping by the Co film. The obtained data were compared with the results of modeling the optical absorption of the studied structure at these wavelengths. The simulation was carried out in the COMSOL Multiphysics software package.

The study was supported by the Russian Science Foundation (grant No. 21-79-10353) and RTU MIREA (grant "For young scientists" NICH-56).

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# ULTRA-DEEP WET CHEMICAL ETCHING OF GAAS UPON FABRICATION OF MMWAVE SENSORS

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Up to date, GaAs have been widely used in a variety of millimeter wave (mmWave) components and circuits. Electronics based on GaAs is ultra-fast and can be used at room temperature with no degradation of its performance. However, high permittivity of this material complicates design of on-chip input optics and power distribution networks.

Thus, mmWave circuits often suffer from an excessive substrate thickness due to moding effects, and it should be thinned for proper signal processing. To keep mechanical rigidness, substrate thinning can be performed locally which results in the appearance of so-called membrane structures.

Nowadays, mechanical thinning and inductively coupled plasma (ICP) — reactive ion etching (RIE) are usually used for geometry forming purposes upon GaAs processing. Mechanical thinning can be performed by surface grinding machines (e.g., SGM-7000A, MPS R400CV). This method allows fast (up to 60 µm/min) material removal along the entire substrate surface at the expense of surface roughness reaching 1–3 µm. It also requires flip-chip mounting of the sample which could be harmful for it and does not allow one to form complex geometries with position-dependent profiles.

ICP etching works super effectively for situations when implementation of smooth and/or strictly vertical faces is essential [1]. This method, however, requires use of special equipment such as ICP source and airlock chamber for treating toxic gases (e.g., Cl, $B_2$). Etching rates typically achieved for ICP-RIE are about 0.5 µm/min [2]. Reported maximum etch depth of 100–200 µm was achieved by ICP-RIE on 635 µm thick GaAs wafer with an etching rate of 6–8 µm/min [3].

In this paper, we report on the simple and reliable method of ultra-deep wet chemical etching of GaAs justified upon fabrication of mmWave Schottky diode detectors. The detector design is described elsewhere [4]. Local membranes in bulk semi-insulating GaAs were fabricated as follows. The AZ1512 resist was used as a protective coating due to its high resistivity to the etchant components and high suitability for lithography processes.

Dual-sided system of alignment marks was used to further co-align input optics elements on front side of the substrate with corresponding back metallized membranes. Infrared transparency of GaAs was used to cross-measure positions of the alignment marks on front and rear surfaces of the substrate. The observed offsets were accounted for during the photolithography of windows in protective coating. An orthophosphoric acid based etchant was used. Etching process was carried out in 2 steps (2×20 min) with stirring and heating sample in etchant up to 40 °C.

Visual inspection was performed via optical microscope between the steps. Rear surface of the substrate was further covered with a 30 µm thick layer of aluminum by thermoresistive evaporation. In the end, samples of mmWave Schottky diode detectors utilizing 133±35 µm thick membranes were fabricated. Their matching with a rectangular WR-6.5 waveguide was measured over the frequency range of 118–178 GHz. The measurements revealed input reflection losses from -15 to -30 dB up to 166 GHz. This frequency also corresponds to a 3 dB roll-off in the detector sensitivity, which reaches a few hundreds of picowatt for unit frequency bandwidth. No degradation of the detector performance down to 118 GHz was observed. The experimental results agree well with electromagnetic modeling.

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# HIGH ENERGY CHERENKOV-TYPE TERAHERTZ EMISSION FROM A LARGE-SIZE SI-LINBO$_3$ STRUCTURE PUMPED BY A TI:SAPPHIRE LASER

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Generation of strong terahertz pulses plays a key role in the progress of nonlinear terahertz science. Strong terahertz pulses are mostly generated by optical rectification of femtosecond laser pulses in $LiNbO_3$ (LN) and organic crystals [1]. Due to a large velocities mismatch in LN, a tilting the pump pulse front or using a Cherenkov radiation mechanism are required [1,2]. The efficiencies of both approaches are close and ~0.1-1% [1,3]. The Cherenkov scheme, however, requires focusing the pump pulse in one or two dimensions. This limits the pump pulse energy and, as a result, the generated terahertz energy. For example, tens of nJ terahertz energy is typically generated in 50-μm thick and 10x10 mm$^2$ in size LN layer attached to a output Si prism pumped by a μJ-level laser [3].

Here, we demonstrate experimentally scaling the terahertz energy up to μJ-level using a large-size (35x50 mm$^2$) Si-prism coupled LN layer pumped by a hundreds of μJ-energy Ti:sapphire laser. We also show that nonlinear pump distortion affects significantly the distribution of the terahertz emission along the generating structure.

A large-size terahertz emitter 35×50 mm$^2$ in size with 55-μm thick LN layer and rectangular Si prism with 42° apex angle was manufactured. The beam of a Ti:sapphire laser (5 mJ, 70 fs, 1 kHz) was expanded by a cylindrical lens in one (vertical) direction to a 50-mm size and then focused (in horizontal direction ) to a 20-μm wide line to fully illuminate the LN layer. Cherenkov radiation of terahertz radiation was emitted to free space through an output Si prism and measured by a calibrated pirodetector (Gentec).

Figure 1(a) shows that for 70-500 fs and positive chirp (pump pulse is compressed in the crystal), the efficiency saturates at about 0.2%. For longer durations, the saturation efficiency drops. Pulses with a negative chirp yield smaller efficiency. The maximum terahertz energy is above 0.5 μJ. Figure 1(b)-(d) shows that for low pump energies and chirped laser pulses terahertz fluence increases in the middle and rear part of the emitter. This can be explained by compression of the laser pulse in the LN layer. For high pump energies, emission is mostly from the first several mm. To explain the obtained results we made numerical modeling taking into account kerr nonlinearity and multiphoton absorption. The calculations qualitatively explain the obtained results.

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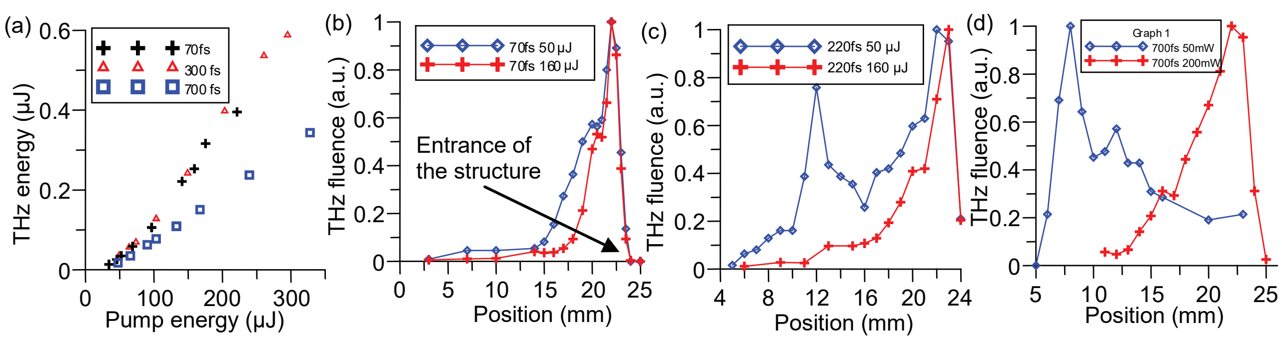


Fig. 1. (a) Terahertz energy as a function of the pump energy for different durations of the chirped optical pulse. (b-d) Distribution of the terahertz fluence along the exit facet of the Si prism for (a) 70 fs, no chirp, (b) 220 fs,, positive chirp, and (c) 700 fs, positive chirp. Red crosses — low pump energy (50 μJ), blue diamonds — high pump energy (200 μJ). Entrance facet corresponds to 24 mm.

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## AN ANTIREFLECTION COATING FOR A TERAHERTZ ISOLATOR

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Nonreciprocal radiation transmission is of great importance for the protection of sources or detectors from backscattering, and undesired radiation routing. Terahertz (THz) radiation finds its application in different systems for imaging, wireless communications, and sensing. However, the lack of THz nonreciprocal devices limits the performance of such THz systems. Recently, several approaches have been proposed for the realization of terahertz one-way transmission devices. Among them, traditional devices based on magneto-optical material [1,2] allow broadband isolation with moderate losses. The basis of such devices is a permanent magnet, which possesses a high dielectric constant and as a consequence high Fresnel reflection losses. To improve the isolator performance, it's necessary to reduce the reflection losses at the air-magnet interface. The most common way for the realization of antireflection coating is in the usage of a quarter-wave film deposition with a refractive index $n_{AR} = \sqrt{n}$. However, this approach is only applicable for narrowband reflection dampening and requires rare materials with a specific refractive index. Alternatively, subwavelength surface modification can be used for the damping of reflection losses over a broad frequency band. In our work, we present a THz isolator with reduced reflection losses in forward propagation and power transmission at least equal to 50% within the 0.1-0.3 THz. The anti-reflection coating has been fabricated in form of the subwavelength pyramid structure at the hexaferrite surface.

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## DEVELOPMENT OF F-THETA LENS FOR THZ IMAGING SYSTEM

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The dispersion of complex permittivity in THz frequency range provides information on low-frequency molecular vibrations and structural properties of matter. This allows the use of modern methods of THz spectroscopy and imaging to solve a wide range of applied problems in the areas of research of physical properties of new materials [1], quality control of pharmaceutical and chemical products [2], nondestructive control of composite materials and ceramics [3] and even cancer diagnostics [4]. Terahertz (THz) imaging is of particular interest, where scanning a planar surface is the objective of the imaging system. Instead of spherical lenses, f-theta lenses can be used as focusing optics in such systems. Such lenses are designed to provide a linear displacement of the beam as a function of the deflection angle, resulting in a constant scan rate on a planar surface. F-theta lenses produce constant spot size and imaging resolution depending on the deflection angle, which eliminates distortion at the edges of the field of view [5]. Although f-θ lenses are widely used in other parts of the optical spectrum, their design and the effect of material properties on lens performance in the THz frequency range have not been widely studied.

In this paper, robust numerical method to design custom scanning f-theta lenses in the THz range will be presented. The optical performance of lenses designed using commonly used polymers for THz optics manufacturing will be compared, namely high-density polyethylene (HDPE), polytetrafluoroethylene (PTFE), polymethylpentene (TPX), cyclic olefin copolymer (COC), and cycloolefin polymer (COP).

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# THERMALLY ISOLATED RUTHENIUM NANOBOLOMETER FOR ROOM-TEMPERATURE TERAHERTZ SENSING

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Among different kinds of room-temperature THz sensors, bolometers based on thin-film metallic absorbers draw researchers' attention with their relatively simple fabrication technology, and purely active impedance. The latter allows wideband matching with antennas and operation at high frequencies. Previously, micro-bolometers based on Nb, NbN, Ti, and Pt thin films located directly on a substrate were investigated. Studies show, that initial moderate voltage responsivity $S_v$ of such bolometers may significantly increase, when the absorber is thermally decoupled from the bulk substrate via either suspending it, or placing it on a thin membrane. However, long suspended ultra-thin film stripes have poor mechanical stability and durability, and are difficult to fabricate.

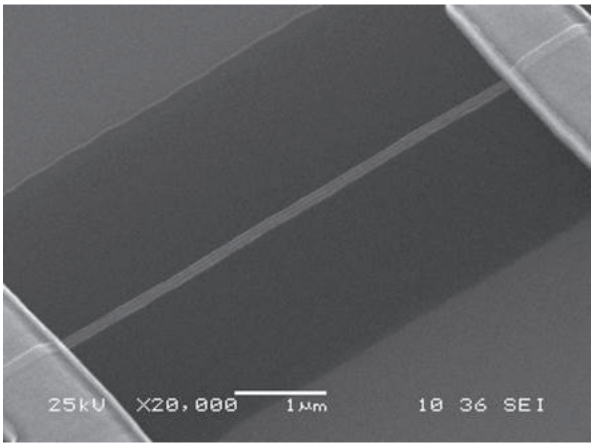


Fig. 1. SEM image of Ru absorber on top of XPMMA layer.

We propose an uncooled THz sensor, in which the absorber is separated from the substrate by a thin layer of a polymer. This allows fabrication of high aspect ratio metallic nanowires, thermally isolated from the substrate, but still located on the surface of a hard film. We fabricated and tested a number of bolometers with absorbers based on ruthenium 20 nm thin films, deposited on top of a layer of cross-linked PMMA (XPMMA) (Fig. 1). Crosslinking changes PMMA properties, significantly increasing its chemical, thermal, and mechanical stability, allowing XPMMA to withstand the heating of the absorber. The absorbers themselves were long — 6 µm, and narrow — 100 nm, Ru nanowires, fabricated using electron-beam lithography (EBL) and magnetron sputter deposition. PMMA crosslinking was also obtained with EBL.

The DC measurements have shown that the voltage responsivity of the sensors has reached 250 V/W. The value of electrical NEP estimated for the Ru bolometers is $2\times10^{-11}$ W/√ Hz [1]. This value is comparable to the suspended Ti absorber, however, employing a layer of XPMMA makes the fabrication process easier and has a big potential for further sensor optimization.

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## MAGNETICALLY CONTROLLED BAND-PASS FILTER OF TERAHERTZ RADIATION

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The work presents a magnetically controlled band-pass filter of THz radiation based on magnetic fluids. The experimental prototype of a band-pass filter consists of a cell with a magnetic fluid and a system of electromagnets. Several variants of cells filled with manufactured samples of magnetic liquids, differing in their properties, have been prepared (solid magnetic phase material, size and concentration particles). Under the influence of an external magnetic field, periodic needle-shaped agglomerates form inside the cell.

The band-pass filter is controlled by varying the value of the external magnetic field in the range from 0 to 57.2 mT. The filter was characterized using a terahertz spectrometer real time THz-TDS, in the transmission mode, in the range from 0.2 to 1.5 THz. It is show that the frequency and bandwidth of the band-pass filter depend on the material of the solid magnetic phase, on the size of the particles and on their quantity per unit volume, as well as on the value of the external magnetic field.

The developed filter demonstrates good repeatability. Provides high transmittance in the bandwidth radiation and low transmission in the suppression areas.

A mathematical model is proposed. The model is a two-dimensional analog of an experimental prototype of a magnetically controlled band-pass filter THz range based on a magnetic fluid. As a cell is considered two-dimensional square area with magnetic fluid in combination with the Navier-Stokes hydrodynamics equations, the convective transport equation on the level function and the system of Maxwell equations.

The finite element method was carried out by calculate the dynamics of a magnetic fluid depending on the properties of magnetic fluids and on the value of the external magnetic field. Calculations were performed changes in the spectral characteristics of THz radiation, passing through the formed structures. The resulting calculations qualitatively consistent with experimental data.

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## NONCOLLINEAR ELLIPSOMETRIC DETECTION OF TERAHERTZ WAVES: A COMPREHENSIVE STUDY

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Electro-optic (EO) sampling of terahertz fields by femtosecond laser pulses is an established technique of terahertz detection [1]. For efficient detection, the condition of the optical-terahertz synchronism should be fulfilled. In the standard collinear detection scheme [2], this condition can be achieved only in a specific crystal for a given wavelength λ of the sampling laser pulse, for example, in ZnTe for a Ti:sapphire laser with λ = 800 nm. Recently [3], a noncollinear detection scheme based on the Cherenkov-type synchronism between the optical and terahertz pulses was proposed. Noncollinear geometry allows one to perform efficient EO sampling in different crystals with various lasers, in particular, with inexpensive compact fiber femtosecond lasers (λ = 1.55 μm).

In this paper, we present an analytical model of noncollinear ellipsometric EO sampling detection of terahertz waves. The model allows to predict the EO signal in various practical situations.

We apply it, for example, to a 1-cm thick GaAs crystal and the probe beam wavelength λ = 1.55 μm. In this case, the Cherenkov angle in the crystal is about 12°. Figure 1(a) shows the EO signals calculated for the optical beam widths of 100, 200, and 500 μm.

For the beam width of 100 μm, the signal reproduces well the terahertz waveform. An increase in the beam width leads to an increase in the duration and decrease in the amplitude of the EO signal, which can be explained by the filtering properties of the noncollinear detection scheme. Figure 1(b) shows that filtering leads to the cutting off of the high-frequency part of the terahertz spectrum. For efficient detection, the optimal beam width is 25-100 μm.

The beams with smaller widths suffer from strong diffraction broadening, which deteriorates the optical-terahertz interaction at high terahertz frequencies.

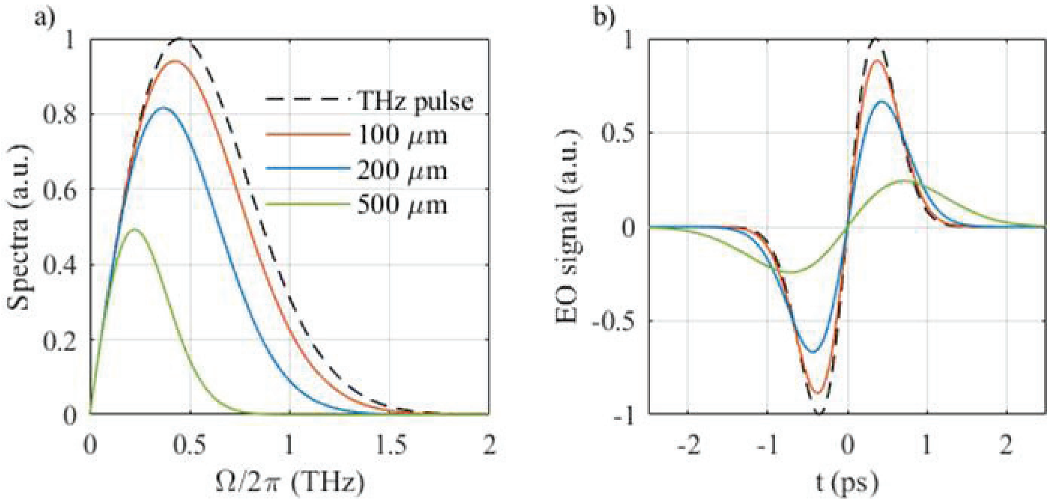


Fig. 1. (a) EO signals and (b) corresponding spectra for different probe beam widths. The dashed lines represent the waveform and spectrum of the measured terahertz pulse.

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## 3D PRINTED BROADBAND FRESNEL LENS MADE OF COC TOPAS

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To solve the problem of terahertz beam manipulation, there are different types of the optical elements. Refractive lens for THz frequency range show no chromatic aberration due to weak dispersion, but they exhibit high signal attenuation. For typical converging lenses their attenuation is higher near the centre than in the peripheral regions. This "boosts" geometrical aberrations of the lens.[1] Metalens and GRIN lenses [2-3] can also be used, however, in the case of using them, we are faced with the problem of high absorption and reflection of terahertz radiation (metalens), manufacturing complexity (GRIN lens) and inability to control the broadband beam (both). A broadband diffractive Fresnel lens can be used to solve the problem of manipulating a broadband terahertz beam. Its advantages are weak absorption of terahertz radiation, lower weight and cost.[4] Strong chromatic aberration of such diffractive element might be decreased by multiplying maximal phase retardation of Fresnel lens multilevel phase structure by p to create the $p^{th}$ order kinoform.[5] In this work the spectrum of the broadband Fresnel lens made of COC TOPAS in the frequency range of 0.1 — 2 THz was experimentally obtained for the first time. The possibility of using a Fresnel lens to control a broadband terahertz beam was investigated. The effect of material (ABS, PLA, COC TOPAS) and small deviations from the true refractive index on the performance of the Fresnel lens was studied, and also the broadband Fresnel lens with the TPX refractive lens was compared, measured using time domain spectroscopy.

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## FREE-STANDING WIRE GRID WIDE-ANGLE ULTRAWIDE BAND POLARIZERS

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Polarizers make it possible to obtain polarized radiation from radiation of arbitrary polarization. The electric field of electromagnetic wave is transmitted if polarized perpendicularly and reflected if polarized parallel to the polarizer grid array. Due to the great demand for such products, there are many principles which polarizers can be based on: liquid crystals, carbon nanotubes, thin films of aluminum on silicon dioxide, and aluminum films deposited on silicon at the Brewster angle [1]. Most of the polarizers types cannot avoid losses since there will always be a reflection from the substrate and absorption losses [2]. Free-standing fine-wire grids, parallel strands of fine wire, are deprived of this deficiency due to the absence of any substrate and behave as low-loss polarizers at DC and submillimeter wavelengths. They can withstand high power of the radiation without losing their characteristics, unlike film polarizers [3,4]. The polarizing efficiency depends on the wire spacing, which can easily be varied. These characteristics make the grids a simple and versatile spectroscopic component.

In this paper the improved method for manufacturing free-standing fine-wire grids is described. Measurements of the power reflectivity and transmissivity of grids design in the frequency range of 0.1-2 THz are presented. The extinction ratio of polarizers is not less than 30 dB in the ultrawide frequency band from DC to 2 THz. The manufacturing method allows fabricating polarizers with a clear aperture from 2 to 6 inches with potentially to expand it to 9 inches.

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## DESIGN AND INVESTIGATION OF A NARROWBAND TERAHERTZ FILTER BASED ON FABRY–PÉROT ETALON

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The Fabry-Pérot filter (FPF) was calculated and optimized in this work using the ANSYS® HFSS R19 tool. The fundamental grid design was based on the "classic" geometry of square-packed cells with square-shaped hales (Fig., on the left). On a polypropylene (PP) film, grid reflectors were applied.

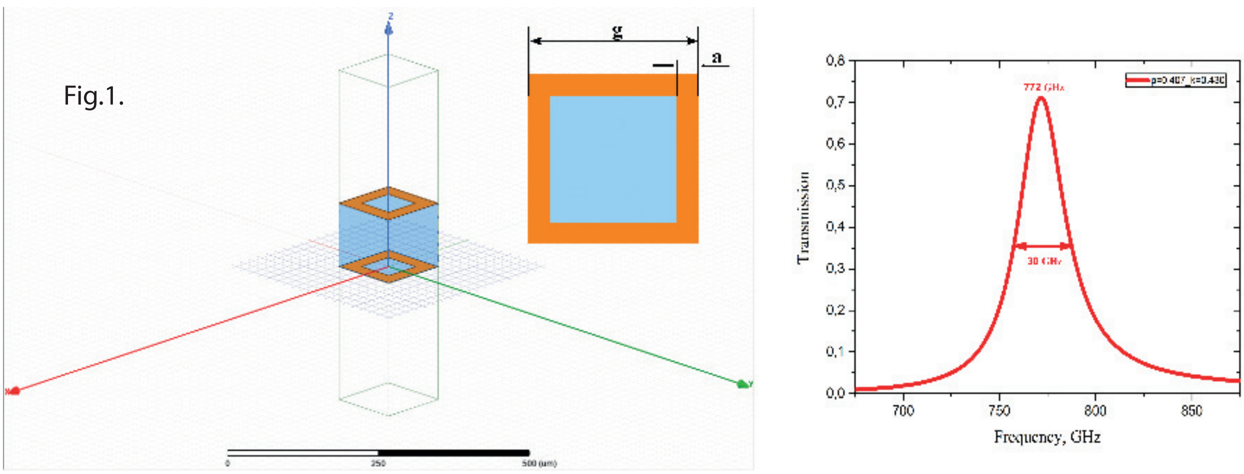


Fig.1.

The film samples we had available and the proximity of this value to the wavelength of the fundamental resonance of the FPF (λ=372 µm) led us to put the PP film's thickness about 120 m; aluminum grids have a thickness of 0.4 m.

In the initial stage, calculations for preliminary searches were done for various parameter ratios a/g (in the figure) between 0.1 and 0.8. Further, a code was written in the Python environment to determine the precise geometric parameters of the unit cell, and for the given circumstances, the values a/g=0.430 and p=0.407, where a=29.75 µm, g=108.63 µm, were obtained.

As a result, we were able to achieve FWHM=3.8% at maximum transmission Tmax=70%, which is quite close to the required specifications (Fig. on the right). Although the acquired maximum frequency of 772 GHz is lower than the required frequency of 806 GHz, this discrepancy is made up for by changing the radiation's angle of incidence on the structure.

FPF samples were created by thermal deposition of aluminum on top of polypropylene films based on the simulation results. These FPFs were measured on a terahertz pulsed spectrometer at normal radiation incidence and at a horizontal angle rotation from 0° to 50° with a 5° step. When rotated by 20 degrees, 801 GHz is detected, which is the result that is most like the required value (806 GHz). The study's findings revealed a good agreement between the simulation results and the manufactured FPF samples.

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## TAPERED COUPLING INTERFACE FOR A THZ INTEGRATED WAVEGUIDE

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Significant recent advances in big data processing, augmented reality systems, and ultra-high-definition video streaming have created a need to dramatically increase the wireless data transfer rate. To solve this issue, it is necessary to develop a communication system operating at higher frequencies, especially at terahertz (THz) frequencies. The use of radiation of this range is associated with a number of difficulties related primarily with strong absorption of THz radiation by water vapor contained in the air. The use of THz transparency windows will make it possible to create a system operating at short distances [1]. It will be the in-house system, similar to Wi-Fi, but with much higher data transfer rate (of 1 Tbps and higher) [2]. Another problem is that the standard approach based on the use of metal waveguides will not allow creating such systems, since the losses in metal waveguides at THz frequencies are large even at small lengths of the waveguides (of several tens of mm). The possible solution of this problem is the use of fully dielectric waveguides [3]. But the coupling of these waveguides with other devices is currently a relevant task.

