Research Highlights from the Novosibirsk 400 W average power THz FEL

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Abstract: The first stage of the Novosibirsk high power free electron laser (NovoFEL) was commissioned in 2003. It is a CW FEL based on non-superconducting, low-frequency (180 MHz) single-pass accelerator-recuperator with the following parameters: the electron energy is 12 MeV; charge per bunch is 1,5 nC; the bunch repetition rate is 5.6 to 22.5 MHz; the maximum average current is 30 mA; the bunch duration is 40 to 100 ps. The radiation spectral range is 110 - 240 μm at the first harmonics, 60 - 117 μm and 40 - 80 μm at the second and third harmonics correspondingly. The maximum average power is up to 0.4 kW for the first harmonics. The maximum average power of the second and third harmonics is 2% and 0.6% with respect to the first harmonics. The maximum peak power is 1 MW, and the repetition frequency is 5.6 and 11.2 MHz. The relative spectral width is 0.25 – 1%. The radiation is completely spatial coherent, and the degree of linear polarization of radiation is better than 99.6 %.Laser radiation is transmitted through nitrogen-filled optical beamline to the experimental hall. To provide ultrahigh vacuum in the FEL and accelerator-recuperator, their vacuum volume is separated from the beamline by a diamond window. Four user stations (the diagnostic station, the photochemistry station, the biological station, and the THz imaging station) are in operation now. Two other stations are under construction: the station for introscopy and spectroscopy, and the aerodynamics station. The high average power of the FEL enables development of imaging techniques. Several methods for two-dimensional visualization of THz radiation, including an uncooled microbolometer camera for THz high-speed imaging with a time resolution of 1 to10-2 s, have been developed. Instrumentation for the experimental station is developed and tested (windows, beam splitters, pyroelectric detectors, bolometers, Fresnel zone plates, and kinoform lenses). During the last year the NovoFEL was operating as a user facility. Soft ablation of biological molecules under terahertz radiation has been studied at the NovoFEL during the last three years. Precisely tuning radiation energy, one can achieve the regime when “biological” molecules (DNA, proteins, etc) are “evaporated” without defragmentation. These results can lead to creation of new biotechnologies. Experiments in physics, chemistry, biology, condensed matter and technology at four user stations are surveyed in this paper. Next year we plan to commission the second stage of the NovoFEL, based on the four-track 40 MeV accelerator-recuperator, using the same accelerating RF structure as the first stage. The FELs in the second and fourth tracks are to generate radiation in the spectral ranges of 5-30 μm and 30-100 μm, respectively. The expected power of each FEL is more than 1 kW.

Keywords:THz FEL, Novosibirsk high power free electron laser

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1. Introduction

Exponentially growing number of publications devoted to the development of terahertz sources and applications of terahertz radiation reflects the expectation of a breakthrough to new technologies employing this frequency band. The interest in terahertz radiation is due to its following properties:

radiation is non-ionizing (the photon energy ranges from 0.04 to 0.004 eV);
radiation passes through an opaque media and weakly dispersive materials relatively well, owing to the strong suppression of Rayleigh scattering (1/λ4);
the radiation frequency range includes the region of molecular rotational spectra, vibrations of biologically important collective modes of DNA and proteins, and characteristic frequencies of intermolecular interactions;
terahertz radiation corresponds to the energy region of hydrogen bonds and van der Waals forces of intermolecular interactions.

Invention of the broadband terahertz generators based on short-pulse lasers triggered researches in terahertz imaging and tomography, spectroscopy, biology and medicine, security, and other applications. In applications that require tunable monochromatic coherent radiation, the backward wave oscillators (in the millimeter and high submillimeter regions), injection-seeding parametric generators, and difference-frequency generators are commonly used. However, the average power of all the above mentioned generators is very low.

Another class of sources that can emit terahertz radiation is based on the radiation of relativistic electrons in magnetic structures such as synchrotrons and free electron lasers (FEL). Such sources have a very high brightness and high power. The average radiation power of conventional terahertz free electron lasers in Stanford, UCSB, FOM-Institute, Osaka and KAERI is close to 1 W. Because of relatively low FEL efficiency, the further increase of the output power can be achieved only using energy recovery systems. The capability of such technique has been demonstrated at the near-infrared FEL (JFEL) recently commissioned in Jefferson Laboratory on the base of energy recovery linac. Nowadays it generates tunable monochromatic radiation at an average power of more than 10 kW. The same facility is also used as a 100 W average power radiation source, which emits broadband terahertz radiation when a sub-picosecond electron bunch passes bending magnets (coherent synchrotron radiation in the THz region).

The FEL scheme is demonstrated in Fig 1. Electrons with the energy E = γmc2 fly through the undulator – a special magnet which gives rise to a periodic vertical magnetic field $B_y = B_0 \sin(2\pi z/\lambda_0)$ of the period λ0. Moving in the undulator magnetic field, an electron emits quasimonochromatic radiation. Radiation from the undulator at a zero angle (forwards along the z axis) has the wavelength $\lambda = \lambda_0 \left(1 + K^2/2\right)/\left(2\gamma^2\right)$, where K = eBλ0/(2πmc2) is the so-called undulator parameter. On the other hand, a plane electromagnetic wave that propagates along the undulator axis z (the electric field vector E is directed along the x axis) due to the sinusoidal trajectory of an electron moving through

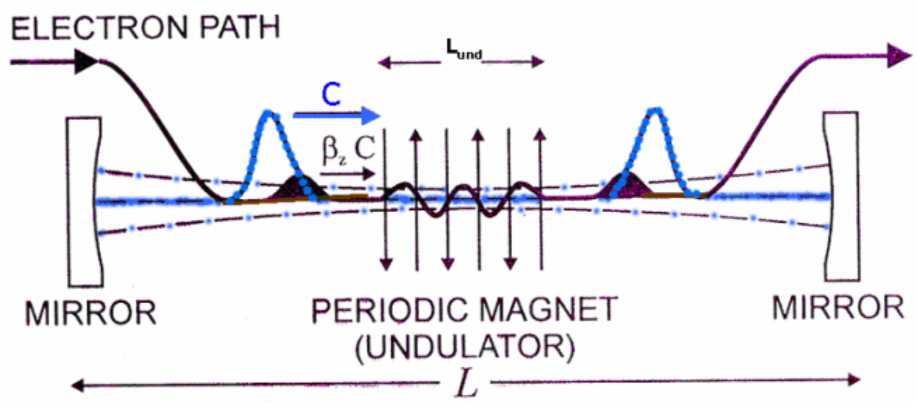


Fig. 1 Scheme of the free electron laser.

