

Numerical simulation of broadband vortex terahertz beams propagation

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Abstract. Orbital angular momentum (OAM) represents new informational degree of freedom for data encoding and multiplexing in fiber and free-space communications. OAM-carrying beams (also called vortex beams) were successfully used to increase the capacity of optical, millimetre-wave and radio frequency communication systems. However, the investigation of the OAM potential for the new generation high-speed terahertz communications is also of interest due to the unlimited demand of higher capacity in telecommunications. Here we present a simulation-based study of the propagating in non-dispersive medium broadband terahertz vortex beams generated by a spiral phase plate (SPP). The algorithm based on scalar diffraction theory was used to obtain the spatial amplitude and phase distributions of the vortex beam in the frequency range from 0.1 to 3 THz at the distances 20-80 mm from the SPP. The simulation results show that the amplitude and phase distributions without unwanted modulation are presented in the wavelengths ranges with centres on the wavelengths which are multiple to the SPP optical thickness. This fact may allow to create the high-capacity near-field communication link which combines OAM and wavelength-division multiplexing.

Introduction

In optical communications different physical properties of an optical wave such as amplitude, phase, polarization and wavelength are used for data encoding and multiplexing. However, it was discovered in 1992 that particular light beams also possess an angular orbital moment (OAM), which represents a new informational degree of freedom. Contrary to spin angular momentum (SAM), which is associated with circular polarization of light and thus can only assume two possible states; orbital angular momentum is related to the spatial distribution of the intensity and phase of an optical field and has an infinite number of eigenstates [1].

The Poynting vector of light beams carrying OAM (also called vortex or spiral beams) has an azimuthal component along the beam, thus, such beams have an optical vortex along the axis. The well-known example of such beam is the one with an azimuthal phase dependence of $\exp(il\varphi)$, where φ is an azimuthal coordinate and l is topological charge (the number of twist in a wave front per unit wavelength [2]). Such beams have helical phase fronts with the number of intertwined helices and the handedness depending on the magnitude and the sign of topological charge, respectively [1]. The topological charge indicates the orbital angular momentum state number and can take any integer number. The intensity

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distribution of the vortex beam in transverse direction has a ‘doughnut’ shape with the dark area in the center.

Due to the unique properties of the vortex beams, they can be used in a number of different fields, for example, for the micro-manipulation in biology; for the contrast enhancement and resolution improvement in phase contrast microscopy; for the direct detection of extrasolar planets in astronomy; for the faster data manipulation in quantum information processing [3].

Since OAM has the infinite number of eigenstates it has the potential to exceedingly increase the capacity, security and spectral efficiency of communication systems [4].

Utilization of OAM for communications is based on the fact that each OAM beam with a different ℓ are mutually orthogonal [5]. That means that the group of beams this different OAM states presents the set of orthogonal modes. Thus, coaxially propagating light beams with different OAM states can be efficiently separated, enabling efficient multiplexing at the transmitter and demultiplexing at the receiver with low crosstalk [6].

High capacity data transmission exploiting quasi-monochromatic OAM beams have been reported for free-space [6] and fiber [7] optical communications. Recent reports have shown that OAM beams can be used for data transmission in radio [8] and millimeter-wave [9] communication links as well as in optical links. However, there is great interest to also show advanced multiplexing approaches at terahertz frequencies due to an increasing demand for much higher speed wireless communications, which can be possibly overcome by the operating frequency shift to the terahertz diapason. Wei *et al.* demonstrated basic functionalities for terahertz (THz) orbital angular momentum (OAM) communications, including the generation, detection, conversion, multicasting and manipulation of OAM at 0.1 THz [10] and 0.3 THz [11] using fabricated 3D printed spiral phase plates (SPPs). However, there is also a possibility to use OAM multiplexing for broadband terahertz communications, therefore, it is necessary to provide the detailed study of the broadband terahertz vortex beam generation and propagation.

Here we present a numerical simulation of propagating vortex beam generated by interaction of the broadband terahertz pulse with spiral phase plate. The aim of the work is to investigate the potential of the conventional SPP for the broadband terahertz communications.