In this work, a taper as a coupling element for a THz waveguide based on metamaterial high resistive silicon

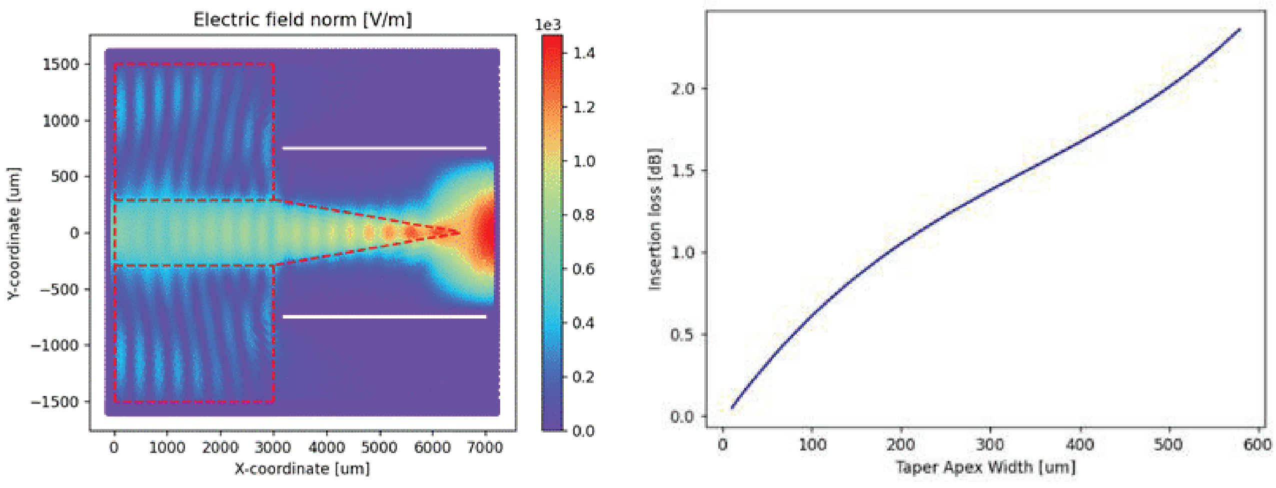


Fig. 1. Results of the simulation: a) electric-field distribution inside the transition from a metal rectangular waveguide to a taper coupled dielectric waveguide; b) dependence of the insertion loss of a taper on its apex width

(HRSi) platform with perforations was studied. The simulation was carried out using a beam propagation method. The frequency of simulation was 150 GHz. A coupling efficiency of the taper with different values of its angle was simulated. The results of the simulations are presented on Fig. 1. The structure of the waveguide with tapers was etched via Bosch process. The measured value of the insertion loss of the taper with apex width of 90 μm is about 0.5 dB, which is in a good agreement with the simulation.

The developed structures will be the basic elements of an array of THz emitters with active adjustment of the radiation pattern. These devises will be a part of the future next-generation THz data communication system with a high data transfer rate.

The study was supported by a grant from the Russian Science Foundation No. 21-72-10119, https://rscf.ru/project/21-72-10119/.

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## 3D PRINTED COMPONENTS FOR SUBTERAHERTZ QUASIOPTICAL TRANSMISSION LINES

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A number of subterahertz radiation applications require transmission lines, which carry out the transformation of the field structure at the output of the radiation source to the required one [1]. Quasioptical components (mirrors and/or lenses) of usual shape may not be sufficient for such conversion, and synthesized elements of complex profile are used [2]. CNC milling is usually used to produce such elements. However, the development of 3D-printing means in recent years allows to produce similar elements much faster and cheaper.

We tested two different technologies to produce components for 263 GHz transmission line of the gyrotron setup. Dielectric lens was printed with FDM 3D printer of SBS (styrene-butadiene-styrene) polymer. This material can be used for continuous power operation of several hundred watts [3]. Alternative method is to use copper deposition on printed plastic structure (CMPS technology). According to test results, both types of elements transform output gyrotron beam into flat top field distribution with good quality and can be used in medium power experimental setups.

This work was supported by RSF grant 21-19-00877.

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## REFLECTIONLESS ANOMALOUS REFRACTION OF THZ BEAMS WITH A MULTI-LAYER METAL-POLYMER HUYGENS' METASURFACE

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The use of terahertz (THz) beams is promising in such areas as sensing [1,2], biomedicine [3], food inspection [4], safety [5], and wireless communication [6]. However, there is a lack of compact and inexpensive components for manipulating THz beams.

One of the promising approaches to managing the characteristics of THz rays is the use of Huygens' metasurfaces (HMSs) [7].

Cascade inductive and capacitive grids [8] HMSs implementation is most suitable in the millimeter and terahertz ranges, as it allows assembling HMS from several dielectric substrates bearing separate metal sheets with a pattern. Printed circuit board (PCB) and photolithography technologies can be used to make such layers. At frequencies up to 1 THz and above, photolithography provides sufficient accuracy.

We suggest adding extra layers to the observation to enhance the number of degrees of freedom. The efficiency of such a multi-layer structure can be increased by the proper selection of the transmission parameters of individual meta-atoms.

However, the technological challenge is to select suitable substrates and find the proper procedure for placing multilayer material without deformation and additional losses.

In this work, we synthesize and experimentally demonstrate a refractor made as a 5-layer Huygens metasurface in the transmission mode with an anomalous refraction of 55° at 0.166 THz, having a low level of undesirable scattering and achieving an experimentally measured transmission efficiency of 55%, parasitic diffraction losses of 25% and scattering losses of 20%. In addition, we present the technological steps that make it possible to produce such complex multilayer structures with low manufacturing deviations.

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## DIGITAL PHASE SHIFTER ARRAYS FOR BEAMFORMING IN SUB-THZ COMMUNICATIONS

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With 5G communication networks being practically used, research on technological solutions for 6G networks is currently in focus of communication system developers. Intelligent reflective surface (IRS) [1] intended to upgrade capabilities of sub-THz channels, i.e., with carrier frequencies of 100–300 GHz, is among them. IRS is supposed to strengthen the received signal when line of sight of the transmitter is blocked and to mitigate multibeam interference. This is achieved by routing of propagating waves in IRS networks, where each IRS acts as a phase shifter array for beamforming in reflected light. Such an architecture is more efficient in terms of power consumption as compared to the multiple-input multiple-output wireless systems. It is also recently demonstrated that digital phase shifters with 2-bit resolution are promising for IRS up to a carrier frequency of 30 GHz [2,3].

In this paper, we report on the development of a 2-bit digital phase shifter array for beamforming in reflected light at 140 GHz. The array is planar. Each phase shifter in the array is presented by a patch antenna, whose ground plane metallization utilizes a cruciform slot. Distribution of currents along the slot is defined by the configuration of 5 diode switches integrated with it and determines the phase shift upon reflection of a sub-THz wave. In turn, the angle of reflection from the array is determined by the configuration of the phase shifters.

We use electromagnetic (EM) modeling to design the proposed phase shifter array. Both the Floquet port and incident wave analyses are conducted. The array geometry is implemented inside a region structure, whose faces are assigned as perfectly matched layers (or master/slave boundaries if the Floquet port is used). All the metallic surfaces are modeled as perfect conductors.

Subwavelength rectangular structures with predefined sheet impedances, $Z$, are used to model Schottky diode switches. At any given angular frequency, $\omega$, $Z(R_j) \approx R_s + (R_j^{-1} + i\,\omega\, C_p)^{-1}$, where $R_j \approx 0\ \Omega$ and $R_j = R_{j0}$ for ON and OFF states of a diode switch, respectively. Quantities $R_s$, $R_{j0}$ and $C_p$ denote series resistance, nearly zero-bias resistance and parasitic capacitance of a Schottky diode, and $i$ is the imaginary unit. For our Schottky diodes, we can reduce $R_s$ down to a few ohms at the expense of increase in ideality factor by 30%, $R_{j0}$ and $C_p$ are typically equal to 0.45 MΩ and 10 fF.

The EM modeling yields linear dimensions of a phase shifter of $0.4\lambda_0 \times 0.4\lambda_0 \times 0.044\lambda_0$ (length × width × height) and width of a cruciform slot of $0.012\lambda_0$, where $\lambda_0$ is the free space wavelength. Array of rectangular patches is implemented on a $0.012\lambda_0$ thick quartz substrate facing incident EM radiation. Ground plane metallization of patch antennas is spaced by an air gap of $0.02\lambda_0$.

It is implemented on a back metallized quartz substrate with thickness of $0.012\lambda_0$. Diode switches are grouped, and only 2 traces are needed to turn them ON and OFF by DC biasing. Four-state beamforming is observed for such a phase shifter array of 16 elements. Parameters of reflected beams are studied for various $R_s$ and $C_p$ at 14 and 140 GHz.

The study was supported by the Russian Science Foundation grant No. 22-79-10279, https://rscf.ru/project/22-79-10279/.

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# APPLICATIONS

## STATIONARY FLOW OF DENSE MAGNETIZED PLASMA WITH MULTIPLY CHARGED IONS SUPPORTED BY STRONG THZ-RADIATION

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Radiation in the terahertz (THz) frequency range generated by modern high-power gyrotrons is advantageous in terms of supporting plasma with multiply charged ions [1–3]. The high-power radiation is absorbed by electrons of plasma that provides conditions for efficient subsequent ionization by electron impact. For better absorption, electron cyclotron resonance (ECR) conditions can be ensured by placing the plasma flow in an external magnetic field of a strong electromagnet [4].

To date, 0.25 — 1 THz gyrotrons operating in long pulse mode (from 20 μs to continuous wave) are available [5]. This makes it possible to count on the development of steady-state sources of particles and radiation based on the discussed discharge, for example, steady-state sources of multiply charged ions for accelerators or steady-state sources of line radiation of highly charged ions, the line spectra of which contains many strong lines belonging to narrow technological wavelength ranges (13.5 nm ± 1%, 11.2 nm ±1%, etc.) of extreme ultraviolet (EUV) light used for modern lithography [6, 7].

As THz-radiation may support plasmas with relatively high densities of about $10^{16}$ $cm^{-3}$, there is an opportunity to support strongly radiating and at the same time well localized (point-like) discharge with characteristic dimensions of about 1 mm and smaller that is beneficial for further focusing of the generated EUV-light.

Within the report, a gas-dynamic model is presented for a flow of strongly radiating plasma with multiply charged ions, the transverse confinement of which is provided by an external magnetic field, which simultaneously ensures the ECR-conditions in the plasma volume with supporting THz-radiation. Within the model, we describe particle balance for ion fractions with subsequent ionization by electron impact taken into account, total ion-electron momentum balance, energy balance of the discharge including heat transfer from localized heat source (ECR-zone) by the means of nonlinear electron thermal conductivity, energy losses on ionization and line radiation of ions.

Based on results of modeling, conclusions are made about the achievable ion charges, power of line radiation, and the size of plasma formation in the case of supporting the discharge by THz-radiation from modern gyrotrons. Prospects for such THz-ECR-discharge usage in applications are under discussion.

This work was supported by the Russian Science Foundation (project no. 19-12-00377).

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## EPR SPECTROSCOPY AT NOVOSIBIRSK FREE ELECTRON LASER FACILITY: HIGH POWER THZ RADIATION APPLIED TO MOLECULAR MAGNETS

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Large-scale facilities such as neutron research reactors, synchrotron light sources and free electron lasers offer natural science experimentalists the opportunity to perform unique experiments, which determine the cutting edge of experimental data accessible. Novosibirsk Free Electron Laser (NovoFEL) was originally developed to fit the requirements of physicists, chemists, and biologists[1] and featured ultrawide range of radiation wavelength (THz, far- and mid-IR ranges) and very high average power (up to 400 W at 70 cm$^{-1}$). International Tomography Center SB RAS is constructing two endstations at NovoFEL aiming to utilize the unique radiation applied to the field of molecular magnetism: SQUID magnetometer station and X-band (9 GHz) Electron Paramagnetic Resonance (EPR) station. In this work we present the current status of EPR station at NovoFEL which is able to operate in continuous-wave, time-resolved and pulsed EPR modes.[2] The use of these operation modes in combination with the electronic modulation regime[3] of NovoFEL is briefly considered applied to (i) IR-photoswitching studies of copper(II)-nitroxide spin-crossover-like compounds, (ii) THz-induced spin transitions in single-molecule magnets and (iii) spin-phonon interactions in low-spin systems. The ability of NovoFEL to rapidly change the sample temperature by powerful THz-radiation in a controllable way is considered in details. Using the example of the thermo-switchable compound [Cu(hfac)$_2$L$^{Et}$], where L$^{Et}$ is 2-(1-ethylpyrazol-4-yl)-4,5-bis(spirocyclopentane)-4,5-dihydro-1H-imidazole-3-oxide-1-oxyl,[4] we have shown the possibility of pulsed heating with > 60 K amplitude at 7.3 K/ms heating rate. These results are promising for studying the related phenomena, such as thermally induced trapping of metastable states in magnetoactive compounds or thermally activated catalytic and biological processes.

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## HIGH-GRADIENT ACCELERATION OF ELECTRONS BY ULTRASHORT PULSES OF MICROWAVE SUPERRADIANCE

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As well-known, an increase in the accelerating gradient in hollow metal structures powered by an RF field is associated with the development of sources of high-power short-pulse high-frequency radiation. To date, the most powerful (multi gigawatts) nanosecond-scale microwave pulses are produced based on the effect of Cherenkov superradiance (SR) of extended electron bunches interacting with a backward wave in periodical slow-wave structures (SWS) [1,2]. In particular, Ka-band SR sources provide record-breaking power level of 1-2 GW in ultrashort pulses with a duration of about 0.3 ns. It is important that the experiments performed on the generation of multi-GW Ka-band SR pulses [2] have clearly demonstrated a significant increase in the breakdown strengths both in electrode gaps and in electrodynamic structures. This made it possible to extract a subnanosecond radiation pulse from the corrugated SWS despite the fact that the microwave field strength on the corrugated wall was at least 200-270 MV/m, and could be many times higher at the edges of the resonant reflector installed at the SWS input. In such fields, there were conditions for the emergence of plasma due to explosive electron emission on the metal, but the processes of its occurrence and expansion were delayed.

For the experimental observation of high-gradient acceleration of electrons by Ka-band SR pulses, we developed a combined generator-accelerator scheme with two coaxial electron beams formed by a single cathode. The outer tubular beam with an energy of 300 keV and a current of 2.3 kA is used for excitation of a counter propagating 1GW/300 ps pulse of the Cherenkov SR in a periodic SWS. The inner near-axis beam with an energy of 250 keV and a current of 150 A is accelerated by pumping a resonator of the type "pill-box", located at the beginning of the SWS.

The electron energy was determined based on measurements of the internal beam current after the SWS as it passed through aluminium filters (foils) with different thicknesses and, accordingly, with different energy cutoff values. It is found that the energy of a certain fraction of the inner electron beam reaches up to 1.25 MeV. Thus, taking into account the cavity length (0.4 cm) and the initial beam energy, the acceleration gradient of ≈250 MV/m was experimentally demonstrated. This value significantly exceeds the record parameters achieved on the basis of long-wavelength klystrons.

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## OPTICAL CHARACTERIZATION OF $GETE_2$ PHASE CHANGE MATERIAL FOR TERAHERTZ APPLICATIONS

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Recently, photonics of phase-exchange materials (PCMs) has become a new research field as the opti-cal properties of PCMs change during the amorphous-crystalline phase transition [1]. Activation of PCMs phase transition is possible by thermal, electrical or optical effects on the material [2]. The phase transition principles can be used in terahertz (THz) metamaterials [3], affecting their spectral characteristics [4]. By controlling the crystal fraction of the PCM film, multi-level nonvolatile te-rahertz resonance switching states with long retention times can be realized. We investigated the optical, infrared (IR), and THz permittivity properties of thin films of a new PCM GeTe2 during insulator-to-metal transition. Studies of the amorphous and crystalline phases as well as THz spectra are presented and studied using Lorentz and Drude models. It is proposed that the state of GeTe2 can be monitored by observing the intensity characteristics of the 155 cm-1 Raman peak. Molecular dynamics simulations showed that during crystallization, the intensity of the 155 cm-1 mode attributed to Te-Te stretching decreases and disappears during complete crystallization. Using the example of the new GeTe2 PCM, we demonstrate that the properties of PCM-based metasurfaces can be specified at the initial design stage and modified at the experimental stage. It has been shown that this PCM characteristic is of particular interest for achieving dynamic and tunable metasurface functionality. This work was supported in part by the Ministry of Science and Higher Education of the Russian Federation (Grant No. 075-15-2021-1353) for the PCM material characterization; in part by the Interdisciplinary Scientific and Educational School of Lomonosov Moscow State University "Photonic and Quantum Technologies: Digital Medicine" for the sensor creation; in part by the European Union through the European Regional Development Fund project "Center of Excellence" TK141 for the thin film preparation; and in part by the Ministry of Science and Higher Education within the State assignment FSRC "Crystallography and Photonics" RAS for the developements and prospects of THz photonics. The experimental Raman spectra were obtained at Lomonosov Moscow State University using the equipment purchased within the Lomonosov Moscow State University Program of Development.

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# ULTRAFAST HETERODYNE MAGNETIC THZ TIME-DOMAIN SPECTROSCOPY OF OH RADICALS

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Ultrafast terahertz time-domain molecular spectroscopy in real time has been intensively developed at the NovoFEL, starting from work [1]. Many specific non-stationary effects have been demonstrated [2] and many different spectroscopic techniques have been developed [3-7]. At last time, spectroscopic studies of the OH radical, the most important intermediate short-lived component in many chemical reactions of combustion and explosion, have been carried out at NovoFEL [8-11]. In recent work [12] advantage of using of week magnetic field and much more sensitive THz detectors was demonstrated.

In the heterodyne method, Free Induction Decay (FID) signal is obtained from two *sin*- and *cos*-like interference signals between simple FID signal of OH radicals and heterodyne signal which is the NovoFEL pulse coherently extended approximately in 100 times by two mesh Fabry-Perot interferometers. For good coherency of such long pulse, special stabilized regime of the NovoFEL was used [13]. The heterodyne method has a much higher sensitivity (when the signal-to-noise ratio in a simple FID is ~1, this ratio in a heterodyne FID is more than 50) and twice the time resolution, which is very important for the correct display of fast FID signals. Advantage in time resolution was obtained thank to using of FID fields in heterodyne method which have two times slowly modulation than power signal modulation in simple FID spectroscopy method. Additionally we used effect of the phase switching of the optical FID in magnetic field for obtaining *sin*- and *cos*-like interference signals without parasitic noises [14].

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## NULL ELLIPSOMETER FOR MILLIMETER-WAVE DIAGNOSTICS OF COMPOSITE MATERIALS

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Ellipsometry is a highly sensitive optical method for non-destructive studies of interfaces based on measuring the reflection coefficients in two mutually orthogonal planes and capable of detecting optical changes in the near-surface layers as thin as 1/100-1/1000 of the probing wavelength. When adapted to the mm-wave range, ellipsometry is demanded in examining the optically opaque but X-ray-non-contrast materials, e.g. to reveal the near-surface defects in composite-made aircraft wings after/during mechanical loads.

In this work, we present the first experimental realization of the ellipsometer operating near 140 GHz and employing the "null" or PCSA scheme (Polarizer–Compensator–Sample–Analyzer), which fundamental advantage is its non-sensitivity to the intensity variation. A basic theory of null ellipsometry is supplemented with a description of the unique optical components of the PCSA scheme implemented as metasurfaces of specific design. The developed ellipsometer is further tested in retrieving the optical constants of prepregs — a reinforcing base of composite materials made of "pre-impregnated" carbon fibers. The ellipsometric data are compared with the results of prepreg characterization by BWO spectroscopy.

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## USING RADIO INTERFEROMETRY FOR MEASURING FREE SURFACE VELOCITY IN IMPACT EXPERIMENT

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In studying spallation strength of various metals, free surface velocity profiles are mostly registered using the interferometry methods working in the visible and near infrared wavelength range, like VISAR and PDV. These interferometers are demanding on the quality of the reflecting surface. However, often the surface of the sample is not specular, or the reflectivity of the surface deteriorates greatly during the experiment.

Therefore, an interferometer operating in the millimeter wavelength range is of great interest. For this device, the requirements for the quality of the reflecting surface are much lower — the roughness can reach tenths of a millimeter. In addition, experiments can be carried out in matter where optical radiation is strongly absorbed. Systems with millimeter radiation have found application in studies of high-speed gas-dynamic processes [1, 2], ballistic experiments [3] etc.

On fig. 1 a schematic diagram of the interferometric experiment is presented. The device generates two quadrature signals in two separate channels (Ch1 and Ch2 on fig. 1), according to which the displacement and speed of the reflecting surface can be estimated.

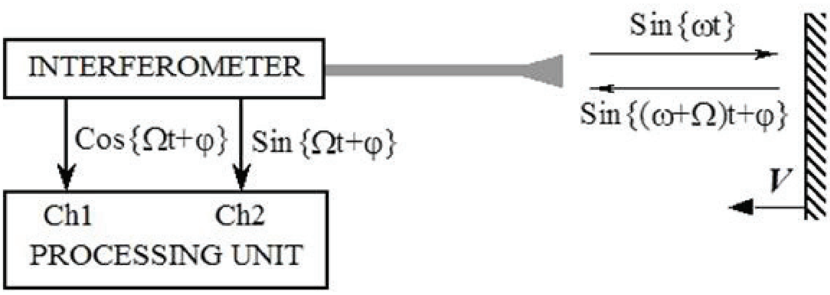


Fig.1. Scheme of the interferometric experiment.

In this paper, a radio interferometer with a wavelength of 3.2 mm was used to measure the velocity of the free surface of a sample subjected to impact loading. The experiments were carried out with samples of aluminum alloy, the properties of which are well studied. Samples with a diameter of 90 mm and a thickness of 10 mm were subjected to impact with a plate made of the same material. The surfaces of the samples were not subjected to polishing. The shock plate was accelerated to the required speed using a gas gun. A series of experiments was carried out with a striker velocity of 200-250 m/s.

Since the specimens and impactors were made of the same material, the maximum free surface velocity had to be close to the impact velocity. According to the results of radio interferometric measurements, a discrepancy between the impact velocity and the maximum velocity of the free surface was obtained within 5%. This difference can be caused both by the influence of the unloading wave, which follows the compression wave and gradually overtakes it, or by a small deviation of the striker from the normal during impact.

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## PROBLEMS OF SUB-TERAHERTZ ASTROCLIMATE RESEARCH AND DEVELOPMENT OF OPTIMAL RECEIVERS FOR MEASUREMENTS OF ATMOSPHERIC PROPAGATION

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To date, large data array of atmospheric absorption in subTHz transparency windows of 3 and 2 mm accumulated over 12 years of direct measurements is available to us. These measurements were obtained on the territory of the Russian Federation and the territories of neighboring states from Svalbard to Uzbekistan [1] using a microwave atmospheric absorption meter MIAP-2 [2]. Based on these measurements and comparisons of the astroclimate parameters, potentially suitable places for installing a subTHz antenna were identified, including one suitable for astronomical observations in the transparency window of the Event Horizon Telescope (EHT) near 230 GHz [3], as well as for use in deep space communications and subTHz radar applications. It is important to note that the EHT project team has long been looking for promising locations for astronomical observatories in order to expand the number of the VLBI interferometer to increase the information content of observations and expand the number of available space sources [4].

Estimations here have been fulfilled based on satellite data and is the result of integration of rather big surface approximately 20 sq. km. There were executed lots of direct measurements from particular places — candidates for subTHz observatories using MIAP-2 radiometer [5].

According to our research, the most promising places for building a subTHz radio telescope are the Caucasus Mountains in Dagestan, and the Suffa Plateau in Uzbekistan. There is a definite interest to some places in Siberia (Moos Khaya in Yakutia and Hulugaysha in Sayany).

However, most part of these measurements performed was short-term within independent short expeditions, due to which the extrapolation of the measurement results for long periods is severely limited. In addition, the recalculation of atmospheric absorption in 3 and 2 mm windows for a 1.3 mm window does not allow estimating fully the technical perspectives and potential possibilities of its use. Due to the lack of verified information on atmospheric absorption in the atmospheric transparency window of 1.3 mm, our team starts development of a portable radiometric complex for research of seasonal trends in changes of atmospheric absorption directly at a wavelength of 1.3 mm.

There are considered various possible ways to develop an optimal receiving structure in the 220-250 GHz frequency range, capable of maintaining its stable characteristics at a high level for a long time and suitable for long-term expeditionary measurements (at least one full year) directly on the open areas of the future observatories. The elemental base intended for use in subTHz receiver is presented, and its electrical characteristics in the radiometric mode for measurements of atmospheric absorption are evaluated.

The development of optimal receivers for measurements of atmospheric absorption was started within the framework of the scientific program IAP RAS state contract # 0030-2021-0001.

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## FORMATION AND MODE IDENTIFICATION OF THE THZ BESSEL BEAMS AT THE NOVOFEL

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The main prospects for the development of the telecommunications industry are currently associated with the expansion of 4G networks and the development of new 5G networks. The further progress of telecommunication technologies is associated with an increase in operating frequencies to the THz range. THz radiation could propagate by directed beams that can experience distortions in the inhomogeneities of the atmosphere and precipitation. In order to eliminate these shortcomings, Bessel beams with orbital angular momentum (OAM), or "vortex beams" can be used. The beams are "non-diffracting" and have the property of self-healing on phase and amplitude obstacles with size smaller than the beam diameter. Moreover, Bessel beams allow transverse-mode multiplexing of communication channels which in turn can increase the budget of the data transmission.

To recognize the original signal in multiplexed beams a spatial filtering is required. For example, it can be based on the principle of correlation reception. The process of such filtering is reduced to finding a correlation between the unknown and a predetermined signal, then the maximum intensity of such interaction (correlation peak) will appear on the output image of the optical correlator. A diffractive optical element with an appropriately selected complex transmission function can be used as a correlation filter matched to the detected mode.

Previously, silicon binary spiral axicons that convert the Gaussian beam of the Novosibirsk free electron laser (NovoFEL) into the Bessel beam with OAM were fabricated and studied [1, 2, 3].

