

CONFERENCES AND SYMPOSIA

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Celebrating 50 years of the laser
(Scientific session of the General Meeting of the Physical Sciences Division of the Russian Academy of Sciences, 13 December 2010)

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A scientific session of the general meeting of the Physical Sciences Division of the Russian Academy of Sciences (RAS) dedicated to the 50th anniversary of the creation of lasers was held in the Conference Hall of the Lebedev Physical Institute, RAS, on 13 December 2010.

The agenda of the session announced on the website www.gpad.ac.ru of the RAS Physical Sciences Division listed the following reports:

(1) **Matveev V A, Bagaev S N** Opening speech;

(2) **Bratman V L, Litvak A G, Suvorov E V** (Institute of Applied Physics, RAS, Nizhny Novgorod) "Mastering the terahertz domain: sources and applications";

(3) **Balykin V I** (Institute of Spectroscopy, RAS, Troitsk, Moscow region) "Ultracold atoms and atom optics";

(4) **Ledentsov N N** (Ioffe Physical Technical Institute, RAS, St. Petersburg) "New-generation surface-emitting lasers as the key element of the computer communication era";

(5) **Krasil'nik Z F** (Institute for the Physics of Microstructures, RAS, Nizhny Novgorod) "Lasers for silicon optoelectronics";

(6) **Shalagin A M** (Institute of Automation and Electrometry, Siberian Branch, RAS, Novosibirsk) "High-power diode-pumped alkali metal vapor lasers";

(7) **Kul'chin Yu N** (Institute for Automation and Control Processes, Far Eastern Branch, RAS, Vladivostok) "Photonics of self-organizing biomineral nanostructures";

(8) **Kolachevsky N N** (Lebedev Physical Institute, RAS, Moscow) "Laser cooling of rare-earth atoms and precision measurements."

The papers written on the basis of reports 2–4, 7, and 8 are published below.*

* Because the paper based on report 6 was received by the Editors late, it will be published in the October issue of *Physics–Uspekhi* together with the material related to the Scientific Session of the Physical Sciences Division, RAS, of 22 December 2010.

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Mastering the terahertz domain: sources and applications

V L Bratman, A G Litvak, E V Suvorov

1. Introduction

The terahertz range, which is intermediate in position between the microwave and optical portions of the electromagnetic spectrum, for a long time remained the least mastered, and seemed to be too short in wavelength for the methods of classical vacuum electronics and too low in frequency for the methods of quantum electronics to be applied. At the same time, this range has several specific features that make it highly attractive for a wealth of basic and applied studies in the areas of physics, chemistry, biology, and medicine [1–3]. The point is that this range comprises many strong lines of rotational molecular transitions, as well as lines of the vibrational and vibrational–rotational transitions of large molecules, including organic ones, which opens up possibilities for their investigation and for selective action on them. Terahertz waves show promise for the diagnostics and spectroscopy of various media, including the development of high-resolution methods of electron paramagnetic resonance (EPR) and nuclear magnetic resonance (NMR). High-power terahertz radiation can be used to produce dense plasmas and control their parameters (controlled fusion, point-like plasma X-ray radiation sources).

Owing to its low photon energy, terahertz radiation is relatively safe for living organisms and can be used for the detection of pathologies and foreign masses by terahertz tomography techniques [4, 5]. Terahertz radiation has a relatively high penetration power and can therefore be used for the detection and identification of objects concealed by clothes, packaging, and even concrete walls. The methods of terahertz time-domain spectroscopy based on the application of broadband coherent pulses provide a fast covering of a broad frequency range, thereby making it possible to reveal the characteristic spectral features ('fingerprints') of different

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molecules. This is important for the detection and identification of plastic explosives, hazardous chemicals, and narcotic drugs, for conducting express analysis of the composition of breathe air for the purposes of diagnosing various diseases, for monitoring the quality of foods, for inspecting agricultural products, and so on [6, 7]. Short coherent terahertz radiation pulses permit studying fast processes. This list does not exhaust the field of possible applications involving the use of terahertz radiation and is constantly expanding [1, 2].

The term 'terahertz range' is used in reference to the frequency range from 0.1 to 10 THz (wavelengths from 3 to 0.03 mm), which covers the short-wavelength part of the millimeter range well mastered by vacuum electronics, as well as the entire range of submillimeter waves and a part of the far-infrared region. Mastering the terahertz range includes creating sources and means of registration, as well as developing diverse applications. Our report is a brief review of the achievements in the generation of terahertz radiation by the methods of classical vacuum electronics and optoelectronics,[1] in addition to several applications of terahertz radiation.

Among the most widespread vacuum sources of coherent terahertz radiation are backward-wave oscillators (BWOs), which rely on stimulated Cherenkov radiation by straight electron beams, and high-power free-electron lasers (FELs) and gyrotrons, which rely on the stimulated bremsstrahlung of curved beams. All these devices have been adequately developed in Russia. Low-voltage BWOs with the oscillation frequency up to 1.4 THz [9], which are manufactured by the ISTOK company, have found wide use in numerous applications in Russia and abroad. The FEL with the particle energy up to 12 MeV created at the Budker Institute of Nuclear Physics (INP), Siberian Branch, RAS, presently provides the record high level of average coherent radiation power in the 1.2–1.8 THz range at the fundamental harmonic of the particle oscillation frequency and also operates at the harmonics of this frequency [10]. As shown in Section 2, the gyrotrons developed at the Institute of Applied Physics (IAP), RAS, demonstrate the feasibility of generating high-power radiation up to the frequencies of at least 1.5 THz for substantially lower particle energies (several tens of keV) than in FELs [11]. Although a start on the use of optoelectronic techniques in the terahertz range was made in Russia later than abroad, it was not long before the area covering the search for new materials and generation techniques and schemes, as well as the demonstration of possible applications, was brought up to date.

