High-Power Terahertz Non-Diffractive Bessel Beams with Angular Orbital Momentum: Generation and Application

Boris A. Knyazev[1,2,3], Yulia Yu. Choporova[1,2,3], Vladimir S. Pavelyev[3,4], Boris O. Volodkin[3], Mikhail S. Mitkov[1,2,5]

[1] Novosibirsk State University, Novosibirsk, 630090, Russia
[2]Budker Institute of Nuclear Physics SB RAS, Novosibirsk, 630090, Russia
[3] Samara State Aerospace University (SSAU), Samara, 443086, Russia
[4] Image Processing Systems Institute of the RAS, Samara, 443001, Russia
[5] Novosibirsk State Technical University, Novosibirsk, 630090, Russia

***Abstract*—Using radiation of the Novosibirsk free electron laser (NovoFEL) and silicon binary phase plates with spiral Fresnel zone patterns, we generated for the first time non-diffracting terahertz Bessel beams with angular orbital momentum ("vortex beams") and topological charges $l = \pm 1, \pm 2$. The amplitude and phase characteristics of the beams at a wavelength of 141 μm were thoroughly investigated and showed excellent agreement with numerical modelling based on scalar diffraction theory. We have demonstrated self-reconstruction of the beams passing non-uniform media. We studied the peculiarity of vortex beam diffraction on different apertures, generated surface plasmon polaritons by the end-fire coupling technique, and discovered unusual features in the mechanism of coupling of the vortex beams.**

I. INTRODUCTION

IN modern optics there are two areas that attract great attention nowadays: beams with angular orbital momentum (AOM) and surface plasmon polaritons (SPPs). Beams with AOM, which are of azimuthal phase structure, are used in manipulation of micro-particles, imaging, communication systems, phase-contrast microscopy, and wide variety of other applications. Surface plasmon polaritons, *i. e.* self-sustained electron plasma excitation travelling along a conductor-dielectric interface and an electromagnetic field localized at the interface, play important role in many physical phenomena and may be used in passive and active devices of all-optical integrated circuits. These two areas did not intersect until 2009, when the generation of surface optical vortices via internal total reflection was suggested. Later, surface plasmon vortices in the visible region were generated in another two works using laser radiation with a circular polarization or Lagguerre-Gauss beam with AOM. In this paper we describe terahertz Bessel beams and examine conversion of vortex beams into SPPs.

II. GENERATION OF VORTEX BEAMS

The experimental setup is shown in Fig. 1. We used as a source of radiation the Novosibirsk terahertz free electron laser [1], which wavelength can be tuned to any wavelength between 90 and 240 μm with the halfwidth $\Delta\lambda / \lambda = 0.01$. In the experiments described, average power of linearly polarized radiation, emitting as a continuous stream of 100-ps pulses at a repetition rate of 5.6 MHz, was about 30 W. A system of two polarizers were applied for both radiation attenuation and change of the polarization plane direction. The phase plates were illuminated with NovoFEL Gaussian beam, which, in the experimental area, possessed 15.2-mm waist and 2500-mm curvature radius and may be with high precision considered as a plane wave.

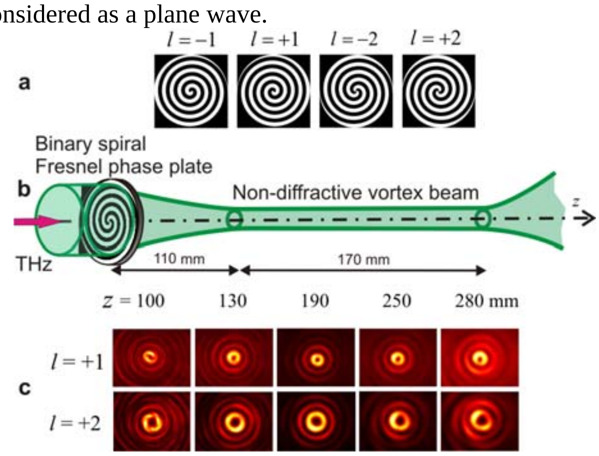

Fig. 1. (a) Phase plate patterns; (b) Beam generation; (c) Beam cross sections.

A Gaussian NovoFEL beam transforms into a pipe-like beam at a distance of 110 mm beyond a phase plate (see Fig. 1, a) of 38 mm in diameter. We examined the amplitude and phase characteristics of these beams during their propagation in free space and found excellent agreement between the experiments and simulations performed in terms of scalar theory of diffraction. The wavefronts of the vortex beams changed from plane to spherical during beam transmission along the optical axis, whereas the cross sections of the beams conserved their profiles. The latter are fitted very well with the Bessel function of the first kind of order 1 for a topological charge of ±1 and of order 2 for a topological charge of ±2. The sphericity of the beam wavefronts was proved experimentally using an interference technique, whereas the beam twist was confirmed in a Young's diffraction experiment, which also enabled us to measure the topological charge values.