This work presents the results of the identification of the Bessel mode of single-mode and multimode vortex beams with topological charges $l$=-1,-2 using binary axicons with helical zones with $l = \pm 1, \dots, \pm 4$. To identify the topological charge of the resulting beam, a combination of one of the axicons and a lens was used.

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## IMPLEMENTATION OF A HIGH-SPEED WIRELESS COMMUNICATION LINE IN THE SUBTERAHERTZ RANGE

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The report is devoted to the description of the development of the concept and the creation of a prototype of a wireless communication line in the sub-terahertz range. The selection of the operating frequency range and the calculation of the characteristics of the communication channel for a transparency window of 220 GHz were made. The required signal power of the transmitter is determined for the selected signal-to-noise ratio of the receiver for reliable transmission of information over the communication channel. The required power of the radiation source when transmitting a signal at a rate of 1 Gb/s over a distance of 1 km was 240 μW. The rationale for the choice of the modulation method and its applicability in the process of developing a block diagram of a transceiver in the frequency range of 200-220 GHz is presented. It is shown that the only suitable modulation scheme is a scheme with frequency multipliers, which does not allow either phase or quadrature modulation to be transmitted to the output without distortion. The only modulation suitable for such a scheme is OOK amplitude-shift keying. A wide frequency band equal to 2.8 GHz, occupied by a signal at a transmission rate of 1 Gb/s, in the specified frequency range occupies no more than 1-2% of the carrier frequency. Increased requirements for the noise immunity of the transmission system are not imposed due to the absence of interference in this frequency range. An analysis based on the developed mathematical models for the passage of an amplitude- and phase-shift keyed signal through diode frequency multipliers that are part of the transceiver of a communication line showed the impossibility of restoring a phase-shift keyed signal at the receiving end with a phase change of 180 degrees at even multiplication factors. The accuracy of restoring the amplitude-shifted signal at any multiplication factors, as well as its amplitude, depend on the slope of the diode I–V characteristic, on the cutoff angle, on the passband and cutoff frequency of the filters.

The calculation of the energy potential of the system showed that it is necessary to use antennas with a gain of at least 50 dB. In constructive and technological terms, the Cassegrain antenna turned out to be the most suitable. Using the ANSYS HFSS CAD system, the antenna characteristics were calculated in the operating frequency range, which made it possible to determine the tolerances for the manufacture of individual antenna elements, take into account inaccuracies in the manufacture and tuning of the antenna. Tests were carried out on the operating layout of the receiving-transmitting communication channel with autonomous power systems using gasoline generators. The BER value was determined indirectly using a calibration table by measuring the signal-to-noise ratio at the output of the IF amplifier of the receiving device of the communication channel.

Experimental studies have been carried out to optimize the block diagram of a communication line in order to increase the bandwidth, simplify the structure as much as possible (reduce incoming microwave nodes), and ensure product replication.

## BROADBAND AND NARROWBAND LASER-BASED TERAHERTZ SOURCE AND ITS APPLICATION FOR SECOND HARMONIC GENERATION IN CENTROSYMMETRIC ANTIFERROMAGNET NIO

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An ideal laser source for nonlinear terahertz spectroscopy offers a versatility of delivering both ultra-intense broadband single-cycle pulses and user-selectable multi-cycle pulses with narrow linewidths. In this report we show a versatile table-top laser-based easy-to-implement THz source that allows to generate single-cycle transients with peak field strength of tens of MV/cm as well as spectrally narrow pulses, tunable within the bandwidth in OH1 nonlinear organic crystal pumped by femtosecond Cr:forsterite laser pulses at a wavelength 1240 nm.

Second harmonic generation at a wavelength of 620 nm induced by the nonlinear interaction of optical femtosecond and terahertz pulses in centrosymmetric antiferromagnet NiO is experimentally studied. The results reveal that the second harmonic intensity is proportional to the square of the applied electric field of broadband terahertz pulses in the range up to 20 MV/cm. Tenfold decrease in the second harmonic intensity induced by narrowband terahertz pulses at the frequency of 1 THz, corresponding to the antiferromagnetic resonance in NiO, was found compared to excitation at a nonresonant frequency of 1.5 THz. Fig.1 shows some experimental results.

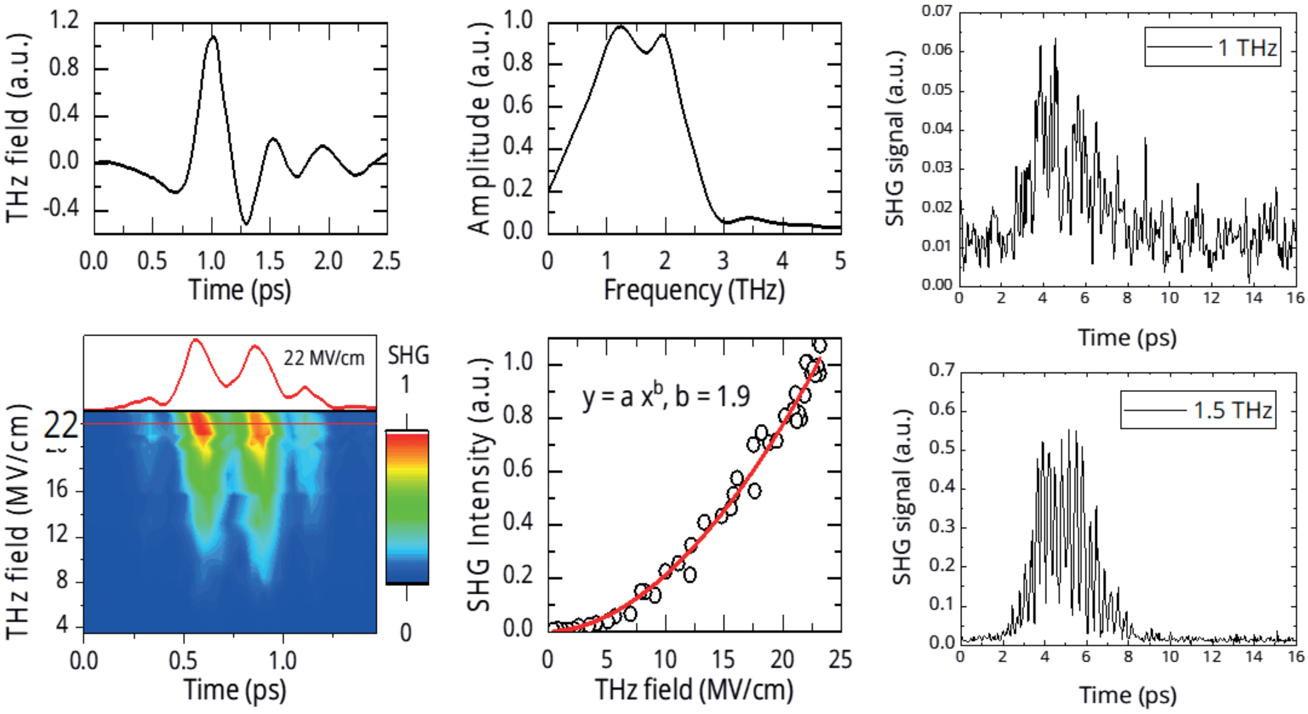


Fig. 1. Waveform and Fourier-transformed spectrum of a broadband terahertz pulse. Dependence of the intensity of the second harmonic on the time delay and electric field strength of a broadband terahertz pulse. Dependence of the large positive maximum at t = 0.6 ps of the intensity of the second harmonic from NiO on the electric field strength of the broadband terahertz pulse. Time profiles of the intensity of the second harmonic at different frequencies of narrow-band THz pulses.

The experiments were performed using the unique scientific facility “Terawatt Femtosecond Laser Complex” in the “Femtosecond Laser Complex” Center of the Joint Institute for High Temperatures of the Russian Academy of Sciences. The reported study was funded by RFBR and ROSATOM according to the research project No. 20-21-00043. The reported study was funded by RFBR, project No. 20-08-00627.

## TERAHERTZ IMAGING AND SPECTROSCOPY FOR HERITAGE SCIENCE

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Heritage science is a field of complex research, located at the junction of the humanities and the fine sciences: history, art history, archeology, sociology and urban studies, and at the same time — chemistry, physics and biology. In our country, a unique school of art history and restoration has been formed, combining the accuracy of the humanistic approach with the careful methods of preserving cultural heritage monuments. This was largely due to the emergence of technical and technological research laboratories at museums and restoration centers.

One of the most difficult problems for museum restorers and technologists is non-destructive studies of multilayer coatings. Traditional museum methods, such as x-ray radiography, infrared reflectography, give an integrated picture of all layers and it is almost impossible to determine the sequence of layers and highlight the layer of interest. For this purpose, the terahertz time-domain spectroscopy (THz-TDS-based) object visualization system can be useful. Due to non-invasive properties of THz radiation, such a system allows to be applied for investigation of an object of art.

The main goal of this study was to test the detecting capacity of such a system to identify layers of paint below the surface. We have used a unique test-object, mimicking the most common tasks for painting investigation. The image of paints on canvas was recorded using the TeraPulse LX (TeraView, UK) system with a spectral range 0.06 THz — 6.00 THz. Due to the high sensitivity of THz radiation to the distinction between the optical properties of painting materials, this experiment allowed us to obtain detailed information about the structure and spectroscopic data of layers of objects and pigments, and determine the shape of invisible elements without damaging the canvas. Thus, the THz imaging method can be very useful in restoration work designing, determining defects in the structure of paintings materials, as well as when searching for hidden objects under layers of paint.

Our research is dedicated as well to the investigation of image processing methods applied to THz images of painting. To our best knowledge, there is no comprehensive research on enhancement of THz images of art objects. Previous research in THz imaging concerned different image processing methods but were not applied to the objects of art. However, artworks appeared to be more complicated to reconstruct and process by means of THz imaging, which might be related to the specific structural data, unique for every object.

Algorithms of enhancement were created and applied to the images of painting's inner layer. The details on these images became sharper and more distinguishable. The results were quantified by PSNR value, which increased in every case. The intensity histograms and the intensity spectra before and after processing were compared. The obtained results can be regarded as positive and, therefore, these image processing methods can be interesting for the purposes of artworks investigation before restoration.

## MICROWAVE INTERFEROMETRY OF CHEMICALLY ACTIVE PLASMA

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An important task of applied plasma chemistry is to study the parameters and properties of active low-temperature plasma [1,2]. However, the use of standard diagnostic methods to determine plasma parameters is limited due to the special properties of chemically active substances. In this work, the discharge in plasma of hydrogen, argon, and volatile compounds of halides BF3, SiF4, GeF4 at a pressure of 0.5 Torr was studied. Using the non-contact method based on direct registration of the phase shift of the probing radiation with a frequency of 58 GHz, the values of the average plasma electron density in the transverse direction of the cylindrical column were measured at various heating powers and ratios of the components of the plasma-forming mixture. The method used makes it possible to increase the accuracy of measurements and reduce the effects associated with the scattering and absorption of the useful signal by the plasma.

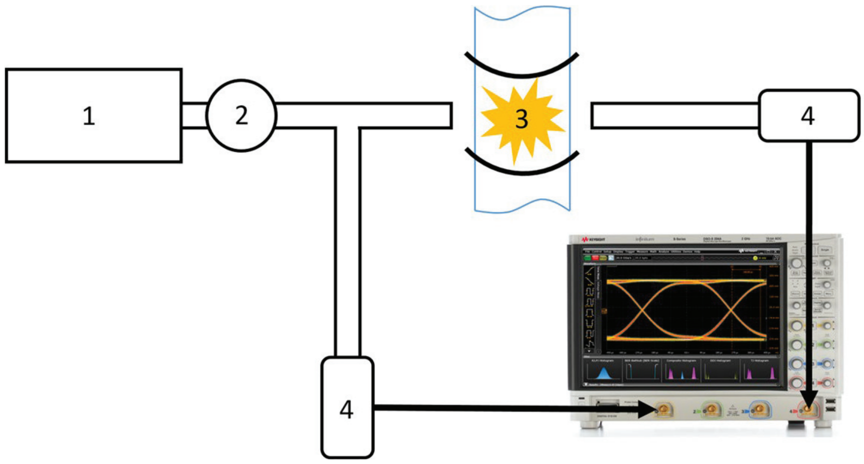


Fig. 2. Scheme of microwave probing of plasma: 1—source of millimeter radiation with a frequency of 58 GHz; 2—insulator; 3 — gas-discharge quartz tube; 4—coaxial-waveguide transition.

Figure 2 shows the scheme of microwave probing of plasma [3]. A stabilized Gunn diode with a radiation frequency of 58 GHz was used as a source of millimeter radiation (2.1). The original signal is divided into a reference and probing. Part of the millimeter radiation passes through the quartz gas discharge tube (2.3) (in the region between the turns of the inductor) and partially enters the open end of the receiving path waveguide, where the phase of the transmitted signal is recorded. The CWT signals were recorded using a Keysight Infinium DSO Z594A oscilloscope with a bandwidth of up to 59 GHz and a sampling rate of up to 160 GS/s. To determine the electron density in the discharge, it is necessary to measure the phase difference between the reference and transmitted signals in two situations: without plasma and with plasma.

The difference between these values is equal to the phase shift of the probing radiation introduced only by the gas-discharge medium. It was experimentally shown that the addition of argon to the mixture of gases with SiF4 led to an increase in the electron density by a factor of 2–5, and for a mixture of gases with BF3, on the contrary, to a decrease by a factor of 4–5.5. Taking into account the fact that the degree of electron affinity for both halides is quite close, it is difficult to explain the result obtained in terms of the electron density balance due to changes in the ionization and electron attachment rates. For GeF4, the addition of argon led to a relatively small decrease in the electron density, which also disagrees with the classical conclusions about the relationship between the degree of electron affinity and the actual electron-withdrawing ability of fluoride. By itself, the addition of argon to the plasma gas causes a complex change in such plasma parameters as electron temperature and EEDF.

The high accuracy of determining the average electron density along the direction of the probing beam opens up wide opportunities for in-situ control of plasma parameters and optimization of plasma-chemical synthesis processes. This study was supported by a grant from the Russian Science Foundation (Project No. 20-13-00035).

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## FARADAY EFFECT ON THE ABSORPTION LINES OF PARAMAGNETIC MOLECULES. EXPERIMENTS WITH THE CW LASERS AND TIME-DOMAIN EXPERIMENTS AT THE TERAHERTZ NOVOFEL

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The effect of rotation of the polarization plane in a magnetic field is compared in experiments with a cw laser and in time-domain experiments. The experiments were carried out on narrow absorption lines of the hydroxyl radical (OH) in the gas phase. A cw quantum-cascade laser was used. The pulse experiments were performed at terahertz NovoFEL. In a longitudinal magnetic field, the OH absorption line splits into a right-hand and left-hand circular polarization components, which leads to a rotation of the polarization plane after the sample. In experiments with a cw laser, it was found that the angle of rotation is proportional to the optical density of the medium (concentration of absorbing molecules), but its magnitude is less then optical density by about an order of magnitude. Typical values were on the order of $10^{-3}$ for optical density and $< 10^{-4}$ for rotation angle. In the time-domain experiments, the effect looks like a rotation of the polarization plane of free induction signal (FID) [1,2] in a magnetic field. After the FEL excitation pulse, the induction polarization plane begins to rotate [3-7]. Large rotation angles are observed; for induction signals with a duration of the order of 10 nsec, the angle can exceed 90 degree [3,5]. In contrast to experiments with cw lasers, the angle of rotation does not depend on the concentration of absorbing molecules. The modulation effects of free induction in a magnetic field are studied in detail. A nonmonotonic dependence of the angle of rotation on time is shown [7]. The effect of phase switching with a change in the direction of the magnetic field is demonstrated [8].

The study was supported by a grant of the Russian Science Foundation (project No 19-73-20060).

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# INFLUENCE OF MICROWAVE FIELD FREQUENCY ON THE TRANSFORMATION OF ASPHALTENES. PROSPECTS FOR THE USE OF MICROWAVE PROCESSING FOR MINING AND PROCESSING HEAVY OIL

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About 70% of the world's fossil energy reserves include heavy oils and their derivatives. A promising method for the development of heavy oils can be the use of microwave exposure with metal-containing catalysts. In-situ catalysts have been developed, after the injection of precursors of which nanosized oxides-sulfides of transition metals are formed in the reservoir rock [1]. A combination of microwave impact on the reservoir and nanosized catalysts for destructive hydrogenation is considered [2]. The processes that take place in this case are little studied. The main publications in the world is devoted to the study of the microwave field together with catalysts only at a frequency of 2.45 GHz [3]. To create new technologies for the development of heavy oil fields, the focus of research should be directed to the transformation of asphaltenes. They determine the high viscosity and difficulty in production. In several studies, the influence of the microwave field on the transformation of asphaltenes was studied based on the study of the composition of individual oil fractions after exposure [4][5].

Therefor changes in the composition of individual oil fractions are determined by the destruction of asphaltenes in the oil composition. At the same time, it is important to find the conditions and characteristics of microwave treatment that are aimed at the impact on asphaltenes and not on heating the water or surrounding minerals. In the research conducted, the sample rocks with heavy oil was investigated using different electromagnetic frequencies and the effectiveness of the oil tank compared to different frequencies in laboratory conditions. The oil rock sample was exposed to microwave radiation with frequencies of 1.6, 2.0 and 2.5 GHz (N1, N2, and N3 respectively). For the initial oil and after experiments on microwave exposure, a group analysis was determined.

The results showed that the amount of asphaltenes in the frequency of N1, N2, N3 decreases from 12 wt.% to 6.4, 8.5 and 7.0 wt.%, and the content of saturations increase from 24.2 wt.% to 29.2, 36.8 and 25.3 wt.% respectively. The chromatogram of the samples after exposure to a microwave field in three frequency of N1, N2 and N3 shown that a significant influence of the frequency of the microwave field on the composition of the fraction of saturated hydrocarbons was recorded. When the frequency is increased from 2.5 GHz to 2.0 GHz, the intensity of the peaks corresponding to normal C22-C35 alkanes decreases, and when the frequency is reduced to 1.6 GHz, on the contrary, it increases. This difference may indicate the effect of the frequency of the microwave field on the degree of asphaltene conversion associated with the dealkylation of high-molecular-weight asphaltenes.

The next stage is planned to study the effect of a high frequency microwave field on the transformation of heavy oil in the presence of nanoscale catalysts.

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# SPECTROSCOPY

## COMPLEX REFRACTIVE INDEX MEASUREMENTS ON BOROSILICATE GLASS IN ULTRA-WIDE SPECTRAL RANGE

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Borosilicate glasses are widely used in various fields of technology. In particular, optical windows from a borosilicate crown glass K108 are often utilized in optical and optoelectronic devices. An important application are windows for the protection of optoelectronic devices from microwave (MW) frequency interference, in which a conductive film of indium tin oxide is deposited on the borosilicate glass substrate.

In the present work, we investigated interaction of electromagnetic radiation with the borosilicate glass K108 and determined its complex refractive index $\tilde{n} = n + ik$ where $n$ is the refractive index and $k$ is the extinction coefficient. All the samples were fabricated at TYDEX, LLC, Saint Petersburg, Russia [1]. Reflection and transmission spectra were measured in an ultra-wide spectral range which covers optical, terahertz (THz) and MW frequency regions. Four different spectrometers were used. As far as we know, similar studies that would cover such a wide range of radiation frequencies have not previously been carried out on any glasses or crystals.

In each spectral region, an appropriate experimental technique was used. In the MW region (frequencies from 2.5 to 24 GHz), the transmission and reflection spectra were measured in such a way that Fabry–Pérot oscillations were detected. Then $n$ and $k$ were found using the Airy formulas.

In the THz region (frequencies of 0.1–1.6 THz), the method of time-domain spectroscopy was used. The transmitted waveform recorded for the sample of 3 mm thickness in a time interval of 130 ps contained the first echo signal. The waveform recorded without sample was used as a reference. The magnitude and phase of the complex transmission function were found after computing the complex Fourier transform of the transmitted waveforms [2]. Spectral dependencies of $n$ and $k$ were determined from the phase spectrum and magnitude spectrum, respectively.

The radiation reflection and transmission in the optical spectral region (0.75–1000 THz) were studied by means of a Fourier-transform infrared spectrometer and diffraction grating spectrophotometer. The spectral resolution was chosen to suppress Fabry–Pérot interference in the glass plate under study. If the transmittance exceeds 0.01, the determination of the $n$ and $k$ spectra turns out to be the simplest (the reduced Airy formulas are appropriate). In the case of lower transmittance, which was observed at the frequencies from 0.75 to 69 THz, both $n$ and $k$ were determined from the reflection spectrum only using a method based on the Kramers-Kronig relation [3].

Finally, we determined spectral dependencies of the real part, $\mathrm{Re}\varepsilon = n^2 - k^2$, and imaginary part, $\mathrm{Im}\varepsilon = 2nk$, of the dielectric permittivity of the glass over the entire studied frequency range (2.5 GHz — 1000 THz). There are three bands of anormal dispersion on the spectral curve of $\mathrm{Re}\varepsilon$. In these bands, the refractive index decreases with increasing frequency. Each band of anormal dispersion is related to a strong absorption band which is characterized by a high value of $\mathrm{Im}\varepsilon$. The first absorption band is rather wide (from 1.2 to 4.5 THz). It can be attributed as so-called Boson peak [4]. Two other absorption bands represent sharp peaks at the frequencies of 13.7 and 30.0 THz. They are associated with the lattice-vibration modes, namely, Si-O-Si bending mode and Si-O stretching one [3]. Similar peaks are a common feature of the silicate glasses while their exact spectral positions determined in the present study are a “fingerprint” of the borosilicate crown glass K108. The results of the study can be used to develop protective windows for optoelectronic and photonic devices.

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## THZ-IR DIELECTRIC SPECTROSCOPY OF ASTROPHYSICAL ICES: RECENT ACHIEVEMENTS AND CHALLENGES

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Broadband dielectric properties of interstellar and circumstellar laboratory ice analogues are required to solve important astrophysical problems [1-4]. The complex dielectric permittivity of ices is one of the key parameters in modeling the dust continuum emission, radiative transfer in dense and cold University regions. The complex dielectric permittivity is necessary to understand the physical properties of ices, for comparing the results of laboratory studies and astronomical observations. Recent works of our scientific group [5-6] were dedicated to the broadband spectroscopy of laboratory ice analogues, particularly, carbon monoxide and carbon dioxide ices, with a focus on the development of the original methods for processing the experimental data. We developed a method to find the broadband optical properties of ices, based on the direct reconstruction of the complex refractive index of ices in the terahertz (THz) range from the THz pulsed spectroscopy (TPS) data and the use of the Kramers-Kronig relations to additionally prepare the Fourier-transform infrared (IR) spectroscopy (FTIR) data for the reconstruction. Inevitably emerging uncertainties introduced by the Kramers-Kronig relations are eliminated by merging the THz and IR data. The obtained results are analyzed in terms of analytical Lorentz dielectric models with attribution to particular vibrational modes. There is a great scope for further research with a lot of challenges in the context of ice structure analysis, the study of scattering in ice in the IR frequencies and in other unanswered questions.

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## INVESTIGATION OF THZ RADIATION PARAMETERS IN CO/WSE2 AND CO/IRMN3 STRUCTURES

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Among the various types of THz emitters using various physical effects, spintronic emitters have many advantages, such as: wide bandwidth, high efficiency of THz radiation generation, ease of controlling radiation parameters, including polarization and amplitude [1,2]. Such advantages allow the use of spintronic emitters in various devices used in the fields of medicine, science and security. In this work, Co/$WSe_2$ and Co/$IrMn_3$ films on a sapphire substrate were studied. The efficiency of THz radiation generation from the surface of experimental samples was investigated by the standard technique of terahertz spectroscopy with time resolution, in geometry for transmission. Optical pulsed radiation with a wavelength of 800 nm was used as the pump beam. During the experiment, the dependences of the amplitude of THz radiation on the delay time between the pumping and probing beams were obtained, the efficiency of THz radiation generation was estimated. From the time forms of THz signals, their frequency spectra with a width of ~ 3 THz are obtained by the Fourier transform method. The dependence of THz radiation generation on an external magnetic field is investigated. THz hysteresis loops are obtained, indicating the rotation of THz polarization.

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# DYNAMICS OF WATER MOLECULES IN ENDOHEDRAL FULLERENES

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Endohedral fullerenes or endofullerenes are complexes of C60 fullerene and a small molecule or ion inside. The particular case of water endofullerene (often denoted as $H_2O@C_{60}$) presents several unique opportunities to both fundamental and applied physics. Firstly, C60 cages spatially separate neighboring water molecules, diminishing the influence of hydrogen bonds. This separation allows one to quantitatively investigate low temperature quantum rotation of $H_2O$ in great detail. Experimental and computational studies show that water molecule retains remarkable degree of rotational freedom with the addition of a translational "center of mass motion" mode [1, 2]. Secondly, water exhibits the phenomenon of spin-isomerism. Every molecule has one of the two possible nuclear spin states — ortho-water (I = 1) or para-water (I = 0). The optical transitions between them are forbidden. Still, the ortho-para-conversion process has been observed even at the low temperature of 5 K, when the thermally activated channels do not contribute to the conversion rate. Investigation of isolated water molecules can help us understand the mechanisms of this process. The third opportunity relates to possible applications for quantum computing. After being excited with short terahertz pulse water molecules begin their rotation with decoherence time of more than 10 ps [3]. We investigate single-particle and collective energy states of $H_2O$@C60 complex by measuring absorption resonances with time-domain terahertz and Fourier-transform infrared spectroscopy techniques (see example in Fig.1). In the present talk, we will discuss mechanisms responsible for the observed absorption phenomena. The research was supported by RSF project 23-22-00105.

