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Deflection of terahertz vortex beam in nonpolar liquids by means of acousto-optics

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Abstract

Acousto-optic diffraction of terahertz vortex beams was studied for the first time. It was shown that nonpolar liquids are the most promising acousto-optic media in the terahertz range. Possibility of vortex beam wide-angle deflection was demonstrated. Experimental research was performed for cyclohexane, hexane and white spirit. The experiments were carried out at the Novosibirsk free-electron laser.

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Introduction

The concept of vortex light, introduced in work [1], is used for specification electromagnetic field with orbital angular momentum. Phase function of such field depends on the azimuthal angle φ as $\exp(il\varphi)$, and orbital angular momentum (OAM) of one photon equals to $l\hbar$, were l is a topological charge being equal to some integer and $\hbar$ is the Dirac constant. This implies that OAM can be much greater than the spin angular momentum. Thanks to this fact, in particular, communication channel capacity can be substantially enlarged. Some kinds of the vortex light beams, e.g. with Bessel profile, have a unique character – their structure remains constant under a large propagation distance. Therefore, there are two possible applications of the vortex light: communication and micro-particle managing [2, 3].

There are several methods of the vortex beam formation with specified OAM by using special diffractive optical elements of different kinds. Today the main task is development of new methods to control parameters of the vortex light beam in real-time. One can change OAM via second harmonic generation in nonlinear crystals [4]. Therefore the OAM of generated radiation equals to doubled OAM of the pump radiation. The OAM can be changed also due to the interaction of electromagnetic radiation with acoustic wave, i.e. acousto-optic (AO) interaction based on photoelastic effect. Acoustic wave induces periodic perturbation of permittivity. Such structure represents itself a phase diffraction

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grating moving with the sound velocity. It is well known that the OAM conservation law holds for the AO diffraction on sound wave with OAM equal to l_s [5, 6, 7]. As it immediately follows, electromagnetic radiation in m diffraction order has OAM $l_m = l_0 + m \cdot l_s$. Thus there is an opportunity for managing OAM of vortex light beams and recording information by means of AO methods.

The majority of publications related to the diffraction of vortex beams on ultrasound is devoted to the AO interaction in optical fibers with small diffraction angles of about 1° [5, 6]. The fiber technique makes it possible to concentrate light and sound beams in small volume and therefore to increase diffracted light intensity I_1. It has to be emphasized, that the radiation of visible spectrum range has been employed in these works, and there are no published data on the AO interaction of vortex light beams in terahertz (THz) spectrum range. This fact is related to extremely small diffraction efficiency $\xi = I_1/I_0$, which is inversely proportional to the square of radiation wavelength λ. Here I_0 is the incident light intensity. In this paper we examined AO diffraction of vortex THz beam on the acoustic wave with zero OAM as a first step of the cycle of research.

Materials and methods

Although sources of coherent THz radiation has been developed in the past twenty years, there are a few techniques for the real-time control of THz radiation parameters [8]. Among these techniques, the AO devices has a number of advantages such as small operating time of about 1 μs, portability and low driving electrical power of several Watts. It is well known that diffracted radiation intensity I_1 is proportional to the unique medium character called AO figure of merit (AOFM) [9]:

$$M_2 = 4\frac{(\rho\partial n/\partial\rho)^2}{\rho V^3}, \tag{1}$$

where n – refractive index, ρ – density, V – sound velocity and $\rho\partial n/\partial\rho$ – elastooptic constant, which can be calculated by Lorentz-Lorenz equation:

$$\rho\frac{\partial n}{\partial\rho} = \frac{(n^2-1)(n^2+2)}{6n}. \tag{2}$$

As follows from relations (1) and (2), the AOFM is proportional to the sixth power of n. Since the values of sound velocity and density are nearly the same for the most of AO media, the main requirements for efficient AO interaction are transparency of an AO media in the THz range and a high value of its refractive index. Note that such combination of properties is uncommon. The most promising crystalline material is germanium (Ge), which has the highest refractive index $n = 4$ and a relatively small absorption coefficient $\alpha = 0.75$ cm^{-1}. However, the diffraction efficiency ξ was found to be equal to $\xi = 0.05\%$ per 1 Watt input electrical power [10]. It was revealed that other AO crystals have strong absorption or sufficiently less value of the refractive index. Therefore another media must be investigated as prospective AO materials.

It is well-known that first experimental demonstration of the AO interaction was performed in liquid. In spite of the fact that the refractive index of common liquids is low $n \approx 1.4$, it is possible to achieve acceptable levels of the diffraction efficiency ξ thanks to high values of the elastooptic constant. However, liquids have stronger sound absorption than solids, and polar liquids are opaque in the THz range with absorption coefficient $\alpha > 10$ cm^{-1} due to the intermolecular interaction and the presence of hydrogen bonds [11]. Analysis of published data [12, 13, 14] has shown that only nonpolar liquids are transparent in the THz range, and cyclohexane (C_6H_{12}) has the smallest value of the absorption coefficient $\alpha = 0.37$ cm^{-1} at $\lambda = 130$ μm.

Experimental investigation of AO interaction was carried out employing Novosibirsk free-electron laser (NovoFEL) as a source of high-power monochromatic THz radiation [15]. Experimental schematic is shown in Fig. 1. Because of a large wavelength λ of THz radiation, THz beams suffer of strong diffraction if they are obstructed by any aperture. For this reason in our experiments we did not use any diaphragm. The linearly polarized NovoFEL beam with wavelength $\lambda = 130$ μm was incident on a diffractive element 2. We used two elements, which were silicon binary phase axicons with spiral configuration of zones [16]. Diameter of the both axicons was equal to 30 mm. After passing the axicons, NovoFEL beam was transformed into Bessel vortex beam with the topological charges equal to $l = \pm 1$ and $l = \pm 2$. At a distance of $z = 110 \div 260$ mm behind axicon, where the vortex beam was completely formed, the experiments has shown that the beams were "nondiffractive," which is beneficial for AO deflection. Cross-sections of