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Acoustooptic operation of optical vortex beams

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ABSTRACT

Using acoustooptic (AO) cells based on TeO_2 crystal and silica glass, we have experimentally shown for the first time that the intensity profile and the phase structure of the vortex beam are preserved under AO Bragg diffraction. As a result, the vortex beam can be deflected due to AO diffraction, whereas the acoustooptically operated vortex beams can be efficiently used in such novel branches of optical technology as optical trapping and controlled addressing of the beams with different orbital angular momentums.

1. Introduction

Optical vortices bearing nonzero orbital angular momentum (OAM) can be used in different branches of optical technologies, e.g. in quantum computing [1], quantum communications, beam focusing below diffraction limit [2], and microparticle manipulation [3]. Simultaneous availability of OAM ($l = 0, \pm 1, \pm 2...$) and spin angular momentum ($\sigma^{+,-}$) in an optical beam increases the number of possible states $|\sigma^{+,-}, l\rangle$ in which the information can be encoded [4]. Therefore, any photon can carry arbitrarily large amount of information distributed over its spin and orbital quantum states [5]. This is why controlled addressing of the beams with different quantum states has become an important problem, when using photons as carriers of encoded information. In addition, spatial operation of the vortex beams acquires a fundamental character if one deals with optical trapping of microparticles. Mechanical methods such as gimbal-mounted mirrors [6], computer-controlled galvanomirrors [7] and piezoelectric mirrors [8], along with electrooptic and acoustooptic (AO) methods, are among the main techniques used for spatial operation of optical beams with the purpose of microparticle trapping [9–11]. Note that all of the methods mentioned above deal with the Gaussian beams. It is also known that some of the methods for optical trapping are based on the effect of radiation pressure. They are associated with gradient forces [12,13] (including the pressure of evanescent field [14] and that appearing in the vortex beam [3]) or, alternatively, photophoretic forces [15,16]. Each of the methods related to different types of optical beams reveals both advantages and drawbacks. For example, the trapping based on the radiation pressure and the Gaussian beams is applicable when manipulating with non-absorbing dielectric particles characterized by relatively high refractive indices, whereas the photophoretic forces are limited to trapping of absorbing particles only. The beams that bear nonzero OAM can be used for nondestructive manipulation of absorbing particles and the particles with low refractive indices, which is important for many biologic applications [17].

The most common technique employed to deflect the optical beams mentioned above is based upon AO effect. Here the beams can easily be deflected via changes in the acoustic wave frequency, while the efficiency of Bragg diffraction can be

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controlled by the acoustic power (see, e.g., Ref. [18]). Moreover, two consecutive AO cells make it possible to implement 2D deflection and addressing of microparticles to any desirable places, with high enough spatial resolutions. An AO deflector spatially controls optical beams. It makes use of acoustic frequency-dependent diffraction angle, so that the change in the angle $\Delta\theta_d$ as a function of the frequency change Δf is given by $\Delta\theta_d = \lambda\Delta f/v$ (with λ being the wavelength of optical radiation and v the acoustic-wave velocity). The technology based on AO deflectors is successfully used in tunable filters, scanners, radio-frequency spectral analyzers, etc. As a single example, we would mention that it has enabled practical implementation of Bose–Einstein condensation for which the 2001 Nobel Prize in Physics has been awarded. Another application of AO deflection is optical trapping of small molecules.

As a matter of fact, the effect of exchange by the angular momentums between the acoustic and optical beams under AO diffraction has already been successfully demonstrated (see Refs. [19,20]). However, the AO diffraction itself represents a complicated process which can be accompanied by changing degree of coherence of Bragg-diffracted optical waves [21]. The acoustic field can be inhomogeneous inside the cell due to divergence of the acoustic wave, mutual interference, internal reflection, etc (see, e.g. [22]). This can lead to different actions of acoustooptic grating on the incident vortex beam at different points of the cross-section of this beam. In principle, the latter can lead to instability or even destruction of the phase structure of a helical mode. Hence, it would be vital to clarify whether the vortex beam can be deflected by AO gratings without destruction of the phase structure of the vortex. This is of primary importance for the quantum communications, quantum computing and microparticle manipulation. In this paper, we demonstrate that the vortex beams can indeed be deflected by AO cells such that the phase distribution in their cross sections is preserved.

