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RESEARCH OPPORTUNITIES AT TERAHERTZ NOVOSIBIRSK FREE ELECTRON LASER

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Introduction

Exponentially growing number of publications devoted to development of terahertz sources and applications of terahertz radiation reflects the expectation of a breakthrough to new technologies, which employ this frequency band. Invention of the broadband terahertz generators based on short-pulse lasers [1, 2] triggered researches in terahertz imaging and tomography, spectroscopy, biology and medicine, security, and other applications. For the applications, which require tunable monochromatic coherent radiation, the backward wave oscillators (in millimeter and high submillimeter region) [3], the injection-seeding parametric generators [4], and difference-frequency generators [5] are commonly used. A review describing in detail such sources is given in [6]. Though the average power of all the above mentioned generators is very low, their appearance initiated rapid progress in the application of terahertz waves in physics, chemistry, biology and medicine, as well as for security. The development of terahertz-based techniques in technology and industry is still considered.

Another class of sources, which can emerge high power terahertz radiation, is based on the radiation of relativistic electrons in the magnetic structures like synchrotrons and free electron lasers (FEL). Such sources have a very high brightness and high power [7]. Average generation power of conventional terahertz free electron lasers at Stanford, UCSB, FOM-Institute and Osaka (see review [8]) is close to 1 W. Because of relatively low FEL efficiency further increasing the output power can be achieved only using the energy recovery systems. Capability of such technique has been demonstrated on recently commissioned in Jefferson Laboratory a near-infrared FEL (JFEL) based on an energy recovery linac [9]. Nowadays it generates coherent radiation at 10 kW average power. The same facility is used also as a 100-W average power radiation source [10], which emerges ultra-short coherent broadband terahertz pulses when a sub-picosecond electron bunch passes a chicane (the pulse slicing technology).

A new narrowband Novosibirsk terahertz free electron laser (NovoFEL) was recently commissioned [11]. Spectral power density of the above mentioned sources is shown in Fig. 1. In this paper we specify the NovoFEL characteristics, describe existing user stations and stations under construction, mention in brief on the results of most interesting experiments being performed, and consider further research opportunities for study condense matter, flames and gas flows.

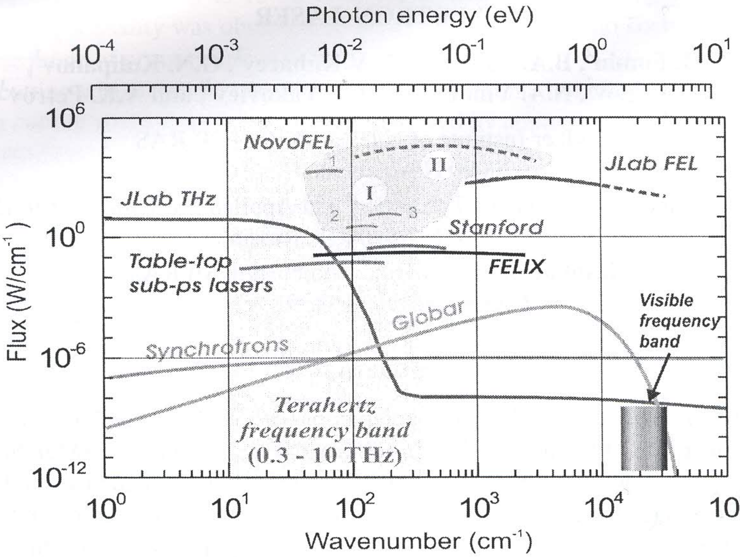

Fig. 1. Spectral power density vs. wavenumber for the light sources.
I (1 – 3) – Flux of the fundamental mode and harmonics of existing NovoFEL; II – anticipating flux of the second stage of NovoFEL (under construction).