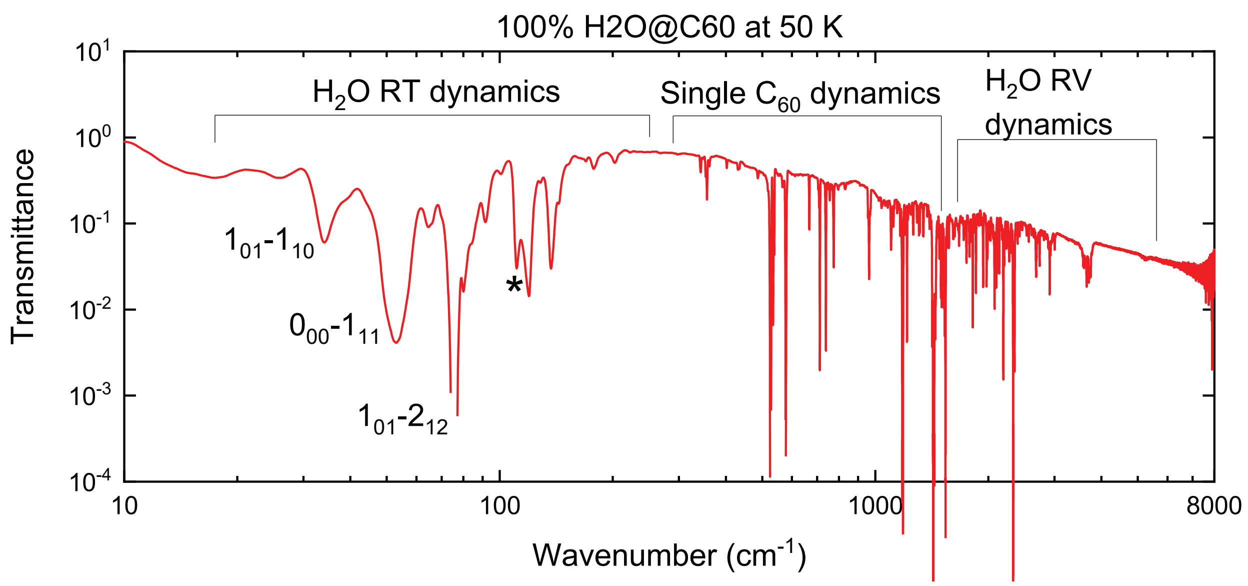


Fig. 1. Broadband transmittance spectrum of 100% $H_2O@C_{60}$ at 50 K. Horizontal brackets show spectral regions of $H_2O$ rotational-translational (RT), rotational-vibrational (RV) excitations and a region of fullerene molecular vibrations. Asterisk marks the position of pure rotational transition.

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# CONTROL OF THE NUCLEI SPIN STATES COHERENCE IN HBN AND SIC CRYSTALS BY OPTICAL, MICROWAVE AND RADIO FREQUENCY PULSES

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Optically polarized electron spins of defects in solids serve as a valuable platform for development of an advanced quantum technologies and are widely used as a tool to probe unconventional many body quantum physics in condensed matter [1].

The main explored solid-state platforms with these respects are diamond with negatively charged nitrogen vacancy defects and silicon carbide (SiC) with vacancy-related defects [2]. Distinctly new platform for potential realisation of mentioned above scenarios has been recognised only recently by demonstration of optically addressable spin states of defects in two-dimensional van der Waals (vdW) material, namely hexagonal boron nitride (hBN). hBN is formed by 2D atomic layers of $sp^2$-hybridized nitrogen–boron atoms that are coupled through weak vdW interactions. Its ultra-wide-bandgap ($Eg \approx 6$ eV) naturally grants the existence of deep level defects with optical transitions well below its bandgap. Decades of intensive studies of the negatively charged nitrogen-vacancy defect in diamond gave rise to the development of quantum technologies based on solid-state spin defects.

Quantum sensing, quantum information processing and realization of the exotic states of matter utilizing optically polarized spin-triplet states (S=1) of the NV defect, are only the few examples. Direct analogous of the $NV^-$ defect in diamond has been discovered in much more friendly semiconducting material, such as Silicon Carbide (SiC).

The latter opens the possibility to transfer protocols previously developed for diamond on the much more matured semiconductor platform. SiC is the wide bandgap material ($E_g \approx 2.4$-$3.2$ eV, depending on the polytype) widely used in semiconducting technologies. Spin defects well isolated within the SiC band gap have shown to be generated down to the single-defect level and possess unique properties, such as ultra-long spin-relaxation times, and narrow optical transitions in the nearinfrared range. These allowed to put forward the defects in SiC as spin-photon interfaces, single photon emitters, quantum sensors, and coherent microwave amplifiers [1, 3].

In this paper, the results of the study of the features of electron-nuclear interactions of triplet centers with magnetic nuclei are demonstrated. The methods of electron paramagnetic resonance and electron-nuclear double resonance were used to study transitions between nuclear spin states on a multifunctional Bruker Elexsys E680 spectrometer (W-band, $\nu_{mw} = 94$ GHz). The radio frequency generator for initiating nuclear transitions (nuclear magnetic resonance) has a sweep of 0.1 — 200 MHz with an output power of 150 watts. Using various pulse sequences with a combination of optical, microwave and radio frequency sources, we were able to investigate the dynamic characteristics of the nuclear subsystem of SiC and hBN crystals.

The values (Cq) and symmetries of the quadrupole and hyperfine interactions of the vacancy (VB) with distant boron nuclei in the second coordination sphere in a two-dimensional boron nitride crystal are established. The nuclear stimulated echo was recorded and the corresponding oscillation Rabi was performed at different capacities of the radio frequency source.

This research was funded by the Russian Science Foundation grant No. 20-72-10068.

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## THZ, RF AND X-RAY SPECTROSCOPY OF MN-DOPED SRTIO$_3$ SINGLE CRYSTALS

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Strontium titanate SrTiO3 is a canonical example of a quantum paraelectric. Its doping with manganese ions unlocks its potential as a quantum multiferroic candidate. However, up to now, the specifics of incorporation of the manganese ions into the perovskite $ABO_3$-type lattice of $SrTiO_3$ and its impact on structure–property relationships are debatable. We prepare Mn-doped $SrTiO_3$ single crystals, $SrTi_{1-x}Mn_xO_3$ (x=2 at. %), and study it with terahertz (THz) and radio-frequency (RF) spectroscopy. We clearly observe THz ferroelectric soft mode, whose dielectric strength Δε grows while cooling and coincides with the lower-frequency RF permittivity, and whose frequency behavior follows the Cochran law [1]. Qualitative and even quantitative similarities of the temperature-dependent soft mode parameters in $SrTi_{1-x}Mn_xO_3$ with those in pure $SrTiO_3$ indicates no strong effect of Mn doping on the suppression of the ferroelectric instability. At the same time, using high-precision X-ray diffraction, we discover clear fingerprints of the displacement disorder of Mn cations in the perovskite B-sublattice. Moreover, near the temperature of the antiferrodistortive phase transition (105-110 K), the off-center Mn position is shown to split in two, providing the unequal potential barriers distribution for possible local atomic hopping. We believe that such hopping is responsible for the two Arrhenius-type relaxation processes we observe below 1 MHz. The processes have similar activation energies (35 and 43 meV) and attempt frequencies ($1 \times 10^{11}$ and $\sim 1.6 \times 10^{10}$ Hz), suggesting similar relaxation mechanisms. Such mechanism has been reliably confirmed for A-substituted $Sr_{1-x}Mn_xTiO_3$ [2] but was overlooked in B-substituted samples. To the best of our knowledge, this is the first time that an off-center position of Mn in B-substituted $SrTiO_3$ has been observed, which expands our understanding of the dielectric and possible multiferroic properties of quantum materials.

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## EXPERIMENTAL BENCH FOR MEASURING ELECTROMAGNETIC PROPERTIES OF MATERIALS IN THE MILLIMETER FREQUENCY RANGE 75 TO 110 GHZ

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The active development of millimeter wavelengths, which has been outlined in recent years, is due to a number of factors that distinguish this radio frequency band from others. In the millimeter range, radar and guidance systems, telecommunication technologies, remote sensing of the Earth, radio astronomy, medicine, unmanned vehicles and many other areas find their implementation [1]. For this reason, the development of high-precision methods for measuring radiophysical properties and electromagnetic parameters of materials in the millimeter frequency band is an important direction in the development of modern microwave technology. As is known, in the short-wave part of the millimeter waves (2.7—4 mm) there is the W-band, which occupies the frequency band from 75 to 110 GHz. We note the main directions of using the W-band: radar guidance and aiming systems, sensors in experimental automatic vehicles, including unmanned vehicles, high-precision studies of weather phenomena, satellite communications.

This work is devoted to the developed experimental bench, which provides measurements of the frequency dependences of reflection and transmission coefficients of materials samples and coatings, as well as complex dielectric permittivity and magnetic permeability in the frequency range 75–110 GHz. The proposed method is based on the S-parameters measurements of a quasi-plane electromagnetic wave using broadband lens horn antennas and a vector network analyzer. During the measurement process, a test sample is placed on the diaphragm located in the near zone of the horn antennas. While measuring the reflection coefficient a matched load in the form of a pyramidal block of radar absorbing material is mounted in the area behind the diaphragm. In order to reduce errors in measuring S-parameters, a set of special calibrations with background subtraction is used. With a view to separating a desired signal against the background of spurious re-reflections (noise), a time-domain procedure is performed using the Kaiser-Bessel window.

As an example, Fig. 1 shows the frequency dependence of the complex dielectric permittivity of a fused quartz sample, measured using the experimental bench in the frequency bands 2—40 GHz and 75—110 GHz. It can be seen from the above graph that the experimental results obtained demonstrate good convergence with the literature data [2], from which it is known that the dielectric permittivity of quartz is practically frequency-independent and $\varepsilon \approx 3.8 + j0.001$.

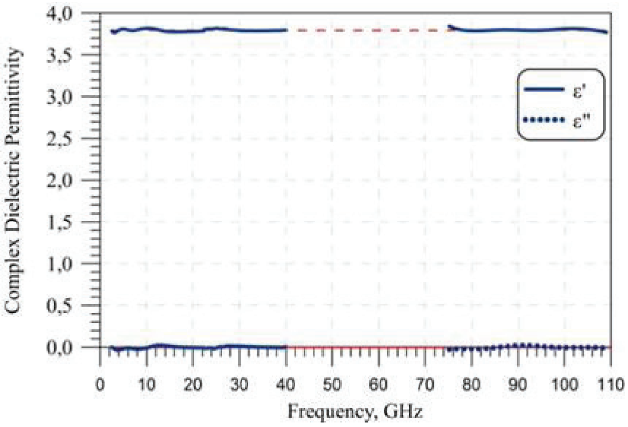


Fig. 1. Measured frequency dependence of complex dielectric permittivity of fused quartz sample in the bandwidths 2—40 and 75—110 GHz.

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## SINGLE-PARTICLE AND COLLECTIVE STATES OF DIPOLAR COUPLED WATER MOLECULAR NETWORK

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Since separate water molecules possess large electric dipole moment (1.85 Debye) their mutual ferroelectric/antiferroelectric ordering mediated by dipole-dipole coupling can be expected. In liquid water or water ice such ordering does not happen due to intermolecular hydrogen bonds that overwhelm dipolar interaction. The existence of a so-called "water ferroelectricity" has been the subject of debate for decades. It is believed that water ferroelectricity can play crucial role in a variety of phenomena and areas of natural sciences. It turned out, however, that a detailed study of the phenomenon is hampered by the difficulties of its implementation in laboratory conditions. For years, corresponding experimental results remained controversial, so that the community had to be "satisfied" with theoretical considerations and computer simulations of possible ordering of $H_2O$ molecular dipoles.

We found an ideal workbench for studying single-particle and collective effects, including ferroelectricity, in ensembles of dipole–dipole coupled water molecules. It is provided by hydrated dielectric crystals of the beryl family. The crystals contain separate $H_2O$ molecules isolated within nanosized voids formed by the lattice ions. Being only weakly linked to the ions and separated by 5–10 Å, the water molecules do not experience H-bonding (interaction length 1–2 Å); nevertheless, they interact via longer-range dipole–dipole coupling (interaction length 10–100 Å). This kind of network is of broad interest and of fundamental importance since it provides with the opportunity to study not only the famous "water ferroelectricity" phenomenon, but also diverse quantum physics of electric-dipolar systems whose properties should be qualitatively different from those occurring in well studied systems with magnetic moments.

We have discovered quantum paraelectricity [1,2] and fingerprints of quantum critical behavior [3]-of a network of $H_2O$ molecules hosted by the hexagonal matrix of beryl crystal lattice. In orthorhombic matrix of a relative crystal, cordierite, we have observed an order-disorder type ferroelectric phase transition [4], at around 3 K, into a complex ferroelectrically/antiferroelectrically ordered state of polar $H_2O$ molecules. In addition to collective phenomena, we studied single-particle excitation of translational and librational types of separate nano-confined $H_2O/D_2O$ molecules [5,6]. Our recent research shows influence of internal pressure on incipient ferroelectricity and quantum state of nano-confined water molecules [7].

The research was supported by the Russian Science Foundation, Grant 22-22-00091.

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# THZ AND MICROWAVE SYSTEMS

## DEVELOPMENT AND EXPERIMENTAL STUDY OF A POWERFUL GYROTRON COMPLEX WITH A GENERATION FREQUENCY OF 32.9 GHZ

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One of the important tasks of vacuum electronics is the creation of radiation sources with an operating frequency of several tens of GHz and a power of more than 10 kW for the modern ion beam sources [1,2]. The purpose of this work was to create a gyrotron system based on a continuous wave technological gyrotron with operating frequency of 32.9 GHz.

A number of functional and structural units of the gyrotron was designed and tested for the new device:

The magnetic system was comprised of an axially symmetrical oil-cooled solenoid with the diameter of the bore equal to 60 mm. The magnet produced a magnetic field of up to 0.61 T at the operating current of 130 A. Also, a cathode coil with air cooling and an operating current of about 2 A were used to adjust the magnitude of the magnetic field and the angle of inclination of the magnetic field line in the gyrotron electron gun.

The radius of the resonator was chosen at 10.185 mm, with the $TE_{0,2}$ mode operating at the second harmonic of the cyclotron frequency as the desired operating mode. The Q-factor of the cylindrical resonator was 2500. Numerical simulations have predicted that at an operating voltage of 22 ± 2 kV, the region of optimal operating currents lay in the range of 1.5–2.2 A. The tubular helical electron beam was formed by a diode-type magnetron-injection gun. A high-temperature emitter made of lanthanum hexaboride ($LaB_6$) has effectively produced a beam with a current density of 1.2 A/cm$^2$. The spent electron beam was intercepted by a collector in the form of a hollow copper cylinder with water cooling. In any operating regime of the device, the maximum power density did not exceed 0.4 kW/cm$^2$. The energy output system consists of a circular waveguide and a boron nitride window with a diameter of 32.6 mm. The output of energy was carried out in the operating mode ($TE_{0.2}$) along the axis of the gyrotron.

At the first stage of the development, the numerical modeling of electron-wave interaction processes was carried out using the ANGEL software package [3]. The dependences of the starting current and output power on the magnitude of the magnetic field of the solenoid were defined, as well as on the parameters of the electron beam (pitch-factor, accelerating voltage). The resonator profile was optimized to achieve good efficiency and low mode conversion. The simulation of the output power showed the possibility of achieving an output power of over 12 kW at an accelerating voltage of 22 kV and an electron beam current of 2.5 A with a generation efficiency of more than 20%.

In the experimental tests of the gyrotron, the design power of 10 kW was achieved at an accelerating voltage of 22 kV and an electron beam current of 1.9 A. The generation efficiency was 25.7%. The maximum power of 14 kW was obtained at an accelerating voltage of 23 kV and an electron beam current of 2.2 A, with a generation efficiency of 27.6%.

This work was supported by the IAP RAS project 0035-2021-0027.

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## NUMERICAL SIMULATION OF A GYROTRON WITH A QUASI-OPTICAL RESONATOR FOR SPECTROSCOPIC APPLICATIONS

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The gyrotron is a powerful source of electromagnetic radiation in the millimeter and submillimeter wavelength range. In a number of its applications, especially in spectroscopy and media diagnostics, there is a tendency to increase frequency of radiation and expand the frequency tuning range. Since the frequency of gyrotron radiation at the fundamental cyclotron resonance is close to the cyclotron frequency of electrons, their advance into the subterahertz and terahertz frequency ranges is limited by the parameters of magnetic systems.

A possible solution to the problem is to switch to operation on harmonics of cyclotron frequency. However, the density of the spectrum increases and the problem of mode competition intensifies. One of the solutions to this problem is the use of a quasi-optical resonator in the gyrotron. A significant reduction of the resonator's eigenfrequency spectrum density makes it possible to excite the high-order modes in the sub-THz and THz ranges. At the same time, the possibility of mechanical movement of mirrors opens up the possibility of smooth broadband frequency tuning.

This paper presents the results of numerical simulation of a gyrotron with a confocal two-mirror quasi-optical resonator operating on the fundamental cyclotron resonance.

The working mode $TEM_{080}$ was chosen, which corresponds to the radiation frequency of 263 GHz. Calculations of both the "cold" longitudinal and transverse structures of the resonator field are carried out considering ohmic and diffraction losses. The optimal value of the coupling factor for this configuration is found and curves of starting currents and efficiency are constructed for both operating and neighboring modes to assess the problem of mode competition.

The electron-optical system is considered as a triode magnetron-injector gun, which has proven itself well in a classical gyrotron operating at a frequency of 263 GHz. With a beam current of 0.4 A and an accelerating voltage of 15 kV, the required value of the anode voltage for various distances between the center of the emitter and the center of the magnetic field were found within the framework of the single-speed beam model, which provide the necessary beam radius and pitch factor close to 1.3.

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## FREQUENCY TUNING IN TERAHERTZ QUANTUM CASCADE LASERS INDUCED BY CURRENT AND TEMPERATURE

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The possibility of frequency tuning in terahertz quantum cascade lasers (THz QCLs) is crucial for their practical applications, such as spectroscopy. The simplest means to tune the QCL frequency is to make use of temperature and current variations. In this work we performed a series of spectral measurements for a number of THz QCLs based on a GaAs/Al0.15Ga0.85As active region with frequencies in the range of 2.3 to 4.1 THz. The QCLs had a double-metal Au waveguide and operated in pulsed mode with 5-15 us pulses at a 1 kHz repetition rate. We present the spectra of the lasers measured at fixed operating points as well as with current scanning in a wide temperature range from 5 to 120 K. Using the obtained emission spectra, we consider the relative contributions of different lasing frequency drift mechanisms with regard to the drift caused by both the heatsink temperature variations and the Joule heating.

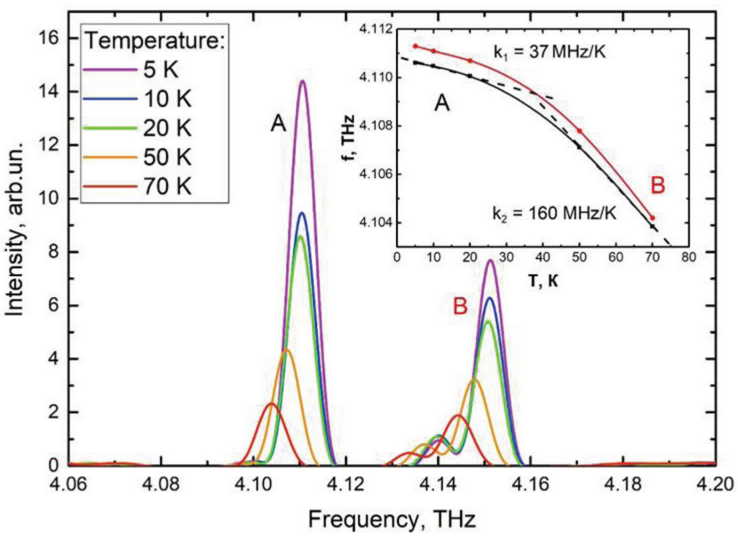


Fig. 1. Emission spectra of a 4.1 THz QCL at 5-70 K measured at a fixed operating point of 1.03 A with 10 μs / 1 ms pulses. Inset: temperature drift of the mode frequencies (4.11 THz (A) and 4.15 THz (B)). Total temperature tuning range for the A mode is 6.76 GHz. The tuning rates $k_{1,2}$ correspond to the lower and higher temperature regions.

## THZ PLANAR SURFACE PLASMON MICHELSON INTERFEROMETER

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Plasmon interferometry has found wide application in optical sensor devices in the visible range due to such features of surface plasmons (SPs) at these frequencies as short propagation length (which meets the requirement for miniaturization of sensors) and concentration of the SP field in the metal surface vicinity, that results in high sensitivity of SP devices to changes in optical characteristics of the sensor layer on the metal surface [1].

In the THz range, where the SPs propagation length extends to tens of centimeters, plasmonic interferometers can be effectively used to control quality of the metal surface and metallized mirrors of macroscopic dimensions as well as to determine the effective permittivity of metal coatings used in plasmonic THz integrated circuits; additionally, THz SP interferometers can be employed for investigations of thin dielectric films on metal surfaces, and for various sensor applications [2].

To date, various SP interferometric schemes suitable for refractometry of conducting surfaces in the THz range have been designed [3]. Most of them have not yet been implemented, while the tested devices have significant limitations. Recently, the scheme of the first THz SP planar Michelson interferometer was approbated [4]. The interferometer design, its technical characteristics [3] and the technique for determining the complex refractive index of SPs from the interferograms obtained with it will be presented in the talk. The SPs were excited by the Novosibirsk free electron laser radiation with the wavelength of $\lambda_0$=141 μm on flat surfaces with gold sputtering, coated with ZnS layers of thickness from 0 to 3 μm. Based on the measurement results, the value of the effective permittivity of the deposited gold was found; it turned out to be an order of magnitude smaller than that of bulk crystalline gold.

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## TERAHERTZ DETECTOR BASED ON MICROSTRUCTURED BISMUTH-ANTIMONY SOLID SOLUTION

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Terahertz photonics technologies are used in such areas as non-destructive defect testing, object moisture control, astronomy, biomedical diagnostics, etc. So it needs to develop low-cost, sensitive, easy made, room temperature THz sensors for such applications. THz detectors mainly made of semiconductors have the problem in the difficult manufacture process. In this paper, we propose a low-cost, sensitive, easy made, room temperature THz detector based on thin-film thermoelectric materials. A microstructured bismuth-antimony design was used to increase the sensitivity of THz detector. A numerical simulation of the detector design was performed to optimize a overheating of the microstructure for THz radiation at a certain frequency. A temperature map of THz detector heating during the exposure of 30 mW power radiation at the frequency of 0.14 THz was numerically and experimentally obtained and analyzed. DC and AC voltages induced on the sample at THz exposure were measured at the different orientations of detector feed lines relatively to THz electric field polarization. An increase in response of the microstructured detector to the radiation at 0.14 THz frequency in comparison with a continuous structure detector was shown.

## TECHNOLOGIES OF FREQUENCY SELECTIVE SURFACES AND METASURFACES FOR HIGHLY EFFECTIVE SPECTRAL AND POLARIZATION DISCRIMINATION IN THE TERAHERTZ BAND

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We review the results of extensive R&D activity focused on elaborating high-performance instrumental solutions for spectral and polarization discrimination in the THz band using technologies of frequency selective surfaces and metasurfaces. The high-contrast and low-insertion-losses polarizers, quasi-optical filters of different types (band-pass, low-pass, high-pass), and spectral/polarization-selective thermal detectors operating in the range of 0.05-5 THz are considered. The key fabrication techniques including photolithography on flexible polymeric substrates, electroplating, deep X-ray lithography, and micropatterning with femtosecond laser pulses are described. The issues of design optimization, spectral characterization, and practical applications for the developed devices are discussed.

The presented solutions are distinguished by outstanding experimental performance passing ahead of competitive devices available in the market of THz instrumentation.

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## APPROACHES TO STUDYING THE EVANESCENT FIELD OF SURFACE PLASMONS USING THZ RADIATION FROM THE NOVOSIBIRSK FREE ELECTRON LASER

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One of the applications of terahertz surface plasmons (SP) propagating along the conductor-dielectric interface is the surface refractometry. The conductor can be a metal, a dielectric (in the absorption line), or a doped semiconductor. Based on the measured characteristics of the SP (propagation length along the interface, phase velocity, and depth of penetration of the SP field into the dielectric), it is possible to restore the optical properties of the conductor, which is important for the quality diagnostics of surfaces and thin films, for sensor applications, etc. [1] The obtained optical properties of materials can be used to create THz plasmonic integrated circuits. [2] In contrast to the visible range, all noble metals have high conductivity in the THz frequency range, as a result of which the SP field in the dielectric is weakly coupled to the surface and there are large radiation losses of plasmon intensity even at small roughnesses and inhomogeneities [3].

In this paper, we will consider experimental approaches to measuring the attenuation of the intensity of the SP evanescent field: the probe method with external modulation and modulation by the oscillations of the probe itself, as well as the registration of the field arising after the SP diffraction at the edge of the conducting surface. A solution to the inverse problem of finding the optical constants of a metal surface from the depth of penetration of SP using numerical methods is presented.

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# INCREASING EFFICIENCY OF THE TERAHERTZ GENERATION IN MG:LINBO$_3$ CRYSTAL BY OPTIMIZING THE ANGULAR DISTRIBUTION OF THE OUTPUT RADIATION

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Among the various methods currently being developed to generate THz radiation, the approaches using pulsed optical lasers and nonlinear crystals [1] allow to obtain the most powerful [2] THz radiation within tabletop systems. Nevertheless, the possibilities of working outside the crystal with the total angular amount of THz radiation generated using these methods are extremely limited, because the highly divergent THz beam, originally generated inside the crystal, cannot simply be brought out without significant losses at the crystal boundaries. Moreover, even if the waves escaped in the open space, they propagate in a very wide cone which cannot be fully focused further neither on the object of study nor on the detector.

