Available online at www.sciencedirect.com

ScienceDirect

Nuclear Instruments and Methods in Physics Research A 575 (2007) 63–67

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

www.elsevier.com/locate/nima

Techniques for introscopy of condense matter in terahertz spectral region

V.S. Cherkassky[b], V.V. Gerasimov[b], G.M. Ivanov[c], B.A. Knyazev[a,b,*], G.N. Kulipanov[a], L.A. Lukyanchikov[b,c], L.A. Merzhievsky[b,c], N.A. Vinokurov[a,b]

[a]Budker Institute of Nuclear Physics SB RAS, 630090 Novosibirsk, Russia
[b]Novosibirsk State University, 630090 Novosibirsk, Russia
[c]Institute of Hydrodynamics SB RAS, 630090 Novosibirsk, Russia
[d]Institute of Semiconductor Physics SB RAS, 630090 Novosibirsk, Russia

Abstract

Feasibility study of the introscopy of solids and biological objects using high-power terahertz-free-electron laser radiation was performed. A complete set of quasi-optical elements (beam-splitters, windows, mirrors, zone plates and kinoform lens), detectors (bolometers, piroelectric detectors) and imagers (thermograph, luminescence quenching thermal image plate and thermosensitive visible-light interferometer) for the terahertz spectral region have been developed. Detection of hidden amino acids by means of the terahertz shadowgraphy was demonstrated. Because of strong effect of diffraction, we suggest employment of Toepler and holography schemes for the introscopy of objects in the terahertz spectral region.

PACS: 41.60.Cr; 85.60.G; 87.50.Hj

Keywords: Terahertz imaging; Introscopy; Free-electron laser

1. Introduction

The radioscopy, examination of the inner structure of opaque objects using X-rays or other penetrating radiation, is a widely used method of the introscopy for technical and medical imaging. It cannot be applied to the examination of the objects or subjects that are sensitive to the ionizing radiations, as well as to the objects that are practically completely transparent to this radiation. The development of sources of terahertz (submillimeter) radiation opens up possibilities for the non-ionizing introscopy of the condense matter, which that can be by analogy called "terascopy". Techniques for the terahertz imaging and introscopy with low-power sources are surveyed in Refs. [1–3]. The use of a high-power terahertz-free electron laser extends the capabilities of terascopy.

Novosibirsk high-power free-electron laser (NovoFEL) based on the energy recovery linac [4] emerges monochromatic radiation with the relative linewidth of 0.3–1%, which can be precisely tuned within the wavelength range of 120–240 μm, as a continuous train of 70 ps pulses. Maximum radiation average power reaches 200 W (at the repetition rate of 5.6 MHz). Recently [5], we developed two experimental methods for the visualization of terahertz images and applied them to the introscopy of a number of objects. In this paper, we discuss specific features of the optical systems designed for the introscopy of condense matter with free electron laser and give as an example the shadowgraphy of Teflon tablets containing amino acids.

---

*Corresponding author. Budker Institute of Nuclear Physics SB RAS, Lavrentieva Ave., 11, 630090 Novosibirsk, Russia. Tel.: +7 383 339 4839; fax: +7 383 330 2167.

E-mail addresses: B.A.Knyazev@inp.nsk.su, Knyazev@inp.nsk.su (B.A. Knyazev).

0168-9002/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2007.01.025

2. Optical components and radiation recorders

Each optical system consists of a source, optical elements and an imager. Because of the complete spatial and temporal coherence of NovoFEL radiation and the large wavelength of terahertz radiation, multiple-beam Fresnel reflection plays an important role when the radiation passes through the optical systems. To obviate the multiple-beam interference, it is reasonable to use in the optical systems rather thick or very thin windows and beam splitters. The interference, reflection and absorption for silicon, germanium, mylar and polypropylene—the materials best suited for the terahertz spectral region—are described in detail in Ref. [6].