the undulator changes the electron energy. For the mentioned above “resonance” wavelength the propagation of the wave is synchronized with the motion of electron in the undulator: after passing each undulator period, the electron lags behind the electromagnetic wave by exactly one radiation wavelength. Then the energy variation increases linearly along the undulator. As this energy variation depends on the moment of time when the electron enters the undulator, half of the electrons gains energy, and the other half looses it. So, electron energy modulation takes place in the undulator in the presence of synchronous electromagnetic wave. Due to the dependence of the electron velocity on their energy the energy modulation leads to the electron density modulation. The resulting electron beam is ‘sliced up’ into microbunches, which are spaced by the radiation wavelength λ. All microbunches emit radiation coherently (in a proper phase) with the initial electromagnetic wave. So, amplification of the input electromagnetic wave takes place. Reflection by the two mirrors of the optical resonator returns the amplified radiation to the undulator entrance and the amplification repeats. In other words, the feedback (mirrors) converts the FEL amplifier to a FEL oscillator.

The advantages of FELs as compared with other types of lasers are as follows:

(1) radiation can be generated with any desired wavelength between 1 mm and 1 Å (the range between 1 mm and 130 Å has already been achieved);

(2) tuning of the monochromatic radiation wavelength can be performed through varying the magnetic field in the undulator or the electron energy;

(3) the ‘working medium’ in an FEL is a relativistic electron beam that is capable of generating radiation of high average power up to 106 W (a power of 104 W has already been achieved).

The main disadvantages of FELs are their large dimensions and high cost. Therefore, the fields suitable for FEL application are those that are not accessible to conventional lasers.

2. The high power terahertz range FEL for the Siberian Center of Photochemical Research

The creation of high power FEL based on a four-track energy recovery linac (ERL) with a maximum energy of 40 MeV is close to completion at Budker Institute of Nuclear Physics SB RAS. The planned range of wavelength is between 240 and 5 μm; the expected radiation power varies from 1 kW in the long-wave range up to 10 kW in the short-wave range.

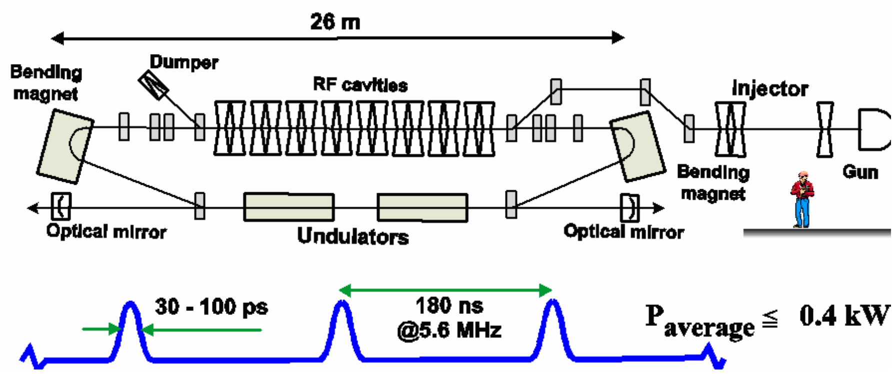


Fig. 2 Layout of the Novosibirsk terahertz FEL based on a one-track ERL (NovoFEL).

Fig. 3 General view of the Novosibirsk terahertz FEL (NovoFEL).

Three years ago, the first phase – a terahertz FEL based on a one-track ERL (NovoFEL), the layout and general view of which is shown in Figs. 2 and 3 – was put into operation [1]. A 2 MeV electron beam from the injector is accelerated up to 12 MeV in the main accelerating structure and then arrives to the undulator, where it loses part of its energy by radiation. After that, the electron beam returns in the deceleration phase to the main accelerating structure, slows down, and lose energy, which practically drops to the injection energy value. Then the beam gets into the dump. An optical resonator with an undulator inside is used in our terahertz FEL, similarly to nearly all existing FELs. The distance between the mirrors is chosen to be such that the light beam accumulated in the optical resonator propagates synchronously with the electron bunches. This permitted us to achieve generation in the terahertz region with relatively small peak currents (10 A). Main parameters of the accelerator are listed in Table 1.

	Status	Plans
RF wavelength, m	1.66	1.66
Bunch repetition rate, MHz	2.8-5.6 – 11.2	90
Maximum average current, mA	30	150
Maximum electron energy, MeV	12.8	14
Normalized beam emittance, mm ×mrad	32	15
Electron bunch length in the FEL, ns	0.07	0.05
Peak current in the FEL, A	10	20

Table 1 Parameters of the 1st stage accelerator-recuperator

The FEL is installed in a long straight section of a single-orbit accelerator – recuperator. It consists of two undulators, a magnetic buncher, and optical resonator. Both electromagnetic planar undulators are identical. The length of an undulator is 4 m; its period is 120 mm; the gap is 80 mm, and the undulator parameter K is up to 1.2. The buncher is just a three-pole electromagnetic wiggler. It is necessary to optimize the relative phasing of the undulators and now ii is used at low longitudinal dispersion Nd < 1.

Both laser resonator mirrors are spherical, the curvature radius of 15 m, made of gold-plated copper, and water-cooled. There is a hole at the center of each mirror. It serves for mirror alignment (with the He-NE laser beam) and output of small amount of radiation. The distance between the mirrors is 26.6 m. The forward mirror has a hole of 3.5 mm in diameter, and the rear one has a hole of 8 mm in diameter (see Fig 4). The calculated transparency of the mirror with the 8 mm hole is 1.5 % at a wavelength of 150 micron. The measured round-trip losses are near 7% at this wavelength. Output radiation passes through two windows that separate the FEL and accelerator vacuum from the atmosphere. An additional iris and a normal-incidence quartz window are installed after the forward mirror. After the rear one, there is a diamond window, tilted at the Brewster angle.

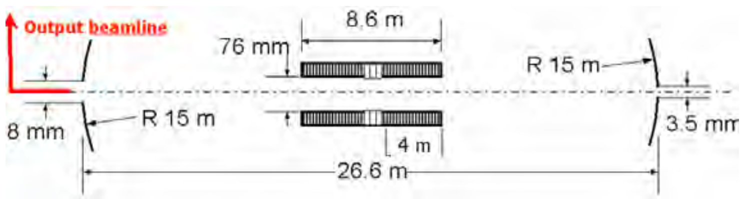


Fig. 4 Layout of the optical resonator of the NovoFEL.

On April 4, 2003, lasing in the range of 120 μm was obtained at the 1st stage FEL (see Fig 5).

