Full vector measurements of converging terahertz beams with linear, circular, and cylindrical vortex polarization

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Abstract: The complete vector information of converging terahertz (THz) beams with linear, circular, and cylindrical vortex polarization are precisely measured by using a THz digital holographic imaging system. The transverse ($E_x$, $E_y$) and longitudinal ($E_z$) polarization components of the THz fields around the focal point are separately obtained utilizing the detection crystals with different crystalline orientations. The measured results are in good agreement with the theoretical expectations. This imaging technique provides an effective way for revealing the vector diffraction properties of the THz electro-magnetic waves.

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References and links

1. Introduction

Understanding the diffraction properties of electromagnetic waves is an important basis for both physical optics and applied optics. Under the paraxial approximation, a light field can be generally described with the scalar diffraction theory and the polarization property of the light field is usually ignored. However, the vector characteristic of the light field plays an important role and should be considered in the non-paraxial regime. Specially, its longitudinal field distribution must be paid great attention. Some special beams, such as the radially polarized beam [1, 2], double-ring-shaped radially polarized beam [3], and the sinh-Gaussian polarization component, have been investigated due to their intriguing longitudinal components. These special beams can be applied in particle accelerators [5], high-resolution microscopes [6], and optical data storage [7], optical trapping [8], and so on. Many techniques have been proposed to measure the longitudinal component of the light beam. L. Novotny et al. utilized the fluorescence of signal molecules with fixed absorption dipole orientations to probe the longitudinal field distribution [9]. S. Quabis et al. combined a knife-edge method with the tomographic reconstruction to determine the three dimensional intensity distributions around the focal point of an optical system [10]. G. Miyaji et al. measured the longitudinal component of a radially polarized laser beam by imaging the laser-induced birefringence of a Kerr medium [11]. C. Eoffey et al. developed a far-field detection system which is composed with a confocal microscope, an axial and a linear polarizer to probe the longitudinal components of the electric and magnetic optical field [20]. Unfortunately, only the intensity distribution of the longitudinal component can be obtained by using these methods and the phase information is lost completely.

Terahertz (THz) sensing and imaging techniques have been widely applied in basic research and industrial fields due to the distinctive advantages of the THz radiation [13–17]. By using the electro-optic sampling method, both amplitude and phase information of the...
THz signal can be simultaneously obtained. In addition, the transverse and longitudinal components of the THz field can be separately measured by using detection crystals with different crystalline orientations. In previous reports, the field distribution of the longitudinal THz component has been observed on the surface of a plasmonic device [18] and in the free space [19, 20]. However, the experimental time was consumed and the sampling rate was limited in these works because the THz images were built by the raster scanning method.

In recent years, a THz digital holographic imaging system with high resolution, enough signal-to-noise ratio, and polarization detection ability has been developed. This system has been applied in various areas, including the measurement of THz waveguide modes [21], performance demonstration of the THz metasurface elements [22], and observation of the diffraction process of the THz field [23]. In this paper, this imaging system is adopted to coherently probe the vector fields of converging THz beams with linear, circular, and cylindrical vortex polarization, respectively. The transverse and longitudinal components of the THz field around the focal point are achieved by employing a <110> or a <100> ZnTe crystal, respectively. Besides, the vector diffraction theory is adopted to simulate the propagation of vector THz beams and a good agreement between the experimental results and theoretical expectation are found.