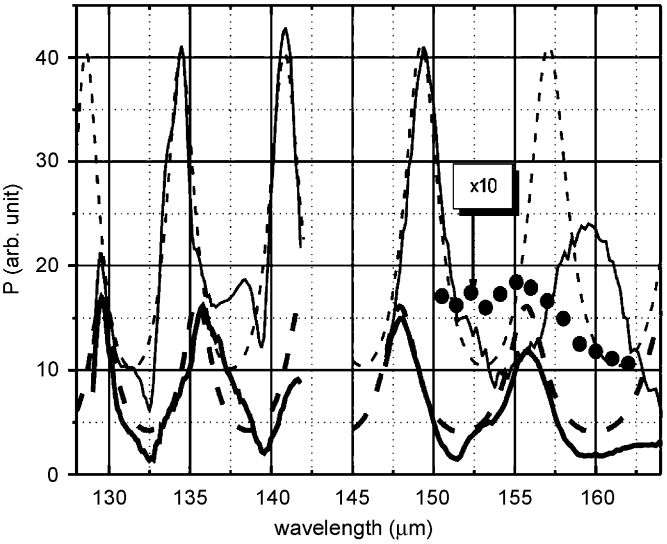

Fig. 1. Spectral sensitivity of two samples of bolometers with crystal absorber (solid curves) and a bolometer with a cone absorber (dotted curve). Dashed curves are the simulations of crystal absorption vs. wavelength for the values of *nl* giving best fit to the experimental data.

Multiple-beam interference in the terahertz region does considerably affect the spectral sensitivity of crystal bolometers. Fig. 1 demonstrates variation of the sensitivity for two samples of IMO-4C bolometers vs. wavelength (solid lines). Simulations of crystal absorption vs. wavelength (dashed line curves) were made with values *nl* (*n* and *l* are the refractive index and the crystal length, respectively) selected to give best fit to the experimental data. The absence of sensitivity variations with wavelength for an IMO-3 bolometer with a non-crystal absorber (dotted curve) reinforces the statement that the reason of the sensitivity variations is the multiple-beam interference. Variations of sensitivity with wavelength are individual for each sample of the crystal detector that has to be taken into account for any difference scheme.

The element, which drastically determines both sensitivity and time and space resolution of an imager, is the recording system. In our case, it consists of a screen visualizing terahertz radiation and a final recorder. Two imaging systems for the terahertz radiation, a FIR–NIR converter with a thermograph as the final recorder and a thermosensitive glass-plate interferometer with a red probe laser and a camcorder as the recorder, are described in Ref. [5]. Now, we have applied a Micken Instruments thermal image plate (TIP) detector initially intended to display mid-infrared laser radiation to terahertz radiation imaging. Schematic of the imaging system is shown in Fig. 2. A mercury lamp excites visible luminescence of a phosphor screen. Terahertz radiation exposes the screen and causes thermal quenching of the luminescence. Image of the screen is recorded with a digital camcorder.

Luminescence quenching for the screen #8, normalized to the initial luminescence intensity, is presented in Fig. 2.

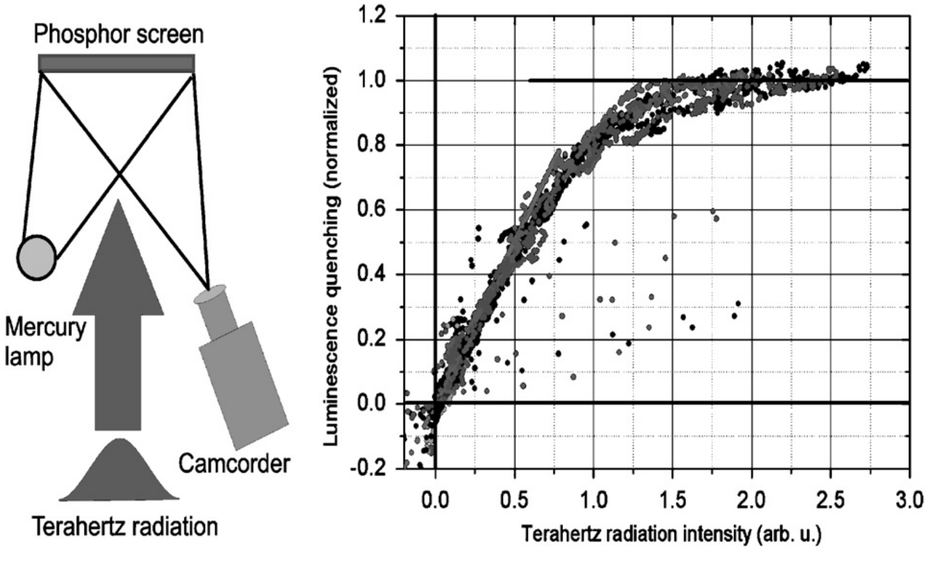

Fig. 2. Layout of the imaging system based on the thermal image plate and luminescence quenching as a function of terahertz radiation intensity for the plate #8. Measurements were performed at the ambient temperature of 26 °C for terahertz radiation wavelength of 130 μm.