Now, NovoFEL radiation is transported from the accelerating hall to a number of user and diagnostic stations by a 40 m optical channel. The length of the channel will be increased to 60-70 m soon. The system gives rise to two constrained problems. The first one is the creation of windows for high-power submillimeter radiation (now the NovoFEL CW power is up to 400 W and will be increased in the near future). The second problem is the low-absorbing medium of the channel. A medium of vacuum is certainly ideal, but it causes a problem with very expensive CVD diamond vacuum windows. The diamond has a very high refractive index and, therefore, very high reflection for the normal incident

Fig. 5 Console room of the NovoFEL. On April 4, 2003, lasing in the range of 120 μm was obtained at the 1st stage FEL. At present, this FEL is the most powerful generator of the terahertz radiation with tunable wavelength (120-235 μm for the 1st harmonics).

angle. Thus, the Brewster angle has to be set, which makes the windows big and expensive. In addition, we also need a fast shutter to prevent destruction of the CVD diamond after probable breakdown of one of the user windows. For this reason, now we use a nitrogen-filled channel with thin polypropylene windows at a near normal pressure. A principal scheme of the beamline system and a view of THz beamline are shown in Fig. 6 and 7. The main problem of this system is radiation absorption by water vapor. A special drying system was created to decrease the negative effect.

The radiation emerges as a continuous train of 30 - 100 ps pulses at a pulse repitition rate of 2.8; 5.6; and 11.2 MHz. At present, the laser generates coherent tunable radiation in the fundamental mode in the spectral range from 120 to 235 μm with a peak power of 0.6 MW and maximum average power up to 400 W (at 11.2 MHz). The minimum measured relative spectral width of laser radiation was 0.003 FWHM. Radiation parameters of the 1st stage of the NovoFEL are listed in Table 2. Thus, the average power spectral density can reach about 1 kW/cm-1, which is several orders of magnitude higher than in other existing sources in this spectral range (see Fig 8). The high average power of radiation (up to 400 W) in combination with the high peak power (up to 0.6 MW) allows performing of high power density experiments.

	1st harmonics	2nd harmonics	3rd harmonics
Wavelength, μm	120 – 235	60 – 117	40 – 78
Relative line width at half height, %	0.3 – 1.0	0.2 – 1	0.1 – 1
Maximum average power, W	400	6	2.4
Maximum peak power, kW	600	9	3.6
Pulse duration, ps	40 – 100	40 – 70	40 – 70
Pulse repetition rate, MHz	2.8 – 5.6 – 11.2		
Linear polarization degree, %	> 99.6		
Gaussian beam diameter at a user station, mm	60		

Table 2 Radiation parameters of the 1st stage NovoFEL

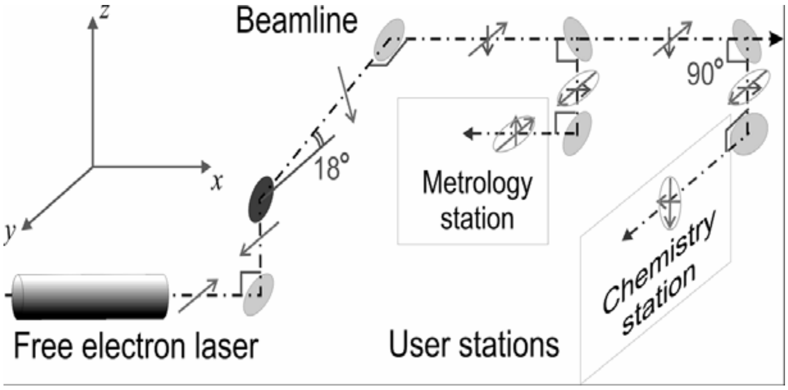


Fig. 6 Scheme of the THz beamlines from the NovoFEL.

Fig. 7 General view of a THz beamline.

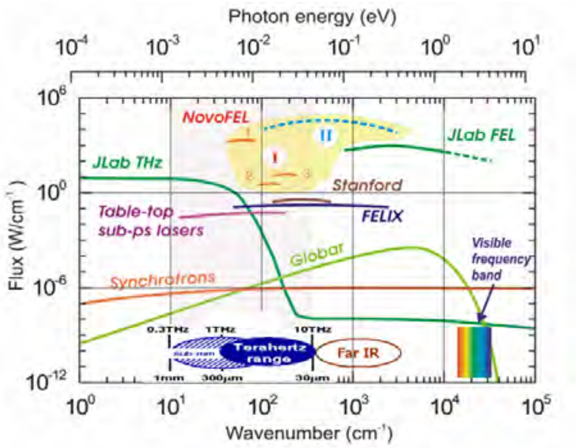


Fig. 8 Averaged spectral power of various radiation sources: the Novosibirsk FEL (Russia): I – the terahertz device in operation, where arcs I, 2, 3 are the numbers of radiation harmonics, II – the infrared device in assembly; JLab FEL – the FEL of the Jefferson Laboratory (USA); JLab THz – the coherent SR source utilizing beam-bending magnets; FELIX – the infrared FEL of the Institute of Plasma Physics (Netherlands).

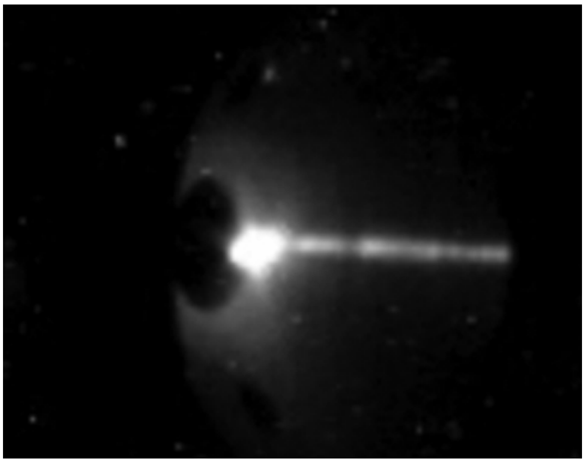


Fig. 9 Continuous optical discharge in a focus of a parabolic mirror.

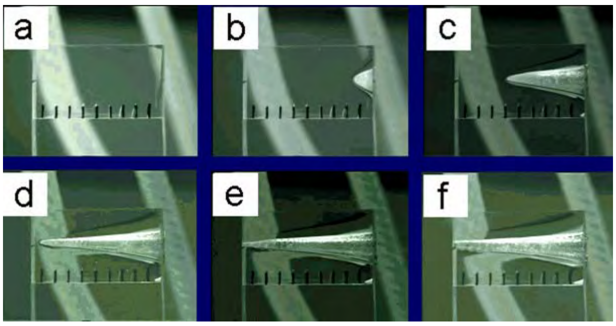


Fig. 10 Ablation without burning under unfocused NovoFEL laser beam in a 50 mm organic glass slab with an exposure time of three minutes.

