RUSSIAN ACADEMY OF SCIENCE
Lenin Order of Siberian Branch
G.I. BUDKER INSTITUTE OF NUCLEAR PHYSICS

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FIRST EXPERIMENTS ON HIGH POWER NOVOSIBIRSK TERAHERTZ FREE ELECTRON LASER

Budker INP 2005-37

Novosibirsk
2005

First experiments on high-power Novosibirsk terahertz free electron laser

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Abstract

Newly commissioned Novisibirsk free electron laser generates coherent monochromatic radiation, tunable in the range 120–170 μm, as a continuous train of 30–100 ps pulses at the repetition rate of 2.8–11.2 MHz. Maximum average output power is 400 W. Unique experiments, including continuous optical discharge sustained by terahertz radiation in the atmospheric pressure argon and air, ultra-soft nondestructive DNA ablation and lensless submillimeter holography, are reported.

PACS numbers: 41.60.Cr, 52.50.Jm, 42.30.-d, 42.40.-i, 87.50.Hj

Exponentially growing number of publications devoted to development of terahertz sources and applications of terahertz radiation (see e. g. [1]) reflects the expectation of a breakthrough to new technologies which employ this spectral region. Invention of the broadband terahertz generators based on femtosecond lasers 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), the injection-seeding parametric generators, and difference-frequency generators are commonly used. Average power of all the above mentioned generators is very low.

High power terahertz radiation can be obtained with free electron lasers (FEL). For example, a near-infrared FEL, recently commissioned in Jefferson Laboratory (JFEL) [2], now generates coherent radiation at 10 kW average power. The same facility is also used to extract 20 W average power broadband ($1 - 20$ cm^{-1}) coherent terahertz synchrotron radiation, when a sub-picosecond electron bunch passes a chicane [3]. A new narrowband Novosibirsk terahertz free electron laser (NFEL) was recently commissioned [4]. Spectral power density of the above mentioned sources is shown in Fig. 1, where we adopted in part data from Ref. [3, Fig. 2]. In this paper we describe in brief NFEL parameters and report on the results of first experiments with high power terahertz radiation.

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 deliver monochromatic radiation from 3 to 300 μm with several-kW average power [5]. The 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 [2, 6] 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 injection energy 1.5 MeV.

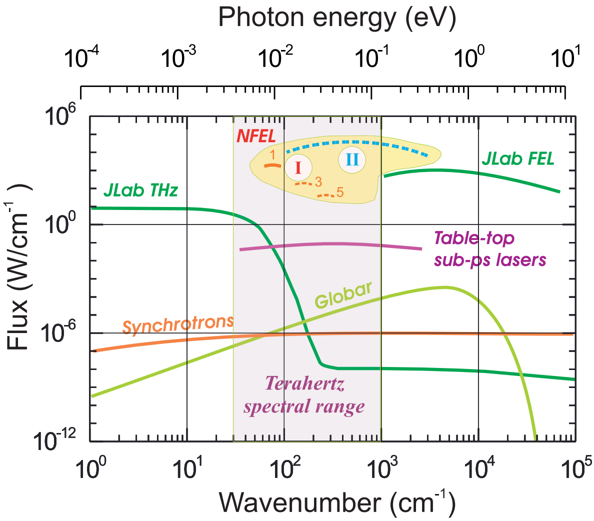

Figure 1: Spectral power density of the terahertz sources. The curve *1* corresponds to the first harmonic of NFEL radiation. The curves labelled with figures *3* and *5* show expected flux of third and fifth harmonics. The dashed curve is the project flux of the NFEL second stage.

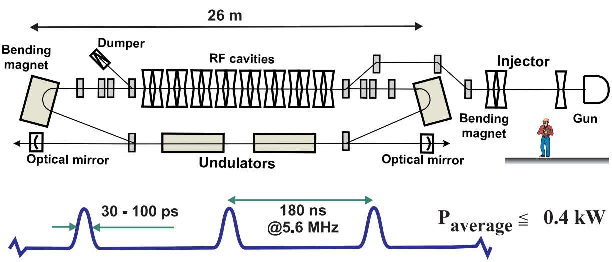

Figure 2: Schematic of the Novosibirsk terahertz free electron laser and radiation intensity vs. time.

The undulators with the total length of eight meters are formed with the alternating-sign electromagnets with 12 cm period. Sub-millimeter laser radiation is generated in open two-mirror resonator and extracted through 8-mm opening in one of the mirrors. The radiation is emerged as a continuous train of 30 – 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 170 μm with peak power of 1.0 MW and maximum average power up to $P_{\text{ave}} = 400$ 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 1.2 kW/cm^{-1}, which is to our knowledge several orders of magnitude higher than in other existing sources in this spectral region (see Fig. 1).