2. Methods

OAM-carrying beams can be generated by modulating the phase delay distribution with phase modulating devices, such as q-plates, fork diffraction gratings, spiral phase plates (SPPs) and diffractive hologram displayed on spatial light modulator. In our work, we have simulated the conversion of the input Gaussian beam into OAM beam using SPP model. The SPP is a refractive optical element that can impose azimuth dependent phase retardation with an azimuthally varying thickness. The optical thickness of our SPP model increases in proportion to the azimuthal angle around the central point of the plate, and keeps constant in the radial direction. Thus the SPP introduce a linear phase delay equal to

$$\varphi(x, y) = k(n - 1)h(x, y), \quad (1)$$

where $k=2\pi/\lambda$, λ – radiation wavelength, n – refraction index, a $h(x,y)$ – function describing relief of the plate.

The initial beam represents 2 ps terahertz Gaussian pulse with frequency range from 0.1 to 3 THz and with central frequency of 0.6 THz (500 mkm). The spatial amplitude distribution of the initial pulse is shown in figure 1(a) and spatial thickness distribution of the SPP is shown in figure 1(b). The simulated SPP material is Teflon with refraction index 1.46 for the terahertz range. It should be noted that in this work we are not considering the attenuation and dispersion effects of the terahertz radiation in Teflon and in the air. The maximum thickness of the SPP is 1.162 mm thus SPP produce the vortex beam with topological charge one at the frequency 0.56 THz.

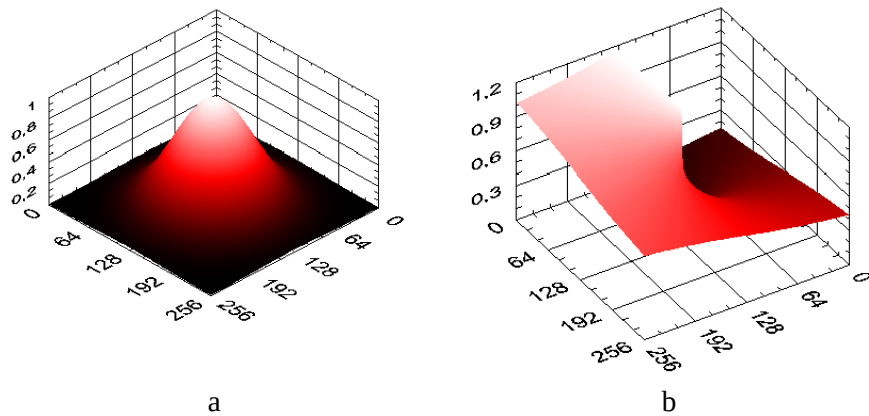


Figure 1. Spatial amplitude distribution of the initial pulse (a) and simulated spatial thickness distribution of the spiral phase plate (b).

For the field distribution calculations of the propagated helical beam we used an algorithm based on the scalar diffraction theory, which is described in details in [12]. We considered the incident terahertz beam as a sum of monochromatic components and therefore, the propagation of each frequency component was calculated independently.

3. Results and discussion

Using methods described above, we simulated the formation of an optical vortex in the SPP illuminated by a broadband terahertz pulse with a Gaussian amplitude distribution. The results presented here were obtained at transverse dimensions $D_x \times D_y = 50 \times 50$ mm of the calculation domain and a grid of 256×256 elements. The field structure is calculated at the distances 20-80 mm.