A laser beam focused in the atmosphere with a parabolic mirror (f = 1.0 cm) ignites a continuous optical discharge, as shown in Fig 9. The unfocused laser beam drills an opening in a 50 mm organic glass slab in three minutes (ablation without burning), as shown in Fig 10.

3. NovoFEL as user facility

Four user stations are nowadays in operation and two stations more are under construction (Fig. 11 and 12). They are located in two experimental halls on the first and second floors. Laser radiation is delivered to the user stations through a beamline filled out with dry nitrogen.

The distances between the optical resonator output and the user stations are 17 meters for the first station and 38 meters for the last station. Station names, given by the founders, originate from their initial purposes. All users may carry out experiments at these stations by permission provided by the advisory committee, which approves the submitted proposals.

The metrology station is intended both for the measurement of laser radiation characteristics and for the development of terahertz radiation detectors. It is equipped with a monochromator.

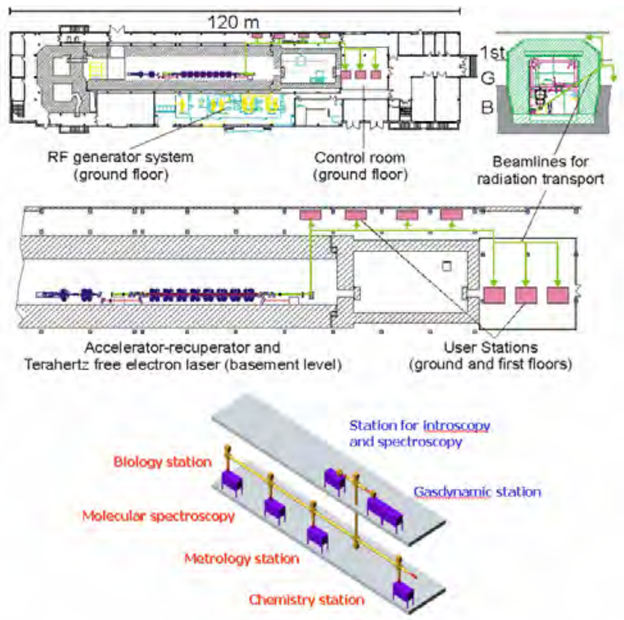


Fig. 11 Layout of the systems of the terahertz FEL and user stations.

Fig. 12 Four operating experimental stations in the lower experimental hall.

4. Development and implementation of THz range experimental equipment

Our center has developed various experimental equipment for the THz range. First of all, there was developed a number of THz imaging techniques based on the relatively high power of radiation [2, 3]. We develop and apply 2D imaging systems of various types. They are commercially available thermal image plates of Macken Instruments Inc. and piroelectric cameras Pirocam III of Spiricon Inc. with 120×120 elements and 12×12 mm in size. Now we are testin new, larger microbolometer matrices of 169×120 pixels and 20×20 mm size produced by the Institute of Semiconductor Physics RAS. The Institute also produces the IR thermographs, which were used in a lot of our experiments after transformation of THz radiation in the IR range by a special screen (see examples in Figs. 13-15).

Spectral investigation can be made with three types of spectral devices: high resolution simple mesh Fabry-Perot interferometers; grating monochromatos, which are especially useful for on-line spectral adjustment and harmonics measurement, and Bruker Fourier spectrometer for fine spectral measurements in a broad spectral range.

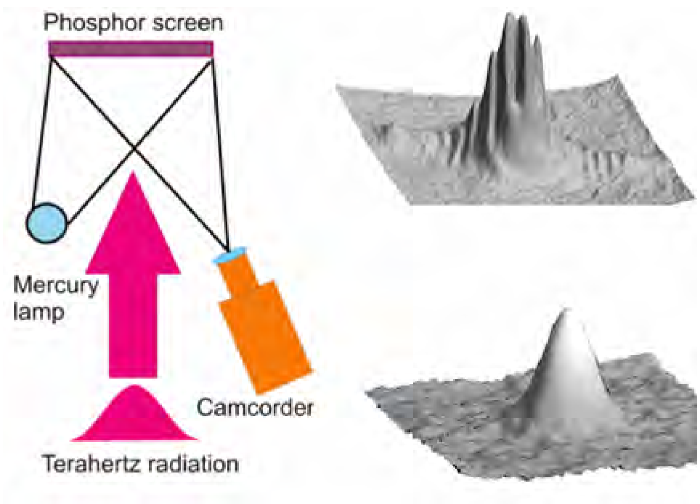


Fig. 13 THz imaging with a “Thermal Image Plate” (TIP).

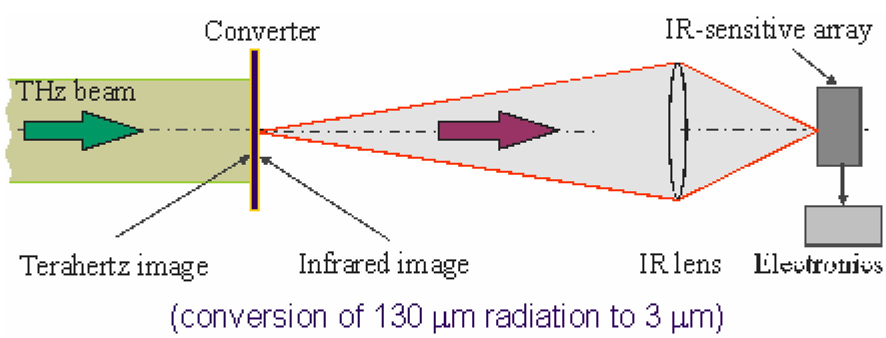
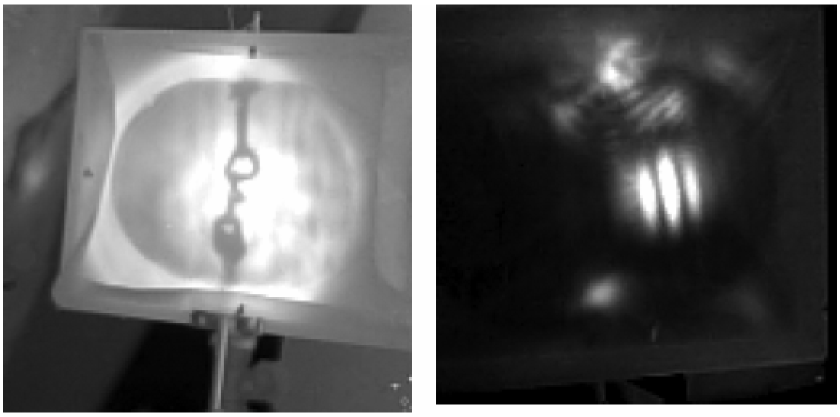


Fig. 14 THz imaging with an IR thermograph. The THz radiation converter is carbon paper.