2. Experimental procedure

In our experiments we have used two different AO cells, an AO deflector based on TeO_2 crystal and a Q-switch made of fused silica. We have chosen TeO_2 because it is one of the most efficient AO materials often used for light deflecting, with the AO figure of merit being as high as 1200×10^{-15} s^3/kg [23–25]. This material is also convenient for AO operation of microparticle trapping. Owing to its high acoustic-wave velocity, silica glass is characterized by the AO rise times ~ 0.5 µs for the light beam diameter 3 mm, which is important for controlled addressing of OAM-bearing beams.

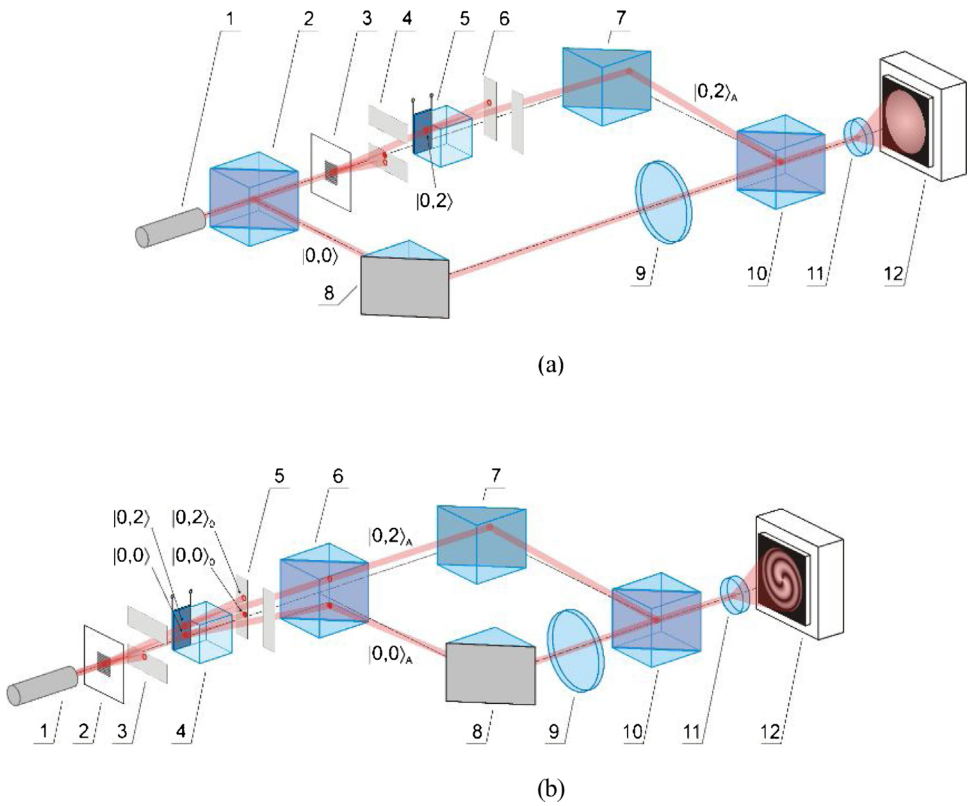

Fig. 1. Experimental set-ups used for studying interference of an acoustooptically diffracted vortex beam with a Gaussian spherical beam: (a) (1) a He–Ne laser (the wavelength 632.8 nm), (3)a computer-synthesized hologram, (4) and (6) diaphragms, (5) an AO cell, (2) and (10) beam splitters, (7) and (8) reflection prisms, (9) an optical lens with the focal length 50 cm, (11) an objective lens, and (12) a CCD camera; (b) (2)a computer-synthesized hologram, (3) and (5) diaphragms, (4) an AO cell, (6) and (10) beam splitters, (1, 7–12) the same as in panel (a).