Invited

IMAGING ATR-SPECTROSCOPY AND INTERFEROMETRY USING INTENSE MONOCHROMATIC TERAHERTZ RADIATION

B. A. Knyazev[1,2], V. S. Cherkassky[2], V. V. Gerasimov[1], and M. G. Vlasenko[1]

[1] Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia
[2] Novosibirsk State University, Novosibirsk, Russia, knyazev@phys.nsu.ru

Introduction

Many impressive results in the terahertz spectral range were achieved with TDS spectroscopy employing broadband radiation sources. Recently developed intense monochromatic terahertz sources give an alternative approach to development of instrumentation in this spectral region. The Novosibirsk terahertz free electron laser (NovoFEL) generates plane-polarized, monochromatic, coherent, continuously tunable terahertz radiation with a low beam divergence [1]. Such beam characteristics in combination with the average power of hundreds of watts enable realization of many classical optical schemes. In this paper we describe implementation of a number of spectroscopic and interferometric techniques using the NovoFEL as a source of radiation and a microbolometer focal plane array (MB FPA) as an image recorder [2].

Imaging ATR spectrometer

Existing imaging attenuated total reflection (ATR) spectrometers for the visible and MIR spectral ranges [3] consist of a Fourier spectrometer coupled with a FPA module. Tunability of FELs in a wide spectral range, as well as a very low beam divergence, enables realization of another kind of imaging ATR spectrometer. The input and output optical systems of the spectrometer are shown in Fig. 1. Scanning the laser wavelength and using a microbolometer camera to record images of the terahertz beam reflected from the ATR element–sample interface, one can retrieve the spatial distribution of spectral characteristics of the sample.

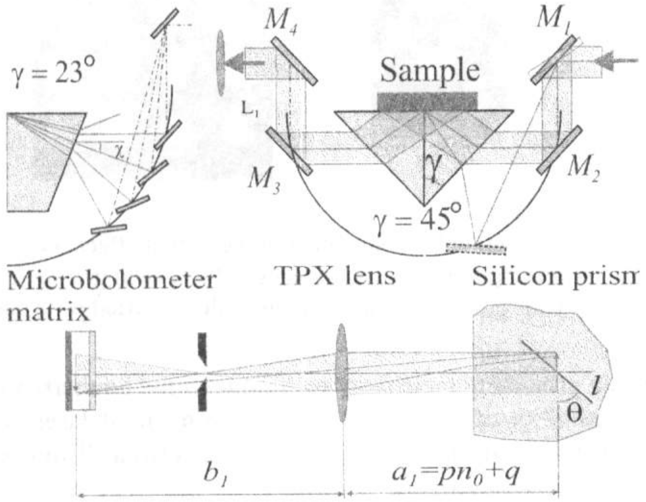

Fig. 1. Schematic of imaging ATR spectrometer with two interchangeable prisms; the incidence angle is changed with the help of the movable mirror M_1

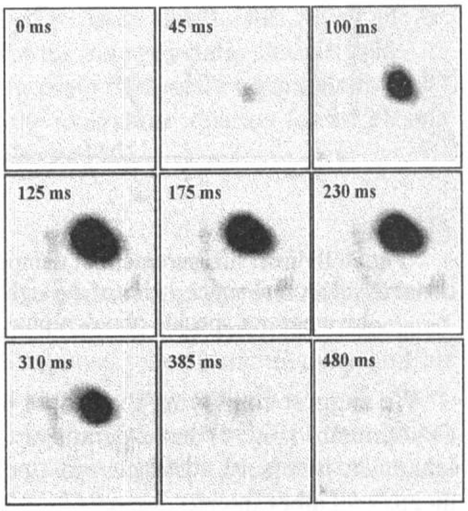

Fig. 2. Frames selected from the "terahertz video" recorded with the microbolometer FPA during injection of ethanol into water

In another operation mode, the ATR spectrometer can be used to study transient processes at the interface at a fixed laser wavelength. Fig. 2 demonstrates real-time images of the terahertz beam reflected from the interface during injection of ethanol into a water pool (the incidence angle was 57 degrees and the laser wavelength was 0.13 mm). Since absorption of ethanol is very low in comparison with absorption of water, the reflection coefficient for areas with the silicon-ethanol interface is close to unity. The pictures show clearly the ethanol drop dynamics, appearance of "jets", and some "trace" at the interface after dissolution of the drop.