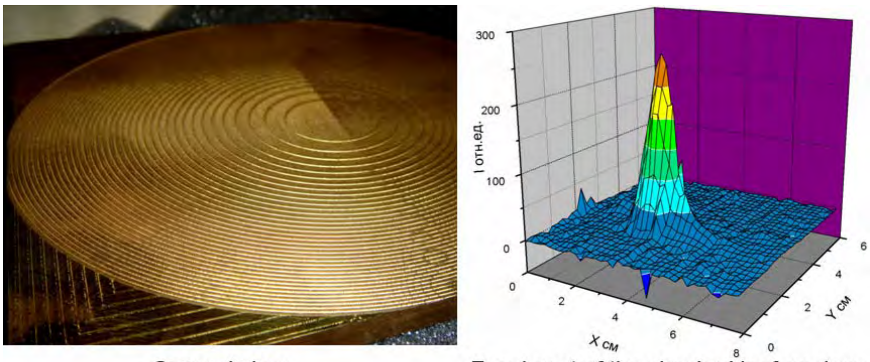


Keys in an opaque paper envelope

Diffraction pattern produced by two circular apertures (d=6 mm, D=14 mm) at the distance of 108 cm.

Fig. 15 Examples of THz images obtained with an IR thermograph.

2D dimension membranous structures of various types are very useful for user application and harmonic separation: non-resonant dichroic high-pass filters, resonant band-pass filters, resonant band-stop filters and diffractive optical elements. For polarizing experiments and attenuation of beam power, we use various polarizers, both made by Cardiff University and our own devices on polyimide and polypropylene substrates. For better filtration of high power radiation, we also need 2D elements without any substrate and much thicker. We plan to produce them with the help of LIGA technology. In addition to usual mirror and lens optics, we develop reflecting diffractive optics elements like kinoform lenses, which are useful for experiments with beams of unusual forms [4].



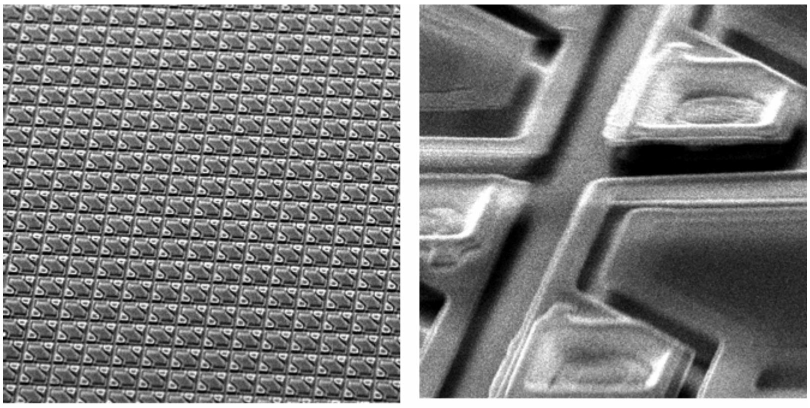
General view

Focal spot of the circular kinoform lens

Fig. 16 140x100 mm kinoform lens.

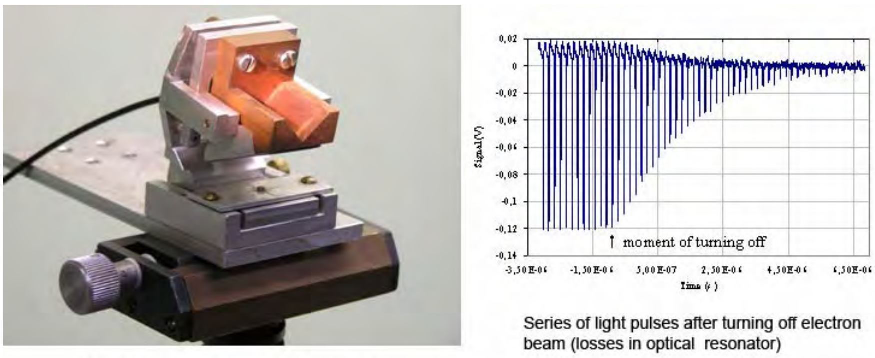
For slow experiments with middle sensitivity, we have commercially available detectors of various types: thermocouples and piroelectric and Holey cells. When we need high sensitivity, we apply liquid helium cooled photoresistive detectors and bolometers [5].

Keeping time-resolved experiments in mind, we have developed Schottky diode detectors of two types: a fast detector with high sensitivity and ultra-fast detector. The latter device has now a rise time of about 20 ps and we plan to decrease the value in the near future. The detector allows us to observe and investigate a time structure of a single FEL light pulse, which is very important for measurement of FEL parameters and their optimization.



Vanadium oxide matrix. Size – 20x20 mm2, number of pixels 169x120

Fig. 17 Development of a room-temperature microbolometer matrix for the terahertz region [5] (the Institute of Semiconductor Physics, Novosibirsk).



High-sensitive Schottky diode detector

Series of light pulses after turning off electron beam (losses in optical resonator)

Fig. 18 Development of Schottky diode detectors.

5. Examples of experiments with THz radiation

5.1. Ablation of biological macromolecules under the action of THz irradiation

The effect of high-power terahertz radiation on biological molecules has already been studied [6]. Terahertz irradiation excites non-covalent molecular bonds (including hydrogen bonds). Mild, non-destructive ablation has been demonstrated for various nucleic acids (phage DNA and plasmids), proteins, and enzymes. We use free electron laser radiation with fine tuning of wavelength from 110 μm to 240 μm, while it is well-known that radiation about 150 μm is capable to excite out-of-the-plane deformation vibrations in intermolecular hydrogen bonds O-H...O and O-H...N. Thus, selective dissociation of these bonds by means of FEL radiation makes it possible to transfer a biomacromolecule to the gas phase (aerosol) with the retention of intramolecular covalent bonds. This allowed development of a new method of mild and non-destructive ablation.

Ablation is defined as the removal of material from the surface of object due to vaporization, chipping, or other erosive processes. In our case, ablation is the transfer of biomacromolecules from solid surface to the aerosol phase under FEL THz irradiation.

