Generation and evolution of the terahertz vortex beam

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Abstract: Based on the complementary V-shaped antenna structure, ultrathin vortex phase plates are designed to achieve the terahertz (THz) optical vortices with different topological charges. Utilizing a THz holographic imaging system, the two dimensional complex field information of the generated THz vortex beam with the topological number \( l = 1 \) is directly obtained. Its far field propagation properties are analyzed in detail, including the rotation, the twist direction, and the Gouy phase shift of the vortex phase. An analytic Laguerre-Gaussian mode is used to simulate and explain the measured phenomena. The experimental and simulation results overlap each other very well.

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References and links


1. Introduction

As special light beams, vortex beams are always interesting members in optics, which possess helical wavefronts, an on-axis phase singularity, and quantization orbital angular momentums [1–3]. Owing to the unique properties, vortex beams have been applied in many industrial and research fields, such as optical micro-manipulation [4, 5], bio-medical [6–8], optical information transmission [9–11], and so on. Researchers have paid more and more attention on investigations about optical vortices. Currently, techniques for generating optical vortices mainly include mode converters [12, 13], computer generated holograms [14, 15], spiral phase plates [16], and so on. Many methods have been proposed to detect optical vortices, such as the measurement of the mechanical torque arising from orbital angular momentum [2, 3], Stokes parameters method [17], dispersion and phase modulation method [18], and the traditional interferometric method [19].

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As a novel far infrared radiation, the terahertz (THz) ray has become a hot topic of optical researches in the past decades and the THz technology has exhibited strong application potentials in many imaging and sensing fields [20–23]. However, there are only considerably less works about the THz vortex beam [24]. In the radio frequency community, a discrete sub-wavelength two dimensional structure concept has been proposed to design reflectarray and lens-array elements for modulating the phase distributions of electro-magnetic waves. Currently, the technique has been rapidly developed for advanced sensing or communications applications [25–30]. In 2011, N. F. Yu et al. proposed a V-shaped antenna meta-surface structure to achieve the phase modulation for cross polarized scattered fields [31]. In 2012, P. Genevet et al. utilized the design to build a vortex phase plate (VPP) and generate an optical vortex in the infrared wave band [32]. In 2013, we extended the structure into the THz wave band and fabricated ultrathin THz lenses and phase holograms [33].

In this paper, the complementary V-shaped antenna structure is applied to mold ultrathin VPPs in the THz wave band. Utilizing a THz holographic imaging system, the complex field information of the generated THz vortex beam with the topological number \( l = 1 \) is coherently measured and its far field propagation properties are investigated in detail. A basis Laguerre-Gaussian mode is used to simulate and explain the evolutions of the intensity and phase of the THz vortex beam. This work prompts the development of ultrathin THz elements and investigations on the THz vortex beams.

2. Designs

![Diagram](https://via.placeholder.com/150)

Fig. 1. (a) A complementary V-shaped antenna phase modulation unit. (b) Eight kinds of complementary V-shaped antenna structures corresponding to phase shifts from \(-3\pi/4\) to \(\pi\) with a \(\pi/4\) interval. (c) Photography of the central region of the designed vortex phase plate (VPP) for \(l = 1\).