2. Classic vacuum sources

Low-voltage compact BWOs [9] provide the output radiation power of the order of 30–1 mW for waves with the frequencies 0.1–1.4 THz. There is also a higher-power but more narrowly used version of a BWO with an electron beam tilted with respect to a slow-wave structure — a 'klinotron,' which operates at frequencies up to a value of the order of 0.5 THz [12]. To improve its efficiency, however, this oscillator uses a mode with substantial reflections of the working wave from the structure ends, which makes this device sensitive to frequency tuning. Among the devices with straight electron beams that show promise for the terahertz range, we also note extended interaction klystrons [13], which give a very high performance throughout the millimeter range, and orotrons (or diffraction radiation generators). The pulsed orotrons recently developed at the IAP jointly with the National Research Institute for Physicotechnical and Radio Engineering Measurements and the Institute of Spectroscopy, RAS, have reached the output frequency 0.4 THz for a relatively smooth electromechanical frequency tuning over a very broad range (up to 1–1.5 octaves) and the output power of several hundred mW [14].

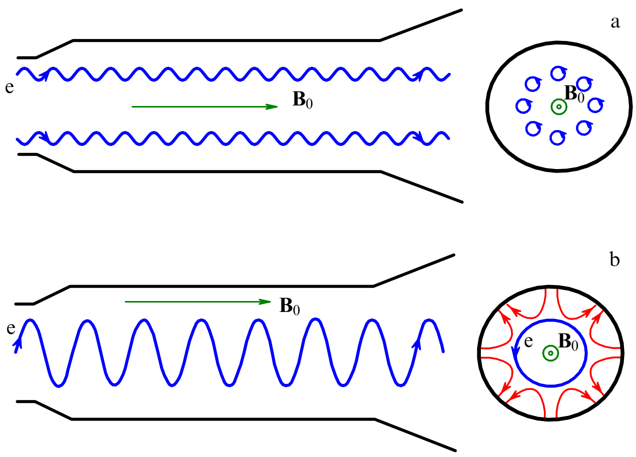

Figure 1. Workspace of (a) a conventional gyrotron with a polyaxial electron beam and (b) a large-orbit gyrotron with a monoaxial electron beam.

Unlike devices with straight electron beams, FELs and gyrotrons use stimulated bremsstrahlung of the electrons that follow periodic trajectories. In these devices, the particles interact with fast eigenwaves. This permits using large-volume open resonators or waveguides as electrodynamic structures and exciting them by high-intensity electron beams traveling far from the structure walls. This allows obtaining a very high output power.

In a gyrotron (Fig. 1), electrons move along helical trajectories in a uniform magnetic field $\mathbf{B}_0$ of a solenoid and interact with the high-frequency field of a cylindrical resonator under the cyclotron resonance condition

$$\omega \approx s\omega_c , \qquad (1)$$

where ω is the field frequency, $s = 1, 2, \ldots$ is the number of a resonance cyclotron harmonic, and $\omega_c = eB_0/m\gamma$ is the cyclotron frequency, where e, m, and γ are the electron charge, mass, and relativistic factor. Of fundamental importance for all particle energies is the nonisochronicity of cyclotron rotation caused by the relativistic energy dependence of the cyclotron frequency, which results in azimuthal bunching of the particles in Larmor circles under the effect of the amplified (seed) wave. For this bunching to develop, the rotational electron velocity should be high enough and the interaction space should be sufficiently long.

To minimize the Doppler broadening of the cyclotron resonance line, modes with the lowest longitudinal wavenumber are used in gyrotrons. Accordingly, for a resonator length much longer than the wavelength, the operating mode field is composed of the waves that propagate nearly transversely to the magnetic field. That is why it is possible to neglect the Doppler correction to the frequency under resonance condition (1) (in detailed calculations, especially for beams with a substantial spread of particle velocities, this frequency shift,

[1] Research in semiconductor terahertz oscillators is reviewed, e.g., in Ref. [8].