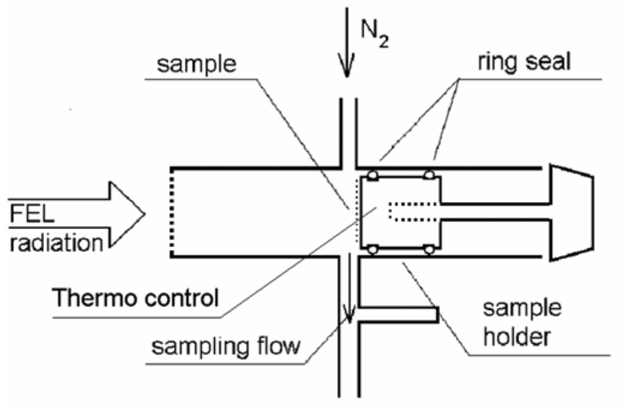


Fig. 19 Scheme of an experimental set for ablation of biological macromolecules under the action of THz irradiation**.**

A sample in a aqueous solution was applied onto a flat support of porous silicon oxide ("Silufol" plates) which was fixed to the butt-end of a metallic piston holder. Filtered gaseous N2 was supplied to the cell in an excessive amount required to exclude the inflow of foreign particles from outside. After the exposure, to stabilize the concentration, the resulting aerosol particles were collected in a 25 L buffer volume, which was used for a series of sequential measurements. The total amount and the size of generated aerosol particles within the diameter range from 3 nm to 200 nm were determined with a diffusion aerosol spectrometer.

The first experiments were made with the aqueous solution of lambda phage DNA, which was carefully pipetted onto a solid porous support ("Silufol" plates). The sample was dried and subjected to 128 μm radiation with a mean power density of 20 W/cm2. No ablation of any particles was detected in the control experiment, when a clean support was irradiated. The ablation of lambda phage DNA (48 tbp) from a solid support resulted in the formation of particles of 70 nm in diameter. In a comparative experiment, we have studied the ablation of a mixture of lambda phage DNA and plasmid DNA pBScript (3.6 tbp). Terahertz radiation of the same wavelength and power density was used to perform the ablation of the above mixture, resulting the formation of particles of 70 nm and 7 nm in diameter, respectively.

The size of particles formed through ablation is represented by two modes only (70 nm and 7 nm), which differ by one order of magnitude in accordance with the relationship between the size of initial DNA molecules under study. The presence of two fractions is also an evidence of separation of two DNAs in the aerosol phase. In the absence of other particles of different size, it would be reasonable to exclude the destruction of DNA molecules under the action of radiation within the used terahertz range. This is the first experimental evidence of soft nondestructive ablation of biological macromolecules under terahertz irradiation.

Another set of experiments under similar irradiation conditions involved the ablation of proteins, lysozyme and horseradish peroxidase. Both proteins formed aerosol particles of single characteristic size, each size correlating with the ratio of their molecular weights – 60 nm (14.2 kDa) for lysozyme and 100 nm (44 kDa) for horseradish peroxidase (Fig. 20).

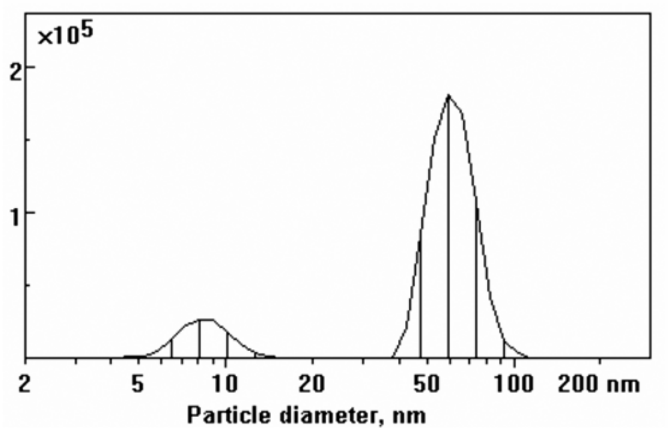


Fig. 20 Distribution of the size of aerosol particles formed as a result of soft ablation of lysozyme (EC 3.2.1.17) and horseradish peroxidase (EC 1.11.1.7).

5.2. Retention of enzymatic activity

The absence of low-sized modes in size distribution observed for macromolecular aerosols in our experiments as well as the correlation between the particle size and its molecular weight (for proteins) and the molecular length (for DNAs) points to the effect of nondestructive ablation under the terahertz irradiation using 128 μm wavelength.

To monitor possible losses or retention of enzymatic activity of horseradish peroxidase, we employed chemoluminescent staining (BioRad). Horseradish peroxidase is a representative of a vast family of plant peroxidases with the main function of utilization of H2O2. Note that, structurally, horseradish peroxidase is formed by a single polypeptide chain associated with a heme located in the enzyme active site. After ablation, horseradish peroxidase collected from the aerosol phase back onto solid filter retained, at least partially, its enzymatic activity. These results provide the first evidences of the possibility of soft FEL ablation of protein molecules with the retention of their functional activity. In the case of horseradish peroxidase, this also suggests that a heme moiety of the enzyme active site remains intact. Thus, ablation under the terahertz irradiation with a 128 μm wavelength does not result in the destruction of the complex enzyme molecule, which retains it enzymatic activity under these conditions.

5.3. Experiments with biochips

The principle of soft nondestructive ablation of biological macromolecules under terahertz irradiation was applied to the technology for direct analysis of target DNA from biochip surface (Fig. 21). A model biochip was prepared for this experiment. A DNA probe is covalently bonded to the biochip surface.

Each biochip has hundreds to thousands of spots on a glass, plastic or membrane support. The biochip system can identify infectious disease strains in less than 15 minutes when testing protein arrays and in less than two hours when testing nucleic acid arrays.

After hybridization the target DNA was bonded to the DNA-probe by hydrogen bonds. By action of terahertz emission we can destroy hydrogen bonds, leave covalent bonds intact and transfer target DNA to the aerosol phase.

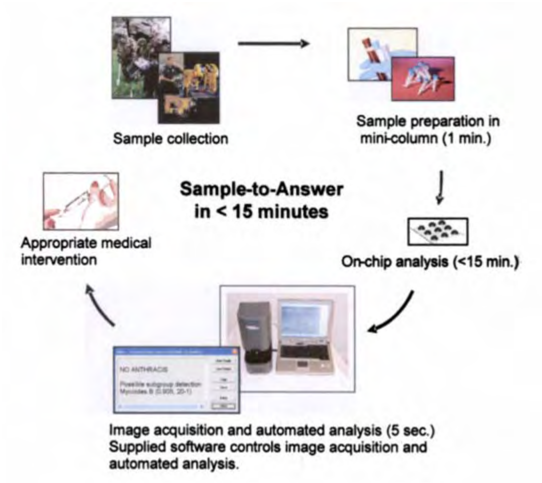


Fig. 21 Principle of the experiment with biochip.