NovoFEL parameters and radiation characteristics

The full-scale Novosibirsk free electron laser is to be based on a four-orbit 40 MeV energy recovery linac (ERL). It is to be built in the nearest future and will emerge monochromatic radiation from 5 to 300 μm with several-kW average power [12]. First stage of the machine Fig. 2 contains the full-scale 180-MHz RF system and accelerator structure, but has only one orbit. It differs from the earlier ERL-based FELs [13] in the low frequency non-superconducting RF cavities and longer wavelength operation range. An electron bunch with energy of 1.5 MeV is injected into the accelerating structure consisting of 16 cavities and accelerated to 12 MeV. Then it transits through two on-line undulators, passes once again through the RF-structure in the decelerating RF phase and is deflected by a magnet to the dumper at the

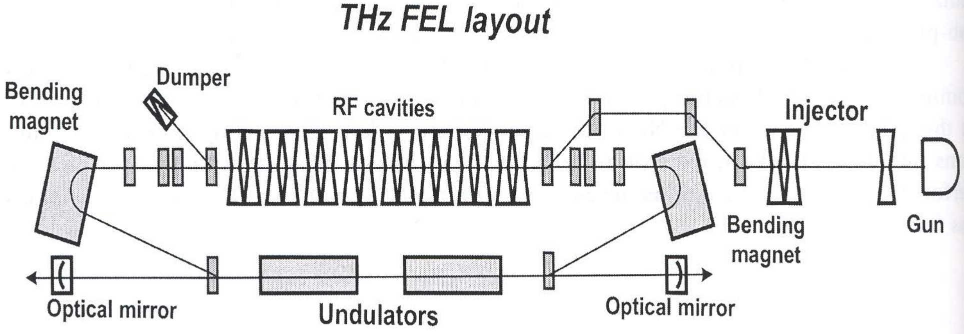

Fig. 2. Schematic of Novosibirsk terahertz free electron laser.

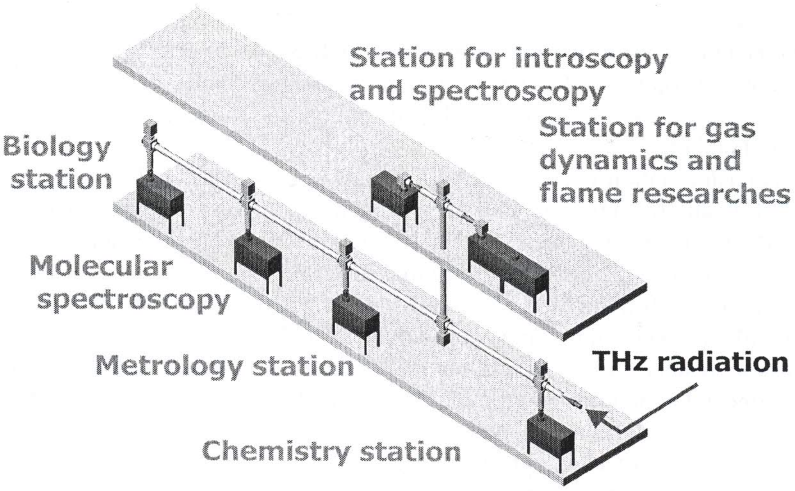

Fig. 3. User stations at Novosibirsk free electron laser.

injection energy 1.5 MeV. The undulators with the total length of eight meters are formed with the alternating-sign electromagnets with 12 cm period.

Laser radiation is generated in an open two-mirror resonator and extracted through 8-mm opening in one of the mirrors. The radiation is emerged as a continuous train of 50 – 100 ps pulses at the pulse repetition rate of 2.8 – 11.2 MHz. At present the laser generates coherent tunable radiation on the fundamental mode in the spectral range from 120 to 240 μm with peak power of 0.6 MW and maximum average power up to $P_{ave} = 400$ W (at 11.2 MHz). Minimum measured relative spectral width of laser radiation was 0.003 FWHM. Thus, the average spectral power density can reach about 1 kW/cm^{-1} that is several orders of magnitude higher than in other existing sources in this spectral range (see Fig 2). Free electron laser radiation is plane-polarized with polarization degree not less then 99.6%. As it was demonstrated experimentally [11, 12], the radiation is completely coherent over the wavefront and has the longitudinal coherence length of 0.6 – 3 cm depending on FEL operating mode. The NovoFEL radiation wavelength can be fine tuning to any value within the above mention spectral range. Such characteristics of NovoFEL radiation enable performing unique experiments in the terahertz region.