According to [33], based on the surface plasmonic resonance effect, eight kinds of complementary V-shaped slit antennas are designed to realize the various phase shifts for the transmitted cross polarized lights. Figure 1(a) shows the design sketch of the antenna on the X-Y plane. Each antenna unit consists of two equivalent rectangular slits connected at one end in a square region with a length \(p = 200\ \mu m\). The slit width \((w = 5\ \mu m)\) is fixed. The slit length \((h)\), the angle \((\theta)\) between two slits and the angle \((\beta)\) between the bisector line of the V-shaped antenna and the Y-axis can be adjusted to achieve the phase modulation of the scattered field. It should be noted that the selection of the complementary structure is to ensure the enough diffraction efficiency of the expected THz spectral component. Figure 1(b) presents eight antenna designs which correspond to the phase distributions of the scattered fields from \(-3\pi/4\) to \(\pi\) with a \(\pi/4\) interval. The first four antennas have \(\theta = 130^\circ, 120^\circ, 100^\circ, 60^\circ\) with corresponding lengths of \(h = 78, 82, 90, 150\ \mu m\), while the \(\beta\) is fixed as \(45^\circ\). The other four units are the mirror images of the first four ones.
To built a VPP with the topological number \( l = 1 \), the required phase distribution in polar coordinates \((r, \alpha)\) can be easily calculated by \( \phi = l\alpha \). The phase values are quantized to eight values. A series of complementary V-shaped antennas are picked in terms of the phase distribution and are filled in the corresponding positions. The designed VPP consists of 40×40 units in the 8×8 mm\(^2\) area. In the experiment, the VPP is fabricated in a gold film (with a 100 nm thickness) deposited on a double-side polished high resistivity silicon substrate (with a 500 \( \mu \)m thickness) using the conventional photolithography and metallization process. The central region of the VPP is shown in Fig. 1(c). The central wavelength of the VPP is 400 \( \mu \)m (corresponding to 0.75 THz), so the thickness of the effective layer of the VPP is only 1/4000 of the wavelength. When the incident THz beam with a horizontal polarization passes through the VPP, the transmitted vertical polarized THz beam has same transmission intensity and the corresponding phase modulation on each antenna unit. Then, a vortex THz field is formed.

3. Results and discussions

3.1 Complex field information of the THz vortex beam

Fig. 2. (a) Terahertz (THz) holographic imaging system. (b) and (c) display the measured intensity and phase distribution of the generated THz vortex beam with \( l = 1 \) at 0.75THz, respectively. (d) The phase curves with the azimuthal angle \( \alpha \) and the radial distance \( r = 1.5 \) mm.

To check the function of the VPP, a THz holographic imaging system [34, 35] is utilized to measure the intensity and phase information of the transmitted cross-polarized THz field. Figure 2(a) shows the experimental scheme. A laser beam with a 800 nm central wavelength, a 100 fs pulse duration and a 1 kHz repetition ratio illuminates a <110> ZnTe crystal (not shown in Fig. 2(a)) to radiate the horizontal polarized THz wave with a 15 mm diameter due to the optical rectification effect. After the THz wave passing through the VPP, the transmitted THz vortex beam with a vertical polarization impinges on the sensor crystal (another <110> ZnTe with a 3 mm thickness). The probe beam with a vertical polarization is reflected onto the sensor crystal by a 50/50 non-polarization beam splitter (BS). In the crystal, the probe polarization is modulated by the THz field to carry the two dimensional THz information. To measure the THz vertical polarization component, the <001> axis of the sensor crystal is perpendicular with the vertical direction [34, 36]. The reflected probe beam is incident into the imaging unit of the system and the THz complex field is extracted by the balanced electro-optic detection technique. The detailed principle
about the imaging system has been published in [34, 35]. By changing the optical path difference between the THz beam and the probe beam, 128 THz temporal images are obtained and the corresponding time window is 17 ps. Performing the Fourier transformation on the temporal signal at each pixel, the intensity and the phase information of the 0.75 THz component is exactly extracted. It should be noted that the refractive index of the silicon substrate is about 3.4 at 0.75 THz [37], so its optical thickness reaches to 1.7 mm and the time difference between the main pulse and echo pulse is about 11 ps. Utilizing zero-padding, the interference effects between the main pulse and echo pulse is removed.

Figures 2(b) and 2(c) show the intensity and phase distributions of the 0.75 THz vortex beam. It should be noted that when the value is less than 0.2 on the normalized THz intensity image, the color of the corresponding pixel is set as gray on the phase map to filter the uncertain noise. It can be seen that the intensity distribution is mainly uniform except for two regions with higher transmissivity. The difference may be caused by the fabrication error. The phase map exhibits the expected variation. The distance between the VPP and the sensor crystal is about 4 mm. Owing to the diffraction, the measured phase presents a smoothly monotonically increase from $-3\pi/4$ to $\pi$ with the azimuth angle $\alpha$. To more clearly observe the phase distribution, the phase data with various $\alpha$ and fixed $r = 1.5$ mm are extracted and plotted in Fig. 2(d). It shows the good linear relationship between the phase and the azimuth angle, which demonstrates that the designed VPP can be applied to form a THz vortex beam well.