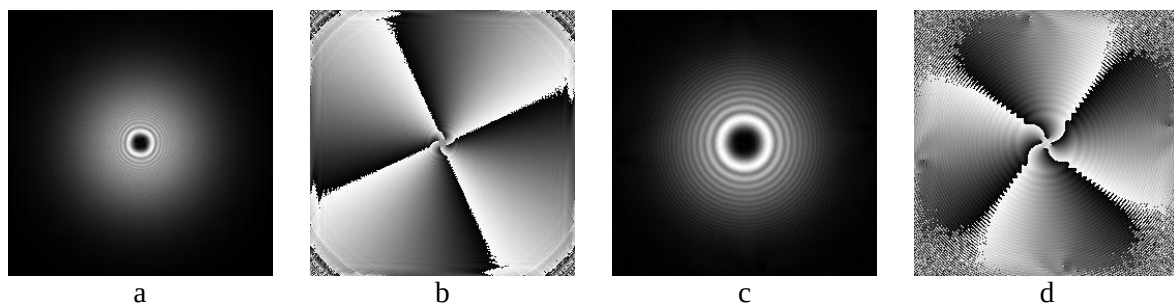


Figure 2. The amplitude (a, c) and phase (b, d) distribution of optical vortex at 2.2 THz (134 mkm) for the distances of 20 mm (a, b) and 80 mm (c, d). The vortex has topological charge four.

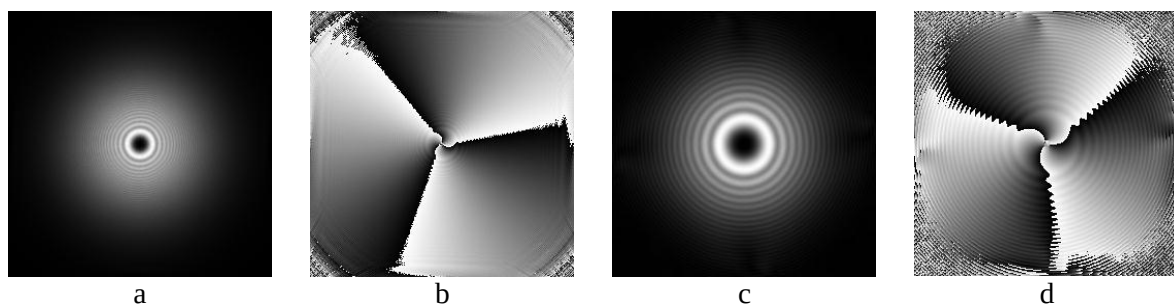


Figure 3. The amplitude (a, c) and phase (b, d) distribution of optical vortex at 1.7 THz (178 mkm) for the distances of 20 mm (a, b) and 80 mm (c, d). The vortex has topological charge three.

As can be seen from equation (1), there are only a few wavelengths for which a total phase shift is an integer value multiple to 2π and, thus, at which the clear vortex structure can be presented. One can see that due to our SPP parameters the clear vortex structure can be presented at 2.2 THz, 1.7 THz, 1.1 THz, 0.56 THz. The results of numerical calculations of the amplitude and phase distribution of optical vortices at these wavelengths for the distances 20 and 80 mm are presented in figures 2-5. The vortices produced by SPP on the listed wavelengths have different topological charges due to the difference in the total phase shifts for each wavelengths.

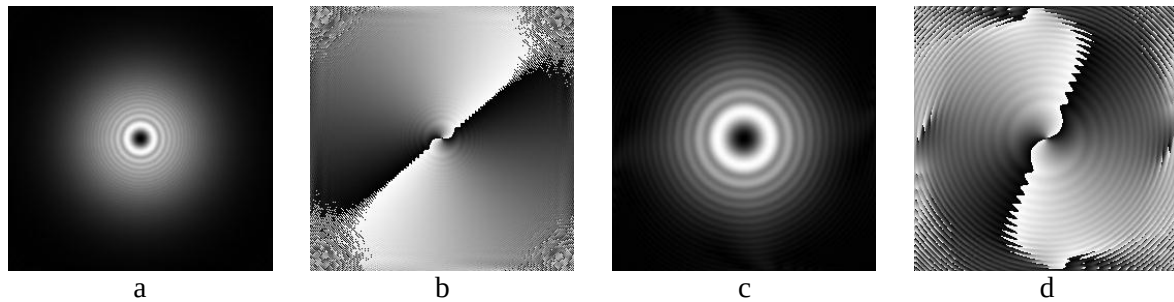


Figure 4. The amplitude (a, c) and phase (b, d) distribution of optical vortex at 1.1 THz (267 mkm) for the distances of 20 mm (a, b) and 80 mm (c, d). The vortex has topological charge two.