Interferometry

Complete spatial coherence of NovoFEL radiation enables development of many metrological schemes based on interferometry and related phenomena. Real-time speckle photography as a first step to speckle interferometry was demonstrated with a 160×120 MBFPA used at a frequency of 2.3 THz. A speckled image of an object (Fig. 3) which was illuminated with radiation diffusely reflected from a rotating scatterer was projected on the focal plane array. Two hundred fifty frames of the terahertz "video" recorded by the MB FPA with a repetition rate of 41 frames per second were used for reconstruction of the amplitude, period, and logarithmic decrement of damped rotational oscillations of the scatterer.

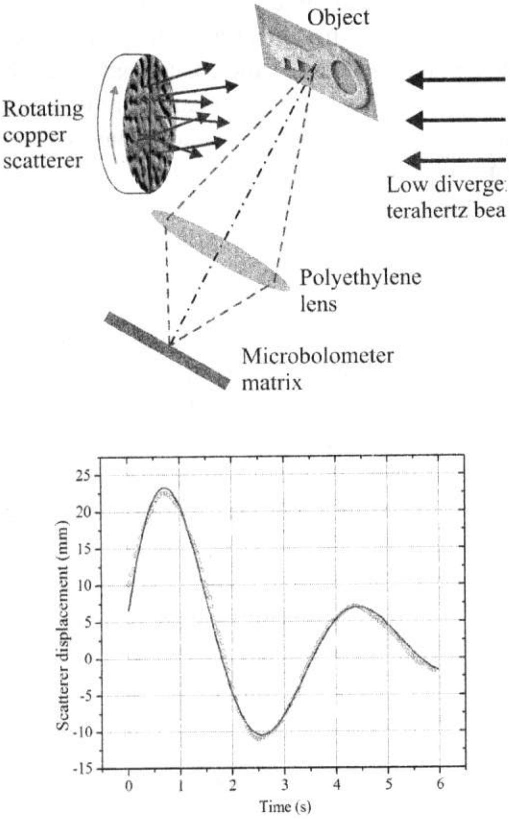

Fig. 3. Indirect measurement of damped rotational oscillation characteristics of a rough sample by means of speckle photography

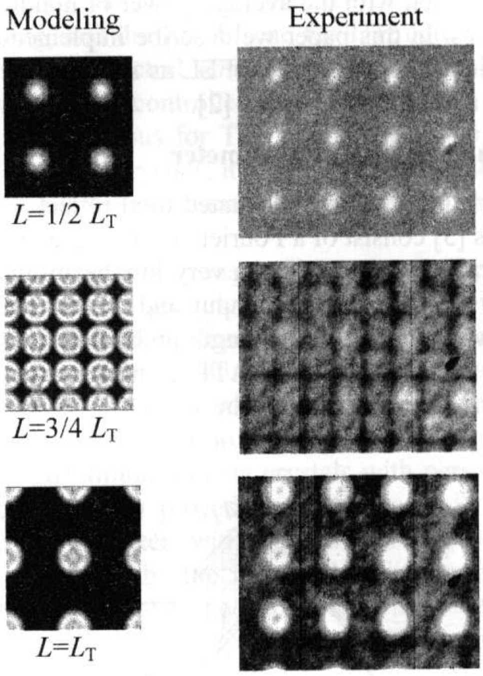

Fig. 4. Demonstration of the Talbot effect at a laser wavelength of 0.117 mm using a 2D Ronchi grating (a grid with 1-mm circular openings with the period p =2 mm)

We suggest employing the Talbot effect as a promising metrology technique in the terahertz range. Experiments (Fig. 4) have demonstrated applicability of this effect to measurement of laser wavelength or, inversely, distances, to study optical non-uniformities or to detect wavefront distortion by means of Talbot interferometry ($L_T = 2p^2/\lambda$ is the Talbot length).