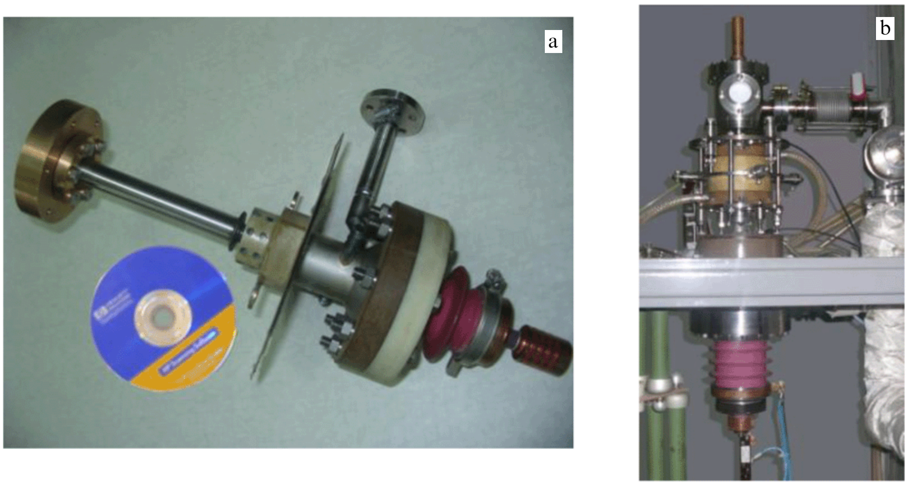

Figure 2. Photographs of pulsed terahertz gyrotrons made at the IAP, which operate (a) at the main cyclotron resonance and (b) at higher-order harmonics.

which is in particular responsible for the inhomogeneous broadening of the cyclotron resonance line, should be taken into account).

Condition (1) implies a formula for the resonance magnitude of the magnetic field,

$$B_0(T) = 35.7\,\frac{\gamma}{s}\,f\ [\mathrm{THz}]\,, \qquad (2)$$

whence it follows that terahertz gyrotrons using the fundamental ($s = 1$) cyclotron resonance require very strong magnetic fields: obtaining a 1 THz frequency requires a field above 36 T. At the present time, such fields can be produced primarily by pulsed solenoids. But when ensuring efficient discrimination against parasitic modes, the high-frequency oscillation can also be obtained at higher-order harmonics, when the working magnetic field is s times lower and can be produced in modern cryomagnetic systems. As a result, for much lower particle energies and far smaller device dimensions, the gyrotrons, according to estimates, are capable of operating at the same or even higher power levels as FELs, at the frequencies up to 1–1.5 THz in pulsed and cw modes.

In the first experiments with terahertz gyrotrons carried out at the IAP in the 1970s–1980s, demonstration experiments were performed on cw oscillation at the second harmonic at the frequency 0.33 THz with a power at the kilowatt level [15] and the 50 μs single-pulse generation at the fundamental cyclotron resonance at frequencies up to 0.65 THz with the peak power $10^4 - 10^5$ W [16]. Following this work, a start was made on the development of high-frequency gyrotrons by several groups in the USA, Australia, and Japan. At present, several organizations, including the IAP, are developing cw gyrotrons with frequencies lying in the range 0.14–0.52 THz, which are intended for EPR spectroscopy and dynamic nuclear polarization (DNP) in the high-field NMR spectroscopy [17–20], as well as for other applications. In the experiment carried out jointly by the IAP and Fukui University (Japan), a high-efficiency cw gyrotron was made at the main cyclotron resonance with the frequency 0.3 THz and the output power 2.7 kW, which uses a so-called liquid-helium-free cryogenic magnet with a field of 12 T [21]. Recently, gyrotrons operating at the main [22], second [23], and third [24] cyclotron harmonics overcame the 1 THz frequency mark. Despite the problems related to the production of high magnetic fields, such oscillators are relatively simple, affordable, and easily reproducible sources of high-power radiation.

It worth noting that in greatest demand currently are high-power subterahertz gyrotrons intended for electron cyclotron plasma heating and control of plasma parameters in controlled thermonuclear fusion facilities; when operated in a quasi-cw regime, they provide the output power 1 MW at a fairly high frequency (170 GHz) [25]. For the level of parasitic mode discrimination reached in the gyrotrons, the peak output power decreases relatively slowly with increasing frequency, but the average output power decreases at least as $\lambda^{5/2}$ due to the thermal problems arising from a decrease in the resonator surface and an increase in the fraction of ohmic losses in its walls.

To increase the output frequency of gyrotrons, a previously employed compact highly robust solenoid was recently improved at the IAP [16]. This allowed strengthening its magnetic field by a factor of two (to 50 T) and, for a particle energy up to 24 keV, generating several modes with frequencies in the $1 - 1.3$ THz range and the peak power 5–0.5 kW at the fundamental cyclotron resonance in a single-pulse mode (Fig. 2a) [22, 11]. Also under development at the IAP is a technology that will allow making relatively simple pulsed solenoids with the magnetic field up to 30 T and the repetition rate up to 0.1 Hz. This will result in the realization of conventional gyrotrons at the main cyclotron resonance and the second harmonic with the oscillation frequency up to 0.8–1.6 THz for the peak power of several hundred kilowatts and the average output power about 1 W.