3.2 Evolution properties of the THz vortex beam in the far field

To investigate the evolution properties of the THz vortex beam in the far field, a silicon lens with a 25 mm focal length and a 25.4 mm diameter is used to focus the THz field and a Z-scan measurement is performed by moving the lens and the VPP together around the focal spot, as shown in Fig. 3(a). The distance between the VPP and the lens is about 4 mm. The position of the focal spot is set as the initial point. The scan range along the Z-axis is from $-20$ mm to 20 mm with the 1 mm scan resolution. On each scan point, the 0.75 THz spectral component is extracted to build the focusing process of the THz vortex beam. The intensity and the phase evolutions of the 0.75 THz vortex beam around the focal spot are recorded in Media 1 and Media 2 of Figs. 3(b) and 3(c). Figures 3(b) and 3(c) show that the intensity and the phase maps with $Z = -20$ mm, $-10$ mm, 0 mm, 10 mm, 20 mm on the X-Y plane. The intensity of the converging THz wave shows a doughnut shape due to the central phase singularity. On the focal plane, the radius of the THz ring beam is about 1.1 mm. The non-uniformity on the ring is attributed to the transmission discrepancy on the VPP (as shown in Fig. 2(b)). In the phase evolution, the phase profile presents a spiral distribution and always rotates in a clockwise sense when the vortex beam approaches or departs the focal spot. Meanwhile, twist directions of the phase before and after the focal spot are opposite.

To explain these phenomena in the phase evolution, the vortex beam is decomposed by a series of basis Laguerre-Gaussian (LG) modes $E_p^l(r, \alpha, z)$, which is given by

$$E_p^l(r, \alpha, z) \propto \left[ \frac{\sqrt{2r}}{w(z)} \right] L_p^l \left( \frac{2r^2}{w(z)^2} \right) \exp \left[-\frac{r^2}{w(z)^2} \right] \exp \left[-i \frac{kzr^2}{2(z^2 + z') + il\alpha + i\Phi_p(z)} \right],$$

where $k$ is the wave number in vacuum, $p$ is the radial index which is 0 for a linear polarized LG mode, $L_p^l(x)$ is the generalized Laguerre polynomial. $w(z)$ is the beam radius at a propagation distance $z$, as given by

$$w(z) = w_0 \sqrt{1 + z^2 / z_n^2}.$$
Parameter $z_R$ is the Rayleigh range and is expressed as $z_R = k w_0^2 / 2$. $w_0$ is the radius of the beam waist. In addition, $\Phi_G(z)$ is the Gouy phase shift, which is an additional phase shift for a beam passing through the focal region. It is given by [24]

$$\Phi_G(z) = (2 \rho + |l| + 1) \text{arc tan}(z / z_R).$$  

(3)

![Diagram of experimental setup for observing the intensity and phase evolutions of the THz vortex beam in the focusing process.](image)

Fig. 3. (a) Experimental setup for observing the intensity and phase evolutions of the THz vortex beam in the focusing process. (b) Media 1 and (c) Media 2 are the intensity and phase maps of the measured THz vortex beam with $Z=-20$ mm, -10 mm, 0 mm, 10 mm, and 20 mm. (d) Phase distributions of the Laguerre-Gaussian (LG) mode with $l$ at $Z=-20$ mm, -10 mm, 0 mm, 10 mm, and 20 mm. (e) Correlation coefficients of the basis LG modes in the measured THz vortex beam.
In our experiment, correlation coefficients of the LG modes in the measured THz vortex beam $E_v$ are calculated by

$$C_{p,l} = \iint E_v (E_v')^* r dr d\alpha,$$

where the asterisk denotes the complex conjugate, $z$, $w_0$ and $k$ are set as 0 mm, 1.1 mm and 157 cm$^{-1}$ (corresponding to 0.75 THz). Figure 3(e) presents the relative charge distribution for the measured vortex beam. It can be seen that the generated vortex field is 87% correlated with the LG mode of $l = 1$, $p = 0$. It means that the main phase properties of the vortex field can be explained by analyzing the analytic expression of the LG mode. According to Eq. (1), the phase distributions of the LG mode with $l = 1$, $p = 0$ at $Z = -20$ mm, $-10$ mm, 0 mm, 10 mm, 20 mm are calculated, as shown in Fig. 3(d). It can be seen that the simulation results are in well agreement with the experimental ones.

