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Multiplexing THz vortex beams with a single diffractive 3D printed lens

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***Abstract*—We present a novel method for experimentally generating multiplexed THz vortex beams by using a single 3D printed element that combines a set of radially distributed spiral phase plates, and a binary focusing Fresnel lens. With this element we have experimentally demonstrated that THz multiplexing can be tailored to fit within a small space on an optical bench. Results are presented beside numerical simulations, demonstrating the robust nature of the experimental method.**

***Index Terms*—Diffraction, diffractive lenses, Vortex lenses, Multiplexed vortex beams**

I. INTRODUCTION

The singular properties of terahertz radiation, such as good penetration and low scattering through various dielectric materials, non-ionizing photon energy, and broad spectral bandwidth, motivated the growing of THz photonics. Research in this field was benefited from the development of more efficient emitters, detectors, and optical components such as refractive and diffractive lenses, gratings, beam splitters, polarizers, and retarders [1, 2]. Recently, it has been demonstrated that even low cost 3D printing technology can be employed to construct non-conventional diffractive THz lenses [3-7]. In this way, technological improvements regarding THz beam shaping in the form of vortex beams, are of interest because, although such beams have found a large number of applications in the visible domain (e.g., in sensing, microscopy and astronomical imaging, trapping and manipulating of matter, and communication technologies) [8-12], few works have reported applications in the THz domain.

Vortex beams have orbital angular momentum and propagate with helical phase structure characterized by its azimuthally dependent phase $im\varphi$, in which φ is the transverse azimuthal coordinate and m is known as the topological charge. The fact that m can take any integer value motivated its use to encode and transmit information [13]. Therefore, due to its high frequency, THz beams are good candidates for information carrier of the wireless communications. Moreover, vortex beams with different m values can be used as different carriers for multiplexing and transmitting different data streams along the same spatial axis improving the performance of communication systems using electromagnetic waves.

Successful methods used to obtain THz vortex beams include: off-axis holograms [14], quarter-wave plates coupled to a wire polarizer [15], arrays of wavelength-size V-shaped antennas [16], binary phase axicons with spiral configuration of zones [17, 18, 19], and a photopatterned birefringence liquid crystal [18]. Recently, linearly and circularly polarized vortex Bessel beams were generated by employing a quartz THz quarter wave plate, a spiral phase plate, and Teflon axicons with different opening angles [21]. A metasurface based method to generate vortex beams using cross shaped resonators was also proposed [22]. However, most of these methods were demonstrated for single vortex beams. Since multiplexing several data channels has been used to significantly increase the data capacity in optical networks [23-25], in this paper, we examine the creation of composite THz vortex beams representing a superposition of vortices with different topological charges. A multiplexing approach, known as space-division multiplexing [26, 27], has been implemented to a multiplexed vortex THz lens (MVTL) using a 3D printer. The analysis of the THz vortices produced by this structure was performed experimentally and numerically for comparison.

II. DESIGN AND CONSTRUCTION

Our strategy for generating multiplexed THz vortex waves using a single element, consists on the combination of two elements represented as the product of two separable functions: one, having a radial phase dependence that can be expressed in terms of a Ronchi-type periodic function with period p in the variable $(r/a)^2$ as

$$\phi(r) = \pi\, rect[(r/a)^2 - 0.5]\, rect\left[\frac{mod[(r/a)^2+0.5p-1,p]}{p}\right] \quad (1)$$

where a is the radius of the lens. The other element is a multiplexed spiral zone plate, which only has a phase dependence (linear) on the azimuthal angle. In this element N non-overlapping annular zones are arranged using the space division multiplexing technique.

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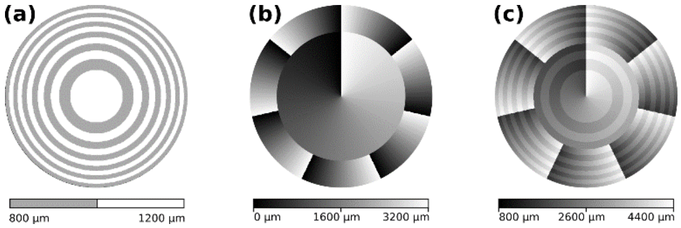

Fig. 1. Design of a multiplexed THz vortex lens. a) Base FZP using (1) with $p = 1/6$, b) Multiplexed vortex SPP with topological charges inner part and outer part. c) Composite vortex lens as the superposition of a) and b). Gray levels represent the lens thickness.

$$\tau(\theta) = \left\{ \begin{array}{c} m_1\theta, \quad 0 \le r < r_1 \\ \ldots \\ m_j\theta, \;\; r_{j-1} \le r < r_j \\ \ldots \\ m_N\theta, \; r_{N-1} \le r < a \end{array} \right\} \qquad (2)$$

In this way the transmittance of the lens is given by equation $T(r,\theta) = e^{i[\phi(r)+\tau(\theta)]}$.