The start-up of ablation was controlled with a aerosol spectrometer and then the target DNA was collected to the filter for subsequent analysis. The experiment was carried out in the same open side cylindrical glass cell. The ablated target DNA was amplificated by the Polymerase Chain Reaction. The polymerase Chain Reaction products were identified by electrophoretic analysis. The electrophoretic analysis proved the identity of the initial and ablated DNAs. The sequence analysis proved the sequence identity of the initial and ablated DNAs. So, the target DNA was kept intact and stayed suitable for Polymerase Chain Reaction and sequence analysis.

It should be noted that the method of nondestructive ablation allows one to transfer large proteins and DNA molecules to aerosol. This makes it possible to analyze biochip hybridization products from a single spot by its direct analysis. We plan to use this technique for standardization of biochip production.

5.4. Rotation of the polarization plane by helical structures

The study of rather unusual novel objects has been started. They at the Institute of Semiconductor Physics SB RAS have suggested a novel technology allowing fabrication of precise 3D shells of various shapes and arrays on their basis. Some examples of realized 3D shell-structures are presented in Fig. 22.

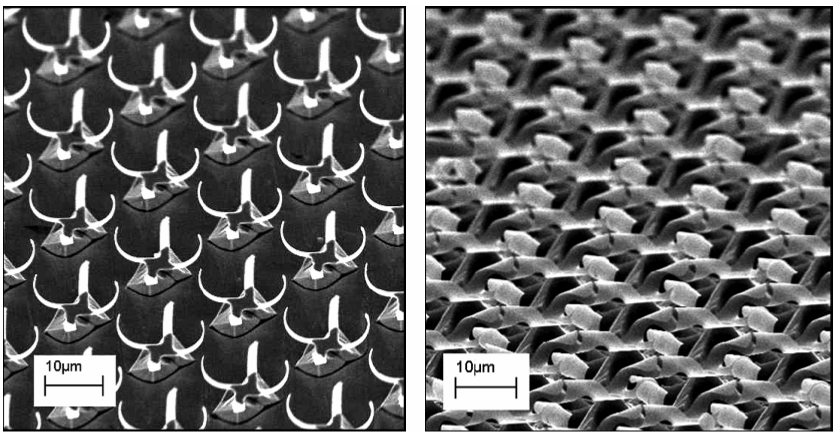


Fig. 22 Examples of realized 3D shell structures.

Such structures can be made of different materials including metals and doped semiconductors. The multiformity of configurations, repeatability of shapes, and scalability of sizes make arrays of such shell-structures very attractive as a basis for novel artificial composite media with tailored electromagnetic properties for different spectral ranges including the THz one.

The fabrication of arrays of helices having high optical activity in the THz range is a challenging task for up-to-date technology. An array of precise metal-semiconductor helices rotating the polarization plane of THz radiation was created at the institute of semiconductor physics (Novosibirsk) using a recently developed method of nanofabrication [7]. The basic principle of this method is as follows: strained heterofilm is grown on a substrate. When detached from the substrate, it transforms into a shell of minimal energy under the action of internal strains. A two-dimension array of helices was fabricated from metal- semiconductor film In0,2Ga0,8As/GaAs/Ti/Au (8/45/3/50 nm). It had the following parameters: unwound helix's length of 75 μm; width of 3 μm; diameter of 10 μm; pitch of 40 μm; array density of 500 helices/mm2; the distribution of helices over the substrate was two-dimensional, uniform, and chaotic with the axes of helices parallel to the substrate.

Experiments at the Novosibirsk free electron laser showed a high resonant rotation of polarization plane by a fabricated chiral structure [8]. It was a first demonstration of artificial chirality in the THz range. The polarization orientations of incident and transmitted waves were found with a rotating polarizer and detector. At a wavelength of 142 μm, the polarization rotation angle α was equal to 17° (Fig. 23). The dependence of the rotation angle on the wavelength was abrupt and attributed to the half-wavelength resonance along helix (the rotation angle fell to 3°at a wavelength of 139 μm).

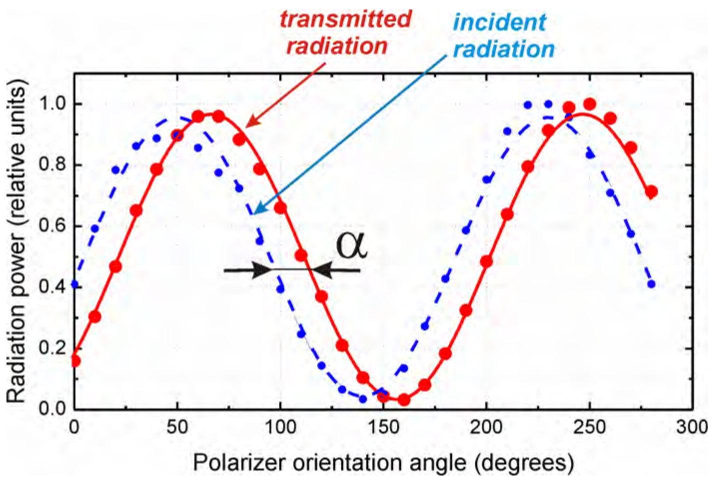


Fig. 23 Radiation power as a function of polarizer orientation angle (λ=142 μm, α = 17°).

The sharpness of polarization rotation angle resonance in the THz range was due to the high Q-factor of helices and precise tuning of all helices in an array to the same resonant frequency. The polarization rotation angle demonstrated by a monolayer of helices with a thickness of just 1/10 of the wavelength was by a factor of some tens larger than the rotation angle for the best liquid crystals of comparable thickness (in wavelengths). The significant rotation angle and sharp resonance make the observed effect promising for different THz applications and open up new possibilities in communication, biomedicine, chemistry, security, imaging and spectroscopy. The full compatibility of the used method with the IC technology facilitates high-speed dynamic control over polarization. The rotation of the polarization plane of microwave radiation has no such practical value as the artificial chirality effect demonstrated in the THz range. Hhowever, these experiments are useful for modeling interaction of helices with radiation.

The scalability of the effect and used nanostructuring technique allows fabrication of such "solid-state liquid crystals" for different spectral ranges - from microwave to optical.