The plot contains more than 2500 experimental points. It is evident from the curve that the response of the screen is linear at least up to 50% of the initial luminescence intensity; moreover, using this calibration the relative intensity of the incident terahertz radiation can be measured up to 80% quenching. The thermal image plate possesses a good spatial and time resolution because the final recorder operates in the visible light. It has to be emphasized that the relative intensity of incident terahertz radiation is retrieved from the ratio of the luminescence quenching and the reference luminescence intensity. It does not depend on any geometrical parameters, for example, camcorder characteristics and its position, and appears to be a very convenient method for relative measurements. The only parameter that can be taken into account is the initial temperature, variation of which shifts the coordinate origin in Fig. 2 along the calibration curve. The thermal image plate recorder can also be adapted to the absolute measurements, for example, by the calibration with the thermosensitive interferometer (TSI), which is an absolute power meter (see Ref. [5]).

3. Terahertz shadowgraphy

Shadowgraphy is a powerful technique for the introscopy in the X-ray spectral region. A short radiation wavelength enables easy obtain high-resolution images. We examined a shadowgraphy system with the NovoFEL as a terahertz radiation source. The terahertz beam at the workstation with practically plane wavefront (divergence was about 0.003 rad) had the diameter of about 50 mm. The beam was incident normally upon three tablets pressed from Teflon powder. The upper tablet, placed at the top of the triangle (see Fig. 3), consisted of the pure Teflon (extinction coefficient is 0.7 cm^{-1} in this spectral region), whereas the other two contained inside small amounts of L-glutamine and L-cystine. Absorption spectra of these amino acids recorded by Bruker IFS 66VLS Fourier transform spectrometer are also presented in the figure.