As a demonstration, we propose a MVTL that consists on the combination of two spiral phase functions with different topological charges m_1 and m_2, designed to work at 0.625 THz, and made of PA6 polyamide (absorption coefficient = 3.9 cm^{-1} and refractive index n = 1.6). Other 3D printed material were studied in Ref. [4].

The MVTL composition from its components is shown in Fig. 1. On the one hand, the MVTL (Fig. 1a) was designed with alternate zones of thickness t_1=0.8 mm and t_2=1.2 mm which have been calculated to provide a phase shift π between the zones for the design wavelength of $\lambda = 480\ \mu m$, and using the following expression: $\Delta t = t_2 - t_1 = \lambda/2(n-1)$ On the other hand, the spatially multiplexed THz Spiral Phase Plate (SPP) (Fig. 1b) has two parts. The inner part, with topological charge $m_1 = -1$ is a circle of radius 14.67 mm that covers the 4 inner rings of the FZP. The outer part, with topological charge $m_2 = 7$ has an annular shape with an outer radius 25.4 mm and covers from the 5th to the 12th of the FZP. In each part, the thickness of the SPP depends on the azimuthal angle around the center of the SPP, as

$$h(\theta) = mod(m\theta, 2\pi)\frac{\lambda}{2\pi(n-1)} \qquad (3)$$

Thus, a total phase shift of $|2\pi m|$ will be imprinted on the electromagnetic wave by each part of the SPP. Taking into account that this approach requires extreme precision in the pitch of helical surface, in order to reduce the fabrication errors we incremented the thickness in each point of the SPP by a constant factor $k = 4$ providing an effective topological charge of km.

In this way for the plate in Fig. 1b), $0 \le h \le 3.2\ mm$. Thus, the final THz design, shown in Fig. 1c), results as the superposition of the plates in Fig. 1a) and Fig. 1b).

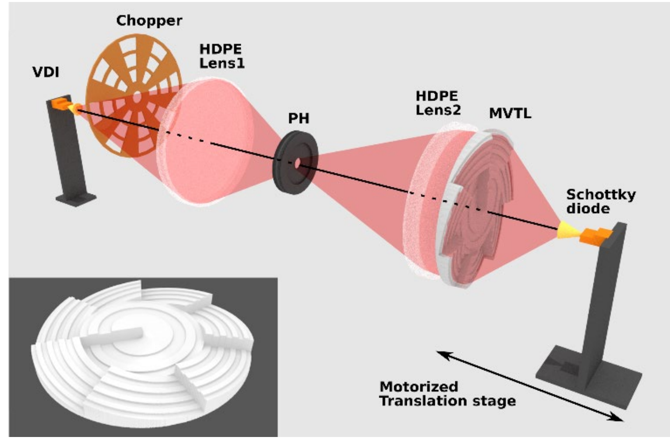

Fig. 2. Experimental setup for obtaining multiplexed THz vortex beams. The inset shows a CAD design of the MVTL experimental model.

III. Experimental Setup

The experimental setup for obtaining multiplexed THz vortex beams is shown in Fig. 2. A frequency multiplier based on Schottky diode (Virginia Diodes, Inc. Charlottesville, VA. USA), was used as a source of radiation. The source was equipped with a waveguide, which ends in a horn antenna producing linearly polarized Gaussian beam at 0.625 THz. In our case the electric field was perpendicular to the ground. The beam was focused on a pinhole (2 mm diameter) by a high density polyethylene (HDPE) refractive lens. Then, the radiation was collimated, by a second HDPE lens, and directed onto the MVTL. The intensity distribution after the MVTL was scanned with a Schottky diode detector VDI (Virginia Diodes, Inc. Charlottesville, VA. USA) also equipped with horn antenna (WR-1.5), having a 2.4 mm aperture diameter. As each component of our experimental setup was a passive element that do not changed the polarization of the input beam, the detector was aligned to have the same orientation of the source. The detector was mounted on a 3D motorized stage which allows high precision movement. To measure the signal from the detector, a lock-in system (Stanford Research Systems SR830), based on modulation at 187 Hz and a mechanical chopper, was used.

The inset in Fig. 2 shows the experimental model, which was designed using a CAD software (blender.org) and constructed with a 0.3 mm spatial resolution by an online 3D printing service (i.materialise, Leuven, Belgium). The MVTL was made from a polyamide granular powder by selective laser sintering technique. The diameter of the constructed lens was 50.8 mm, and the FZP has the main focal distance (first diffraction order) of 112 mm.

IV. Results

Beam transverse irradiance profiles provided by the composite helical beam were recorded after the MVTL, along the optical axis in 1 mm intervals with an accuracy of 2 μm. Experimental results at five different planes are shown in Fig. 3 in comparison with numerical results computed using the Fresnel-Kirchhoff nonparaxial scalar diffraction theory [6].