2. Experimental Setup

In this work, a THz digital holographic imaging system shown in Fig. 1(a) is utilized to characterize the diffraction features of the converging THz beams with different polarization. The used light source is a Spectra-Physics laser amplifier system with 800 nm central wavelength, 50 fs pulse duration, 1 kHz repetition ratio, and 900 mW average power. The femtosecond laser is divided into the pump beam with 890 mW to generate the THz radiation and the probe beam with 10 mW to detect the THz radiation, respectively. A <110> ZnTe crystal with 3 mm thickness [is not shown in Fig. 1(a)] is used to radiate the THz wave via the optical rectification effect. The diameter of the THz beam is about 21 mm. The incident THz beam with the linear polarization (x direction) is focused by a silicon (Si) lens with a focal length of 25 mm. In the path of the probe beam, a half wave plate (HWP) and a polarizer (P) are used to adjust the probe polarization for measuring different THz polarization components [24]. The probe beam is reflected into a detection crystal by a 50/50 non-polarization beam splitter (BS). In the crystal, the two dimensional THz field information is loaded on the polarization change of the probe beam. The modulated probe beam is reflected into the imaging module of the system, which consists of a quarter wave plate (QWP), a Wollaston prism (PBS), two lenses (L1 and L2) and a CY-DB1300A CCD camera (Chong Qing Chuang Yu Optoelectronics Technology Company). The CCD camera is synchronously controlled...
with a mechanical chopper which is inserted into the path of the THz beam to capture the image of the probe beam. The THz information is extracted by using the balanced electro-optic detection technique [24] and the dynamic subtraction technique [25]. The imaging area is 8 mm × 8 mm and the number of pixels of a THz image is 300 × 300. The principle of the imaging system has been detailedly discussed in [24]. To acquire the THz temporal images, the optical path difference between the THz beam and probe beam is successively changed using a delay line. The scan time window is 17 ps and the step is 0.13 ps. The amplitude and phase distributions of each spectral component can be obtained by performing a Fourier transformation on the THz temporal signal at each pixel.

To measure the vector THz field, the detection crystals with different crystalline orientations are used. When the transverse THz components are measured, a 1 mm thick <110> ZnTe is chosen as the detection crystal. If the polarization of the probe beam is parallel to the <001> axis of the ZnTe crystal, the horizontal component $E_x$ can be obtained; If the angle between the polarization of the probe beam and the <001> axis of the ZnTe crystal is 45°, the vertical polarization component $E_y$ is obtained [24]. When the longitudinal THz component $E_z$ is measured, a 1 mm thick <100> ZnTe crystal is selected. In this case, the optimal angle between the polarization of the probe beam and the <010> axis of the ZnTe is 45° [19].

To characterize the focusing processes of THz beams with different polarization, some optical elements are utilized. As shown in Fig. 1(b), a quartz THz quarter wave plate (TQWP) is used to convert the primitive linear polarization into a circular polarization. A TQWP and a THz wire radial polarizer (TWRP) are used to convert the linear polarization into a cylindrical vortex polarization [26–28], as shown in Fig. 1(c). The properties of these elements will be discussed in Section 3. These elements are mounted in the path of the THz beam, as shown with the dashed box in Fig. 1(a). A Z-scan measurement is performed by moving these elements and a Si lens together around the focal point to record the evolution of the converging THz beam. The focal point is set as the origin. The scan range is from −10 mm to 10 mm and the scan step is 1 mm.

3. Results and discussions

3.1 Linear polarization

First of all, the focusing process of a THz beam with linear polarization is investigated. The polarization of the THz field is along the x direction. The amplitude and wrapped phase distributions of the transverse component $E_x$ for 0.7 THz on the x-z plane are shown in Figs. 2(a) and 2(b), respectively. The focusing process can be clearly observed in Fig. 2(a). The diameter of the focal spot is about 0.7 mm and the focal depth is about 6.5 mm. In the phase map, the phase variation is in good agreement with the focusing properties of a Gaussian beam [23]. The color of the pixel whose amplitude value is less than 20% of the maximum value is set as gray to filter the phase noise in the phase image. In addition, the linear phase shift $kL$ ($k$ and $L$ are the wave number and the optical path of the THz beam) is removed because that the optical path of the THz beam remains unchanged during the Z-scan measurement. The amplitude and phase distributions of $E_y$ for 0.7 THz are shown in Figs. 2(c) and 2(d). Their features are very similar to those of $E_x$ except for the very weak amplitude. The $E_y$ component appears here is mainly caused by the incomplete linear polarization of the generated THz radiation. The degree of the polarization $(I_x - I_y)/(I_x + I_y)$ on the optical axis is calculated to check the variation of the THz polarization during the focusing process [29], where $I_x$ and $I_y$ are intensities of $E_x$ and $E_y$, respectively. The result is plotted in Fig. 2(e). It can be seen that the degree of polarization almost keeps a constant 1 around the focal point, which demonstrates that the THz
polarization is not influenced during the focusing process. In the experiment, the numerical aperture (NA) of the THz lens is about 0.39. With such low NA, the polarization of the THz field cannot be influenced [30].