These characteristics of laser radiation enable performing unique experiments in the submillimeter spectral range. For the demonstration of capabilities of the laser as a high-power terahertz source the laser beam (at $P_{\text{ave}} \approx 100$ W) was focused with an off-axis parabolic mirror ($f = 10$ mm) in the atmospheric pressure argon or air directly at the laser output. The continuous optical discharge (COD) has been obtained for both gases. It observed as permanent or fluctuating small plasma ball in the mirror focus (Fig. 3,a). Simple estimations shows that neither field ionization nor multiphoton ionization cannot initiate the discharge, whereas it can be ignited by the collisional ionization mechanism [7].

Extremely high, in comparison with plasma relaxation rate, ignition frequency distinguish this discharge from conventional CODs and statistical effects may play a role in the discharge ignition. Being once produced, the plasma ball has no time to recombine or expand between the laser pulses and this provides further discharge sustaining. Detailed study of the discharge can bring an advance in our understanding of this phenomenon. One of the promising practical application of the discharge may be investigation of the effect of local energy deposition on supersonic flow structure to the decrease of aerodynamic resistance [8]. Besides the conventional for this technique energy deposition by discharge ignition, our laser enables controllable gas heating by tuning the laser wavelength over absorption lines of the atmospheric gases (e.g. water).

Other demonstration of high intensity of laser radiation is ablation of poly(methyl methacrylate) (PMMA). A 5-cm PMMA block was placed directly in the accelerator hall at a distance of 30 cm in front of the laser output. An argon flow blew out the air from the crater and prevented PMMA burning. A conical opening in the block was drilled during 155 seconds (Fig. 3,b). High average power in combination with very high peak power enables employment of NFEL for experiments in the fields of material processing, high-power-density radiation-material interaction, and non-linear physics.

Further experiments have been performed on user stations out of the accelerator hall. To transmit the radiation to the stations, a 14-m beamline guiding terahertz radiation from the laser had been constructed. The beamline is

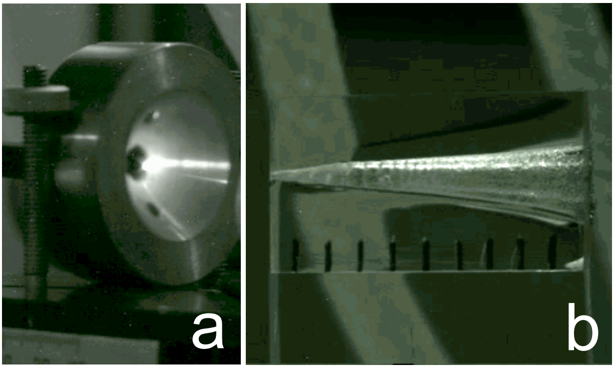

Figure 3: Interaction of the laser radiation with matter: (*a*) continuous optical discharge in the focus of a parabolic mirror and (*b*) the opening in PMMA drilled by non-focused laser beam; distance between the marks is 5 mm. In this experiments the wavelength was 130 μm and the average power of radiation was about 100 W.

separated from the accelerator vacuum with a 0.8-mm thick CVD-diamond window. Since water and CO_2 molecules have a great number of absorption lines in the submillimeter spectral range, the beamline is filled out with dry nitrogen at the atmospheric pressure and isolated from the atmosphere at the output with a thin polyethylene film. Areal distribution of the terahertz beam at the output is close to Gaussian one $I(r) \sim \exp(-2\,r^2/w^2)$ with $w = 41$ mm. The beam is practically linearly polarized. It was confirmed by measurements of transmittance of a QMC Instruments thin-film photolithographic polarizer (model P10: 5 μm copper stripes with 10 μm period on 9 μm polypropylene film), which gives $T_\perp = 0.93 \pm 0.03$ and $T_\| = 0.0037 \pm 0.0003$ (The last value is close to the calculated transmission for TM-wave).

One of the priority programs for NFEL is biological experiments. The extremely large radiation wavelength of our laser enables "ultra-soft" ablation of large biological molecules (DNA, proteins) without their denaturation in contrast to the existing lasers operating in the substantially short-wave spectral region (see, i. e., [9]). In first experiments on ablation of DNA samples small fragments appeared at high power density but for an optimal terahertz power density the absence of small fragments in the ablative material have been clearly demonstrated (Fig. 4).