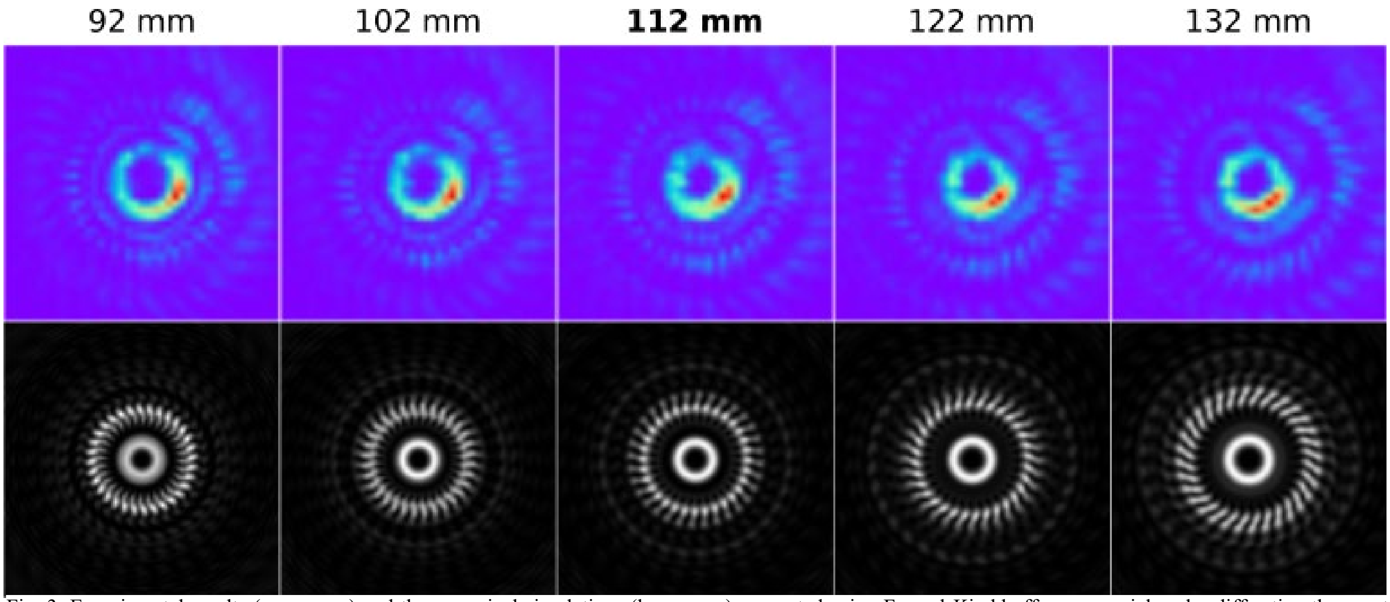

Fig. 3. Experimental results (upper row) and the numerical simulations (lower row) computed using Fresnel-Kirchhoff non-paraxial scalar diffraction theory at different transverse planes around the MVTL focal plane (z = 112 mm).

As expected the two main vortices are in focus at the MVTL focal distance, the inner vortex corresponds to the topological charge $m_1 = -1$, while the outer vortex corresponds to the topological charge $m_2 = 7$. The last one also exhibits a complex structure with a cosenoidal azimuthal variation. In fact, $k(m_2 - m_1) = 32$ lobes appear, as it was expected by the theoretical analysis [28].

Despite of the differences between the physical lens and the theoretical design, due to the limitations of the 3D printer resolution (especially near the center of the plate), the agreement between theory and experiment can be appreciated in Fig.3. Additional vortices, seen in the experimental results, are the consequence of non-integer steps heights of the lens designed for only one spectral component. Other sources of discrepancy between experimental and theoretical results are the inhomogeneities of the index of refraction and the finite size of the lens. Multiple reflections and standing waves in the MVTL, may also lead to azimuthal modulations in intensity [29].

V. Conclusions

We have demonstrated the feasibility of realizing THz multiplexed vortex beams, with 3D printing technology. PA6 phase lenses were constructed and tested using 0.625 THz beam in a simple experimental THz setup. The experimental results were in good agreement with the simulations despite some sources of errors, demonstrating the robustness of our proposal. In this way, this work extends to the THz domain previous use of phase optical elements in the visible domain [30] that could find many applications in THz technologies. For instance, there have been recent growing interest in applying vortex beams to wireless communications [31] and through mode multiplexing, vortex beams can tremendously increase the capacity of communication systems.

These novel techniques, developed for utilizing THz spectrum can be improved to achieve very high efficiency. In this sense, it has been demonstrated that dependencies of the vortex radius and width on topological charge can be controlled [30], and, therefore, multiplexed THz vortex rings can be produced efficiently.

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