Fig. 2. Focusing process of a linear polarization THz light. (a) Longitudinal amplitude distribution and (b) corresponding phase distribution of $E_x$ around the focal point when a linearly polarized THz radiation is focused. The frequency of the radiation is 0.7 THz. (c) The corresponding amplitude and (d) phase distributions of $E_y$. (e) Degree of polarization on the optical axis.

Utilizing a <100> ZnTe crystal, the longitudinal component $E_z$ of the converging THz beam is measured. The measured amplitude distributions for the 0.7 THz on the planes of $z = -10$ mm, $-5$ mm, 0 mm, 5 mm, and 10 mm are presented in Fig. 3(a), respectively. The corresponding cross-sectional distribution of $E_z$ on the x-z plane ($y = 0$ mm) is shown in Fig. 3(c). A dipole like distribution of $E_z$ can be found, which is caused by the rotational symmetry breaking of the THz polarization after the Si lens [31]. On the focal plane, the minimum value of $E_z$ appears on the optical axis ($x = 0$ mm) and its two maximum values occur around $|x| = 0.4$ mm. The maximum value of $E_z$ is about 20 times smaller than that of $E_x$ shown in Fig. 2(a). It should be noted that the <110> and <100> crystals with the same thicknesses have the identical detection efficiencies [18]. The corresponding transverse and longitudinal wrapped phase maps of $E_z$ at different scan points are shown in Figs. 3(e) and 3(g), respectively. It can be seen that the y-z plane ($x = 0$ mm) is an interface of the phase maps. The phase difference of $E_z$ on two sides of the y-z plane is $\pi$, which implies that the propagation directions of $E_z$ are opposite on the two sides of the y-z plane. It can be understood that the minimum of $E_z$ appears on the optical axis is caused by the destructive interference of the fields on the two sides of the y-z plane. The experimental phenomena are in good accordance with the previous reported results [1, 19, 31].
Fig. 3. (a) Measured and (b) simulated transverse amplitude distributions of the $E_z$ component on the planes of $z = -10$ mm, $-5$ mm, 0 mm, 5 mm, and 10 mm, respectively. The polarization of the focused 0.7 THz radiation is linear. (c) Measured and (d) simulated longitudinal amplitude distribution of the $E_z$ component on the $x$-$z$ plane. Corresponding (e) measured and (f) simulated transverse wrapped phase maps. (g) Measured and (h) simulated longitudinal phase distributions.

To further confirm the measurement results, the evolution of $E_z$ during the focusing process is simulated by using the Richards-Wolf formula [32]. Around the focal point, the longitudinal component $E_z$ can be expressed as

$$E_z = -2A \cos \phi \int_0^{\alpha} \sqrt{\cos \theta} \sin^2 \theta J_1(kr \sin \theta) \exp(jkz \cos \theta) d\theta,$$