In the operation at the main cyclotron resonance and the second harmonic, in terahertz gyrotrons, as in the millimeter range, tubular polyaxial electron beams are most frequently used (Fig. 1a). In the operation at higher-order harmonics, a stronger electron–wave coupling and a higher level of parasitic mode discrimination are realized for a nearly monoaxial (Fig. 1b) configuration of the electron beam, which is coaxial with an axially symmetric resonator. Under this geometry, which is used in the so-called large-orbit gyrotrons (LOGs), the field of the azimuthally rotating mode with an azimuthal index s perfectly coincides near the axis with the field of the $2s$th rotating multipole, which rotates synchronously with electrons that rotate in Larmor circles in

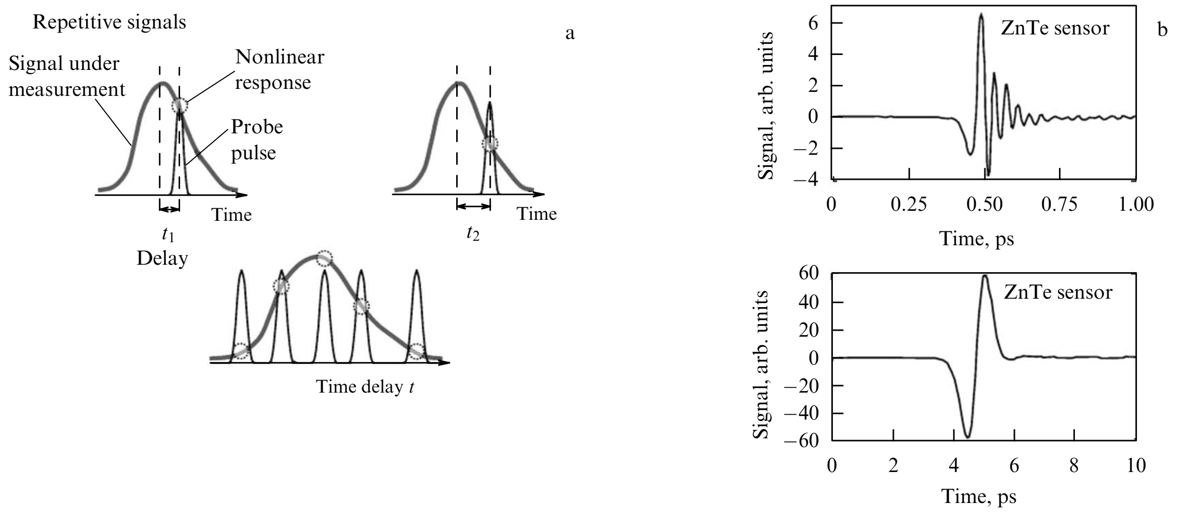

Figure 3. (a) Principle of optical sampling for measuring the waveform of terahertz pulses and (b) examples of measured waveforms with different characteristic time scales.

the resonance magnetic field. That is why these modes experience the strongest coupling to the electrons and the modes with other azimuthal indices are not excited (a strong selection rule).

A large-orbit gyrotron with the particle energy 50–80 keV and a 10–14 T field was developed at the IAP. It selectively generates several modes at the second and third harmonics at the frequencies 0.55–1.0 THz, which are record high for devices of this type, in 8 μs pulses with the peak power 0.3 – 1.8 kW for the pulse repetition rate 0.1 Hz (Fig. 2b) [24]. These devices can operate with relatively low magnetic fields attainable for modern cryomagnetic systems. Presently, a LOG with a lower particle energy (30 keV) and a lower magnetic field (5 T) intended for cw operation at the second, third, and fourth cyclotron harmonics with the output power 3–0.1 kW at frequencies 0.26–0.52 THz is being fabricated at the IAP. With 15 T cryomagnets, which are reasonably affordable at present, it is possible to create similar sources with frequencies up to 1.6 THz.

The limitations on the output power of terahertz gyrotrons related to superhigh field production, the discrimination against parasitic modes in oversized systems, and the ohmic heating of the resonator result in a decrease in the average output power at the fundamental cyclotron resonance to the level of 200–70 kW at frequencies of 0.3–0.5 THz. When operating at the second and third cyclotron harmonics (including the use of LOGs), it will be possible to attain frequencies of 1–1.6 THz with the output power ranging into the kilowatts.

3. Production and detection of coherent broadband terahertz pulses by optoelectronic techniques

The advent and advancement of femtosecond laser technology, which permits obtaining a high peak output power for a moderate average power, underlie the breakthrough in mastering the terahertz range owing to the possibility of using nonlinear effects in various media, both for the generation and for the detection of pulsed coherent broadband radiation. For example, we specify the radiation parameters offered by the Spitfire-Pro laser system used in an IAP facility dedicated to optoelectronics research: the wavelength 0.8 μm, the energy 2–3 mJ in 50 fs pulses, and the pulse repetition rate 1 kHz, corresponding to the peak power 50 GW and the intensity 5–10 GW cm^{-2} in the focusing to a spot with a characteristic size of 100 μm.

The first demonstration experiments on the generation of pulsed free-space terahertz radiation and its detection were carried out in the early 1980s using 'fast' semiconductors (with characteristic photoconductivity rise and decay times lying in the picosecond range) [26] and nonlinear electrooptical crystals [27]. The generation is provided by the rectification (nonlinear detection) of femtosecond laser pulses. As a result, in detecting pulsed terahertz radiation, a unique possibility emerges of measuring the so-called waveform of terahertz pulses, i.e., the temporal dependence of the electric field, which is due to the high repetition rate of the generated terahertz pulses and their high pulse-to-pulse reproducibility. This permits performing 'optical scanning' by varying the delay of optical probe pulses relative to the terahertz pulses that pass through a photoconductor in which the induced voltage is determined by the magnitude and sign of the low-frequency (THz) electric field, or through a nonlinear electrooptical crystal in which the induced birefringence is also determined by the magnitude and the sign of the low-frequency electric field (the linear Pockels effect). Figure 3 outlines the principle of optical sampling for waveform measurements and provides examples of measured waveforms with different characteristic time scales.