Acknowledgements

This work was supported in part by SB RAS Integration Grant 89/9, grant RNP.2.1.1.3846 from the Russian Ministry for Education and Science, and grant from the Russian Foundation for Basic Research. Authors are indebted to the NovoFEL team for their assistance in the experiments.

References

1. G.N. Kulipanov, N.G. Gavrilov, B.A. Knyazev et al. *Terahertz Science and Technology*, 2008, **1**(2), 19 p., http://www.thznetwork.org.cn/Journal/index.asp.
2. M.A. Dem'yanenko, D.G. Esaev, B.A. Knyazev, G.N. Kulipanov and N.A. Vinokurov. *Appl. Phys. Lett.* 2008, **92**(13), 131116, 3 p.
3. S.G. Kazarian, J. Van der Weerd. *Pharmaceutical Research*, 2008, 25(4), 853–860.

Invited

FEL RADIATION USE FOR LARGE BIOMOLECULES ABLATION

S. E. Peltek[1], **T. N. Goryachkovskaya**[1], **A. S. Kozlov**[3], **A. K. Petrov**[3],
M. A. Scheglov[2], **V. A. Mordvinov**[1], **V. M. Popik**[2]

[1] Institute of Cytology and Genetic SB RAS, Novosibirsk, Russia
[2] Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia
[3] Institute of Chemical Kinetics and Combustion SB RAS, Novosibirsk, Russia

The main goal of this work is: an investigation of a possibility of using terahertz radiation for transfer biomacromolecules and nanoparticles from a solid surface into the aerosol phase. We have show that this process is nondestructive – the ablated molecules conserve primary structure. We applied this technique to standardization of the biochip production and express analysis of nanoparticle's size. We named the process of biomacromolecule and nanoparticle transfer into the aerosol phase the soft nondestructive ablation.

To check the nondestructive character of the soft nondestructive ablation method of biomacromolecules under action of trahertz emission we used three different bioanalytical techniques. First, to monitor a possible loss or retention of the enzymatic activity of a horseradish peroxidase sample we employed histochemical staining. After ablation, horseradish peroxidase particles were collected from the aerosol phase onto the solid filter. By the method developed by BioRad company we checked that the horseradish peroxidase sample retained its enzymatic activity after ablation. Second, by comparison of the electrophoretic mobility of the original and the ablated horseradish peroxidase samples we proved that this complex protein was undamaged. Major part of the enzymatic activity is associated with the high molecular weight fractions. This fraction was very similar to the control sample. Third, we present the experiments proving the nondestructive character of ablation by the MALDI-TOF technique. It was shown a very good correlation of the molecular mass-spectrum of native and ablated horseradish peroxidase samples.

Ablation of the mixture of DNA plasmid pUC18 (2.8 tbp) and lambda phage DNA (48 tbp) was carry out. To prove the nondestructive character of the soft nondestructive ablation method of DNA macromolecules we transformed E. coli competent cells by the ablated plasmid. We compared of the electrophoretic mobility of plasmids extracted from E. coli transformed by native and ablated plasmid samples. The electrophoretic mobility of both samples was the same.

The principle of soft nondestructive ablation of biological macromolecules under terahertz irradiation was applied to the direct analysis of the target DNA from biochip surface. The synthetic DNA-probe of 17 nucleotides was covalently bonded to the surface of a silicone plate. A target DNA from 90 nucleotides was hybridized to the DNA-probe like on the usual biochips. The target DNA on the biochip model is fixed by the hydrogen bonds. By action of terahertz emission we can destroy the hydrogen bonds, left the covalent bonds intact and transfer the target DNA into the aerosol phase. Start of ablation was controlled by the aerosol spectrometer and then the target DNA was collected to the filter for the subsequent analysis by sequencing. After ablation the target DNA was collected by the filter washed out and amplified by PCR. The target and ablated DNA sequences were identical. So we have got the method for the direct analysis of the target DNA.

Acknowledgements

The research was supported by Federal agency for science and innovations foundation № 02.512.11.2068 (2007), RAS foundation № 27.8/69 (2009-2010), SB RAS foundation № 39 (2009-2010).