Unfortunately, this problem currently is poorly investigated. So the main goal of this work was to construct a Si coupler [3] providing an increase of the THz signal output and facilitating its subsequent collimation. For this purpose, direct theoretical calculations of the angular distributions of the output THz wave intensity were made. In these calculations, we considered the model of sideways generation of THz radiation in a Mg-doped lithium niobate crystal (Mg:LiNbO$_3$) with a Si prism coupler by optical rectification (OR) of femtosecond laser pulses. Despite the fact that cylindrical, spherical and cone-shaped output surfaces of the Si coupler can be more effective, numerical simulation and experimental study were carried out for the simplest method of manufacturing such elements when a plano-spherical Si-lens is superimposed on a flat surface of a triangular Si-prism.

A theoretical model has been proposed for calculation of the frequency-angular distribution of THz radiation, taking into account the influence of nonlinear processes that occur with violation of the exact longitudinal phase matching condition. Examples of the angular distributions are numerically calculated and analyzed for the radiation power densities at 1 THz inside the crystal, inside and outside the Si couplers with different exit surfaces. Experimentally, the temporal dependences of THz electric field and the spectral power density distributions were measured for different shapes of the Si couplers (Fig. 1). Comparison of the theoretical and experimental results demonstrates advantages of the convex output surfaces of Si couplers and validity of the developed theoretical approach for further modeling the improved Si elements.

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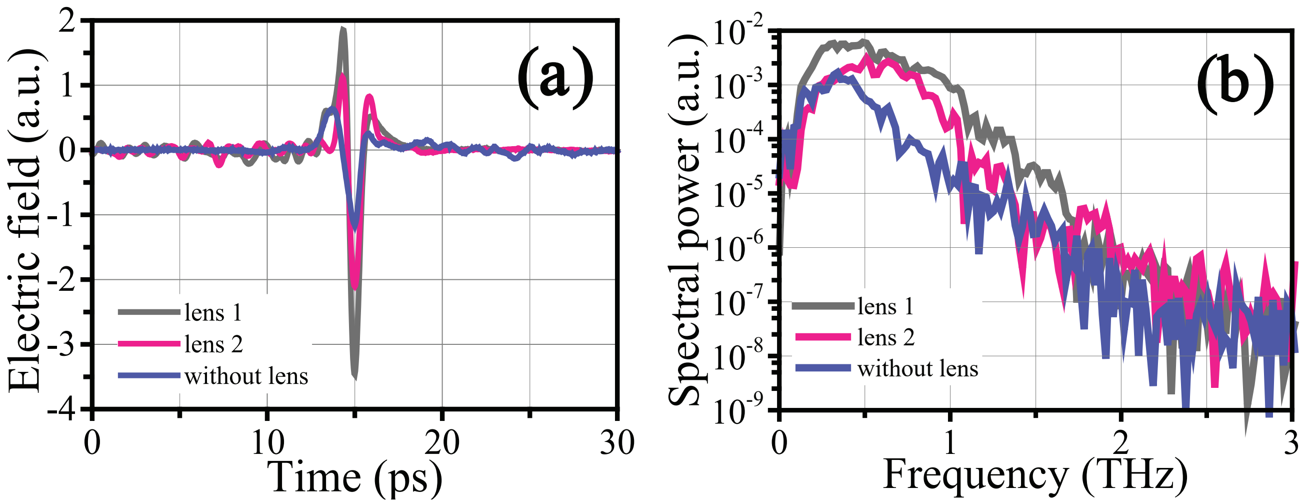


Fig. 1 Experimental temporal dependences of THz electric field (a) and the spectral power density distributions (b) obtained using three different configurations of Si elements on the crystal side surface.

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## PLASMON PROPERTIES OF GRAPHENE WITH AN ARBITRARY DIRECTED ELECTRIC CURRENT

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Microstructures based on graphene can be used to detect and amplify terahertz (THz) radiation [1]. In particular, the plasmonic properties of such structures are being actively studied [2], the amplification of THz plasmons in graphene with direct current was observed experimentally [3].

In this work, we investigate the plasmonic properties of graphene with a direct electric current (DC-current) arbitrarily directed relative to the direction of plasmons propagation in graphene. In this case, the graphene conductivity describes in the tensor form. Frequency ranges in which the real part of elements of the graphene conductivity tensor takes negative values are determined. It is shown that, at realistically achievable values of DC-current in graphene, amplification can occur at THz frequencies. It is shown that in the case of a DC- current flowing at an angle to the plasmon wave vector, the off-diagonal elements of the graphene conductivity tensor become comparable to the diagonal ones and can make a significant contribution to the dispersion and amplification of surface plasmons in graphene. The dispersion characteristics and amplification of THz plasmons in graphene with an arbitrarily directed direct current are studied.

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## RECENT ADVANCES IN SUB-TERAHERTZ DEVICES FOR INDUSTRIAL AND RESEARCH APPLICATIONS

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Generation and detection of electromagnetic radiation in terahertz ans sub-terahertz range remained far from a routine for a long time. Recent progress in this area have made possible applications that previously seemed unfeasible, such as broadband wireless communications, industrial imaging for aims of non-destructive quality control, not to mention terahertz spectroscopy and research applications [1, 2]. The importance of mastering this frequency range necessitates the further development of sources, receivers and devices for processing and converting terahertz radiation, as well as the integration of these elementary devices into complex installations. This abstract summarizes recent advances of our team in the field of sub-terahertz devices and applications.

Our team recently developed a novel system for linear transmission scanning with operating frequency around 300 GHz and spatial resolution better than 2.3 mm [3]. This system was tested and proved to be useful for non-destructive testing and security screening applications. This scanner is based on either GaAs/AlGaAs or Si detectors with two-dimensional electron system [4], which makes it easy for mass production.

The other significantly upgrowing area is the development of components and systems for controlling terahertz beams. Such components can be not only passive, but also active, i.e. allowing to controllably modify the terahertz beam depending on control signal of some kind. In the area of passive components, main achivements are related to phase wave plates. Such wave plates statically change the radiation phase with spatial resolution, creating a required beam profile in the image plane [5]. Such waveplates could be easily produced with common 3D printers, which makes them very cheap and fully customizable. The most significant example of an active system for terahertz beam manipulation is a phased antenna array. Recently our team designed and developed a new kind of fast electrically controllable semiconductor based phase shifter, which tunes the phase up to 41° at frequencies of up to 0.27 THz [6], which makes it a promising component for creating scalable active phase antenna arrays.

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## METAMATERIALS FOR ANTIALIASING FILTRATION AND HARMONIC MIXING IN TERAHERTZ TIME-DOMAIN SPECTROSCOPY

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We propose an approach to improve the accuracy and speed of a terahertz time-domain spectrometer based on antialiasing filtration or harmonic mixing. Both techniques are based on signal filtering to narrow the frequency band of the THz signal, which allows increasing the sampling interval in accordance with the Nyquist–Shannon theorem. Thus, it is possible to reduce the measurement time or increase the accuracy due to the greater signal acquisition and averaging. The designs of microstructural interference-based low-pass filters for anti-alias filtering and a narrow bandpass filter for harmonic mixing are presented. The concept was verified by comparing measurements made under normal conditions with measurements made using filters. A reduction of the spectrometer scanning time by 12 times and an increase in measurement accuracy due to eliminating a long-term signal drift were shown.

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## APPLICATION OF COVARIATION MEASUREMENT FOR CALIBRATION OF QUANTUM EFFICIENCY OF ANALOG DETECTORS

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The process of parametric downconversion (PDC) represents the decay of photons of monochromatic radiation (pump) with a frequency $\omega_p$ on pairs of correlated photons at lower frequencies, $\omega_s + \omega_i = \omega_p$ [1]. When studying twin beams produced under a frequency degenerate PDC [2], the covariance, the noise reduction factor (NRF) and other related characteristics are usually considered as non-classical parameters, which are determined based on measurements of the current readings of optical detectors of the signal and idler PDC channels. We propose to consider properties of biphotons with extremely different frequencies, when the signal photon frequency $\omega_s$ is very close to the pump frequency, while the idler frequency $\omega_i$ hits the terahertz range. Under the high parametric gain conditions, it would be more convenient for recording and utilizing the quantum properties of optical-terahertz fields. We consider a theoretical approach that can be applied to detectors operating in the analog recording mode. The method is based on the fact that the signal and idler beams generated by PDC have the same fluctuations in the number of photons for any parametric gain coefficient. Applicability of the detector calibration method based on the measurement of NRF, previously developed for photon-counting detectors only, is studied. The fluctuations in the single-photon pulse amplitudes of non-countable detectors are taken into account.

When operating in analog mode, the elementary single-photon pulses generated by the sensitive element of the detector are superimposed on each other and, as a result, the total time-varying output current is recorded $i(t)=\sum_{k=1}^{m} q_k f(t-t_k)$, where m is the number of elementary single-photon pulses generated by the sensitive element during the current detection. For the current recording mode applicable to detectors of any type, the relationship between the current NRF $\sigma^{(anal)} \equiv \frac{Var(i_s'-i_i)}{<i_s'>+<i_i>}$ (here, $i_s' \equiv i_s <i_i>/<i_s>$) and the quantum efficiency $\eta_i$ is obtained as

$$.\sigma_{red}^{(anal)}/<q_i>=\frac{\alpha(\varepsilon_s+1)\langle q_s\rangle/\langle q_i\rangle+(\varepsilon_i+1)}{2}-\frac{\eta_i}{1+\kappa_s}\left[1-\langle N\rangle\left(\frac{\kappa_i+\kappa_s}{2}+\frac{\varepsilon_s(1+\kappa_i)+\varepsilon_i(1+\kappa_s)}{2}\right)\right]$$

Here, a parameter $\varepsilon_j \equiv Var(q_j)/\langle q_j\rangle^2$ is introduced for each of the detectors to characterize the degree of fluctuations of single-photon pulses [3]. Although the measurement of NRF using non-countable detectors does not allow us to directly characterize the degree of two-photon squeezing in the PDC field, the possibility of determining the quantum efficiency of such detectors from the NRF still remains. However, in this case, in addition to direct measurements of the NRF, an additional involvement of several approximation procedures will be required. At same time, when measuring the quantum efficiency of uncountable detectors by the normalized covariance $\tilde{N} \equiv <\delta i_s \delta i_i>/(<i_i>+<i_s>)$, the requirements are much simpler: there is no need to use a single-photon detector in the signal channel, it is not necessary to register only correlated modes in the idler channel. It suffices to narrow down the set of signal channel modes so that only modes matched with at least a part of the SPDC modes recorded by the idler detectors fall into them. The accuracy of the measurement should also be higher than that of NRF measurement, as it does not involve multiple approximation procedures.

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## RADIOVISION IN THE TERAHERTZ RANGE: PROBLEMS AND PROSPECTS

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An analysis of the current state of research and development in the field of radiovision for the terahertz range of electromagnetic radiation was carried out in the work. Various sources of terahertz radiation are considered: photoconductive antennas, IMPATT diodes, Schottky diodes, and others, as well as modern video cameras for this range and their main characteristics for recording and studying THz images in various spectral regions.

The results of studies of the intensity distribution in THz radiation beams at different wavelengths for photoconductive antennas using THz radiovision, as well as the possibilities of studying scattering processes during reflection and transmission of THz radiation for various materials, are presented.

The prospects for the use of THz radiovision in the development of security systems for the detection of explosives and other hazardous substances and materials are studied.

Particular attention is paid to analytical applications, in particular, the possibility of detecting trace amounts of various substances on the surface. The possibility of finding and detecting explosive microcrystals was demonstrated, with the detection level being ~1 μg.

The possibilities of recording THz images of objects at different distances and behind obstacles in the "transparency windows" of the atmosphere are considered.

The prospects for the use of THz radiovision in holography, tomography, and also as a method of non-destructive testing in the development of THz metamaterials (in particular, based on organic semiconductors and nanohybrid materials) are considered.

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## THZ PHOTOCONDUCTIVE ANTENNAS KIT FOR 780 NM FEMTOSECOND LASER INPUT

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Photoconductive antennas (PCA) are widely used to generate and detect both pulsed [1] or quasi-pulse [2] broadband and continuous wave [3] radiation in the terahertz (THz) range. These devices form the basis of many terahertz imaging [4] and spectroscopy [5] systems that have shown promising applications in various industries and research areas.

Antennas PCA-SL-50-50-780 and PCA-D-50-7.2-780 manufactured by TYDEX, LLC form an ideal pair of antennas (emitter-detector), on the basis of which it is possible to build a broadband terahertz spectrometer working in the frequency range of 0.1-2.5 THz. We have developed a design of universal adjustment block for implementation in almost any THz devices with optical pumping from free space. The PCA kit design is based on the optical cage system and can be easily modified for both collimated and focused THz beam measurements.

THz photoconductive antennas kit has the following characteristics:

- optical pumping by a femtosecond laser with the wavelength of 780 nm, a pulse duration of 120 fs, a typical power of 10 mW (maximum power of 30 mW);
- unipolar bias voltage is up to 70 V;
- modulation frequency is up to 90 kHz;
- dynamic range at a frequency of 0.3 THz is up to 65 dB;
- frequency range is 0.1-2.5 THz.

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## STANDARD-FREE MEASUREMENT OF QUANTUM EFFICIENCY IN THE CASE OF AN ANALOG DETECTOR

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The standard-free absolute method was proposed in 1980 by D.N. Klyshko for calibration of quantum efficiencies of single-photon photodetectors. The method is based on measuring fluxes of quantum-correlated pairs of photons ("biphotons") generated by spontaneous parametric down-conversion (SPDC) and does not require the use of any pre-calibrated detectors or sources [1]. Now it is widely used in the modern quantum optical technologies, but so far is not adapted for analog detectors that generate single-photon photocurrent pulses with strongly different amplitudes and thus cannot operate in the photon counting mode. Among such devices, for example, are the majority of incoherent far infrared and terahertz wave detectors. The goal of this work was to create a modified Klyshko method for calibrating the quantum efficiency of such non-counting analog-type detectors. In order to find out how to calibrate detectors in the terahertz range, first we started our work with optical analog detectors [2]. This is explained by the fact that the known to be accurately calibrated photon-counting detectors, which are necessary for application and verification of results of our new approach, are easily accessible in the optical range only.

At this step we have explored the possibility of calibrating the cathode quantum efficiency of an analog photomultiplier tube (PMT). The pump source in the SPDC set-up was a single-mode diode laser with a wavelength of 405 nm. A bismuth triborate (BiBO) crystal was used as a nonlinear medium The SPDC *ooe*-type process proceeded in a degenerate mode. After a proper preprocessing, the set of experimental data consisted of charge distribution histograms detected in signal and idler SPDC channels. By special modeling of the histograms, the average number of photoelectrons, emitted by PMT cathode during the detection time, was obtained. By measuring the biphoton correlation function, the mean number of incident photons was determined. This made it possible to estimate the quantum efficiency of the PMT cathode (Fig.1).

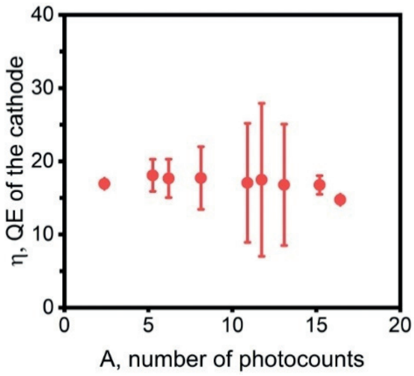


Fig. 1. Vertical axis: Quantum efficiency of the PMT cathode determined under different levels of incident radiation power. Horizontal axis: the mean number of PMT cathode photoelectrons, corresponding to these power levels.

Results of the developed modified Klyshko method were verified by measuring the same radiation flux by the PMT and by an independently pre-calibrated single-photon detector. The proposed approach can be further developed for calibration of spectral responsivities of various analog detectors, including the terahertz incoherent receivers.

This work was supported by the Russian Science Foundation, project No. 22-12-00055.

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## TERAHERTZ GENERATION OPTIMIZATION IN A OH1 NONLINEAR ORGANIC CRYSTAL PUMPED BY A CR:FORSTERITE LASER

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In recent years, OH1, DAST, DSTMS, HMQ-TMS and other organic nonlinear crystals with high coefficient of second-order nonlinearity have been widely applied [1, 2]. They are pumped by infrared laser radiation with a wavelength between 1200 and 1600 nm. A significant advantage of these organic crystals is high conversion efficiency of about a few percents. Radiation of titanium-sapphire lasers with a wavelength of 800 nm converted by an optical parametric amplifier (OPA) into the required spectral range is commonly used for pumping such crystals. Femtosecond Cr:forsterite laser with a wavelength of 1240 nm is an alternative source for pumping organic crystals. Applying such a laser made it possible to obtain THz pulse energy of 0.9 mJ in DSTMS [3] crystal, as well as to demonstrate efficient conversion in DAST and OH1 with a high quality of THz beam spatial distribution [4].

In this report, we present the results of experimental investigations of terahertz radiation generation conversion efficiency in a OH1 nonlinear organic crystal pumped by femtosecond laser pulses at 1240 nm wavelength and influence of OH1 crystal thickness on the terahertz generation. Fig.1 demonstrates the conversion efficiency of THz radiation as a function of the optical pump fluence for OH1 crystals with different thicknesses and dependence of the THz pulse energy on the thickness of the OH1 crystal at the maximum pump fluence of 16 mJ/cm$^2$.

The experimental data are approximated by the sine squared function to determine the optimal thickness of the nonlinear crystal, taking into account the coherence length. The maximum energy and conversion efficiency are achieved for the OH1 crystal thickness of ~1 mm. It should be noted that the obtained experimental data are in a good agreement with previously published calculations [1, 4].

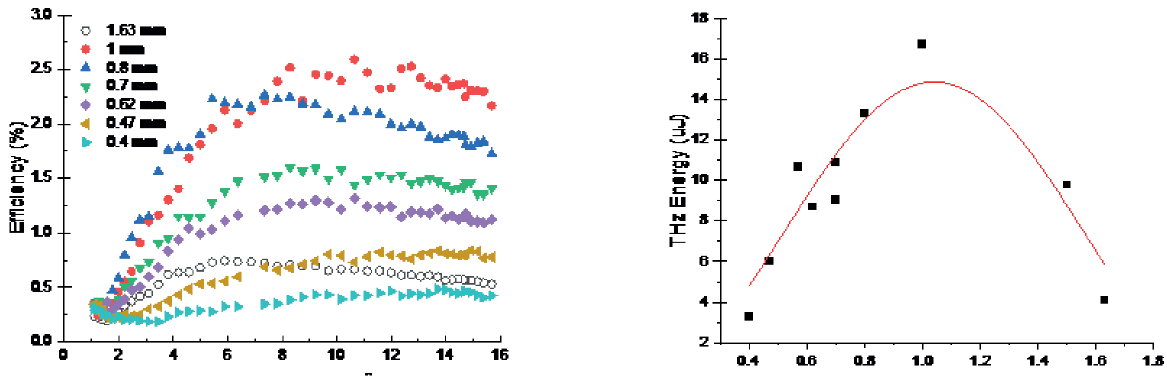


Fig. 1. Conversion efficiency of THz radiation versus pump fluence for various OH1 crystal thickness and THz pulse energy as a function of the OH1 crystal thickness at the maximum pump fluence of 16 mJ/cm2 (the dots are experimental data; the line is the approximation by the sin x2 function).

The study were carried out within the framework of the scientific program of the National Center for Physics and Mathematics (project 4.2). The reported study was funded by RFBR and ROSATOM according to the research project No. 20-21-00043. The experiments were performed using the unique scientific facility "Terawatt Femtosecond Laser Complex" in the "Femtosecond Laser Complex" Center of the Joint Institute for High Temperatures of the Russian Academy of Sciences.

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## REFLECTOMETRIC INDICATION OF POLARITON RESONANCE ON THE INSB SURFACE IRRADIATED BY TERAHERTZ RADIATION

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The possibility of achieving polariton resonance on the InSb surface irradiated by terahertz (THz) radiation and its indication by the amplitude-phase characteristics of reflected beam is considered. It is shown that the achievement of surface polariton resonance (SPR) on a semiconductor sample is possible under the influence of THz radiation [1], if its frequency is comparable to the plasma frequency ωp of the semiconductor (more precisely, $\omega \lesssim \omega_p/\sqrt{2}$). This condition is met, in particular, by indium antimonide. It has been established that one can achieve and indicate the SPR on a semiconductor, satisfying the above condition, by employing the Otto scheme of the ATR (attenuated total reflectance) method when scanning either the angle of incidence or the frequency of THz radiation; the existence of SPR is evidenced by both the presence of a resonant dip in the intensity of the p-component of the reflected radiation and a sharp change in its phase. Note that, the ellipsometry can be effectively used to specify the SPR as this method enables one to measure simultaneously both the ratio of amplitudes and the phase difference of both components of the probing radiation [2]. We suppose that the reflectometric indication of the SPR phenomenon may be effectively employed in the THz microscopy of semiconductor surfaces [3] (similar to microscopy of the surface plasmon resonance of conductive surfaces in the visible range), since magnitude of the decrease in intensity and phase jump of the *p*-component of reflected radiation accompanying the SPR strongly depend on the state of the surface under study.

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## TERAHERTZ WAVE DETECTING IN $GA_{50\%}SE_{(50-X)\%}S_{X\%}$ CRYSTALS AT A TELECOM WAVELENGTH

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$Ga_{50\%}Se_{(50-x)\%}S_{x\%}$ crystals, where x takes values 0, 1.5, 6, 8, 11, as a detector of terahertz pulses at a laser wavelength of 1.55 µm were studied. The optical and terahertz properties of crystals are measured, including refractive indices, coherence lengths and electro-optical coefficients. The possibility of using this crystal as a detector of terahertz radiation at a telecom wavelength is shown. To conduct the experiments terahertz time-domain spectrometer on a basis of Er- fiber laser at a wavelength of femtosecond pulses 1.55 µm was assembled.

For the detection the polarization-optical method based on the Pokkels effect was used. As a result of the study, the time forms of the detected THz radiation were obtained. It was shown that the $Ga_{50\%}Se_{44\%}S_{6\%}$ sample has the highest detection efficiency at the wavelength of laser radiation 1550 nm. The detection efficiency was evaluated based on the maximum signal amplitude. It was obtained that for pure GaSe $r_{eff}$ = 0.975 pm/V, for the most efficient crystal $Ga_{50\%}Se_{44\%}S_{6\%}$ $r_{eff}$ = 1.262 pm/V. These results are in good correlation with other studies at another wavelengths.

The authors acknowledge core facilities "VTAN" (Novosibirsk State University) for the access to its experimental equipment.

## TERAHERTZ WAVE DETECTING IN GASE:S CRYSTALS AT A TELECOM WAVELENGTH

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$Ga_{50\%}Se_{(50-x)\%}S_{x\%}$ crystals, where x has values 0, 1.5, 6, 8 and 11, were investigated as terahertz pulse detectors of at a laser wavelength of 1.55 µm. The optical and terahertz properties of the crystals, such as refractive indices, coherence lengths and electro-optical coefficients are measured. At the wavelength of laser radiation 1550 nm, it was demonstrated that the $Ga_{50\%}Se_{44\%}S_{6\%}$ sample has the maximum detection efficiency. The detection efficiency was evaluated based on the maximum signal amplitude. It was shown that for pure GaSe electrooptic coefficient $r_{eff}$ had a value of *0.975 pm/V,* for the most efficient crystal $Ga_{50\%}Se_{44\%}S_{6\%}$ $r_{eff}$ = *1.262 pm/V.* These results are in good correlation with other studies at another wavelengths.

The studies were supported by the Ministry of Science and Higher Education of the Russian Federation, project #FSUS-2020-0029. The authors acknowledge core facilities "VTAN" (Novosibirsk State University) for the access to its experimental equipment.

## 2-OCTAVE ACHROMATIC QUARTER-WAVE PLATE FOR TERAHERTZ APPLICATIONS

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Terahertz time-domain technology has attracted more and more attention of scientists in the recent years. Polarization, as one of the Important properties of electro-magnetic wave, is studied and applied in the terahertz frequency range. Polarimetry is often used to characterize and examine materials. However, THz achromatic waveplate, as is a key component of THz time-domain polarimetry, hasn't been thoroughly studied yet. Waveplates are usually made by optical materials with birefringence, such as quartz and $MgF_2$. There is a proposal using a stake of monochromatic waveplates with optical contact bonding [1,2]. Nevertheless, the given proposal only works for certain frequency range and can't be applied on other frequency range. Several unconventional approaches towards THz achromatic waveplates have been demonstrated, such as silicon grating [3], stacked parallel metal plates [4], metamaterial [5,6] and prism using internal total reflection [7]. However, these solutions are either complicated to be fabricated, or not eligible for wide usage due to losses caused by high absorption for Fabre-Pero interference. In this paper we provide an alternative design of a compact THz achromatic quarter-wave plate working in the frequency range of 2 octaves in THz frequency range. The proposed waveplate consists of 3 quartz plates and is manufactured using optical contact bonding. The thicknesses and the rotation angles of optical axis of each quartz plate are the key parameters of the waveplate. The working frequency range of the waveplate is changeable by modifying the thicknesses and the rotation angles, which can be calculated using a simplified formula. The theoretical and experimental results of retardation and ellipticity angle for 2-octave THz achromatic quarter wave-plate were provided and analyzed.