6. Second stage of the Novosibirsk FEL

Next year we plan to commission the second stage of the NovoFEL, based on the four-track 40 MeV accelerator-recuperator [9], using the same accelerating RF structure as the first stage. The FELs in the second and fourth tracks are to generate radiation in the spectral ranges of 5-30 μm and 30-120 μm, respectively. The expected power of each FEL is larger than 1 kW. In contrast to the 1st stage FEL, the orbits of the second stage are placed in the horizontal plane. Thus, there is no need in dismounting the existing FEL for installing the new ones.

The choice of operation mode for three FELs (the old terahertz one and two new infrared ones) will be achieved by simple switching of the bending magnets.

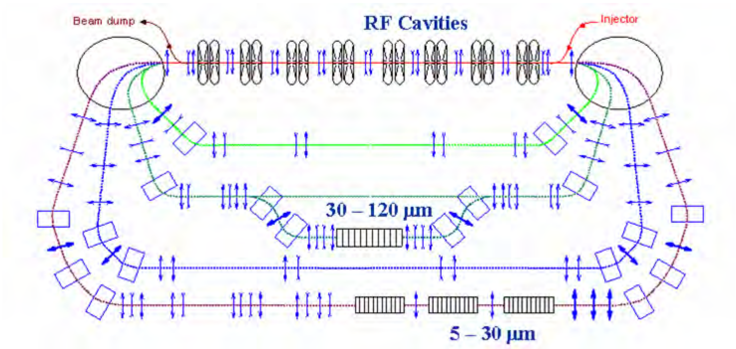


Fig. 24 Scheme of the second stage of the NovoFEL.

The most important applications of such a powerful and expensive machine are in the field of high technologies. We consider the separation of isotopes as an example. The basic process is the selective multiphoton dissociation of molecules. The resonance wavelength range is 2—50 μm. The required pulse energy is not less than 0.1 mJ and monochromaticity is 10-3 — 10-4, depending on the type of reaction. The maximum pressure (as well as the efficiency) in the reactor is inversely proportional to the radiation pulse duration, and at t ~ 10 ps it can exceed the atmospheric pressure.

This process allows mass production of stable isotopes:

28Si is radiation resistant material (space, weapon industry, and nuclear energetics). The thermal conductivity of pure isotope is more than 50% higher than that in a natural mixture. This circumstance provides a great gain in the production of powerful semiconductor apparatus and microchips. 28Si is also used in metrology and in the future technology - spin electronics;

13C is a spin mark for NMR-tomography in the development of new medications and in medical diagnostics;

15N is also a spin mark for the study and current control of the use of nitrogen fertilizers in agriculture and agrochemistry.

Fig. 25 Assembly of the four tracks of the NovoFEL second stage accelerator system is in progress (August 2007).

7. Conclusions

At present, intense work on the creation of powerful FELs (> 1 kW of average power) is carried out worldwide. For the purposes of industrial applications, it is necessary to reach the average power level of about 10 kW.

In some cases, the problem is a rather wide radiation spectrum (usually, not less than 1-3%). For some industrial applications (for example, isotope separation) the required monochromaticity should be not worse than a few hundredths of percent.

The Novosibirsk terahertz free electron laser is becoming a user facility. We invite those researchers who want to perform interesting experiments with a high-power monochromatic coherent tunable THz radiation to carry out them in Novosibirsk.

Acknowledgments

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References

[1] V.P. Bolotin, N.A. Vinokurov, D.A. Kayran et al., Status of the Novosibirsk terahertz FEL, *Nuclear Instruments and Methods in Physics Research*, vol. A543, pp. 81-85, (2005).

[2] Cherkassky V.S., Knyazev B.A., Kubarev V.V., Kulipanov G.N., Kuryshev G.L., Matveenko A.N., Petrov A.K., Popik V.M., Scheglov M.A., Shevchenko O.A., Vinokurov N.A. Imaging techniques for a high-power THz free electron laser // *Nuclear instruments and methods in physics research. Sec. A.* vol. A543, No. 1. - P. 102-109, (2005).

[3] V. S Cherkassky, V. V. Gerasimov, G. M. Ivanov, et al. “Techniques for introscopy of condense matter in terahertz spectral region”, *Nuclear Instruments and Methods in Physics Research A* 575, pp. 63-67, (2007).

[4] V. V. Gerasimov, B. A. Knyazev, P. D. Rudych, and V. S. Cherkassky. Fresnel reflection in optical components and detectors for the terahertz frequency band. *Instruments and Experimental Techniques.* vol. 50, 524–529, (2007).

[5] M. A. Dem’yanenko, V. N. Ovsyuk, V. V. Shashkin, et al. Uncooled 160x120 microbolometer IR FPA based on sol-gel VOx, International congress on Optics and Optoelectronics, *Proceedings of SPIE*, 5957, 340, (2005).

[6] Petrov A.K., Kozlov A.S., Taraban M.B., Goryachkovskaya T.N., Malyshkin S.B., Popik V.M., Peltek S.E. Mild ablation of biological objects under the submillimeter radiation of the free electron laser // The Joint 30th International conference on infrared and millimeter waves and 13th International conference on terahertz electronics: IRMMW-THz2005, Williamsburg, Virginia, USA, Sept. 19 – 23, 2005. – *Piscataway: IEEE*, vol. 1. P. 303-304, (2005).

[7] E.V. Naumova, V.Ya. Prinz, V.A. Seleznev, S.V. Golod, R.A. Soots, V.V. Kubarev, B.A. Knyazev, G.N. Kulipanov, N.A. Vinokurov, Fabrication of metamaterials on the basis of precise micro- and nanoshells.//*Proceedings of Conference "Metamaterials 2007*", Rome, Italy, 22-24 October, p.74-77, (2007).

[8] E.V.Naumova, V.Ya. Prinz, V.A. Seleznev, S.V. Golod, V.V. Kubarev, B.A. Knyazev, G.N.Kulipanov, S.A. Kuznetsov, P.V. Kalinin, N.A. Vinokurov, “Polarization rotation of THz radiation by an array of helices”, *Proc.of Joint 31st International Conference on Infrared and Millimeter Waves and 14th International Conference on Terahertz Electronics*, Sept.18-22, Shanghai ,China,(2006).

[9] Bolotin V.P., Vinokurov N.A., Kayran D.A., Knyazev B.A. et al., *A project of accelerator -recuperator for Novosibirsk high-power FEL // Physics of particles and nuclei letters,* Vol. 3, suppl.1 (Dec.). P. S40-S42, (2006).