Since eigenfrequencies of many objects, including the biological and complex molecules, lie in the terahertz spectral range, tunable NFEL radiation

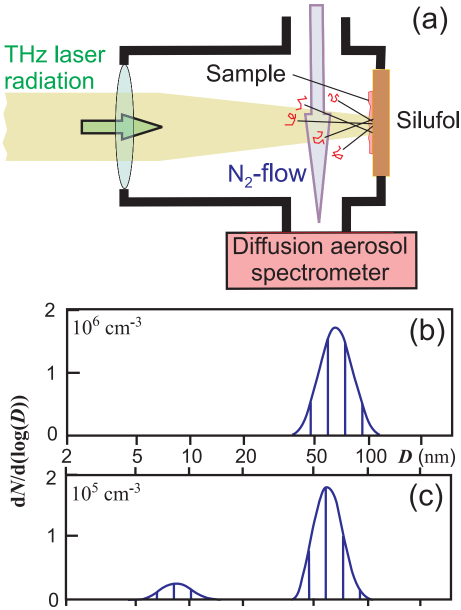

Figure 4: Ultra-soft laser ablation of DNA samples on silufol. (a) The experimental configuration. Size distribution of ablative material recorded with a diffusion aerosol spectrometer for two samples containing (b) a phage DNA and (c) a mixture of the phage DNA with a plasmide DNA (size ratio is close to ten). Wavelength – 120 μm, power density - 20 W/cm^2.

open wide opportunity for spectroscopy. We have recorded absorption spectra of several aminoacids and explosives, which will be published elsewhere. The experiments with molecules of DNA, viruses and cells in dry and wet environment are under consideration. Evidently, simple absorption spectroscopy cannot be applied to water-contained media. In this case, as well as for any strongly absorbing objects, we are going to employ the plasmon-polariton and attenuated total reflection spectroscopy. All spectroscopic instruments are to operate in both normal and "pump-probe" modes.

Special attention we paid to imaging of the terahertz radiation that is important for both laser radiation study and many applications. High power of our laser enables development and application many methods, which may be very different from conventionally used in the submillimeter region [10]. Besides scanning of radiation cross-section with a single bolometer and a pyroelectric detector array, which takes much time, we applied for the visualization several methods based on the heating of absorbing terahertz radiation screens. As a convenient routine instrument we use a 128×128 pixel InAs IR thermograph [11] coupled with the screens non-transparent for both submillimeter and $2.5 - 3$ μm radiation.

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 methods. The thermosensitive interferometer is an "absolute" instrument because thermooptical constants for many materials are tabulated and calculation of the absolute areal energy deposition can be easy done [12]. Both above mentioned methods were described in more detail in [13].

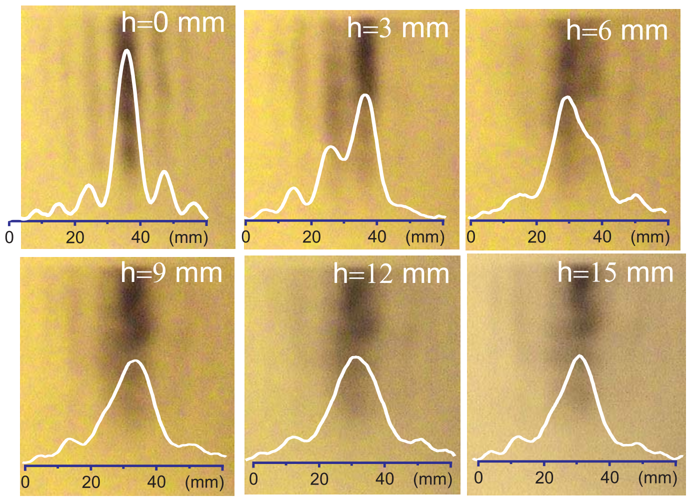

Figure 5: Interference patterns formed by terahertz laser radiation reflected from a Fresnel bi-mirror (h is the longitudinal displacement of one of the mirrors). The images are recorded with a digital video camera SONY DCR-TRV230E using a Thermal Image Plate (detector of radiation based on thermal quenching of phosphor luminescence).