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# OPTOELECTRONICS

## MODELING MICROWAVE-BAND RADIO-ELECTRONIC DEVICES AND SYSTEMS BASED ON MICROWAVE-PHOTONICS APPROACH IN CADENCE AWRDE SOFTWARE

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Microwave photonics (MWP) is an interdisciplinary scientific and technological field that combines the microwave electronics and photonics worlds [1, 2]. Emerging applications for information and communication networks (ICN) of fiber-wireless architecture, sub-terahertz wireless systems, radar, and electronic warfare systems indicate that MWP is set to be a subject of increasing importance. In particular, MWP technology opens the way to super-wide bandwidth transmitting characteristics at lower size, weight, and power as compared with traditional electronic ICNs [3]. For example, in a typical arrangement of MWP-based radio-frequency receiver, a photonic circuit is inserted between two microwave electronic chains (Fig. 1). For direct and inverse transfers of microwave and optical signals there are two interfacing units at their bounds: electrical-to-optical (E/O) and optical-to-electrical (O/E) converters. Between the interfaces there are various photonics units for processing microwave signals in optical domain.

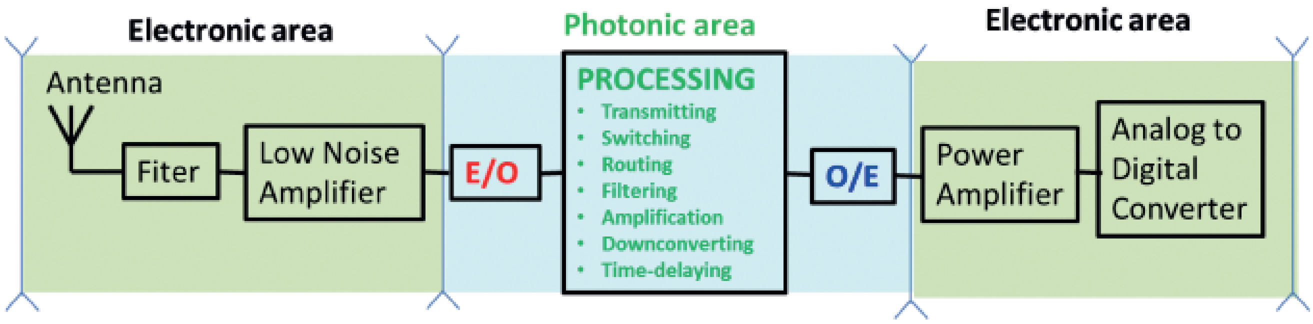


Fig. 1. A typical arrangement of MWP-based radio-electronic receiver.

However, the developer of new MWP devices and systems is facing a problem of choosing an appropriate software tool for their modeling and design. As of today, a system designer is forced to use means of several computer-aided design (CAD) tools because the existing optical and optoelectronic CAD tools (OE-CAD) are not as developed as compared with the CAD tools intended for modeling of microwave devices (E-CAD). On the other hand, operating at symbolic level modern high-power microwave E-CAD tool Cadence AWRDE simply and with high precision solves this problem but there are completely no models of active optoelectronic components in the libraries. The detailed comparison of VPI PDS vs AWRDE is in [4, 5].

To overcome this shortcoming, our team has been consistently developing an approach to the design of MWP elements and devices for more than 10 years using AWRDE E-CAD tool. For today, the results of our R&Ds in this area are published in 4 book chapters, 8 journal papers, and more than 20 conference papers.

In this paper, we review our last studies for designing MWP devices and propose new E-CAD models for the updated microwave and sub-terahertz radio-electronic devices and systems based on MWP approach.

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# SYNTHESIS OF RADIO IMAGES BY MICROWAVE PHOTONICS METHODS

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The radio vision is the most promising method for the maximum possible information about objects to obtain. Below are the basic methods for image synthesis by means of the radio vision:

1. Method of holography. The reference microwave signal is added to the microwave echo signal and then the intensity of an interference pattern is measured and digitized. After digital processing, the image of the object is reconstructed.
2. A method for determining the amplitude-phase distribution in the receiving antenna opening and obtaining an image of the object after digital data processing.
3. The inverse synthetic aperture radar (ISAR) method. This method uses versatile signal processing technique rather than large aperture antennas to identify and reconstruct a moving target.
4. The MIMO (multiple inputs, multiple outputs) method based on distributed radar network.

For all methods, the microwave photonics technology provides a great resolution improvement over the traditional electronic one. The application of ISAR and MIMO methods implemented with microwave photonics technology is studied in detail in [1]. Below, reconstruction of an object using the holography and the amplitude-phase distribution measurement methods realized with microwave photonics is considered.

To form a hologram or measure the amplitude-phase distribution, the signal from each element of the radar phased antenna array (PAA) is fed for modulation to the input port of one arm of a dual-parallel Mach-Zehnder modulator, and a reference microwave signal is fed to the input port of the second arm. At the output of the modulator, the sum of two optical fields is formed, and each is modulated by its own signal. As a result, the signal after photodetector is determined by the interference of the echo wave field at the location of the PAA element and the reference wave, i.e. it is an element of the radio hologram. By measuring such elements of the radio hologram over the entire aperture of the PAA and digitizing them, it is possible to obtain an array of data describing the complete radio hologram. The radio image of an object can be synthesized after performing a fast Fourier transform. Similarly, the amplitude-phase distribution of the echo signal can be obtained using an additional intensity measurement at the output of the low-noise amplifier after each PAA element.

The image reconstruction procedure may require significant computing resources. In this case, it may be much easier to carry out this procedure in the optical range, since the dimensions of the receiving aperture are significantly smaller and focusing lenses are available for the optical range, providing almost instant Fourier transform and observation of the object image in the focal plane. In addition, a wide range of algorithms, technologies and devices designed for optical images processing can be used. The formation of the corresponding amplitude-phase distribution in the optical region of the spectrum can be carried out by evenly distributing the radiation of the master CV laser in a beam of parallel optical fibers whose outputs in space repeat the configuration of the PAA. A phase modulator and a controlled attenuator are installed in each fiber. These elements are supplied with signals proportional to the values of phases and intensities measured at the output of the photodiodes. A lens is installed near the beam slice, in the focus of which the image of the object is formed. Also, instead of the phase modulators and attenuators, a spatial light modulator can be used.

Our measurements of the phase differences and the intensities for the reference and reflected signals in the X range confirmed the effectiveness of the developed techniques, which allows us to proceed in future to the formation of radio images of complex objects.

This study was supported by RFBR, projects 19-29-06108 and 20-07-00768.

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# RESEARCH OF RADIO-PHOTON DEVICES FORMATION AND CONVERSION OF RADIO SIGNALS

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The use of optical methods for the transmission and processing of radio frequency signals in radar and communications is one of the promising areas. The use of radio photonics methods in the creation of units of transceiver equipment for radar and communication can provide a significant improvement in their main performance characteristics: an increase in range resolution and information content, high noise immunity and a decrease in weight and size characteristics. Achieving these advantages is possible due to the introduction of functional units based on electro-optical modulators, demodulators, sources and receivers of an optical signal, optical delay lines and phase shifters, fiber-optic communication lines.

1. Study of parasitic parameters of laser emitters

In the technology of optical transmission systems, direct modulation of the laser pump current is most often used due to its relative simplicity. But there is a limitation of the modulation bandwidth in the microwave range, which is caused by parasitic electrical effects that arise due to the influence of the design of the electrical leads of the laser crystal and the mounting elements required to connect it to the input of the modulating signal. They must be taken into account in the practical implementation of the FOCL prototype. Manufacturers of laser diode modules, noting the main electrical and optical parameters of the module in the description of their products, do not indicate either the impedance of the emitter or its RLC parameters, which include: resistance and capacitance of the crystal, lead inductance, reactance of the emitter case. To ensure the matching of the laser with the driver and the source of the microwave signal, it is necessary to have information about these parameters. These must be taken into account as they can have a significant impact on the bandwidth of an analog fiber optic path.

2. Optoelectronic self-generation of radio signals

An urgent issue is also the development of radio frequency generators operating in the microwave range, with high frequency stability, a wide tuning band, as well as small size and weight. According to the principle of operation and construction scheme, the optoelectronic oscillator is similar to the classical radio frequency oscillator with a delay line in the feedback circuit. A feature of its operation is the multi-frequency nature of the generated oscillations, for which the conditions for amplitude balance and phase balance are met.

3. Heterodyne methods for generating radio signals

An urgent issue is the possibility of pairing a fiber-optic path and a radio channel using the method of optical heterodyning. The principle of this method is that when radiation with several monochromatic frequencies hits the photodetector, its signal will contain the harmonics of these frequencies, as well as the difference and sum frequencies of the initial oscillations. The device, based on the principle of optical heterodyning, was modeled in CAD OptiSystem. A functional diagram of the device has also been developed, capable of simulating the operation of two devices: a coherent optical receiver and an RF signal generator.

4. Radio photonic devices for converting radio signals: multiplier and mixer

One of the main tasks of radio electronics is the development of transceiver and measuring equipment, one of the main components of which can be a frequency mixer. The signal mixer is an important component of transceiver equipment, satellite equipment, information and measurement systems, etc. Diode frequency mixers are the most widely used; such mixers have high speed and low noise level. But promising and fundamentally new are signal mixers built on the element base of radio photonics. The main advantage of such mixers is a wide operating frequency band, limited only by the bandwidth of its optical components.

# THE EFFECT OF TRANSITION FROM SINGLE-MODE TO MULTIMODE GENERATION REGIME IN TWO-SECTION THZ QUANTUM-CASCADE LASERS INDUCED BY CURRENT AND TEMPERATURE

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We investigate the effect of the transition from single-mode to the multimode generation regimes for two-section terahertz quantum-cascade laser (THz QCL). The effect under study was observed for two-section THz QCL with emission frequency of 2.3 THz. The active region of two-section THz QCL is based on a 200-fold repetition of the active module with four GaAs/$Al_{0.15}Ga_{0.85}As$ quantum wells and resonant-phonon depopulation scheme.

The two-section THz QCL has a double metal waveguide separated by two optically coupled sections (see Fig. 1) — active (with gain) and passive, separated by an air gap of 3 μm wide. The studied two-section THz QCL had an active section with a length $L_1$ = 1.8 mm and a passive section with a length $L_2$ from 200 to 300 μm. Thus, the total length of the composite Fabry-Perot resonator was about 2 mm. The spectral characteristics were studied in the temperature range from 50 K to 78 K and in a wide current range from 860 mA to 1.074 A. It was found that, with a change in current/temperature, the generation spectra of the two-section QCL THz range exhibit a single-mode–multimode transition.

To illustrate this effect (see Fig. 2), a map of transitions in the generation modes of a two-section THz QCL is presented, which shows that single-mode generation exists in a limited range of temperatures and currents. The dark area corresponds to the operation of the laser in the multimode generation mode, the light area indicates the single-mode generation mode.

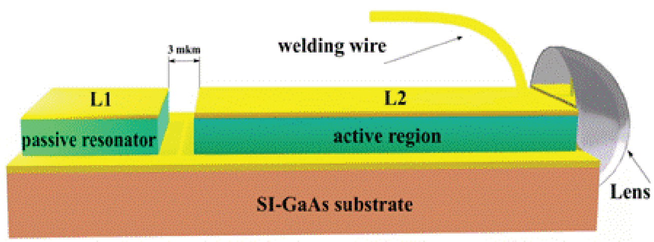


Fig. 1. Scheme of a two-section QCL with double metal waveguide.

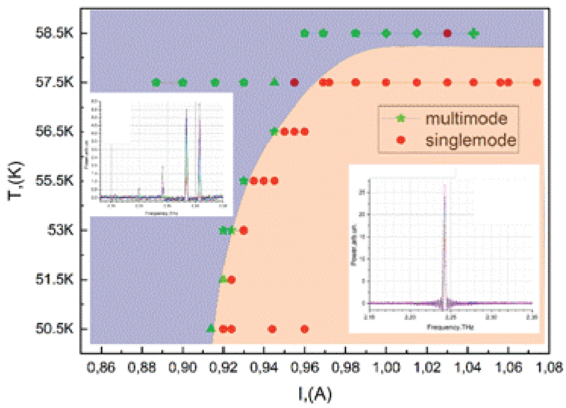


Fig. 2. Single-mode/multimode transition in two-section THz QCL induced by current and temperature.

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# BALLISTIC-TO-HYDRODYNAMIC TRANSITION AND COLLECTIVE MODES IN TWO-DIMENSIONAL ELECTRON SYSTEMS IN A MAGNETIC FIELD

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The relatively recent discovery of the hydrodynamic regime of electron transport in such materials as graphene, GaAs-based quantum wells, and Weyl semimetals was accompanied by an extensive development of the hydrodynamic theory of electronic transport, including the description of the high-frequency dynamics of the two-dimensional electronic system located in a magnetic field. Of particular interest is the so called "collisionless" hydrodynamic model describing viscous electron fluids in highly mobile materials [1,2,3], within which the appearance of "transverse magnetosound" modes, arising due to resonant perturbation of tangential stresses, was predicted [3]. On the other hand, ballistic transport regime models in materials with high mobility theoretical models predict the presence of Bernstein modes [4], the resonance effect of which on magnetoabsorption has been recently experimentally discovered [5.] While theories of an intermediate regime between hydrodynamic and ballistic transport already exist for two-dimensional electron systems in a zero magnetic field [6], the same is not true for electrons in a nonzero magnetic field. In this paper, a model is constructed to make a continuous transition from the ballistic mode to the hydrodynamic mode in a magnetic field. The nonlocal high-frequency conductivity, which is a necessary block for calculating many characteristics of the light-matter interaction is calculated. The transformation of the dispersion of two-dimensional magnetoplasmonic modes during such a transition is investigated in detail.

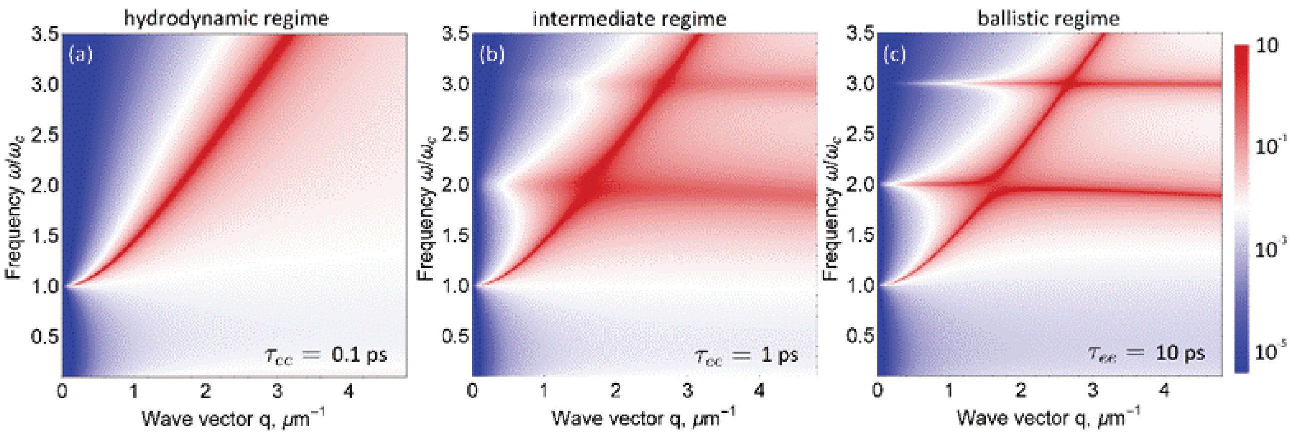


Fig.1. Dispersion curves of magnetoplasmons visualized using the loss function in graphene at cyclotron frequency $f_c$ = 1 THz.

Calculations demonstrate the following evolutionary picture: the ordinary magnetoplasmon in the hydrodynamic regime acquires more and more pronounced splitting at multiple cyclotron frequencies as the frequency of electron-electron collisions decreases, and in the ballistic limit acquires the form of Bernstein modes.

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# TERAHERTZ ANTENNAS BASED ON $BI_{2-X}SB_XTE_{3-Y}SE_Y$ FILMS

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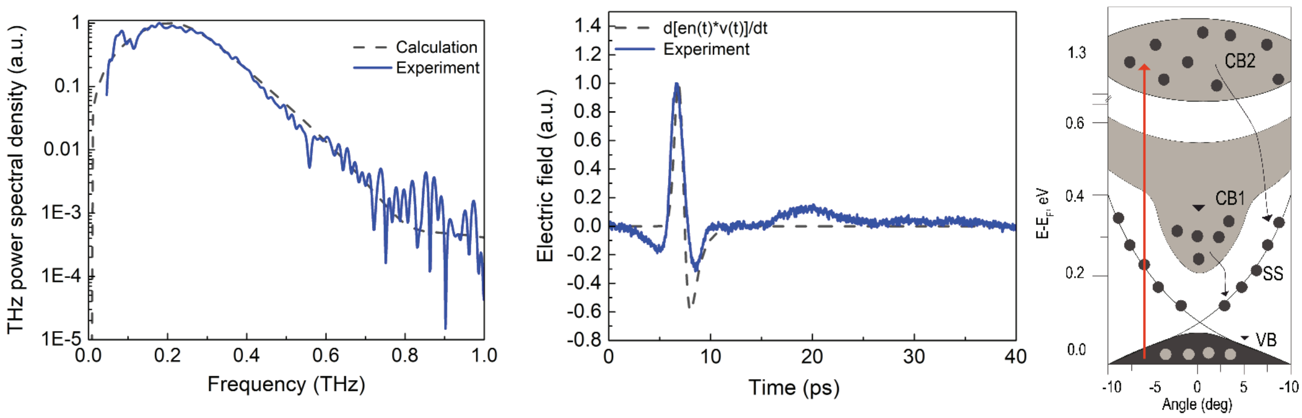
Recently, researchers have shown an increased interest in fundamentally new quantum materials called topological insulators (TIs). The key feature of TIs is the presence of topologically protected surface states, the dispersion curve of which has the shape of a Dirac cone. This leads to zero effective mass and high mobility of the free carriers, which provides an opportunity to use TIs as a promising material for THz photoconductive antennas (PCAs) and other THz devices. Considering the PCA as a resonator and separating the contributions of the electrodes and the active layer to the emitted THz field, we calculate its theoretical THz field waveforms and spectra. For this, the following simplified system of differential equations was solved, the solution of which is the speed of free carriers *v(t)* and their concentration *n(t)* [1]. To take into account the impact of electrodes [2], the transfer function of PCA was found, and the resulting semi-empirical formula for the intensity spectrum of the emitted THz field was obtained. The experimental waveform of the THz field and the power spectra are shown in Figs.1(a) and (b). Also, they were calculated using (1) and (2) by varying the value of $\tau_c$, which helps to predict the possible mechanism of free carriers relaxation in TI, which is schematically shown in Fig.1(c) according to [3]. Initially, the transfer of carriers to the second conduction band is carried out by irradiating the TI using the optical pumping of Tl-Sa laser (0.78 µm). After that, the carriers pass between different energy bands: CB2->CB1 and CB1->SS. All these transitions contribute to the efficient time $\tau_c$.

This work was done under Financial support of the Russian Science Foundation (Grant No. 22-22-00758).




(a) (b) (c)

**Fig. 1**: (a) Waveform of the emitted THz field, (b) power spectra, (c) schematic mechanism of the relaxation processes in TI.

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## TOPOLOGICAL INSULATOR FILMS FOR TERAHERTZ PHOTONICS

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Nowadays topological insulators [1] are considered as extremely promising materials for terahertz photonics [2]. The outstanding properties of massless electrons in surface states, due to their topological protection against backscattering, lead to huge mobility values [3]. High nonlinear properties in the visible [4] and terahertz [5] frequency ranges make topological insulators one of the best nonlinear materials for generating the high harmonics.

In this work, we present and analyze the results on the generation of the third terahertz harmonic in topological insulators with a chalcogen-ordered tetradymite structure. An analysis of the experimental results indicates the possibility of obtaining higher conversion efficiency to the third harmonic in topological insulator than even in graphene. A consistent kinetic theory of third harmonic generation in topological insulators has been developed. The generation of terahertz radiation in a photoconductive antenna based on a thin film of topological insulator is experimentally demonstrated and numerically calculated.

This work was done under Financial support of the Russian Science Foundation (Grant No. 22-22-00758).

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## THZ AND MULTI-THZ LASING FROM HGCDTE QW HETEROSTRUCTURES

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HgCdTe solid solutions have been in a spotlight of modern semiconductor physics due to its paramount importance for infrared detectors. Recent works show that HgTe/CdHgTe quantum wells is a promising material for the field of coherent infrared sources: stimulated emission from HgCdTe-based waveguide heterostructures was obtained at the wavelengths up to 31 μm [1], in the range of a Reststrahlen band of AIIIBV materials, where modern quantum cascade lasers yet can not operate [2]. It makes HgCdTe one of the few candidates along with graphene and lead chalcogenides for the material of so-called Reststrahlen optics.

Despite the possibility of achieving amplification in a wide range of wavelengths and temperatures, laser generation in HgCdTe heterostructures has not been obtained for long-wave sources (more than 5 μm). In this work laser action from ridge resonators formed by ion etching.

Structures under study were grown by MBE on semi-insulating GaAs (013) substrates with ZnTe and CdTe buffers [3]. After their characterization ridge resonators were formed on the surface of the structure using photo-mask and ion beam etching. The edges of the stripes were additionally polished using focused ion beam in order to improve the reflectivity. Processed samples was mounted on the cold finger of a closed-cycle helium cryostat (T = 8 — 300 K). Optical excitation from the top of the structure was provided by a pulsed near-IR OPO (10 ns, 10 Hz, $\lambda_{exc}$ = 2 — 2.3 μm). Emission was guided to a FTIR spectrometer Bruker Vertex 80v operating in the Step scan mode and detected by an MCT photodetector. As-grown QW HgTe/CdHgTe structure demonstrated emission with rather low (~200 W/cm$^2$) threshold. Line width of its spectrum was ~ 40 cm$^{-1}$. After processing the spectrum was split into a set of 8 narrow lines less than 0.2 cm$^{-1}$ wide which do not move with the changes in temperature or pumping power, and thus are attributed to the modes of the resonator. The distance between the observed lines is does not correspond to the modes of Fabri-Perot resonators with the length of 3 — 8 mm, suggesting that they are caused by the transverse modes of the formed ridges. Compared to unprocessed structure the spectrum occupies the same range, so in order to achieve the plausible single-mode operation it is necessary to obtain stimulated emission with lower line width, use shorter ridges and prevent the transverse modes. Also first time obtaine laser generation from microdisks resonators close of room temperature (260K) at the spectral range from 3-5 μm (one of the atmospheric window).

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## TOWARD 3D PLASMONIC GRATINGS IN PHOTOCONDUCTIVE THZ EMITTERS AS AN EFFICIENT TOOL FOR HIGH-SPEED THZ SPECTROSCOPY

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Photoconductive antennas (PCAs) are intensively used in THz time-domain spectroscopic and imaging setups thanks to their reliability, cost-effectiveness, simplicity of fabrication, and the flexibility in the designing of antenna electrodes [1,2] compared to the existing THz devices [3,4].

We have proposed and realized the very first design of a photoconductive antenna-emitter [5] with 3D plasmonic grating featuring a high-aspect ratio $h/p \sim 0.8$ between the height of Au plasmonic electrodes ($h$), that is the electrode thickness, and the grating period ($p$), which does not require high-power laser systems for efficient operation. By using numerical simulation, we developed a 3-stage optimization of the plasmonic grating geometry with respect to maximal transmission of the incident optical light and determined the optimized parameters of the grating design (see figure 1). The increase in $h/p$ significantly changes the electric field distribution owing to the excitation of higher-order plasmon guided modes in the Au slit waveguides leading to the 10-fold enhancement of the emitted THz power (see figure 2) [6]. We believe that our efficient design can overcome the existing specific problems of the THz spectroscopy providing the pathway toward high-speed imaging.

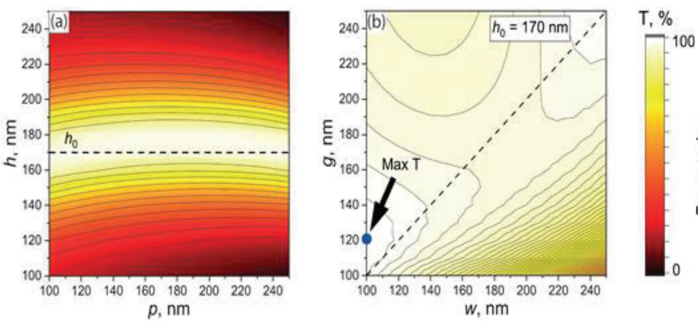


Fig. 1. Simulation results: (a) the height of Au nanoridge vs. period of the grating p (here w=g=p/2, where parameters g and w are the grating width and the grating gap respectively). Parameter h0 denotes the thickness of plasmonic electrodes corresponding to maximum transmission of optical light through the plasmonic grating T ~ 73% for λ = 800 nm; (b) width vs. gap dependence for the chosen parameter $h_0$ = 170 nm. The blue bold dot on (b) shows the chosen pair of grating geometry parameters (w, g) = (100 nm, 120 nm).

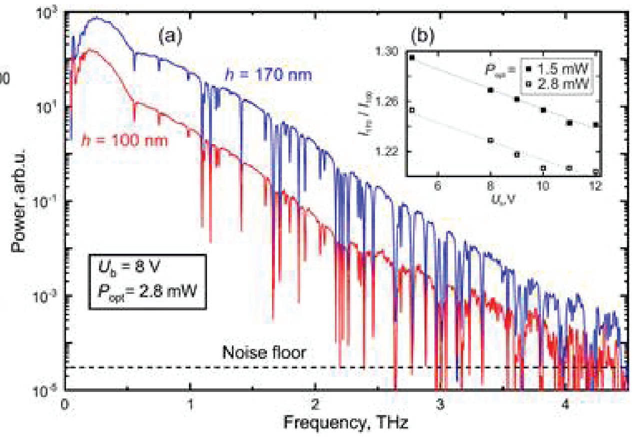


Fig. 2. Experimental results for the PCAs with different height h of the Au nanoridge: (a) the measured THz spectra; (b) the ratio i170/i100 demonstrating the photocurrent enhancement in a 170 nm thick grating PCA compared to the 100 nm thick grating antenna-emitter vs. Ub for different Popt.