where $(r, \phi, z)$ is the cylindrical coordinate of an observation point, $J_1(kr \sin \theta)$ is the first order Bessel function of the first kind, $\theta$ is the angle between the THz beam and the optical axis, $\alpha = \sin^{-1}(NA/n)$ is the maximum convergence angle of the THz beam and is equivalent to $23^\circ$ in the experiment, $n$ is the refractive index in the image space and $A$ is a proportionality constant. The transverse and longitudinal distributions of the amplitude of the calculated $E_z$ are shown in Figs. 3(b) and 3(d), respectively; the corresponding phase distributions are shown in Figs. 3(f) and 3(h). The experimental results are in good agreement with the theoretical expectations, which further confirms the accuracy of the experiment.
In order to analyze the longitudinal component $E_z$ in detail, the data along the line $z = 0$ mm in Fig. 3(c) is extracted to exhibit the transverse distribution of $E_z$ on the focal plane. To present the longitudinal distribution of $E_z$, the data along $x = 0.4$ mm in Fig. 3(c) is chosen for avoiding the central dark line along $x = 0$ mm. Meanwhile, the amplitude profiles of $E_x$ along $z = 0$ mm and $x = 0$ mm in Fig. 2(a) are also extracted. To compare the sizes of focal points for $E_x$ and $E_z$, these data are normalized relative to their own maximums. The normalized transverse and longitudinal amplitude distributions of $E_x$ and $E_z$ are plotted in Figs. 4(a) and 4(b), respectively. In Fig. 4(a), it can be seen that the size of the dark region of $E_x$ is about 0.24 mm, which is determined by the distance of two off-axis lobes. In addition, the focal depth of $E_z$ is 6.7 mm, which is approximately the same size as that of $E_x$, as
shown in Fig. 4(b). To observe the dispersive properties of $E_z$, the transverse and longitudinal profiles of 0.3 THz, 0.5 THz, 0.7 THz, and 0.9 THz components are extracted and plotted in Figs. 4(c) and 4(d), respectively. The dark region sizes are 0.55 mm, 0.35 mm, 0.24 mm, and 0.18 mm, respectively. The corresponding focal depths are 13.4 mm, 7.8 mm, 6.7 mm, and 4.4 mm. It can be concluded that the dark region and the focal depth of $E_z$ gradually decrease with the frequency of the THz wave increasing. Additionally, the focusing ability of $E_z$ for lenses with different NAs is also checked. Another Si lens with 50 mm focal length is used to focus the THz wave. The transverse and longitudinal distributions of the $E_z$ components for 0.7 THz are presented in Figs. 4(e) and 4(f), respectively. The dark region and the focal depth of $E_z$ are 0.43 mm and 20 mm, respectively. It shows that the focusing effect of $E_z$ is weak with a smaller NA. These features are the same as those of the transverse component $E_x$ [23].

3.2 Circular polarization

![Fig. 5.](image)

A circularly polarized light is often utilized in a general optical system. Therefore, the vector characteristics of a focused circularly polarized THz beam are also investigated here. As mentioned in Section 2, a 0° cut quartz TQWP (TYDEX Company, Russia) with 2.9 mm thickness is used to change the linear THz polarization into the circular polarization. The central frequency of the TQWP is 0.7 THz and its effective frequency range is about 0.15 THz. The angle between the crystalline axis of the TQWP and the x-axis is adjusted as 45° to ensure the larger component is along the y direction. The amplitude distributions of $E_x$ and $E_y$ along the optical axis and their subtraction $\phi_y - \phi_x$. 

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For 0.7 THz on the x-z plane are shown in Figs. 5(a) and 5(c), respectively. Their corresponding wrapped phase maps are shown in Figs. 5(b) and 5(d). It can be seen that the focal spot sizes and focal depths of these two components are approximately equal. Their phase distributions also present the similar evolutions during the focusing process. The phase values \( \varphi_x \) and \( \varphi_y \) along the optical axes (x = 0 mm) in Figs. 5(b) and 5(d) are extracted and plotted in Fig. 5(e). The phase distributions for both \( E_x \) and \( E_y \) manifest the coincident variation tendency. On each curve, the phase difference between the values at \( z = -10 \text{ mm} \) and \( z = 10 \text{ mm} \) is about \( \pi \), which is due to the Gouy phase shift [23]. The subtraction between \( \varphi_y \) and \( \varphi_x \) is also presented in Fig. 5(e). It almost keeps a constant \( \pi / 2 \). It shows that the THz beam always maintains the circular polarization during the focusing process.