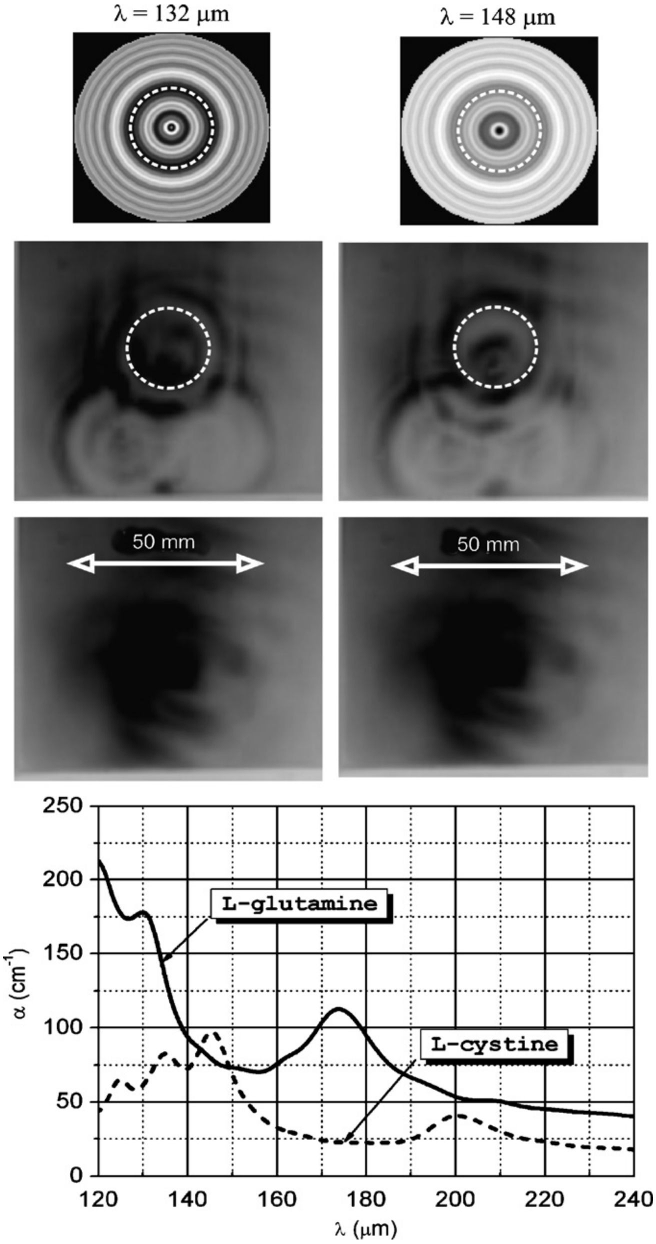

Fig. 3. Terahertz shadowgraphy with Novosibirsk free-electron laser as a source and the thermograph as a recorder. The laser beam cross-section is shown in the lower frames. Three tablets with the thickness of about 4 mm, pressed from Teflon powder, were placed in the beam at the distance of 40 cm in front of the thermograph screen. Two lower tablets contained amino acids. Amino acid absorption coefficients vs. wavelength are given in the plot. Diameter of the tablets is traced with dotted lines. The results of simulation of plane wave diffraction at a pure Teflon tablet are presented at the top.

A thermal image plate #8 was mounted in the path of the terahertz beam at the distance of 400 mm behind the tablet set. Areal distribution of terahertz radiation at the screen was recorded for several radiation wavelengths with both the luminescence quenching system and the thermograph. Two frames of spatial distribution of the initial beam, taken with the thermograph, are presented at the lower pictures in Fig. 3. Two frames above were recorded by the thermograph when 132 and 148 μm laser radiation passed through the tablets. The comparison of transparencies of lower tablets at two wavelengths gives evidence that L-glutamine and L-cystine are contained in the left tablet and the right one, respectively. The sharpness of the pictures is far from perfect. Obvious reason of the imperfectness is the effect of diffraction. Two diffraction patterns for the pure Teflon tablet were calculated taking into account Teflon absorption. They are presented at the top of Fig. 3. The result of simulation correlated well with the patterns experimentally observed.

4. Quasi-optical and holography systems for monochromatic terahertz imaging

The above-described experiments give clear evidence that one of the ways to eliminate the diffraction problem and to obtain high-quality images in the terahertz region is the employment of quasi-optical systems. Key elements for designing such systems are lenses or focusing mirrors. For high-power monochromatic radiation, there is no alternative to the application of the reflective optical elements. We have fabricated three reflective zone plates and a parabolic kinoform mirror. Since these elements were destined for focusing of terahertz radiation under the right angle relative to the incident beam direction, they were elliptically shaped and had dimensions 10 cm × 14 cm. Design and operational characteristics of these elements, as well as a simulation technique for the diffraction of oblique beams reflecting from a diffractive optical element, are described in detail in Ref. [7]. The kinoform mirror with the focal distance of 250 mm designed for $\lambda = 130\,\mu\text{m}$ produced the focal spot of 0.9 mm in diameter, whereas simulated focal spot size for the parallel beam was 0.45 mm. The difference may be a consequence of imperfectness of the mirror surface, wavelength deviation, inaccuracy of optical system adjustment and, probably, monochromatic aberrations.

We have carried out first experiments on imaging with the above-described kinoform lens, which demonstrated a reasonable quality of images, though some image distortion still has to be explained. There are two ways to overcome this problem. On the one hand, the distortion can be eliminated by numerical correction of recorded image. On the other hand, a kinoform lens with the profile emulating off-axes parabolic mirror, obviously, will allow getting over the problem.

We suggest the application of the quasi-optical Toepler scheme with a knife-edged screen [8] for the introscopy of the phase objects. This scheme is commonly used in the visible spectral region and to our knowledge never was used in terahertz. A Toepler scheme for the examination of mechanism of solid damage is now under construction.