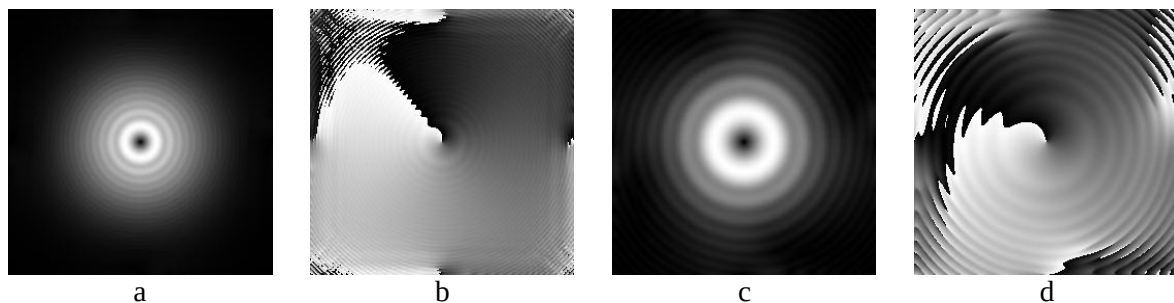


Figure 5. The amplitude (a, c) and phase (b, d) distribution of optical vortex at 0.56 THz (535 mkm) for the distances of 20 mm (a, b) and 80 mm (c, d). The vortex has topological charge one.

Amplitude and phase distributions on the other wavelengths are expected to have the unwanted modulation in the amplitude and phase distributions as shown in figure 6. However, as figure 7 illustrated, this modulation is not presented or is very slight in the frequency ranges around frequencies at which pure vortex structure is presented, for example, for ranges 2.2 - 2.3 THz; 1.66 - 1.7 THz; 1.1 - 1.15 THz and 0.54 - 0.58 THz. Therefore, these spectral ranges are channels with different OAM states and it is possible to use wavelengths-division multiplexing for each channel.

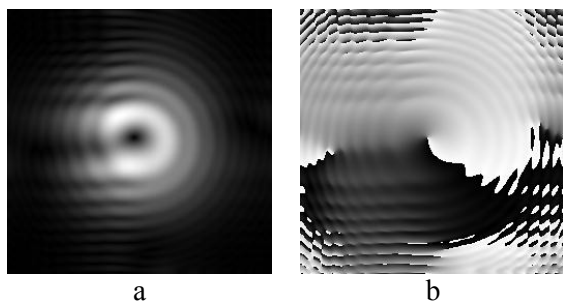


Figure 6. The example of amplitude (a) and phase (b) distribution of optical vortex with unwanted modulation at 0.42 THz (714 mkm) at the distance 50 mm.

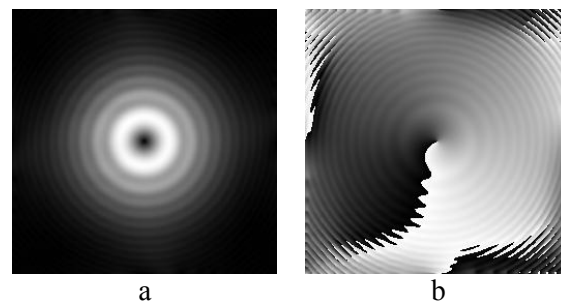


Figure 7. The example of amplitude (a) and phase (b) distribution of optical vortex without unwanted modulation at 0.55 THz (545 mkm) at the distance 50 mm.

In conclusion, the simulation-based study of the propagating in non-dispersive medium broadband terahertz vortex beams generated by a spiral phase plate showed that the amplitude and phase distributions without unwanted modulation are presented in the wavelengths ranges with central wavelengths which are multiple to the SPP optical thickness. This fact may allow to create the high-capacity near-field communication link which combines OAM and wavelength-division multiplexing.

Acknowledgments

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