Invited

DEVELOPMENT AND APPLICATIONS OF FREE ELECTRON LASERS: STATUS AND PERSPECTIVES

N. A. Vinokurov, E. N. Dementyev, B. A. Dovzhenko, Ya. V. Getmanov, B. A. Knyazev, E. I. Kolobanov, V. V. Kubarev, G. N. Kulipanov, A. N. Matveenko, L. E. Medvedev, S. V. Miginsky, L. A. Mironenko, V. K. Ovchar, V. M. Popik, T. V. Salikova, M. A. Scheglov, S. S. Serednyakov, O. A. Shevchenko, A. N. Skrinsky, V. G. Tcheskidov, Yu. F. Tokarev, P. D. Vobly, and **N. S. Zaigraeva**

Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia, vinokurov@inp.nsk.su

Free electron lasers (FELs) provide coherent radiation in the wavelength range from 0.14 nm to 1 mm. They use phenomenon of stimulated undulator radiation. Undulator radiation means radiation of relativistic electron, moving in undulator – special magnet, which creates such periodic alternating field, that electron trajectory lies near a straight line (undulator axis). Traveling through undulator electrons amplifies collinear electromagnetic wave if the last one has wavelength $\lambda = d/(2\gamma^2)$, d is the undulator period, and γ is particle full energy, divided over its mass.

During last 30 years, Budker INP developed many FELs. The last one is in operation since 2003 [1]. It is CW FEL based on an accelerator–recuperator, or an energy recovery linac. Full-scale Novosibirsk free electron laser facility is to be based on the four-orbit 40 MeV electron accelerator-recuperator (see Fig. 1). It is to generate radiation in the range from 5 micrometer to 0.24 mm [2, 3]. Mooving from injector (1), electrons pass through accelerating structure (2) four times, then loose part of energy in the FEL (4), and then, after four decelerations in the same RF structure, come to the beam dump (5).

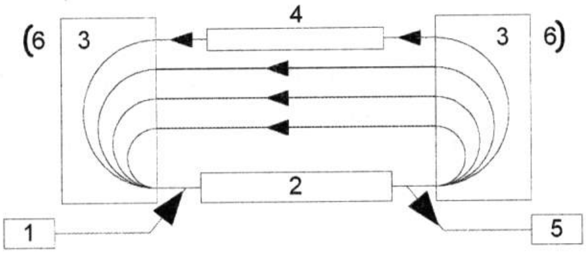

Fig. 1. Scheme of the accelerator-recuperator based FEL. 1 – injector, 2 – accelerating RF structure, 3 – 180-degree bends, 4 – undulator, 5 – beam dump, 6 – mirrors of the optical resonator

The first stage of the Novosibirsk free electron laser (Fig. 2.), based on the energy-recovery linac, uses one orbit, which lies in vertical plane. The FEL generates coherent radiation, tunable in the range 120–240 micron. The radiation time structure is a continuous train of 40–100 ps pulses at the repetition rate of 2.8–22.5 MHz. Maximum average output power is 500 W, the peak power is more than 1 MW [4, 5]. The minimum measured linewidth is 0.3%, which is close to the Fourier-transform limit. Five user stations are in operation now. Two other are in progress.

The design and manufacturing of the full-scale four-turn ERL is underway. An artistic view of the machine is shown in Fig. 2. The new four turns are in the horizontal plane. One FEL is installed at the fourth orbit (40 MeV energy), and the other one at the bypass of the second orbit (20 MeV energy).

Two first orbits, including bypass and undulator, were assembled last year. The circulation (two accelerations and two decelerations) of average current 9 mA was achieved. The first lasing of the FEL at bypass was achieved this spring. The radiation wavelength may be tuned from 40 to 60 micron. The maximum gain is about 40%. The significant (percents) increase of beam losses took place during lasing. The optimization of the used beam deceleration is in progress.

To transmit the radiation from the FEL to user stations, the beamline from the accelerator hall to the user hall was built. The beamline is filled by dry nitrogen. It is separated from the accelerator vacuum by the diamond window, and from the air by the polyethylene windows. After installation of nitrogen dryer, we obtained almost complete transparency of the beamline.

