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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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Keywords: acousto-optics, vortex beam, terahertz radiation, nonpolar liquid

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

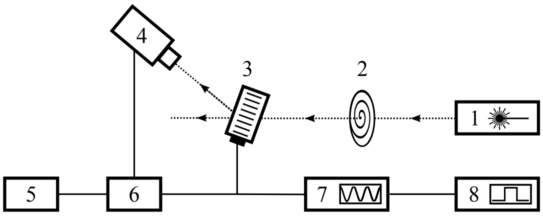

Fig. 1. Schematic of the experimental setup: 1 – NovoFEL; 2 – diffractive element; 3 – AO cell; 4 – Golay cell; 5 – personal computer; 6 – lock-in amplifier; 7 – radio frequency signal generator; 8 – pulse generator.

the beams did not change (Fig. 2), and diameter of the first ring was equal to $D_1 = 1.7$ mm for the wave with $l = \pm 1$ and $D_2 = 3.2$ mm for $l = \pm 2$.

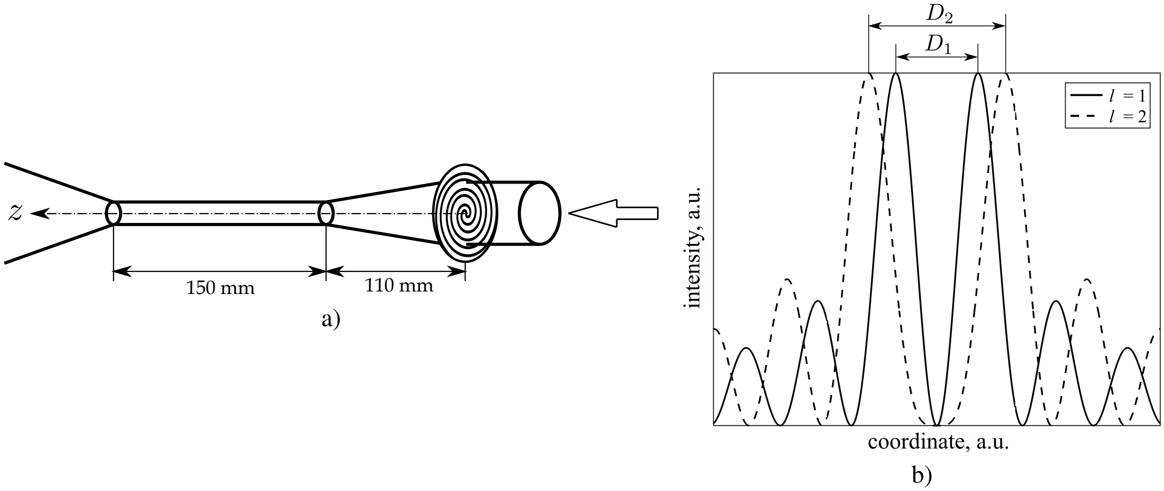

Fig. 2. Bessel vortex beam: a) generation from NovoFEL beam; b) beam cross-section for different topological charges.

The third element of experimental setup was an AO cell, four-wall duralumin camera with two polished teflon windows. The optical path was equal to 4 cm, while thickness of the windows was about 1 mm. The AO cell was filled with liquid under study (hexane, cyclohexane or white spirit), and the vortex THz beam was incident on the AO cell at the Bragg angle. Teflon is transparent in the THz region, $\alpha = 2.75$ cm^{-1}. Since its refractive index, $n = 1.445$, is approximately equal to the refractive index of nonpolar liquids [17], the multipath interference in the windows can be neglected. A circularly shaped piezoceramic transducer was employed for sound generation. In this case the diffraction efficiency ξ does not depend on the piezoelectric transducer diameter

$$\xi = \frac{2\pi}{\lambda^2} M_2 P_{\mathrm{a}}, \tag{3}$$

where P_{a} – acoustic power, which is approximately equal to the driving electrical power.

When the incident vortex THz beam crosses the sound beam, it splits into two beams. First of them propagates in the direction of incident beam and corresponds to the transmitted radiation. The second one deflects on the doubled Bragg angle in accordance with Bragg condition $\vec{k}_{\mathrm{d}} = \vec{k}_{\mathrm{i}} + \vec{K}$ and corresponds to the diffracted radiation. Here $\vec{k}_{\mathrm{d}}$ and $\vec{k}_{\mathrm{i}}$ are the wave vectors of diffracted and incident radiation, while $\vec{K}$ is the acoustic wave vector.