The other technique, which, on the contrary, allows using diffraction to obtain a good picture, is the holography. Since the coherence length of the Novosibirsk FEL is about 2–3 cm, which is much longer than the coherence length of commonly used picosecond and femtosecond pulse length sources, it may be used as a source for holography schemes. A variant of the holography system, which is destined for the introscopy of solids, is also under construction (Fig. 4). The holograms will be digitally recorded and images digitally retrieved.

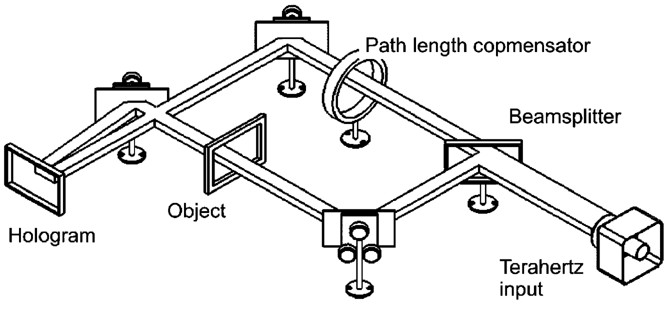

Fig. 4. Layout of the terahertz holography system with Novosibirsk free-electron laser as a source.

5. Conclusion

Novosibirsk free-electron laser, because of high-power and large coherence length of the radiation, is a prospective source for the introscopy of solids in the terahertz spectral region. The elements for quasi-optical and holography systems, as well as radiation detectors, had been selected and examined using high-intensity terahertz radiation. Special attention was paid to the development of diffractive optical elements.

Three imaging systems developed for the visualization of intense terahertz radiation are complementary to each other. The near-IR thermograph is rather sensitive and user-friendly recorder, but it possesses a low resolution. Besides, it records "screen temperature", which hardly can be transformed directly into the absorbed energy, because the surface emissivity of the screen usually is not known. Thus, it is the most convenient for tracing quasi-optical systems and preliminary image examination.

The thermal image plate employing the thermal luminescence quenching enables performing excellent measurement of relative intensity distribution. TIP response is linear within 50% of the incident terahertz radiation. It has a good spatial resolution and can be used for precise imaging. TSI has a good time resolution but because of large thermal capacity of the glass plate it can operate only with a long while between measurements. However, TSI can be employed for the absolute calibration of TIP at any terahertz wavelength. The experiments on shadowgraphy of amino acid containing Teflon tablets have demonstrated the feasibility of the terahertz introscopy at Novosibirsk free-electron laser.

Acknowledgments

This work was supported in part by grants 174/06 and 22/06 from the Siberian Branch of Russian Academy of Science and by Grant No. RNP.2.1.1.3846 from the Ministry of Education and Science of Russian Federation. Authors are indebted to V.V. Kubarev, who first applied the thermal image plate to the visualization of intense terahertz radiation, V.V. Kotenkov, A.N. Matveenko, I.P. Mikhailovsky, P.D. Rudych[2], T.V. Salikova, S.S. Serednyakov, and M.A. Scheglov for assistance in carrying out this research project.

References

[1] S.P. Mickan, X.-C. Zhang, Int. J. High Speed Electron. Syst. 13 (2003) 601.
[2] S. Wang, X.-C. Zhang, J. Phys. D 37 (2004) R1.
[3] J.F. Federici, B. Schulkin, Feng Huang, et al., Semicond. Sci. Technol. 20 (2005) S226.

[4] V.P. Bolotin, N.A. Vinokurov, D.A. Kayran, et al., Nucl. Instr. and Meth. A 543 (2005) 81.

[5] V.S. Cherkassky, B.A. Knyazev, V.V. Kubarev, et al., Nucl. Instr. and Meth. A 543 (2005) 102.

[6] V.V. Gerasimov, B.A. Knyazev, P.D. Rudych, V.S. Cherkassky, Fresnel reflection in optical elements and detectors for terahertz spectral range, Instrum. Exp. Tech., in press, Preprint BINP 2006-23, 2006, 〈http://www.inp.nsk.su/publications〉 (in Russian).

[7] V.S. Cherkassky, B.A. Knyazev, Herald of Novosibirsk State University—Physics 2(1) (2007) 3 (in Russian).

[8] G.S. Settles, Schlieren and Shadowgraph Techniques: Visualizing Phenomena in Transparent Media, Springer, Berlin, 2001.