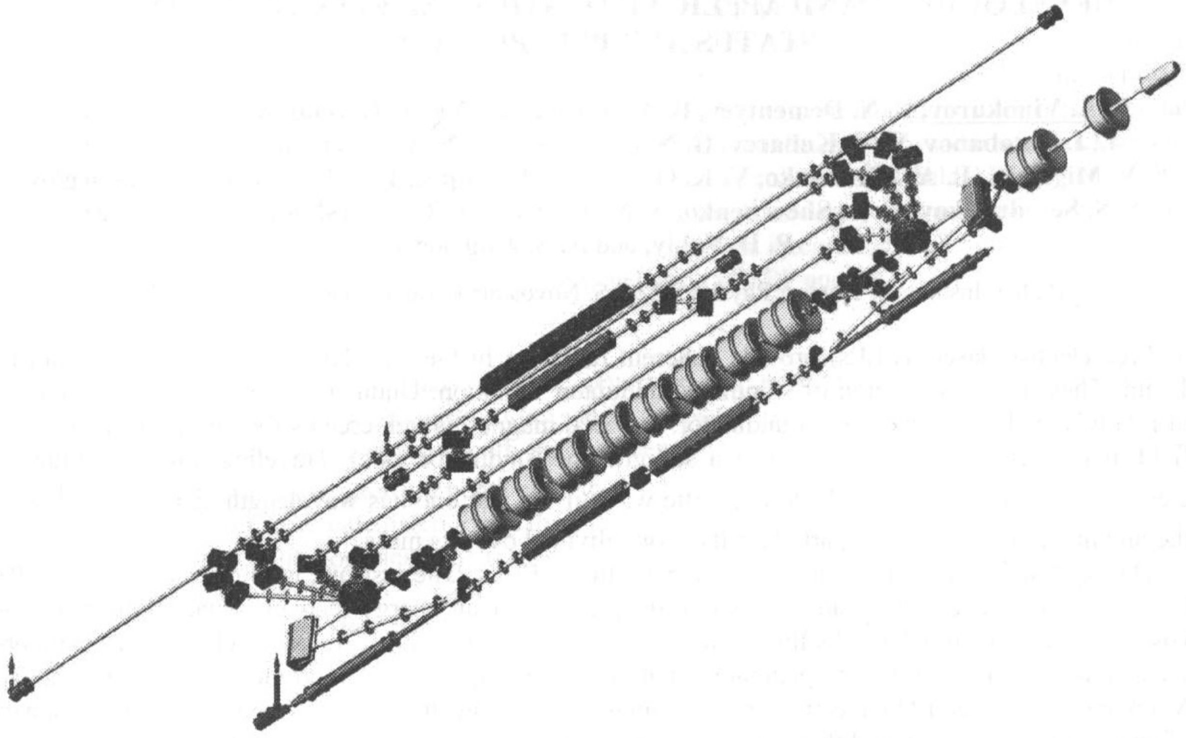

Fig. 2. The full-scale Novosibirsk high power FEL (bottom view) with three FELs

Now radiation is delivered to 5 stations. Two of them are used for measurement of radiation spectrum, and other three – for users. In particular, the terahertz ablation of DNA and other biologically relevant molecules was performed [6]. It was shown, that transfer from surface occurred without molecular destruction. The radiation of second FEL will be merged to the existing radiation beamline by the end of this year. Commissioning of the third FEL is expected next year.

Acknowledgements

This work was supported in part by SB RAS under Integration Grant 89/9.

References

1. E.A. Antokhin et al., *NIM A*528, 2004, 15–18.
2. N.G. Gavrilov et al., *IEEE J. Quantum Electron.*, QE-27, 1991, 2626–2628.
3. V.P. Bolotin et al., *Proc. Intern. Conf. FEL-2000:* Durham, USA, 2000, II-37-II-38.
4. V.P. Bolotin et al., *NIM A*557, 2006, 23–27.
5. E.A. Antokhin et al., *Problems of Atomic Science and Technology*, 2004, **1**, 3–5.
6. A.K. Petrov et al., *Dokl. Russian Acad. Nauk*, 2005, **404** (5), 1–3.