The high reproducibility of the generated terahertz pulses is illustrated by the results in Ref. [28] on the phase stabilization of cw radiation in the 100 GHz range, in which high-order harmonics of a terahertz-pulse-repetition frequency (about 100 MHz), clearly resolved for harmonic numbers of the order of several thousand, were used as a reference signal. Using this stabilization system allowed obtaining a record narrow cw radiation line (about 10 Hz at the half-power level).

A comparison of the waveforms of the reference terahertz radiation and the radiation transmitted through samples under investigation underlies numerous applications related to terahertz 'radio-wave imaging' and measurements of the spectra of substances under study in a broad spectral range (so-called time-domain spectroscopy). We emphasize that the Fourier processing of waveforms allows simultaneously measuring the real and imaginary parts of the permittivity. The detection of terahertz radiation with the use of photodetectors or nonlinear electrooptical crystals, which is well elaborated and commonly accepted presently, is used in a number of commercial devices. At the same time, vigorous studies aimed at a search for new nonlinear materials, new oscillation schemes, the attainment of optimal parameters, as well as fundamental studies are still in progress. Below, we briefly discuss some of them.

In crystals with the group velocity of optical radiation exceeding the phase velocity of terahertz waves, the Cherenkov generation mechanism is possible when a low-frequency pulse of nonlinear polarization of the medium travels at a speed that exceeds the phase velocity of the terahertz radiation. This situation is realized, for instance, in planar sandwich structures developed by the IAP in cooperation with Nizhny Novgorod State University. These structures consist of a glass (BK7) [29] or metal [30] substrate, a nonlinear crystal layer ($LiNbO_3$) several tens of micrometers thick, and a silicon prism. Nonlinear polarization is induced due to rectification of optical radiation in the $LiNbO_3$ layer, and then the Cherenkov terahertz wave wedge passes through the silicon prism; the terahertz radiation is extracted through a bevel prism face. A record high optical-to-terahertz radiation conversion efficiency (of the order of 10^{-3}) was reached. The theoretically expected generation efficiency is higher by about an order of magnitude [31, 32], and the improvement in sandwich structure fabrication therefore gives hope to improve the experimental efficiency. With the use of a metallic substrate, it is also possible to control the spectrum of the terahertz radiation by changing the gap between the nonlinear crystal and the substrate.

Record high values of the terahertz pulse energy (up to 10 μJ), which corresponds to the record high terahertz field intensity (up to 10^7 V cm^{-1} in focusing to a spot 200 μm in diameter), were obtained at the Prokhorov General Physics Institute (GPI), RAS [33]. The generation scheme relies on the optical rectification of high-energy (30 mJ) femtosecond laser pulses with a tilted intensity front propagating through a wide-aperture ($30 \times 30 \times 10$ mm) nonlinear lithium niobate crystal. The tilt angle of the intensity front corresponds to the Cherenkov condition, which substantially increases the time of interaction between the radiated terahertz pulse and the nonlinear low-frequency polarization excited in the medium.

Considerable recent attention has been focused on the plasma mechanisms of terahertz radiation generation involving atmospheric air breakdown induced by focused femtosecond radiation. These generation techniques offer certain advantages over nonlinear rectification in solids: the absence of a 'damage threshold,' allowing the use of arbitrarily high intensities of laser radiation in principle; the absence of clearly defined resonances, which 'cut' appreciable portions from the spectrum of generated terahertz radiation; and a high generation efficiency of several schemes. Furthermore, in remote monitoring systems, it is possible to bring the plasma source and the terahertz radiation detector quite close to the object under inspection. A feature of the modern stage of research on the terahertz radiation generation in a laser-induced spark is that experimental research sometimes takes the lead over the theoretical one and that the theoretical models under consideration often fail to provide a quantitative interpretation of the whole set of experimental data. In this case, one complication arises from the necessity of three-dimensional simulation of the self-consistent dynamics of the focused laser field and the plasma resulting from ionization of the air. Another complication is associated with finding the distribution of low-frequency currents responsible for terahertz radiation; these currents arise from the relaxation of the wave of initial conditions, created at passing a short ionizing optical pulse, in the formed plasma column.

Extensive experimental research into the generation of terahertz radiation in a laser-induced spark was carried out at the dedicated facility at the IAP, which was designed for investigations in the area of optoelectronics. It was shown, in particular, that the imposition of an electric field of about 10 kV cm^{-1} (close to the threshold of air breakdown at atmospheric pressure) increases the generation efficiency by more than a factor of 200 [34] and that the addition of the second harmonic to the optical radiation at a 10% level (with the appropriate phasing of the 1st and 2nd harmonic fields) results in an efficiency increase by more than four orders of magnitude [34, 35]. Furthermore, original findings were reported concerning the radiation pattern and polarization of the terahertz emission from the laser-induced spark, which refute the existing notion that the characteristics of terahertz radiation and the distribution of low-frequency currents in a laser-induced spark, which are responsible for this radiation, are axially symmetric.