User stations at NovoFEL and selected experimental results

Four user stations are nowadays in operation and more two stations are under construction (Fig. 3). They are located in two experimental halls at first and second floors. Laser radiation through a beamline filled out with dry nitrogen is delivered to the user stations as it shown in Fig. 3. Distances between optical resonator output and the user stations are 17 meters for the first station and 38 meters for the distant station. Station names, given by the founders, originate from their initial meanings. Outer users may do experiments at these stations by permission of the owners after the advisory committee approves the submitted proposal.

The metrology stations is intended both for the examination of laser radiation characteristics and for the development of terahertz devices. It is equipped with a grating monochromator, a mesh Fabri – Perot interferometers, scanning piroelectric 1D-arrays, various calorimeter for the measurement of absolute radiation power, fast Schottky-diode detector and other instruments. Spectral characteristics of FEL radiation can be also studied in detail using a special outlet of the beamline delivering radiation to Bruker IFS 66v Fourier spectrometer. Using this equipment, optimal conditions for the generation fundamental mode and higher harmonics were discovered, as well as the dependence of the generation line shape on electron accelerator condition was studied [14].

The chemistry station is equipped with a mass-spectrometer and is to be used for study interaction of terahertz radiation with metal-organic complexes in gas phase and on surfaces [15]. Most interesting results at this station can be obtained when the next stage of NovoFEL will generate radiation in mid-infrared spectral range.

First experiments on the biology station were directed to study ablation of crystal minerals, fullerene-like molybdenum complexes, polymers, and biological macromolecules [16]. The most impressive results were obtained for the ablation of biological macromolecules. Under certain experimental conditions macromolecules were ablated without destruction. Moreover, a complicated enzyme (horse radish peroxidase) kept to be active after ablation. This result promises much for the biotechnological applications.

The molecular spectroscopy station is destined for the experiments on molecular gas spectroscopy. Experiments on the observation of coherent effects in rotational transitions (free nutation, photon echo, self-induced transparency) are to be performed in the station [17]. The station was also used for the development of terahertz imagers and quasi-optical systems, as well as for holographic experiments.

Quasi-optical systems for high-power terahertz radiation

The visualization of terahertz radiation is required for many applications. There are a number of imaging systems for the terahertz range, but most of them designed for the operation with low average power sources (see a review article [6]). Extremely high average power of NovoFEL radiation, from one hand, requires revising the applicability of materials in the terahertz region, and, from other hand, enables development of 2D image recorders using the thermal effect of radiation.

Though there are many materials commonly used in the terahertz optics, their transparency is substantially less than for the optical materials using in the visible range. This feature becomes critical when one designs the optical systems for high power terahertz radiation. We have examined a number of materials and selected the materials which can be used as beam-splitters, windows and prisms at the user stations [18]. We have fabricated and studied reflective diffraction optical elements for focusing of terahertz radiation to overcome the radiation-damage limit intrinsic to the refractive optics. Reflective zone Fresnel plates appear to be a convenient element for focusing the monochromatic terahertz radiation at right angle. Zone plate shortcoming is low diffraction efficiency. To overcome the shortcoming, we fabricated a reflective kinoform lens. Its diffraction efficiency was close to unity, but it can be applied only for focusing radiation at a definite wavelength, for which it was designed.

A number of imaging techniques were developed for 2D-recording high-power terahertz radiation. Simple system developed for scanning terahertz beam cross-section was a 2D-movable pyroelectric detector. Line of 30 piroelectric detectors and 1D scanning are used now for faster beam measurements.

More three imaging systems were developed using the thermal effect of high power radiation. All the systems consist of a "thermal screen" placed across the terahertz beam and a "final recorder" recording response of the screen as a 2D-matrix, from which, in one way or another, terahertz beam power density distribution can be retrieved.