The work was supported by the Russian Science Foundation, project No. 18-79-10195.

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## GATE-CONTROLLED POLARIZATION RESOLUTION AT THE GRAPHENE-METAL INTERFACE

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Polarization, as well as intensity, frequency and phase are commonly used to encode and transmit information. Here, we introduce a graphene-based mid-IR detector with dissimilar contacts metallization, which is able to resolve the polarization of incident radiation [1]. We investigated the photodetectors of transistor geometry. They have a graphene channel separated from the silicon substrate by 300 nm silicon oxide. Photovoltage measurements were carried out by the lock-in technique at a wavelength of 8.6 um. In this work, the photovoltage dependencies on polarization and carrier density of the graphene-metal junction are measured and studied (Fig. 1). A strong polarization sensitivity of the detector was observed because of the electric field amplification due to the lightning rod effect. And the unusual features in the dependencies — polarization-independent points and ranges of the photovoltage sign-flipping with the polarization rotation, are explained by the presence of at least two photovoltage generation mechanisms in the device: isotropic and anisotropic. As a result, a method for polarization determining with a single device based on strong polarization sensitivity and polarization-independent point is proposed. In order to resolve polarization in the full π-range, only two detectors are needed instead of common three. To conclude, we have fabricated, measured and proposed a physical 'backend' of the detector based on a graphene-metal junction. And the features of its sensitivity such as polarization-independence and strong polarization dependence at various gate voltages allowed it to be used as a polarization-resolving detector.

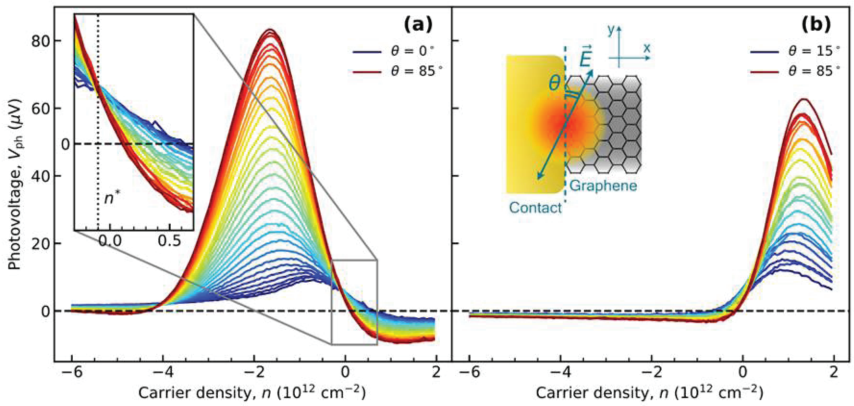


Figure 1.: Dependencies of photovoltage on carrier density and polarization angle at graphene-Ti (a) and graphene-Au (b) junctions. The polarization angle θ is counted from the direction that parallel to the graphene-metal junction (right inset) and varies with 3° step. Inset in (a) magnifies the vicinity of carrier density n* where the photoresponse becomes polarization-independent [1].

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# GENERATION OF TERAHERTZ RADIATION UNDER ELECTRON EMISSION IN A VACUUM DIODE

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The experimental results of pulsed terahertz (THz) radiation generation that occurs in a vacuum diode during electron emission under the action of ultrashort laser pulses are presented in this work. The source operation principle is based on current pulse generation in a vacuum due to the emission of electrons from the cathode surface and the acceleration of these electrons in an electric field [1,2]. A continuous anode, opaque to electrons [3], is used to generate THz radiation in the diode. The deceleration of the electron beam at the anode provides a short current pulse fall time. This time is mainly determined by the Coulomb repulsion of electrons during their acceleration in the interelectrode space. The source of terahertz pulses is a vacuum gap 1 mm thick between the cathode (a flat copper plate) and an anode electrically isolated from it (a flat quartz plate with aluminum metallization deposited in the form of strips with a period of 100 µm or a thin continuous ITO film on the gap side). A constant pressure is maintained at a level of $10^{-6}$ mbar in the electrode gap. A constant voltage in the range of 500 — 4500 V is applied between the cathode and the anode. Electron emission is produced by the oblique incident of a femtosecond laser pulse on the cathode (150 fs pulse duration, 800 nm central wavelength, 2.5 mJ pulse energy, Gaussian beam diameter 12mm at $e^{-2}$ level). The electron emission front propagates over the illuminated area of the cathode at superluminal speed because the laser beam angle of incidence on the cathode at an angle of ~45 degrees (Fig. 1.). The paper presents the measured dependences of the energy of terahertz radiation pulses on the angle of incidence of laser radiation for various emitted charge values. The highest energy in the experiments performed reached a value of 5 pJ at angles of incidence of 60° and emitted charge 500 pC. These results can be helpful to solve tasks of vacuum electronics and to generate THz beams.

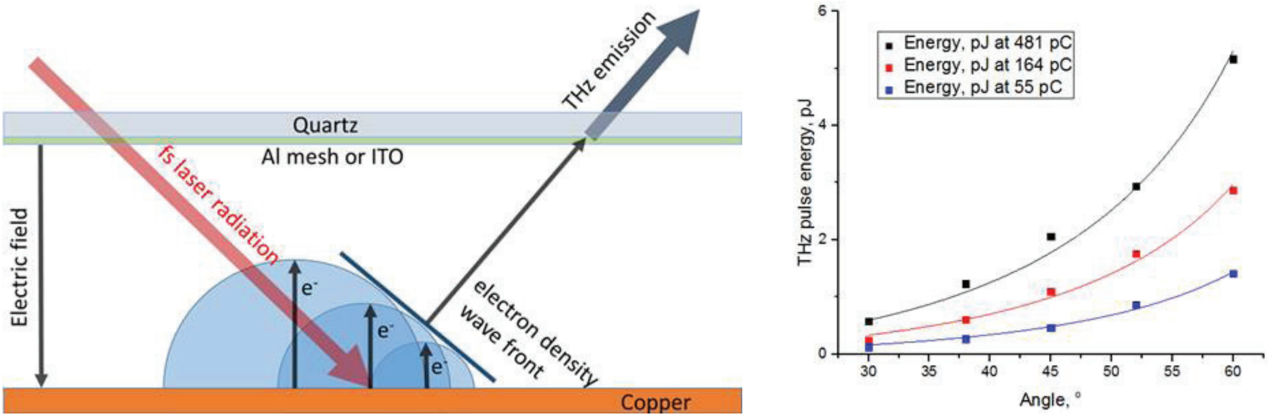


Fig. 1. Principal scheme of THz generation (left) and the measured dependences of the terahertz radiation pulses energy on the angle of incidence of laser radiation for various emitted charge values (squares) with approximation by the squared tangent function (lines) (right).

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# THZ QUANTUM CASCADE LASERS WITH TWO-PHOTON DESIGN

R.A. Khabibullin[1], S.S. Pushkarev[1], R.R. Galiev[1], D.S. Ponomarev[1], I.S. Vasil'evskii[2], A.N. Vinichenko[2], A.N. Klochkov[2], T.A. Bagaev[3], M.A. Ladugin[3], A.A. Marmalyuk[3], K.V. Maremyanin[4], V.I. Gavrilenko[4], D.V. Ushakov[5], A.A. Afonenko[5]

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The possibility of implementing two radiation transitions in the gain module for THz QCL has been shown many times [1,2]. However, the activation of these transitions is achieved at different bias points, which corresponds to the optimal alignment of energy levels for each transition. We propose to add an additional step to the ladder of energy levels in the gain module, equal to the energy of THz photon. Due to the low energy of THz photon, it becomes possible to design the gain module based on the conventional GaAs/$Al_{0.15}Ga_{0.85}As$ heterojunction with two-photon emission at one bias point.

A new lasing scheme with sequential two-photon emission in the gain module for terahertz quantum cascade laser (THz QCL) is proposed and experimentally demonstrated. Unlike the conventional lasing scheme with only one pair of laser levels, here electrons pass through an additional laser level, which is the lower laser level for the first radiation transition and upper laser level for the second one, forming a sequence "resonant tunneling — photon — photon — phonon" (see Fig. 1). The presence of two-photon emission in the gain module reduces the gain saturation with an increase in photon density, which should potentially increase the radiation power. An optimized two-photon design based on GaAs/$Al_{0.15}Ga_{0.85}As$ As four-quantum wells was developed using the balanced equation method [3,4] and grown by two epitaxial techniques — molecular beam epitaxy (MBE) and metal organic chemical vapor deposition (MOCVD). THz QCLs based on both MBE and MOCVD structures have a lasing frequency of 3.8 THz (see Fig. 2) and maximum operation temperature around 100 K.

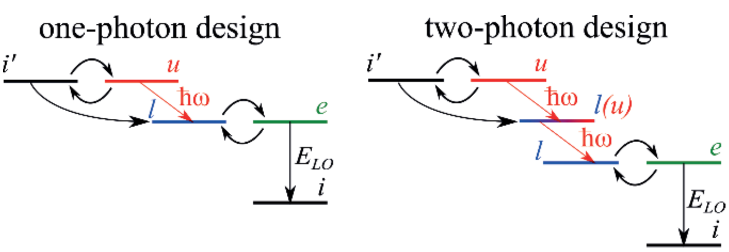


Fig. 1. Schematic diagram of one- and two-photon designs with resonant phonon depopulation mechanism of lower laser level.

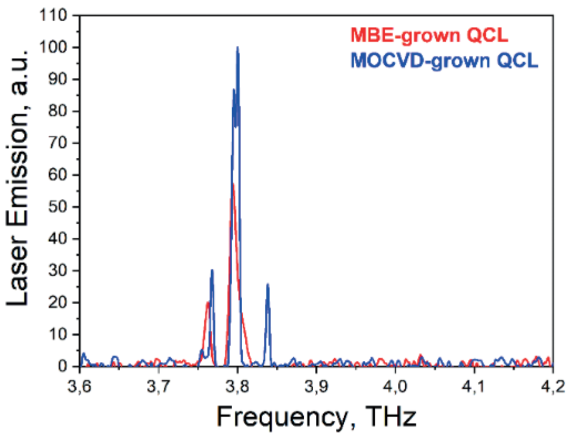


Fig. 2. Emission spectra of MBE- and MOCVD-grown THz QCLs with two-photon design.

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# THZ AND MICROWAVE ELECTRONICS

## STUDY OF THE PHASE LOCKING OF HIGH-POWER GYROTRON OSCILLATORS COUPLED WITH DELAY

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Ultra-high power levels can be attained by power combining of high-power microwave oscillators[1]. It has been demonstrated that relativistic magnetrons, vircators, and backward-wave oscillators can aggregate their powers coherently up to multi-gigawatt power levels. Since arrays of high-power gyrotrons are crucial for applications like the electron-cyclotron-resonance plasmaheating, power combining of gyrotrons has recently gained a lot of attention [2-3]. Phase and frequency locking is a significant problem for coherent power summation. Peer-to-peer locking approaches as well as injection locking have both been extensively researched.

The complexity of the system is dramatically increased by the need to account for the signal propagation delay between connected oscillators since at microwave frequencies this distance significantly exceeds the operating wavelength[4].

The paper is devoted to the study of mutual synchronization (peer-to-peer locking) of two gyrotrons coupled with delay. A theoretical study of synchronization of gyrotrons and other microwave oscillators is usually carried out by numerical simulations using certain well-established models of microwave electronics. Using this approach, it is difficult to provide a fairly complete synchronization pattern. Simplifed models are required, which would allow bifurcation analysis using methods and ideas of nonlinear dynamics.

The study is based on a bifurcation analysis of the modified quasilinear model of two coupled gyrotrons proposed in [5]. A comparison is also made with numerical simulation using the non-stationary theory of a gyrotron with a fixed high-frequency field profile. Using the proposed model,we plot the synchronization domains on the coupling coefficient –frequency mismatch plane of parameters for various synchronous modes, the number of which increases with the delay time. The model also makes it possible to compute the most important output parameters, such as power, efficiency, and oscillation frequency.

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## THEORETICAL ANALYSIS OF THE NONLINEAR DYNAMICS OF THE GYROTRON BASED ON A MODIFIED QUASI-LINEAR MODEL

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One of the most important applications of modern gyrotrons is the plasma heating and current drive in nuclear fusion plants [1]. This requires gyrotrons with an oversized resonator operating in the continuous-wave regime with a power and frequency that currently reach values of 1.5–2.0 MW and 140–170 GHz, respectively. For such gyrotrons, the mode spectrum is very dense due to the operating at very high-order transverse modes, which leads to the excitation of parasitic modes with neighboring azimuthal indices. The mode-competition processes may strongly affect the gyrotron operation [2, 3]. Therefore, the study of mode competition is an important task, for the solution of which the methods of the theory of oscillations and nonlinear dynamics are widely used [3].

In this work, we proceed on the basis of the so-called modified quasi-linear model to study the gyrotron dynamics regimes (see [4]). Within the framework of this model, the excitation equation of the gyrotron resonator by the electron beam current is represented as

$$\frac{dA}{d\tau}+A=I_0\Phi\left(\left|A\right|^2,\Delta_H\right)\cdot A \qquad (1)$$

where $A$ is the complex normalized amplitude, $\tau$ — the normalized time, $I_0$ is the normalized current parameter, $\Delta_H$ is the cyclotron resonance mismatch, $\Phi$ — complex electronic susceptibility, which is calculated numerically using the stationary theory of a gyrotron at various values of the field amplitude and cyclotron resonance mismatch. Then, by interpolating of the calculated susceptibility, its real and imaginary parts are expressed as functions of field amplitude and cyclotron resonance mismatch $\Phi'\left(\left|A\right|^2,\Delta_H\right)$ and $\Phi''\left(\left|A\right|^2,\Delta_H\right)$ that allows further theoretical analysis of the gyrotron oscillation behavior. All variables in (1) are dimensionless; see [3, 4] for more details.

Model (1) does not allow direct analysis of multimode processes. Nevertheless, using the technique developed, for example, in [2], one can find the excitation conditions of parasitic modes and analyze the stability of the operating mode. It is necessary to consider the processes of two-mode interaction (excitation of a parasitic mode against the background of the operating one) and the process of interaction of three modes with a quasi-equidistant spectrum (four-photon parametric decay). In the latter case, the operating mode $TE_{m,n}$ is unstable with respect to the excitation of a pair of modes $TE_{m\pm s,n}$, $s= 1, 2,...$.

Using the developed model, we derive the stability conditions of the single-mode regimes and analyze the domain of stability of the operating mode on the cyclotron frequency mismatch — normalized beam current parameter plane. The obtained boundaries are in good agreement with the results of numerical calculations based on the multimode theory of the gyrotron [5]. The presented technique greatly facilitates the interpretation of the results of numerical simulation, which is a difficult task in the case of a large number of interacting modes [3, 5]. It also allows one to analyze the influence of an external signal and reflections on the boundaries of the stability zone of the operating mode.

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## TERAHERTZ DETECTION AND HILBERT SPECTROSCOPY BY HIGH-$T_c$ JOSEPHSON JUNCTIONS

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With the discovery of high-temperature (high-$T_c$) superconductivity, it became possible, in principle, to realize Josephson junctions (JJ) with THz dynamics described by a simple resistively shunted junction (RSJ) model. These circumstances turned out to be very important when using JJs as detectors and spectrum analyzers, and they stimulated intensive studies of applications of high-$T_c$ JJs in the terahertz frequency range (see, for example, [1]). In this report, I will present the current state of work in this direction.

I will report on the progress in fabrication of epitaxial bicrystal $YBa_2Cu_3O_{7-x}$ JJs [2], development of Hilbert-transform spectrum analyzer integrated in Stirling cooler [3], the broadband JJ detector with the temperature sensitivity NET≤ 30 mK [4], the identification of liquids by their sub-THz reflection [5], when characterizing the output sub-THz and THz radiation from commercial sources [6], as well as new sources based on quantum cascade lasers (QCLs) [7]. Applications of high-$T_c$ JJ in high-energy physics have been suggested and partially realized [8,9]. Advantages of Hilbert-transform spectral analysis as frequency-domain technique will be discussed and compared with conventional sub-THz and THz techniques. Perspective directions of future developments will be presented [10].

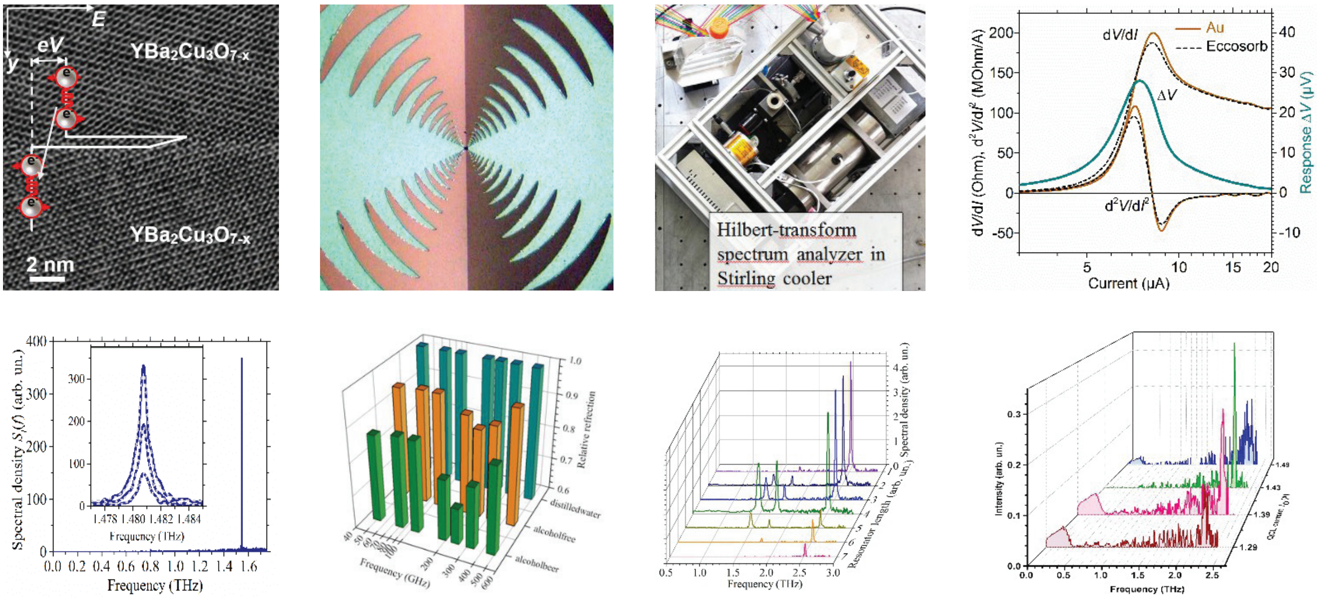


Fig. 1. A set of figures from references [1-10] illustrating the content of the report.

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## PROBLEMS AND SOLUTIONS FOR INCREASING OF THE OPERATING FREQUENCY OF GYROTRONS

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In the second half of the last century, a number of gyroresonance devices were developed. The principle of operation of such devices is based on the synchronous interaction of a curvilinear electron beam and an electromagnetic wave [1–7]. For effective interaction of synchronism condition of electron oscillators with an electromagnetic wave at cyclotron frequency or its harmonics have to be satisfied.

$$\omega \approx n\omega_h + hv_{//}, \quad (1)$$

where $\omega_H$ and $v_{//}$ are the cyclotron frequency and drift velocity of electrons, *n*- is the number of the cyclotron harmonic. Since the interaction of the electron beam occurs with a fast wave propagating practically across the translational motion of electrons ($h \approx 0$), there is no need for small-scale elements of slow-wave systems required for classical vacuum electronics devices, and low sensitivity to the velocity spread of electrons is provided. To implement condition (1) in the THz frequency range, gyrotrons must either operate in very strong magnetic fields or at harmonics of the cyclotron frequency of electrons

Over the past years, powerful high-performance gyrotrons from the cm to submm ranges have been created [2–9], and a number of fundamental scientific areas have been formed, the successful development of which is due to the presence of these sources. For some applications, it is necessary to increase the frequency and power of gyrotrons, but the complexity of the problem is exacerbated by the technical capabilities of modern magnetic systems [8], the problem of mode competition, and a high level of ohmic losses, especially in gyrotrons operating at harmonics of the cyclotron frequency in the submm range [3–7]. Variants of magnetic systems for a further increase in the field and related possibilities for increasing the frequency of gyrotrons are considered. The problems that arise when the frequency of gyrotrons with stationary and pulsed magnetic fields is increased are discussed. A review of the physical factors and features of the main subsystems that limit the power and efficiency of gyrotrons with increasing frequency is carried out. The prospects for gyrotrons are considered from the point of view of further increasing their frequency and power for various applications.

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## THE FIRST EXPERIMENTAL TESTS OF A HIGH-CURRENT RELATIVISTIC MILLIMETER-WAVE GYROTRON WITH MAGNETIC COMPRESSION ELECTRON GUN

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This paper presents the results of the first experimental tests of a high-current Ka-band gyrotron, designed both to prove the operability of this class of devices as sources of sub-gigawatt power in the millimeter wavelength range, and to demonstrate the prospects for mastering sub-terahertz frequencies at a pulse power of several hundred kilowatts when operating in the frequency multiplication mode. In this case, generation at high cyclotron harmonics occurs simultaneously with low-frequency generation at the fundamental harmonic. The power of high-frequency radiation according to numerical simulation is tenths of a percent of the power at the fundamental harmonic [1].

The gyrotron is implemented on the basis of the «Sinus-6» accelerator, which provides electron beams with a multikiloampere current and a particle energy of about 500 keV. To improve the quality of the helical high-current beam, an electron gun with magnetic compression was used. In such a system, the explosive-emission edge cathode is located in a relatively weak magnetic field of about 1 T, with the same guiding field, the primary transverse electron velocities pumping occurs by a short kicker coil. Then the magnetic field increases to a resonant value of about 1.8 — 2 T. As a result the beam is simultaneously compressed and transverse electron velocities increase to a state with a pitch-ratio of about 1. To create a magnetic field of the required configuration, a copper cylindrical shell is placed inside the pulse solenoid, which weakens the field in the cathode region.

In the experiments, two measuring systems were used, consisting of microwave detectors that fixed the envelope of the microwave pulse, as well as mixers and local oscillators to analyze the frequency spectrum of radiation in the Ka-band for the first cyclotron harmonic and in the W-band for the third harmonic. The total energy of the output radiation was measured using a thermocouple calorimeter.

During the experiments, with guiding magnetic field in cavity of 1.9 T, a signal was detected in the low-frequency measuring line at a frequency of 35.7 GHz, corresponding to the calculated frequency of the $TE_{-4,2}$ mode. At the same time, a signal was detected in the high-frequency line at frequency of 107.1 GHz, which exactly corresponds to the triple frequency of the low-frequency signal and presumably corresponds to radiation in the $TE_{12-4}$ mode at the third cyclotron harmonic. The maximum output signal power in this mode reached 35 MW, which is much less than the maximum calculated values [2], while the envelope of the microwave pulse was significantly irregular. It is assumed that these problems arise due to the difference in the beam current in the experiment from the optimal one. In the future, it is proposed to use a double coaxial cathode to control the beam current[3].

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## PLASMON PROPERTIES OF GRAPHENE WITH AN ARBITRARY DIRECTED ELECTRIC CURRENT

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Microstructures based on graphene can be used to detect and amplify terahertz (THz) radiation [1]. In particular, the plasmonic properties of such structures are being actively studied [2], the amplification of THz plasmons in graphene with direct current was observed experimentally [3].

In this work, we investigate the plasmonic properties of graphene with a direct electric current (DC-current) arbitrarily directed relative to the direction of plasmons propagation in graphene. In this case, the graphene conductivity describes in the tensor form. Frequency ranges in which the real part of elements of the graphene conductivity tensor takes negative values are determined. It is shown that, at realistically achievable values of DC-current in graphene, amplification can occur at THz frequencies. It is shown that in the case of a DC- current flowing at an angle to the plasmon wave vector, the off-diagonal elements of the graphene conductivity tensor become comparable to the diagonal ones and can make a significant contribution to the dispersion and amplification of surface plasmons in graphene. The dispersion characteristics and amplification of THz plasmons in graphene with an arbitrarily directed direct current are studied.

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## SIMULATION OF A GYROTRON PROTOTYPE WITH AN ANALYZER OF ELECTRON BEAM PARAMETERS

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At present, numerical methods are widely used for the design of gyro-devices. Models have been developed for calculating the motion of a helical electron beam (HEB) from the formation system to deposition of the spent beam on the collector. However, some models still need experimental verification and refinement. To experimentally measure the distribution of the power density of the HEB deposited on the collector, we are developing a model of a gyro-device with the existing magnetron-injector gun from the technological gyrotron. The transport area and the collector will be manufactured using the CMPS (Chemical Metallization of Photopolymer-based Structures) technology [1]. An array of high-precision SMT172 thermal sensors will be integrated into the collector. At present, testing and development of technologies is being carried out, a section of the collector 5 cm long with eight sensors has been manufactured and experimentally tested.

Simultaneously with the study of the beam power distribution over the collector surface, it is necessary to know the initial parameters of the HEB: the pitch factor and the spread of transverse velocities. To do this, it is supposed to use a classical beam analyzer based on the method of retarding electric field [2]. The analyzer is located in the region of a uniform magnetic field and consists of a diaphragm with a sector cut, a grid, and a collector (see Fig. 1). In this case, the diaphragm and the collector, as well as the body of the device, have a zero potential relative to the ground, and a braking voltage is applied to the grid. The longitudinal velocity component is determined from the collector current cutoff curve. Due to the high power of the electron beam in the operating mode of the gyrotron, the measurements are carried out in the simulation mode. Prior to the manufacture of the analyzer, three-dimensional calculations were performed, which made it possible to determine the most important factors that introduce an error into the results of measurements of the pitch factor and velocity spread, and also calculated the typical values of their measurement errors. The calculations were performed by analogy with [3], however, the electrode position was optimized for the parameters of our gyrotron (accelerating voltage up to 23 kV, beam current up to 2.4 A). We also additionally studied the effect of secondary electron emission on the analyzer operation and calculated a model using a Faraday cup as a collector.