III. BEAM SELF-HEALING

We studied the shapes of the beams passing through both amplitude and random phase masks. In both cases the beams self-reconstructed to some extent, which can be beneficial to development of terahertz radars. Fig. 2 shows self-healing of the vortex beam with $|l|=1$ behind scatterers made of polyethylene foam of different thickness. This feature of the beams can be used in THz radars and inspection systems

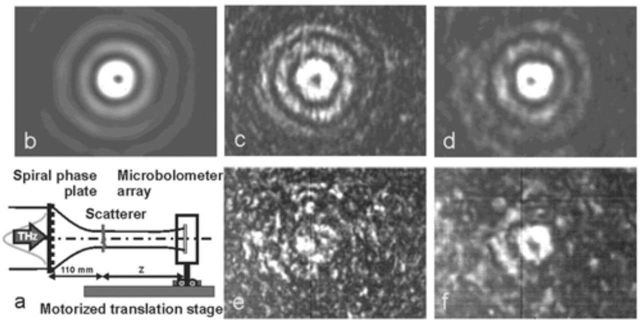

Fig. 2. Bessel beam self-healing. (a) Experimental schematic. (b) Vortex beam at z=110 mm. The beam scattered with a thin polyethylene foam: (c) Z = 60 mm, (d) Z = 115 mm. The beam scattered with thick polyethylene foam: (e) Z = 60 mm, (f) Z = 115 mm.

IV. Generation of SPPs with Vortex Beams

To generate surface plasmons, we applied the end-fire coupling of free radiation to the edge of conductor-dielectric interface, and to separate in space an intense diffracted wave and surface plasmon, we used in the experiments gold-ZnS layers deposited onto a cylindrical glass sector shown in Fig. 3. In previous experiments with non-vortex beams [2] we have learnt that (i) surface plasmons were produced at the input edge and traveled along the cylindrical metal-dielectric interface; (ii) the SPPs power decreased drastically on their way because of radiation losses; and (iii) because of high power of NovoFEL beam we were able to record image of diffracted at the output edge SPP.

Here we first applied the end-fire coupling technique for SPP generation via diffraction of *p*-polarized vortex beams, which intensity distributions are presented in the first column of Fig. 3. We expected to observe SPP generation to be symmetrical relatively the annular beam optical axis. Diffraction of the vortex beams on the cylindrical sample (second column in Fig. 3), however, was non-symmetric. It was radically different comparing to diffraction of conventional beams. Images recorded by the array placed near the output end of the cylindrical surface ($\theta = 45^{\circ}$) clearly testified that surface plasmons, having passed the curved surface and diffracting at the output edge, produced a free wave marked in the fourth column of the figure with yellow arrays. Reliability of this diagnostic technique was proved in [2]. At the intermediate angles we observed radiation losses decoupling tangentially from the curved surface.

It is clearly seen that SPPs were generated on the side opposite to the side where we observed the diffraction spot. This phenomenon needs explanation, while we can now give only a phenomenological one. With a vortex beam, the trajectory of the Poynting vector is spiral, and the azimuthal component of the vector is oppositely directed for different signs of topological charges. Simple analysis shows that in our experiments SPPs were generated with the azimuthal component of the Poynting vector directed into the metal-dielectric surface.

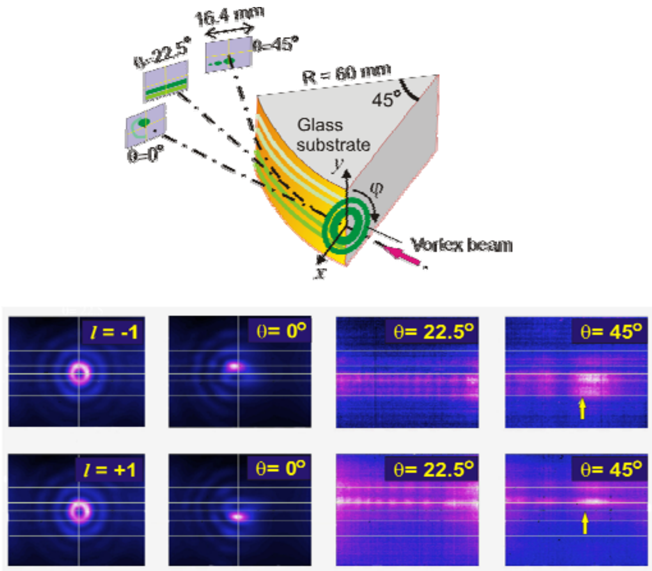

Fig. 3. Surface plasmon polariton generation by the vortex beams. Experimental configuration is shown above. Vortex beams impinged on the cylindrical sample face. The microbolometer array recorded diffraction pattern (in position corresponding to $\theta = 0^{\circ}$), tangentially scattered radiation $\theta = 22.5^{\circ}$), and free wave produced by plasmon diffracted at the end of cylindrical surface ($\theta = 45^{\circ}$). Green stripes mark expected traces of SPPs produced by maxima of vortex beam intensity. Images recorded for the beams with topological charges of opposite signs. ZnS thickness was 1.5 µm. Distance from the input face to the array was 70 mm.

We believe our observation may initiate further experimental and theoretical investigations. It should be emphasized that, besides the experiments on SPP generation by vortex beams, other experiments described in this work were also first performed in the terahertz range, which may by instructive for the readers.

V. Acknowledgments

Operation of the user station TERARAD belonging to the Novosibirsk State University, as well as design and fabrication of the diffractive optical elements, was supported by MES RF and RFBR grant 13-02-97007. The equipment for characterization of DOEs was developed with the support of Russian Science Foundation (project 14-50-00080). The study of beams with orbital angular momentum was supported by RFBR grant 15-02-06444. The experiments were carried out with the application of equipment belonging to the Siberian Center of Synchrotron and Terahertz Radiation.

Referencies

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