The radio frequency (RF) signal (3 MHz) was produced by a generator 7. The RF signal was amplitude-modulated by a square wave with a frequency of 15 Hz formed by a pulse generator 8. Since the diffracted radiation intensity was proportional to the acoustic power, it was also square modulated with the same frequency. Such modulation was necessary for proper functionality of a Golay cell 4 used for detecting THz radiation. It worth mention, that employing a chopper instead of the amplitude modulation of sound leads to higher noise level due to modulation of scattered radiation [10]. To determine intensity of the transmitted radiation, one had to employ an additional chopper with a repetition rate of 15 Hz and a calibrated attenuator to avoid Golay cell destruction. Owing to low level of the diffracted radiation intensity, a lock-in amplifier 6 had been applied, while the digital signal was processed by personal computer 5.

Results and discussion

AO diffraction of the vortex THz beam with $\lambda = 130$ μm was examined in three nonpolar liquids: cyclohexane, hexane and white spirit. The optical properties of these liquids, refractive index n and absorption coefficient α, are listed in Table 1. As one can see, the values of n in liquids are about two times smaller than those in solids. However, dispersion of n in liquids is feebly marked over the all spectrum ranges, and therefore there are no any sharp absorption peaks. Theoretical values of AOFM M_2^{calc} were calculated using published data of given liquid's physical properties [13, 14, 18, 19] and relations (1) and (2).

Table 1. Optical properties of nonpolar liquids in the THz spectrum range and experimental results

liquid	n	α, cm^{-1}	l	ξ/P_a, 10^{-5} W^{-1}	M_2, 10^{-15} c^3/kg	M_2^{calc}, 10^{-15} c^3/kg
cyclohexane	1.421 [13]	0.37 [13]	±1 ±2	5.0 5.7	160 180	600
hexane	1.372 [14]	0.69 [14]	±1 ±2	6.0 6.5	190 200	770
white spirit	–	–	±1 ±2	4.5 4.5	130 140	–

Since performed experiments are pioneer in the THz range, they has been carried out by employing vortex THz beams with different OAM ($l = \pm 1$ and $l = \pm 2$). The diffraction efficiency $\xi \approx 10^{-4}$ was achieved at 3 W input electrical power. As follows from the experimental data in Table 1, the diffraction efficiency for the vortex THz beam with $l = 2$ was slightly higher than the efficiency for the vortex beam with $l = 1$. However, the results were very close to each other, and one may suppose that the diffraction efficiency is practically independent on the OAM of vortex THz beam with small values of l. We had no enough beamtime to perform multiple experiments and verify this conclusion.

The determined values of the diffraction efficiency normalized on the acoustic power ξ/P_a enabled us to estimate the AOFM of nonpolar liquids using equation (3). It was stated that white spirit had the least value of the AOFM $M_2 \approx 130 \cdot 10^{-15}$ c^3/kg among the liquids under investigation, while the highest value $M_2 \approx 180 \cdot 10^{-15}$ c^3/kg was inherent to hexane. The calculated values of AOFM M_2^{calc} were three times higher than corresponding experimentally determined values of M_2. This fact can be explained in the following way. Previously we have found that the acoustic power was equal to the electrical input power. But actually this is not the case as the acoustic impedances of the piezoceramic and the liquids are substantially different [20]. Nevertheless, the theory and the experimental data are in qualitative agreement.

The developed laboratory prototype of AO device enabled us to control the intensity and the propagation direction of the vortex beam independently of one another. Intensity of the diffracted radiation was proportional to the power of input electrical signal, while the deflection angle $\Delta\theta \approx \lambda F/V$ was linearly related to the signal frequency F. Employment of the piezoceramic transducer working at first harmonic frequency $F = 3.0$ MHz made it posible to achieve a large deflection angle. The experimentally determined value of $\Delta\theta$ for hexane was equal to 22°, whereas for cyclohexane and white spirit it was slightly less $\Delta\theta = 19°$. Distinction between the deflection angles corresponded to the difference in sound velocities in these liquids.

Conclusion

To summarize the foregoing, pioneering research of the acousto-optic diffraction of vortex THz beam in nonpolar liquids has been done. It was established that the diffraction efficiencies for vortex beams with topological charges $l = 1$ and $l = 2$ were the same within experimental error. High values of the deflection angle of about several tens of degrees was obtained thanks to low sound velocity in liquids in comparison to solids. Since the diffraction efficiency was about one-hundredth of a percent, the obtained results can be considered as fundamental rather than practical. However, it was shown that acousto-optic devices based on liquids have a better performance than its solid-state analogue in THz range. Therefore our further efforts would be aimed at investigating terahertz vortex radiation diffraction on ultrasound in other liquids as well as at examination of new types of the acousto-optic interaction (for example, diffraction of vortex THz beam on the vortex acoustic beam).

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