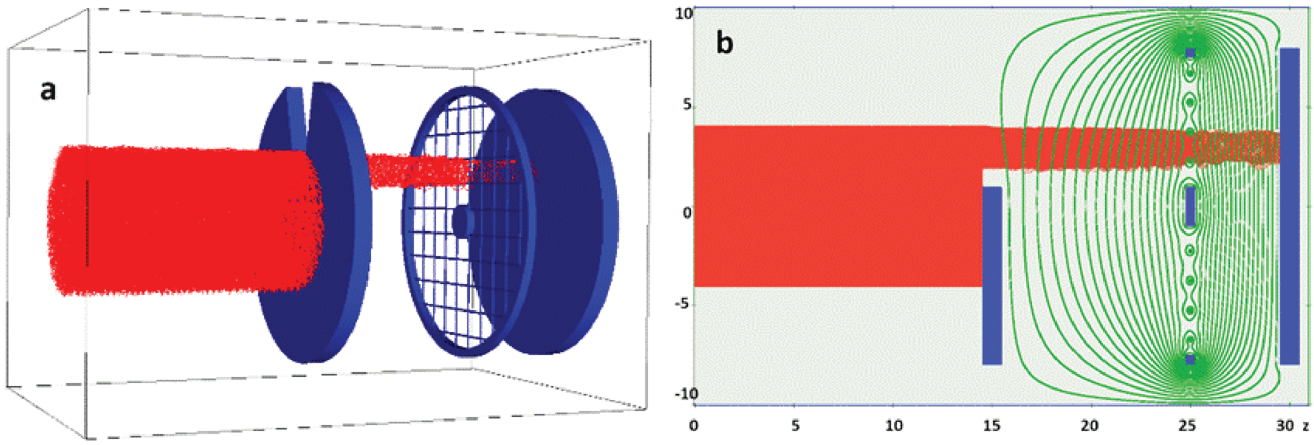


Fig.1. a) 3D view of a beam analyzer b) 2D view with electric potential distribution.

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## OPERATOR APPROACH FOR DESCRIPTION OF ELECTRON TRANSPORT IN TWO-DIMENSIONAL ELECTRON SYSTEMS

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Many applied problems require the description of electron transport in solids. A powerful but very abstract approach is the many-particle formalism [1,2]. More illustrative, albeit less rigorous, is the hydrodynamic model, which has long been used to describe various effects in an electron gas [3–7]. Its applicability formally relies on the dominance of electron-electron collisions in the system, but in practice the applicability of this model is much wider. Thus, terahertz plasma waves are successfully described with its help [4, 5].

Despite the rich history, the hydrodynamic transport model is mainly used to describe specific configurations of physical devices, leaving aside the general properties of electronic transport. These properties are fundamentally different from the properties of a classical liquid, since the electron 'fluid' is compressible and charged. In this work, we develop an operator approach to the equations of electron hydrodynamics using the example of a two-dimensional electron gas. It turns out that the linearized equations of continuity, Navier-Stokes and Poisson can be written in operator form, and with the proper definition of the vector and the scalar product in the resulting Hilbert space, we arrive at a convenient formalism, much like quantum mechanics. This formalism aids at describing the magnetodispersion of sub-mm and terahertz plasma waves in various geometries, and also serves as the basis for constructing a perturbation theory. The constructed theory [8] makes it possible to establish a number of general properties of plasma waves in a two-dimensional electron gas: the conditions for their self-excitation under the action of a constant electric field, the optimal configurations of devices for maximizing the growth rate and the effect of viscosity [9], or the instability of an interedge magnetoplasmon [10].

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## DESIGN AND DEVELOPMENT OF W-BAND VACUUM-TUBE AMPLIFIERS AND OSCILLATORS WITH SHEET ELECTRON BEAM

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The development of terahertz frequency range now attracts a great deal of interest. Compact, portable sources of terahertz radiation with >10 W output power have great prospects for application in wireless communications, high-resolution radar, non-destructive evaluation, and biomedical research [1]. In this paper, we present the results of studies aimed at development of traveling-wave tubes (TWT) and backward-wave oscillators (BWO) with sheet electron beam. Using of a high-aspect-ratio sheet beam provides high current with reasonable current density, which can be attained by existing thermionic cathodes. For interaction with a sheet beam, a staggered dual-grating slow-wave structure (SWS) seems optimal, since it may provide wide bandwidth [2]. We designed a W-band TWT with such SWS. Electromagnetic parameters of the SWS were simulated by COMSOL Multiphysics. 3-D particle-in-cell (PIC) simulation of the TWT driven by a 12-kV, 100-mA sheet electron beam was performed by CST Studio Suite. Fabrication and cold-test measurement of the SWS is discussed. We also studied a W-band BWO with a truncated-sine-waveguide SWS. This SWS is assumed to be driven with a high-current sheet beam produced by a pseudospark-discharge hollow cathode [3]. For microfabrication of the SWS, high-precision computer-numerical-control micromilling was used [4]. The results of cold-test measurements show good transmission properties. Hot-test operation of the BWO was simulated by using CST Studio Suite. Development of sheet-beam electron-optic systems is discussed. Design, fabrication, and experimental testing of the electron gun with high compression of a 100-mA sheet electron beam with 0.1-mm thickness is presented.

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# AUTO-MODULATION OSCILLATIONS IN A GYROTRON WITH A COMPLICATED CAVITY

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Currently, the use of powerful multi-frequency signal in plasma fusion applications is considered actively. One of possible ways here is the use of powerful electron sources operating in the well-known regime of auto-modulations of the output wave signals. However, obtaining auto-modulation regimes (for example, due to a significant excess of the operating current of the electron beam over the starting value) in a traditional gyrotron scheme is very difficult.

In this work, we develop an idea of the use of quasi-regular cavities with short phase correctors as a way to provide excitation of higher axial modes in the high-efficient gyrotron-type regime of the electron-wave interaction [1]. In the simplest case, this is a quasi-regular cavity with one short irregularity placed in the middle and providing a phase shift close to π (Fig. 1). We propose to consider such an approach for ensuring an auto-modulated output signal in a gyrotron with a relatively short operating cavity. In our work, we consider a powerful 70 kV / 45 A / 170 GHz gyrotron with the design being typical for modern megawatt-power-level gyrotrons used in plasma fusion applications. We present the design and preliminary results of simulations of the excitation of a gyrotron with a cavity with an irregularity located in the center. The regular-cavity prototype of this system in the case of a relatively short (7-8 wavelengths) cavity provides the stable single-frequency generation of the lowest near-cutoff axial mode with the output wave efficiency slightly exceeding 30%. In simulations, we consider a gyrotron based on the use of a slightly elongated cavity (~ 10 wavelength) with a short (2.5 wavelengths) inhomogeneity placed in the center and providing a phase shift close to π. At the operating magnetic field close to the optimal value for the regular-cavity prototype, simulations predict a strong modulation of the output power in the build-up regime of this gyrotron (Fig. 1).

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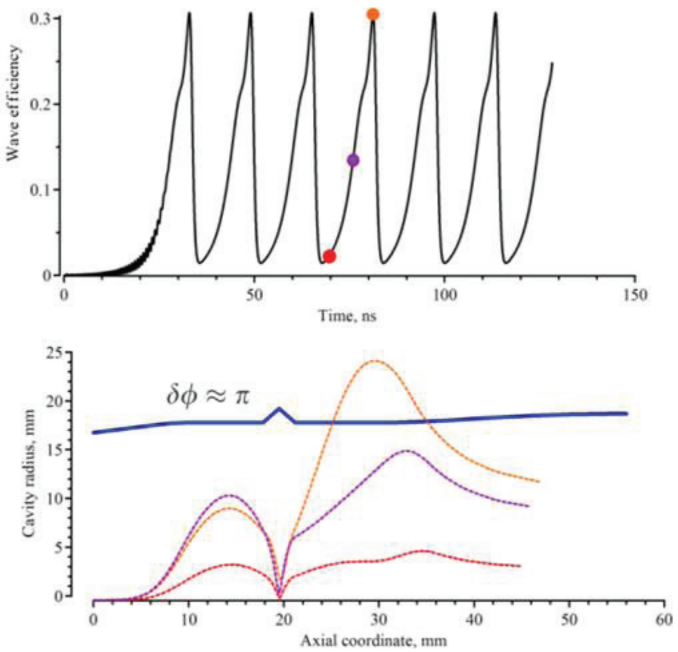


Fig.1. Simulations of a megawatt gyrotron with a cavity modified by a π-shift inhomogeneity. Dependence of the output wave efficiency on the time. Profile of the cavity, as well as calculated axial structures of the excited field at different moments of times corresponding to different points shown in the upper plot.

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## ULTRA-SENSITIVE TERAHERTZ DETECTION WITH 2D TUNNEL FIELD-EFFECT TRANSISTORS

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Tunnel field-effect transistors (TFETs) are considered as main candidates for future low-power electronic circuits. The origin of low-power switching is the steep dependence of source-drain interband tunneling current on the overlap between conduction and valence bands [1]. Despite numerous applications of TFETs in logic circuits, it was not realized that strong (nonlinear) sensitivity of tunnel current to gate and drain voltages also implies efficient rectification of high-frequency signals. Here, we study the operation of tunnel field-effect transistors based on graphene bilayer with gate-induced tunnel junctions as detectors of sub-THz (0.13 THz) radiation [2]. We show high responsivity (~4 kV/W) and low noise equivalent power (~0.2 pW/Hz$^{1/2}$) at $T = 10$ K, which are competing to those of superconducting and semiconducting hot-electron bolometers. Our devices were made of bilayer graphene encapsulated in hexagonal boron nitride. Induction of finite band gap and excess carrier density was achieved by simultaneous action of back and top gates. Short sections of graphene bilayer (~300 nm) close to the source and drain contacts were not covered by the top gate, and were controlled by the bottom one only. Thus, by application of gate voltages of opposite polarity to the gates, it was possible to induce a p-n junction between single-gated and double-gated regions. Further enhancement of gate voltages could result in overlap between conduction and valence bands at the two sides of the junction, thus pushing it to tunneling regime. The radiation is fed to TFET from THz antenna coupled between source and gate, the photovoltage was read out between source and drain. We have found that dependence of photoresponse on top gate voltage differs drastically in the gapless and gapped regimes of transport. In the gapless regime, the voltage responsivity is quite low (max ~0.1 kV/W) and symmetric with respect to charge neutrality point. In the gapped regime (i.e. at finite back gate voltage), the responsivity reaches 4 kV/W, is highly non-linear in intensity, and is strongly asymmetric with respect to charge neutrality. The strongest responsivity is achieved at opposite doping of channel and contacts. We have verified that both current and voltage responsivities grow in the tunneling regime, compared to the regime of intraband ohmic transport.

The observed dependences are in a good agreement with the theory of rectification at gate-controlled junctions near the contacts. Being in a good agreement with current measurements, our theory shows that even higher responsivity can be achieved in TFETs with junction at the middle of the channel, as well as in TFETs with extra 'doping gates' [3].

Preliminary experiments with split-gate field effect transistors based on bilayer graphene confirm this suggestion [4]. We show that both THz photovoltage and photocurrent grow in such split-gate detectors approximately linearly with the induced band gap in graphene bilayer. Moreover, photoresponse is absent in case of uniform channel doping, and re-appears rapidly in the presence of induced tunnel junctions in the channel.

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## TERAHERTZ OPTOELECTRONIC PROPERTIES OF GAPPED BILAYER GRAPHENE WITH INDUCED PN JUNCTION

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Terahertz radiation has many potentially useful applications. Graphene, in turn, is a promising material for creating a highly efficient ultrafast THz photodetector [1]. Bilayer graphene is of particular interest because of the possibility to electrically tune the band gap value in the range from 0 meV to more than 100 meV [2]. However, the net terahertz photoresponse in bilayer graphene depending on the band gap value has not yet been studied.

In this work, we studied the photoresponse and photoconductivity on an induced pn junction in gapped bilayer graphene under 0.13 THz irradiation. The pn junction was induced in a graphene-based field-effect transistor using three gates — one bottom and two top gates, biased independently. The distance between top gates was about 150nm. The dominating detection mechanisms in our structure were resistive self-mixing at room temperature and the photothermoelectric effect with a contribution of photoresponse at tunnel junctions at low temperature. We have shown that both photocurrent and photovoltage increased with an increase in the graphene band gap value. We also presented a study of graphene photoconductivity in our device.

The estimated photoresponsivity and noise equivalent power of our THz detector at 25K is about 10kV/W and 20pW/√Hz respectively.

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## STUDY OF SLOW-WAVE STRUCTURES FOR MULTIPLE-BEAM MINIATURIZED MILLIMETER-BAND TRAVELING-WAVE TUBES

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Development of miniaturized vacuum-tube sources of coherent sub-THz radiation is of primary importance for many applications, such as high-speed data transmission systems, remote non-destructive monitoring, radioastronomy, and spectroscopy [1]. One of the promising devices is a traveling-wave tube (TWT), which can provide high gain, high power, and wide bandwidth [2]. With the increase in operating frequencies, dimensions of the devices decrease proportionally. Therefore, a great attention has been attracted to TWTs with spatially-developed slow-wave structures (SWSs) capable of adopting electron beams with large cross section, such as sheet or multiple electron beams. In this work, the results of study of several types of SWSs for W-band (75-110 GHz) miniaturized TWTs with multiple sheet electron beams are presented. Electromagnetic parameters of the proposed SWSs were simulated by using COMSOL Multiphysics and CST Studio Suite simulation packages. The multiple-layer interdigital-type SWS was studied. Such SWS can be used in a TWT amplifier operating at $+1^{th}$ spatial harmonic. The dispersion characteristics were calculated and it was shown that the beam-wave synchronism is possible in a wide frequency band (~10-20 GHz) at voltages of the order of 10 kV. The interaction impedance of such SWS is 0.5-1 Ω in operating frequency band. Various designs of ladder SWS were considered. In a typical situation, TWT with the ladder SWS operates at fundamental spatial harmonics. Its main advantage is in high values of the interaction impedance (~100 Ω). However, owing to a very strong dispersion of the ladder SWS, such TWT will have a rather narrow bandwidth of 1-2 GHz. Ladder-type SWS with slots of complicated shape was also designed and simulated. The shape and dimensions of the slots allow for control of the dispersion in accordance with the required characteristics of the device. A special attention is paid to the case when such structure exhibits properties of a double-negative metamaterial, i.e., its effective permittivity and permeability are negative. Recently, metamaterial-based vacuum tubes have attracted a lot of interest [3]. In particular, a high-power S-band backward-wave oscillator with complementary split-ring resonator (CSRR) SWS was demonstrated in [4]. We designed a W-band CSRR SWS for a W-band TWT operating at $+1^{th}$ spatial harmonic. The bandwidth is around 5 GHz and the interaction impedance attain values of several ohms.

In addition, an electron optic system (EOS) with compression of triple elliptic electron beam was designed [5]. Current-voltage characteristics were simulated be using CST Particle Studio and nearly 180 mA beam current was predicted. The electron gun is fabricated, and the results of experimental measurements will be presented.

This work was supported by the Russian Science Foundation (grant # 22-12-00181).

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## ANALYSIS OF THE METALLIZATION QUALITY OF 3D-PRINTED MICROWAVE COMPONENTS AT MILLIMETER WAVELENGTHS

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The research and development of the microwave and terahertz-wave devices require rapid manufacturing of many variants of developed components such as various waveguides, couplers, filters, converters, etc. These components typically have complex shape so their fabrication is a challenge for conventional manufacturing techniques. The modern additive technologies allow fast and non-expensive production of any details from various plastics. When metalized, these details could be used as electrodynamical components in microwave devices.

In the Institute of Applied Physics, the technology of chemical metallization of photopolymer-based structures (CMPS) is under development [1]. Though SLA method of 3-D printing from photopolymer is more expensive than FDM printing, it was chosen because it provides high speed of printing and perfect accuracy, with the layer thickness of 10 microns and in-layer resolution of 20 microns. After printing and polymerization, the details are chemically cleaned. Then details are coated by thin copper layer (less than 1 micron) by electroless technique to provide surface conductivity. At the final stage, the copper layer with the thickness about of 10 microns (many skin depths) is deposited by galvanic method.

To analyse the quality of the copper surface layer, the ohmic losses were measured for fabricated single-mode rectangular waveguide components at millimeter wavelength band. At the frequencies of 85-110 GHz, the transmission coefficient through of 100-mm-long waveguide piece were measured to find the insertion losses. However, the losses were too small, so the S-parameter was mostly determined by parasitic reflections at waveguide joints. We have only found the upper limit on ohmic losses level, which is about two times higher than for ideal copper waveguide. To achieve better accuracy, a cavity was made in the form of waveguide piece with irises at both ends, and the Q-factor was measured. At the frequency range of 26-40 GHz, the measured ohmic losses for 3D-printed and metalized waveguide are about of 30-40 % higher than measured losses for copper waveguide.

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## PHOTOCONDUCTIVITY INDUCED BY MICROWAVE RADIATION IN $HG_{1-X}CD_XTE$

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We have observed positive photoconductivity under the action of microwave radiation in thick $Hg_{1-x}Cd_xTe$ film with $x < 0.16$, which corresponds to the inverted band structure and, consequently, to the topological phase. The effect appears at low temperatures $T < 7$ K.

It is shown that one of the possible reasons for the positive photoconductivity appearance in the topological state film is the bolometric effect. An alternative mechanism presumes heating of electrons in the film bulk by the microwave radiation followed by their diffusion to the interface area with the trivial buffer, where they acquire higher mobility, which leads to the positive photoconductivity. Measurements of the photoconductivity kinetics may provide arguments in favor of one of the possibilities above.

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# OPTIMAL ASYMMETRY OF TRANSISTOR-BASED TERAHERTZ DETECTORS

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Detectors of terahertz radiation based on field-effect transistors (FETs) are among most promising candidates for low-noise passive signal rectification both in imaging systems and wireless communications. However, it was not realised so far that geometric asymmetry of common FET with respect to source-drain interchange is a strong objective to photovoltage harvesting. Here, we break the traditional scheme and reveal the optimally-asymmetric FET structure providing the maximization of THz responsivity. We fabricate a series of graphene transistors with variable top gate position with respect to mid-channel, and compare their sub-THz responsivities in a wide range of carrier densities.

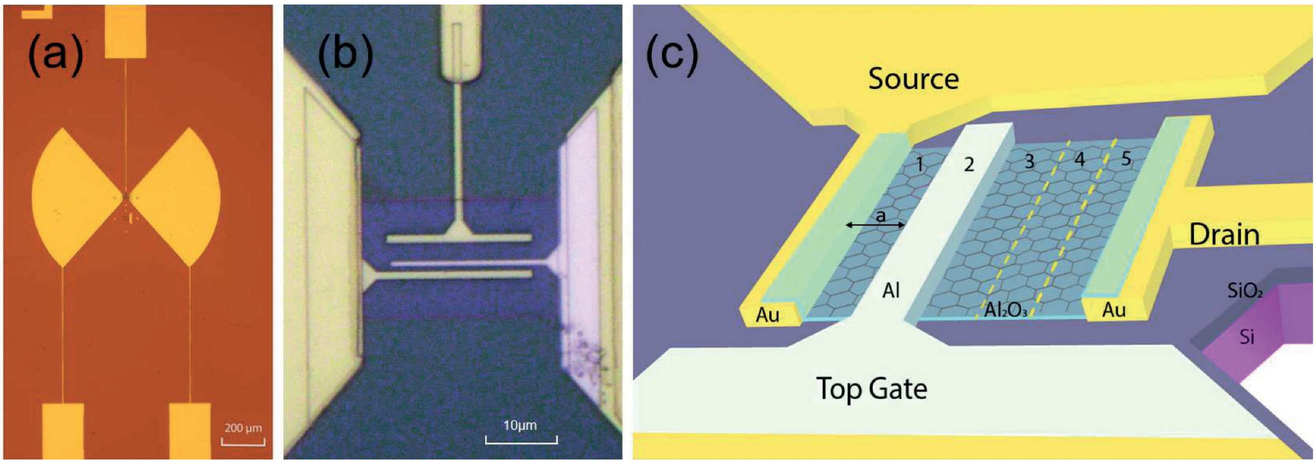


Fig. 1. Antenna-coupled graphene FET as terahertz detector (a) Optical image of the antenna-coupled device. Scale bar is 200 μm (b) Zoomed-in photograph of the gated channel. Scale bar is 10 μm. (c) Schematic of the FET-based detector with asymmetric gate location. Numbers indicate five gate positions used in our study.

We show that responsivity is maximized for input gate electrode shifted toward the source contact. Theoretical simulations show that for large channel resistance, exceeding the gate impedance, such recipe for responsivity maximisation is universal, and holds for both resistive self-mixing and photo-thermoelectric detection pathways.

In the limiting case of small channel resistance, the thermoelectric and self-mixing voltages react differently upon changing the asymmetry, which may serve to disentangle the origin of nonlinearities in novel materials.

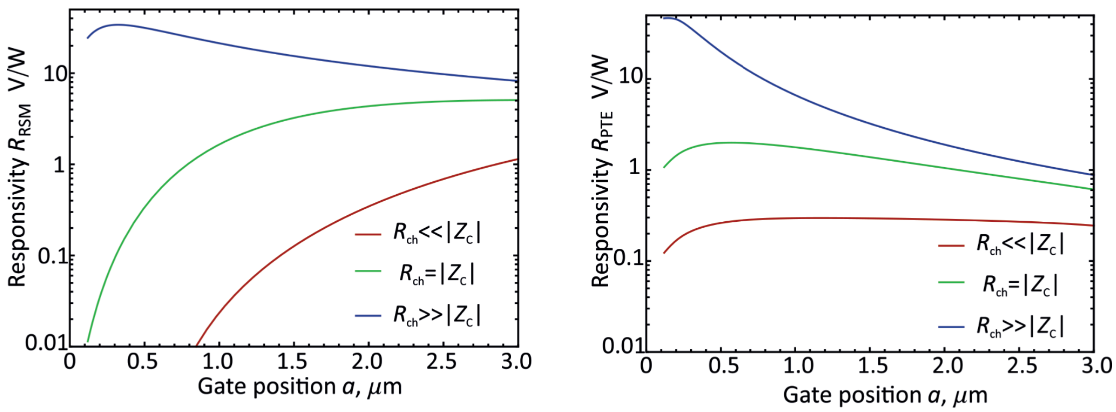


Fig. 2. Calculated dependences of resistive self-mixing (left) and photo-thermoelectric (right) responsivities on gate-to-source separation a for various ratios of channel resistance $R_{ch}$ and top gate capacitor impedance $Z_C=(i\omega Cg)^{-1}$. While for Rch |ZC|both mechanisms are maximised at small a, the trend is reversed for $R_{ch}/|Z_C|$.Blue and green curves plotted for $Z_C$= 100 Ω, red curve for $Z_C$= 1 kΩ. The value of $R_{ch}$ is 100 Ω for red and green curves, and 1.4 kΩ for blue curve.

# EDGE CURRENTS INDUCED BY TERAHERTZ RADIATION IN TWO-DIMENSIONAL SYSTEMS

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The study of the interaction of two-dimensional (2D) structures with electromagnetic field of terahertz spectral range is a central topic of modern solid-state physics aimed at the development of efficient sources and detectors of terahertz radiation. Of special interest is the class of nonlinear phenomena of the second order comprising the generation of direct electric current by ac electric field of radiation and the second harmonic generation. Such effects, in the leading electro-dipole interaction, require the breaking of space inversion symmetry in the system to occur. In small-size samples, the translational and inversion symmetry is naturally broken at the edges, which gives rise to a strong (edge-related) sources of second-order nonlinearity.

Here, we present an overview of non-linear high-frequency electron transport induced by terahertz radiation in 2D structures with the focus on edge-related effects. It is shown that the excitation of the sample by ac electric field at the frequency ω leads to the emergence of edge currents at zero frequency (edge photogalvanic effect) [1,2] and at frequency 2ω (edge second harmonic generation) [3]. The currents flow in a narrow strip at the edge, which is determined by the free path of carriers and the length of the dynamic screening of the terahertz field. The edge photogalvanic current has distinctive polarization dependence. For linearly polarized radiation, the photogalvanic current reaches maxima when the vector of electric field is oriented at the angle π/4 with respect to the edge and vanishes when the field is polarized along or perpendicular to the edge. The current excited by circularly polarized radiation reverses its direction upon changing the sign of the radiation helicity. In the spectral range of intraband (Drude-like) transport, the edge photogalvanic current contains contributions associated with alignment of electron momenta and dynamic charge redistribution near the edge [1]. In the region of interband optical transitions in 2D Dirac systems, the photocurrent is caused by the optical alignment of electron and hole momenta and subsequent scattering of the carriers at the edge [2]. In contrast to the dc edge current, the edge current at 2ω has both parallel and perpendicular to the edge components. Both components have distinctive dependencies on the incident field polarization and emit the electromagnetic field at 2ω with different polarizations [3]. At high frequencies, the spatial profile of the edge current at 2ω contains oscillations caused by excitation of plasma waves.

Considering the important role of edge regions in micro- and nanoscale devices, it is expected that the edge effects can determine the photoresponse of small-size devices and find applications in detectors of terahertz radiation and radiation polarization.

The work was supported by the Russian Science Foundation (project No. 22-12-00211).

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