TECHNICAL DIGEST

MPLP-2016

The VII International Symposium
and Young Scientists School

"MODERN PROBLEMS OF LASER PHYSICS"

Novosibirsk, Russia, August 22 – 28, 2016

mplp2016.laser.nsc.ru

Organized by:

Institute of Laser Physics, SB RAS, Novosibirsk, Russia

Novosibirsk State University, Novosibirsk, Russia

Institute of Spectroscopy, RAS, Troitsk, Moscow Region, Russia

International Laser Center, M.V. Lomonosov Moscow State University, Moscow, Russia

Federal State Unitary Enterprise "VNIIFTRI", Mendeleevo, Moscow region, Russia

Supprted and Sponsored bu:

Federal Agency for Scientific Organizations

Russian Foundation for Basic Research

Novosibirsk Regional Fund of Support of Science and Innovative Activities

The Nauchnoe Oborudovanie group of companies

ББК 22.3
М11

Printed in ООО «Офсет-ТМ»
Order № 486. Printing 168 copy
630117, Novosibirsk. Arbuzova st. 4/27
phone: (383) 332-72-12. e-mail: ofsetn@yandex.ru

ISBN: 978-5-85957-131-4

Recent advances in the terahertz photonics and spectroscopy at Novosibirsk free electron laser

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Novosibirsk free electron laser (NovoFEL) is a user facility [1] consisting of three laser systems emitting monochromatic high-power radiation in spectral ranges from 5 to 240 μm. The first THz laser system is in operation since 2003. It emits radiation as a continuous stream of 100-ps pulses with a repetition rate of 5.6 MHz in the spectral range from 90 μm to 240 μm with a line width less than 1%. In a routine regime, the average power of radiation at the user stations is 50-150 W at λ = 130 μm. A high power radiation, a relatively narrow linewidth and the tunability of the radiation enable performing a wide variety of experiments. In this paper, we survey selected experiments in photonics performed recently at workstations of the facility. Photonics is a rapidly developing field of optics, which is still obviously underdeveloped in the terahertz range. The NovoFEL opened new possibilities for the development of new methods and techniques in the area.

One of the main tasks in the photonics is the transformation of terahertz beams. Optical elements for terahertz waves are rather different comparing with the classical optical elements. A number of silicon diffractive optical elements, which enabled transforming NovoFEL Gaussian beam into the Laguerre-Gaussian and Hermite-Gaussian ones, have been designed and fabricated [2]. Other elements transformed the NovoFEL beam into determined volumes (*i. e.*, a pencil-like beam), or areas (*i. e.*, a uniformly illuminated square). A problem of strong Fresnel reflection was solved by the use of anti-reflection film covering [3].

Using binary phase spiral axicons [4], non-diffractive Bessel beams with angular orbital momentum (vortex beams) with different topological charges were formed. Since such beams have great potential for use in data transmission and remote sensing, we investigated both numerically an experimentally the techniques, which allow to increase a distance of beam propagation without beam divergence. It can be realized by reducing wavelength or expanding the beam with a telescopic system. Another experimentally verified feature of the Bessel beams, which is useful for beam transport, was the ability of these beams to reconstruct themselvs after passing randomly non-uniform media or obstacles blocking several central Bessel rings [5].

Surface plasmon polaritons (SPP) are a subject of special interest in the integrated optics, but SPPs in the mid-infrared and terahertz ranges are still investigated insufficiently. Experiments with the SPP launched using NovoFEL radiation showed that the propagation length of terahertz SPPs is about 10 cm. It appeared to be that the length at the gold-ZnS-air interface has a maximum, when ZnS thickness is about several hundreds of nanometers, which depended on surface quality. Such dependence has not been reported for the visible range. We have found also that THz SPPs can "jump" from one metal-dielectric interface to another one over the air gaps of up to 100-mm width [6]. A novel effect, the dependence of SPP generation efficiency on the direction of vortex beam rotation has been discovered, when the "end-fire coupling" technique was applied for SPP generation. This effect can be exploited for the development of a new type plasmonic key.

Large wavelength of terahertz radiation enabled performing the classical optics experiments when the ratio $\lambda / d \sim 1$, where λ is a wavelength and d is characteristic aperture size. We have studied diffraction of plane and vortex waves on different structures including periodic gratings and meshes (Talbot effect). The patterns observed in the case of vortex beams enables to detect characteristics of the beams.

High power of NovoFEL terahertz radiation enabled ignition of continuous optical discharge (COD) in gases at atmospheric pressure. It was found [7] that a sequence of 66-ps terahertz pulses strikes COD in Ar, He, N_2, Air and CO_2 at a specific power density of about 1 GW/cm^2. Tunability of NovoFEL radiation, enabled to carry out a number of experiments on absorption spectroscopy of molecular gases and flames. In paper [8], OH radicals and NO molecules were detected in flames. In this case, laser generation line width was practically the same as the molecule absorption line, and laser radiation may be assumed to be monochromatic. But, in fact, in some cases several vibrational-rotational transitions of a molecule can lie inside the laser line bandwidth. This feature was used in [9] for fast one-pulse spectroscopy of HBr molecule in the gas phase. Excitation of the molecule with a laser pulse excited $(J=4) \leftarrow (J=3)$ lines of $H^{79}Br$ and $H^{81}Br$ (66.70 μm and 66.72 μm) followed by a complicated free induced decay signal. Molecular spectrum can be reconstructed using a Fourier transform operation, but the induced decay signal for any molecular transition has a unique pattern, which can be used directly for detection of molecule.

The development and assembly of dedicated terahertz focusing system (beamline) was supported by Russian Science Foundation (grant 14-50-00080). The experiments were carried out with the application of equipment belonging to the Siberian Center for Synchrotron and Terahertz Radiation. The authors are grateful to the NovoFEL team for continuous support of the experiments. Binary axicons were designed and fabricated under support of the Ministry of Education and Science of Russian Federation (project 1879), the vortex beams were formed and investigated under support of RFBR grant 15-02-06444, and investigation of the optical discharge was performed under support of RFBR grant 14-22-02070.

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