![Fig. 3](image)

The phase of the LG mode includes three terms $-\frac{kzr^2}{2(z_R^2 + z^2)}$, $l\alpha$ and $\Phi_G(z)$. To identify their functions, the phase distributions of $l\alpha + \Phi_G(z)$ and $-\frac{kzr^2}{2(z_R^2 + z^2)} + l\alpha$ are calculated at $Z = -20$ mm, $-10$ mm, 0 mm, 10 mm, 20 mm, respectively. Figures 4(a) and 4(b) give the theoretical results. In Fig. 4(a), the vortex phase exhibits a clockwise rotation as the propagation distance, which denotes that the $l\alpha$ forms a vortex phase and the term $\Phi_G(z)$ determines the rotation of the vortex phase. In Fig. 4(b), the vortex phase presents a spiral distribution and its twist has an inverse direction after passing through the focal spot, which demonstrates that the term $-\frac{kzr^2}{2(z_R^2 + z^2)}$ converts the vortex phase into a spiral profile and causes the variation of its twist direction.
3.3 Gouy phase shift of the THz vortex beam

To further observe the propagation properties of the THz vortex beam in the focusing process, its Gouy phase shift is also investigated. On different positions of the Z-axis, the central lines (X = 0 mm) of each intensity and phase maps are extracted to exhibit the longitudinal distributions of the THz field, as shown in Figs. 5(a) and 5(c). In Fig. 5(a), the cross section of the ring intensity distribution of the focused THz vortex beam is presented, which is symmetrical along the Z-axis. In Fig. 5(c), the phase evolution of the THz vortex beam in the focusing process is clearly displayed. The phase rotation and the variation of the twist direction can be observed in Fig. 5(c). The longitudinal phase shift around the optical axis only reaches about 1.5\( \pi \) due to the limitation of the measurement range.

To compare with the experimental results, propagation of the LG mode with \( l = 1, p = 0 \) is also calculated from \( Z = -20 \) mm to \( Z = 20 \) mm with the 1 mm interval. The intensity and phase maps are exhibited in Figs. 5(b) and 5(d), respectively. It is clear that the experimental results are in excellent agreement with the simulation ones. To obtain the Gouy phase shift, the paraxial phase values (\( Y = 0.25 \) mm) in Figs. 5(c) and 5(d) are extracted and plotted in Fig. 5(e). The data on the optical axis (\( Y = 0 \) mm) are not selected for avoiding its phase singularity and noise. In Fig. 5(e), the red solid curve and the blue squares represent the theoretical and experimental results, respectively. Both of them present a 1.5\( \pi \) phase change and match each other very well. The phenomena nicely manifest the Gouy phase shift of the THz vortex beam between the front and the back of the focal point.
3.4 THz vortex beams with other topological numbers

To further demonstrate the validity of the VPP design method, other two VPPs with \( l = 2 \) and \( l = 3 \) are designed and fabricated. The photographs of their central regions are shown in Figs. 6(a) and 6(b). The THz imaging system is used to check effects of the two VPPs. The experimental results are presented in Figs. 6(c) and 6(d). It is evident that the expected vortex phase distributions for the 0.75 THz component are formed, which exhibited the linear phase variation in two and three cycles around the optical axis. To check the qualities of generated vortex beams, the vortex phase distributions with \( l = 2 \) and \( l = 3 \) are simulated by using the phase term \( l \alpha \). The simulation results are shown in Figs. 6(e) and 6(f), which are consistent with the experimental results. It indicates that THz vortex beams with higher topological numbers can be generated using this technique.

4. Conclusions

In a conclusion, the ultrathin planar THz VPP is designed based on the complementary V-shaped antenna structures and the THz vortex beam with the topological number \( l = 1 \) is generated utilizing the VPP. By utilizing the THz holographic imaging system, the vortex phase distribution of the THz beam is observed and the propagation properties of the THz vortex beam in the far field are investigated. Taking advantage of the LG mode with
In addition, the experimental results also demonstrated that the THz vortex beams with higher topological numbers can be generated based on the method. We believed that the work is valuable for investigations on special light beams, the exploitation of planar THz elements and the THz information transmission.

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