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Simulation of propagation and transformation of THz Bessel beams with orbital angular momentum

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Abstract

Recently, terahertz Bessel beams with angular orbital momentum ("vortex beams") with topological charges $l = \pm 1$ and $l = \pm 2$ were generated for the first time using radiation of the Novosibirsk free electron laser (NovoFEL) and silicon binary phase axicons (Knyazev et al., Phys. Rev. Letters, vol. 115, Art. 163901, 2015). Such beams are prospective for application in wireless communication and remote sensing. In present paper, numerical modelling of generation and transformation of vortex beams based on the scalar diffraction theory has been performed. It was shown that the Bessel beams with the diameters of the first ring of 1.7 and 3.2 mm for topological charges ±1 and ±2, respectively, propagate at a distance up to 160 mm without dispersion. Calculation showed that the propagation distance can be increased by reducing of the radiation wavelength or using a telescopic system. In the first case, the propagation distance grows up inversely proportional to the wavelength, whereas, in the latter case the propagation distance increases as a square of a ratio of the telescope lenses foci. Modelling of the passing of the vortex Bessel beams through a random phase screen and amplitude obstacles showed the self-healing ability of the beams. Even if an obstacle with a diameter of 10 mm blocks several central rings of Bessel beam, it reconstructs itself after passing a length of about 100 mm. Results of the simulations are in a good agreement with the experimental data, when the latter exist.

Keywords: Terahertz radiation, Bessel beams, beam with orbital angular momentum

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1. Introduction

Beams with orbital angular momentum (OAM), or “vortex beams,” since 1992 [Allen et al. (1992)]] drawn significant attention. These beams can potentially transform many fields of optics and be applied to designing new kinds of devices. In the visible spectral range, they have been utilized, for example, in optical tweezers [Moura et. al. (2015)], optical vortex coronograph [Foo et al. (2005)], and communication systems [Krenn et al. (2014)]. In the latter case, an additional advantage of vortex beams is the possibility of OAM multiplexing. Many kinds of amplitude and phase elements (all of them can be classified as “holograms”) were already applied to vortex beam formation: spiral phase plates [Oemrawsingh et al. (2004), Sueda et al. (2004), Turnbull et al. (1996), Tyson et al. (2008)], a deformable mirror [Heckenberg et al. (1992)], a spatial light modulator [Jesacher et al. (2008)], or a spiral Fresnel zone plate [Weibin et al. (2009]. For completeness, it has to be noted that the application of DOEs to terahertz radiation manipulation and transformation was considered in [Agafonov et al. (2015), Agafonov et al. (2013), Knyazev et al. (2010), Siemion et al. (2011), Siemion et al. (2012), Sypek et al. (2012), Walsby et al. (2007)].

Among the vortex beams, Bessel beams (BB) [McGloin et al. (2005)] are of special interest because of their ability to propagate some distance without divergence, which is potentially beneficial for BB employment in communication systems and remote sensing. Recent publication [Soifer (2012)] showed that wireless communication systems in the terahertz (THz) range had a number of advantages comparing to the systems operating in the optical and radiofrequency ranges. Wireless technologies below 0.1 THz are not able to support Tb/ps links because of capacity limitations, whereas free space optical communication systems in the infrared and visible ranges have practical limitations because of the eye safety limits, the impact of atmospheric effects on the signal propagation (fog, rain, aerosols), high diffuse reflection losses, and the impact of misalignment between transmitter and receiver [Beijersbergen et al. (1994)].

To date, only few publications were devoted to vortex beams in the THz range. First experimental generation of THz vortex Bessel beams was described recently in paper [Choporova et al. (2015)], in which silicon diffractive optical elements (DOEs), binary axicons with spiral configuration of the phase patterns [Knyazev et al. (2015)], were applied for the transformation of a high-power Gaussian beam of Novosibirsk free electron laser [Kulipanov et al. (2015)] into the quasi-Bessel ones. The vortex beams with topological charges $l = \pm 1$ and $l = \pm 2$ were generated at a wave length of 141 μm. In these experiments the beams propagated without diffraction a distance of about 150 mm. This value is not sufficient even for in-door communication systems, and the further experimental studies of THz beam propagation are under consideration.

In this paper we consider methods, which allow extending “non-diffractive” propagation length of vortex Bessel beams formed with binary axicons. Numerical calculations were performed using the scalar diffraction theory. In addition, we investigate self-healing of THz Bessel vortex beams passed through random phase screen, or a non-transparent large-size obstacle.

2. Computer simulation

The computer simulation has been performed using Matlab software for studying beams properties. Numerical modelling of generation and transformation of vortex beams based on the scalar diffraction theory has been performed. Based on Huygens-Fresnel principle, each point of wave front is a secondary wave source (Fig. 1). The diffractive optical element was illuminated by the simulated NovoFEL Gaussian beam. Novosibirsk free electron laser generates monochromatic radiation which wavelength can be smoothly tuned within the range of 5-240 μm. The beam has a Gaussian shape with beam waist of 12 mm.

Distribution of electro-magnetic field $U(\xi,\eta)$ at the distance z behind the DOE with transmittance function $E(x,y)$ can be found through the Fresnel approximation:

$$U(\xi,\eta) = \frac{1}{i\lambda z} \cdot \exp(ikz) \iint E(x,y) \exp\left(i\frac{k}{2z}\left[(\xi-x)^2+(\eta-y)^2\right]\right) dxdy \qquad (1)$$