Theoretical models were elaborated at the IAP with the specific character of the electron distribution function formation under tunnel ionization in the field of optical radiation taken into account. In the zero-dimensional approximation based on the one-dimensional Boltzmann equation for plasma produced in the process of tunnel ionization, approximate expressions were derived for the source of a quasistationary current; the current excitation efficiency was analyzed for a bichromatic breakdown scheme depending on the laser radiation parameters (the relative phase difference, the polarization, the amplitudes of harmonics) [34–36]. Qualitative agreement was reached between theoretical results and experimental data.

A new mechanism of low-frequency current formation was proposed for laser-induced spark plasmas: in the field (tunnel) ionization of gas in the field of linearly polarized laser radiation, anisotropic pressure emerges in the electron subsystem (with preferential direction along the optical field). In the relaxation of the anisotropy, low-frequency currents are also excited in the direction perpendicular to the optical field, which appreciably changes the radiation pattern and polarization of the terahertz radiation. A numerical code [37] was developed whose application enabled providing a detailed explanation for the formation of a quadrupole radiation pattern of the terahertz radiation and its modification under the application of an external electrostatic field, which was observed in experiments [34].

4. Application of terahertz radiation

In recent years, subterahertz and terahertz sources of coherent radiation have been finding a growing number of various uses. In particular, gyrotrons of the megawatt power level with frequencies up to 0.17 THz are used in the electron–cyclotron heating systems of virtually all modern facilities for controlled fusion (CF) with magnetic plasma confinement. High-stability and relatively low-power gyrotrons are used to substantially improve the sensitivity of high-field NMR spectrometers due to polarization of the paramagnetic subsystem with the subsequent transfer of the polarization state to the nuclear subsystem (dynamic polarization of nuclei). A cw gyrotron operating at the second harmonic with the radiation frequency 260 GHz and the output power about 100 W [20], recently developed at the IAP, was validly used for this purpose in experiments [38].

A gyrotron with a high working frequency (0.67 THz) and a high pulsed power (300 kW) operating at the main cyclotron resonance has been developed; it is targeted for use in experiments in the remote location of concealed sources of ionizing radiation by the method proposed in Ref. [39]. According to this method, a high-power terahertz wave beam is focused to a small volume, in which the probability of the occurrence of free electrons and of breakdown initiation is low in the absence of ionizing radiation, but is much higher in the presence of ionizing radiation.

At the IAP, a start was made on a feasibility study of making an extreme ultraviolet source with small geometric dimensions ('a point-like source') for high-resolution projection lithography based on the line radiation of multiply charged ions in a discharge induced by terahertz gyrotron radiation. A comprehensive investigation was carried out of self-sustained and initiated discharges maintained by converging terahertz radiation beams in argon and gas mixtures at near-atmospheric pressures [42].

Figure 4 is a schematic representation of the IAP facility intended for obtaining the spectra and images of the specimens under investigation during the passage of terahertz radiation through them. The duration of one scan required to obtain a spectrum in the 0–10 THz frequency interval with the resolution about 1.5 GHz is of the order of 100 s. In demonstration experiments, over one hundred lines of water and carbon sulfoxide in a gaseous state were identified that coincided with the data of well-known catalogs. For example, Fig. 5 shows the 'spectral portraits' of several solvents and proteins in solutions [40]. The two-dimensional radio images of the objects were obtained by point-to-point scanning as the object under study was moved along two transverse coordi-

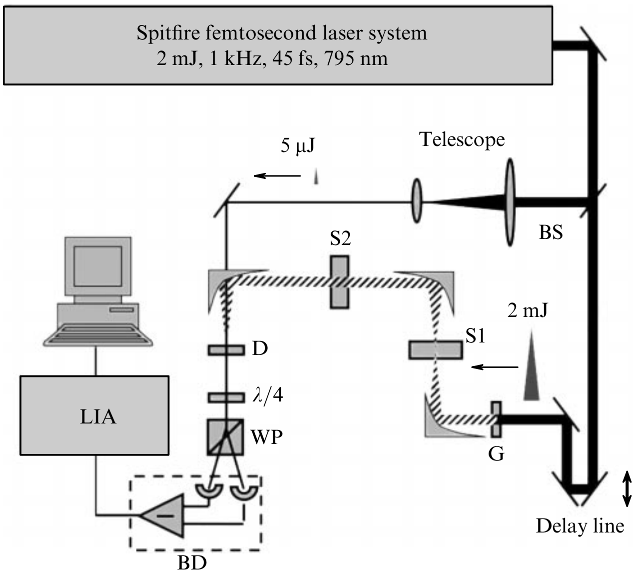

Figure 4. Diagram of the IAP facility designed for optoelectronics research: a delay line makes pulse-to-pulse optical sampling possible, placing a specimen (S1) at the beam waist of terahertz pulses permits obtaining transmission radio images by point-to-point scanning, and placing a uniform specimen in position S2 affords its time-domain spectroscopy. Acoustooptical modulator: BS — beam splitter, WP — Wollaston prism, G — 1 mm ZnTe [110] generator, D — 1 mm ZnTe [110] detector, $\lambda/4$ — quarter-wave plate, S1, S2 — specimens, BD — balanced detectors, LIA — lock-in amplifier. Parameters of a THz pulse: central frequency 0.75–1 THz, spectral width 1–2 THz, duration 0.5–1 ps, field 20 kV cm^{-1}, peak power 3 kW, and conversion efficiency 10^{-6}.