We have examined a system based on thermal quenching of phosphor fluorescence as a terahertz imager. A Macken Instruments Thermal Imaging Plate (TIP), Model 22-B, surface No. 8, was exposed simultaneously to uniform radiation of UV mercury lamp and to terahertz radiation. Luminescence intensity was recorded with a digital video camera, whereas temperature distribution over the plate surface was simultaneously recorded with the thermograph. An example of fluorescence quenching is shown in Fig. 5. The diffraction pattern on the plate was formed by reflection of the terahertz laser beam from two mirrors in the Fresnel scheme ($\theta \simeq 0.3°$). Using the polarizer, we gradually attenuated beam power (for $h = 0$ mm) to calibrate TIP response. It was found that the response is practically linear at least up to 60% quenching. The thermograph detected at that time the surface temperature growing to 38 C while the initial phosphor temperature without terahertz beam was 26 C. High spatial resolution of TIP coupled with a camcoder enables recording of precise terahertz images in real time.

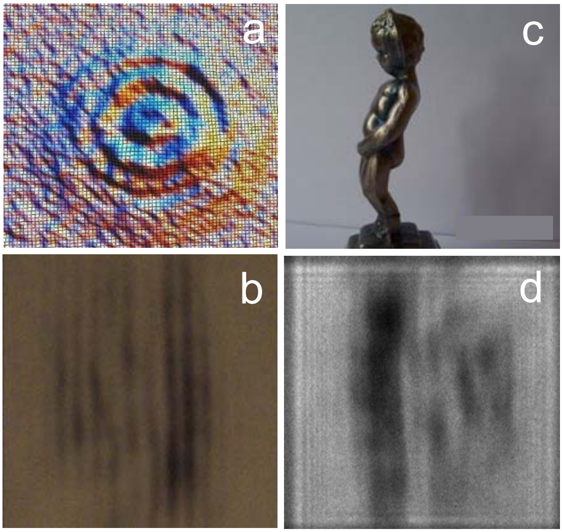

Figure 6: Application of the TIP imager (surf. No. 6) to terahertz holography: (a) 3D-plot of the terahertz beam reflected from a spherical mirror with a 4.5-mm opening at the center; (b) a hologram recorded when a small statuette (c) was posted in front of one of the Fresnel mirrors; (d) the image digitally retrieved from the hologram.

The interference patterns recorded with the Fresnel bi-mirror gave evidence that the laser radiation possess complete transverse coherence. The images from Fig. 5 enable calculation of the time coherence $\tau_c = 2h_c/c$, which appears to be about 50 ps. The same value retrieved from the laser generation spectra obtained using a Fabri-Perot interferometer in different experiments was equal to 80 and 40 ps. Scanning free electron laser wavelength over 2.569 THz CO-molecule absorption line we obtained the same value to be 40 ps. Evidently, that variations of the electron bunch characteristics in the undulators are responsible for variations of the time coherence.

Using the TIP imager we continue our experiments [13] on the terahertz holography. Interferogram Fig. 6, *a* is already a simplest on-axis Gabor hologram. Using standard methods (see e. g. [15]) we reconstructed the hole image. More complex holographic experiment is shown in Fig. 6,b,c,d. To do it we simply used the bi-mirror scheme that is, obviously, not optimal for such experiments. Though the quality of the retrieved image is not good, feasibility of high resolution terahertz holography with TIP imager has clearly demonstrated.

Stable enough operational characteristics of the Novosibirsk free electron laser and the transmission of high power terahertz radiation through the beamline to the user stations indicate the conversion of the machine from the experimental facility to the user facility. The first experiments have demonstrated its great potentiality for experiments in optics, high-energy-density science, chemistry, biology, and other applications.

The authors are indebted to N.M. Bulgakova, V.M. Fomin, G.L. Kuryshev, L.A. Lukyanchikov, V.P. Ostanin, A.M. Shalagin, L.N. Shishkina, V.I. Yakovlev, and P.I. Zubkov for stimulating comments and discussions. We thank S.V. Kozlov, D.N. Root and A.V. Trifutina for assistance in the experiments. Authors are grateful to R. Wylde and K. Wood granted to us the P10 polarizer. This work was supported in part under grant 174/03 from Siberian Branch of Russian Academy of Science. Some results were obtained under grant UR.01.189 from the program "Russian Universities" on the CATRION setup.

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В.П. Болотин и др.

Первые эксперименты на высокомощном Новосибирском лазере на свободных электронах

Budker INP 2005-37

Ответственный за выпуск А.М. Кудрявцев
Работа поступила 8.08.2005 г.

Сдано в набор 13.09.2005 г.
Подписано в печать 13.09.2005 г.
Формат бумаги 60×90 1/16 Объем 1.5 печ.л., 1.2 уч.-изд.л.
Тираж 110 экз. Бесплатно. Заказ № 37

Обработано на IBM PC и отпечатано на
ротапринте ИЯФ им. Г.И. Будкера СО РАН
Новосибирск, 630090, пр. академика Лаврентьева, 11.