As a convenient routine instrument we use a 128×128 pixel InAs IR thermograph coupled with the screens non-transparent for both submillimeter and 2.5 – 3 μm radiation [19]. Other technique, developed for THz imaging, was a thermosensitive interferometer. Red semiconductor laser radiation reflects from two surfaces of a plane-parallel glass plate. Reflected beams interfere on a white screen. When terahertz radiation exposes to one of the plate surfaces, the interference pattern appears because of the thermooptical effect. Terahertz intensity distribution can be then retrieved by a standard digital method. The thermosensitive interferometer is an "absolute" instrument because thermooptical constants for many materials are tabulated and calculation of the absolute energy deposition can be done for monotonic beam distribution [20, 21]. Third terahertz imager is Macken Instruments Thermal Image Plate, based on thermal quenching of phosphor fluorescence [22], possesses good spatial resolution. Using the imagers we performed, in particular, experiments on terahertz holography and introscopy of biological objects.

Applications required high radiation power density

The experiments, which require high power terahertz radiation and could not be performed before appearance of NovoFEL, are a subject of special interest. Two such experiments have been already carried out. In the first experiment the laser beam with a diameter of 8 mm, extracted through the opening in the output resonator mirror, exposed without focusing a 5-cm thick PMMA block. A conical opening in the block was perforated during 155 seconds. The material was ablated without burning and melting directly into gas phase [11]. It is result of combination of high average power with very high peak power. Such radiation feature is favorable for the employment of NovoFEL for study material processing, high-intensity radiation-material interaction, and for non-linear physics experiments.

Other demonstration of high intensity of NovoFEL radiation is a continuous optical discharge first obtained in the terahertz range [23]. The laser beam was focused with an off-axis parabolic mirror ($f = 10$ mm) in the atmospheric pressure argon or air. The continuous optical discharge was observed in both gases as permanent or fluctuating small plasma ball in the mirror focus. Simple estimation shows that field ionization, multi-photon ionization cannot initiate the discharge. Apparently the ignition is coused by collisional ionization mechanism [23, 24]. Besides the conventional for this technique energy deposition by discharge ignition, our laser enables controllable gas heating by tuning the laser wavelength over an absorption line of the gas mixture (e.g. CO or H_2O).

One of the promising practical application of the powerful continuous terahertz radiation may be investigation of the effect of local energy deposition on supersonic flow structure to study the problem of flow control [25]. Not all potentiality has been studied in the aerodynamic challenges with radiation energy. Insufficient data on the issues of resonance interaction between the radiation and high-speed flow are available. Opposite to the aero-optic investigations, which determine the variation of the radiation intensity in the far region, the aerodynamic application needs to determine the conditions in the near region wherein the dominating part of the energy is absorbed. Moreover, in the relative short-wave range of the spectrum (for instance, for the CO_2 laser radiation), the basic absorption mechanisms are caused by the excitation of the vibration-rotating energy levels of molecules, from which the excitation energy transfers into the heat within the time often exceeding the typical flow time scale. This results in insignificant effect on the flow. At the same time, within the terahertz range, the absorbed energy is mainly accumulated in the rotating levels of the molecules. Thus, the velocity of excitation energy relaxation into the gas heat energy is much higher, which can stronger influence the gas-dynamic structure of the flow. The NovoFEL laser source of terahertz range developed in SB RAS enables to carry out such investigations. Moreover, the advance into this range and related extension of the gas breakdown threshold form the conditions approaching (in the field of breakdown physics) to the processes developing in the microwave discharge. Using this radiation source the energy-release region will be restricted by the area of no more than several mm. It will permit to simulate experimentally the local supply of electromagnet radiation energy to different flow regions in respect to the flowed model.

The project with the terahertz -range radiation involved will expectedly bring new results in the field of flow gas dynamics with the external energy supply, aero-optics and physics of optical discharge propagation, which promote better understanding of the interconnected processes of laser radiation absorption and gas-dynamic structure formation in a high-speed gas flow. Such experiments are to be carried out soon (see Fig. 3) at the gas dynamics user station.

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