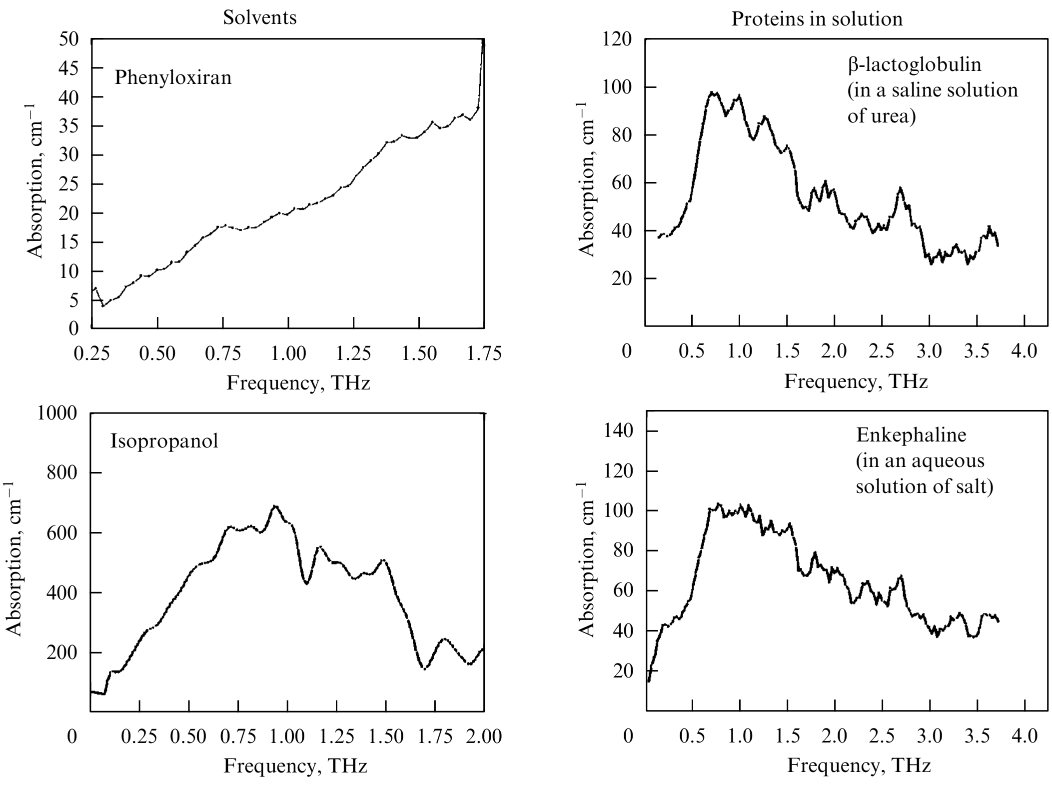

Figure 5. Examples of the 'spectral portraits' of some solvents and proteins in solution.

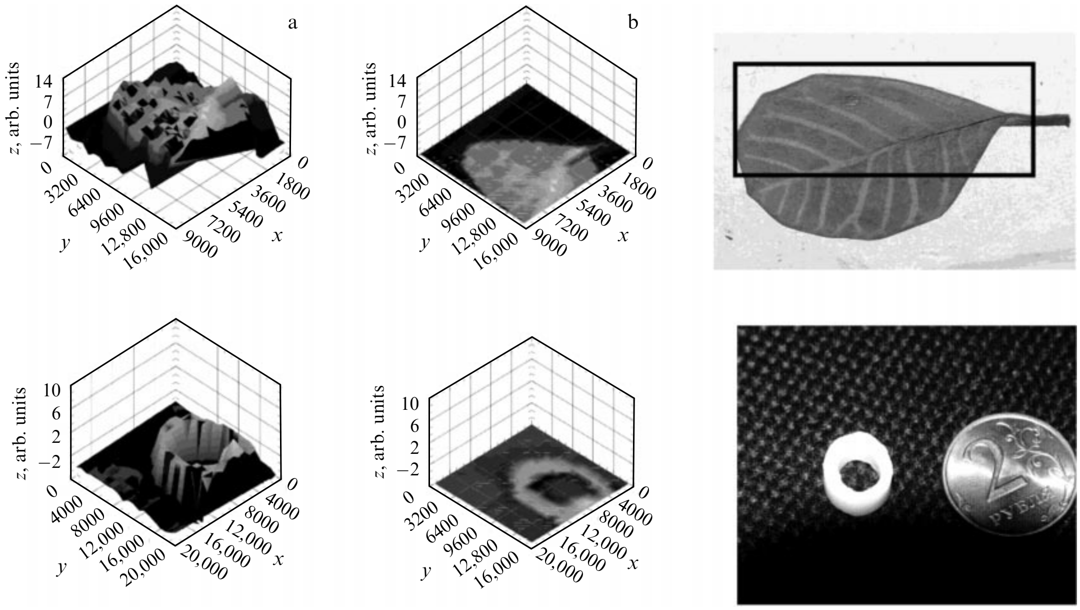

Figure 6. Examples of transmission radio images in the THz range: (a, b) THz radio images for different ways of presentation; (c) optical images.

nates (position S1 in Fig. 4); examples of the images for various ways of presenting the results of processing are given in Fig. 6 [41]. The time taken to obtain one image of an object several square centimeters in size with the resolution about 1×1 mm^2 amounts to almost ten hours under this method, which is suitable only for demonstrations. In this connection, a system presently under development at the IAP is intended for constructing images based on using wide-aperture terahertz beams and high-speed CCD matrices (a CCD is a charge-coupled device). This system will enable obtaining two-dimensional real-time images with a resolution close to the diffraction limit.

One area that shows considerable promise for applications and is under rapid development in many countries is the three-dimensional tomography, which relies on the recording and processing of backscattered terahertz radiation. Among the possible applications, we note the following ones: monitoring of multilayer semiconductor structures during their fabrication, detection of inhomogeneities in stone and concrete structures (flaw detection in new structures and historical monuments, archeology, and so on), investigation of works of art (detection of images concealed under layers deposited later, study of the state of art works prior to their restoration, detection of ancient mural paintings under subsequent layers, including plasterwork), implementation of antiterrorist measures (identification and detection of plastic explosives, toxic agents, and narcotic drugs, inspection of luggage, envelopes, and objects concealed by clothes), and so on. Domestic research in this area is still in its infancy, and its substantial intensification in the near future is called for.

5. Conclusions

At present, the terahertz gap is being efficiently filled both from the side of traditional vacuum electronics and from the side of optoelectronics. Domestic developments in the area of vacuum electronics are at the forefront of the world science. Subterahertz gyrotrons are routinely used in CF facilities with magnetic plasma confinement, as well as in DNP–NMR spectrometers. An output power of $10^2 - 10^4$ W in a pulsed mode has been obtained with relatively compact and accessible gyrotrons with the frequencies up to 1–1.3 THz; cw gyrotrons at the kilowatt power level at the frequencies up to 1 THz are under development. In a short period, domestic femtosecond optoelectronics has been brought up to date in the area involving the quest for new materials, techniques, and oscillation schemes, as well as the demonstration of possible applications. This will permit making the natural transition to the next stage — domestic development of devices for specific applications.

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Ultracold atoms and atomic optics

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1. Introduction

As a quantum mechanical system, the atom is characterized by two sets of degrees of freedom: internal (electron configurations and spin) and external (momentum and center-of-mass position), which can change in the interaction with laser radiation. The physics of ultracold atoms and atom optics made their appearance due to successful investigations into the action of laser radiation on precisely the external degrees of freedom of the atom — its momentum and center-of-mass position. In an elementary 'photon absorption–emission' cycle, the reradiated photon can be spontaneous or induced. The 'stimulated absorption–spontaneous emission' process is inherently dissipative and it is precisely this cycle that underlies the laser cooling of atoms. Numerous laser cooling techniques enable forming atomic ensembles in the range from room temperature to several nanokelvins. Laser cooling and the subsequent evaporative cooling allow obtaining both ultralow temperatures and ultrahigh atomic densities, which in turn permits realizing quantum Bose and Fermi gases. The 'stimulated absorption–stimulated emission' photon process is coherent and forms the foundation of atom optics — a new type of optics of material particles (along with electron and neutron optics), which evolved from the development of the methods of laser cooling and atom localization and which is concerned with the formation, control, and application of the ensembles and beams of neutral atoms.

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2. Laser cooling of atoms

It is common knowledge that one of the main properties of laser radiation is its extremely high effective temperature, which exceeds the solar temperature by many orders of magnitude, even for low-power lasers. This unique property of laser radiation sharply distinguishes it from the light emitted by conventional thermal sources. Owing to this property, laser radiation has gained wide acceptance in thermal material processing. Also considered is its application for the initiation of thermonuclear reactions.

Not immediately evident is the idea of cooling substances by laser light. On the face of it, this seems to be hardly compatible. Nevertheless, not only has it been proved in the past 20 years that lasers can cool atoms moving freely in a low-pressure gas or in an atomic beam, but a new area of research has also emerged — the physics of ultracold atoms. The minimal temperatures attainable presently are as low as several nanokelvins.

The laser cooling of an ensemble of atoms occurs in the resonance or quasiresonance energy and momentum exchange between the atoms and laser radiation. The energy of the atomic ensemble then decreases and the radiation energy increases. Three laser cooling mechanisms are known, which are referred to as Doppler, sub-Doppler, and subrecoil mechanisms.

2.1 Doppler cooling

In the interaction of an immobile atom with monochromatic laser radiation of frequency ν_L, the atom absorbs a resonance photon ($\hbar\nu_L = \hbar\nu_0$, where ν_0 is the optical transition frequency) and experiences a transition from the ground state to an excited one. The photon absorption changes the atomic velocity by the value of the recoil velocity $v_{ret} = \hbar k/M$, where $\hbar$ is the Planck constant, $k = 2\pi/\lambda$ is the wave vector, λ is the radiation wavelength, and M is the atomic mass. The atom can return from the excited state to the initial one with the stimulated or spontaneous emission of a photon. In the stimulated emission, the photon has the same energy and propagation direction as the absorbed photon, resulting in the reverse change of the atomic velocity by v_{ret}. In