The focusing evolution of the longitudinal component \( E_z \) for the circularly polarized THz radiation is also recorded. The transverse and longitudinal amplitude distributions of \( E_z \) with the propagation distance for 0.7 THz are presented in Figs. 6(a) and 6(c), respectively. It can be found that the amplitude of \( E_z \) exhibits a doughnut shape. The inhomogeneous distribution on the light ring is mainly due to the nonuniform of the incident THz beam and measurement errors. The dark region size and the focal depth of \( E_z \) are 0.25 mm and 6.4 mm,
which are nearly the same as those for the linear polarization. The transverse and longitudinal wrapped phase maps of $E_z$ are shown in Figs. 6(e) and 6(g). A vortex variation with the propagation distance can be clearly seen. The rotation direction is always counterclockwise and its twist direction reverses before and after the focal point. To simulate this process, the longitudinal component $E_z$ of the converging circularly polarized light is considered as the linear combination of the longitudinal components $E_{xz}$ and $E_{yz}$ of two focused linearly polarized lights $E_x$ and $E_y$. Therefore, $E_z$ can be expressed as

$$E_z = \exp(-j\pi/2)E_{xz} + E_{yz}. \quad (2)$$

The simulated amplitude and phase distributions of $E_z$ are given in Figs. 6(b), 6(d), 6(f), and 6(h), respectively. The experimental results are in good agreement with the simulation results. It is demonstrated that the vector characteristics of the circularly polarized light can be easily analyzed using the THz digital holographic imaging technique.

### 3.3 Cylindrical vortex polarization

![Fig. 7. (a) Schematic drawing and (b) photograph of the THz wire radial polarizer. (c) Measured amplitude and (d) phase distributions of the $E_x$ component of the unfocused cylindrically vortex polarized light for 0.7 THz and (e) amplitude and (f) phase distributions of the $E_y$ component. (g)-(j) Corresponding amplitude and phase distributions of the simulation results.](image)

Recently, some special beams with the radial polarization have received much attention due to their distinctive focusing properties [1–4] and potential applications in microscopes and optical tweezers [6, 8]. In this work, a TQWP and a TWRP are used to generate a THz beam with the cylindrical vortex polarization [26–28]. The TWRP is composed of an aluminum sub-wavelength grating and is deposited on a 500 μm thick Si substrate, as shown in Fig. 7(a). The thickness $d$ of the aluminum grating is 500 nm, the grating period $A$ is 4.5 μm, and the grating line width $w$ is 2 μm. The TWRP is fabricated with the conventional electron-beam lithography. Its diameter is 10 mm. The photograph of its central region is shown in Fig. 7(b). The complex amplitude of the generated cylindrical vortex beam can be written as
\( \vec{E} = \exp(-j\phi) \hat{e}_r \), where \( \hat{e}_r \) is the unit vector along the radial direction, \( \exp(-j\phi) \) is the Pancharatnam-Berry phase term induced by the geometrical properties of the polarization conversion [26]. The complex field of the unfocused \( E_r \) for 0.7 THz is measured by using the THz imaging system. The measured amplitude and phase distributions of the \( E_r \) component of the cylindrical vortex beam are shown in Figs. 7(c) and 7(d), respectively. The amplitude distribution has a butterfly shape and the phase distribution linearly decreases \( \pi \) after semi-roundtrip with the azimuth angle \( \phi \) increasing. The phase value jumps \( \pi \) after passing through the central line \( x = 0 \) mm [28]. The measured amplitude and phase distributions of the \( E_x \) component are shown in Figs. 7(e) and 7(f), which are the same as those of the \( E_r \) except for a 90° rotation. To confirm the accuracy of the measurement results, \( E_x \) and \( E_y \) are calculated by using \( \cos(\phi) E_r \) and \( \sin(\phi) E_r \) [28]. The simulated amplitude and phase distributions are displayed in Figs. 7(g)-7(j), respectively. The experimental results accord with the simulation results well.

![Image](image-url)

**Fig. 8.** (a) Measured and (b) simulated transverse amplitude distributions of the \( E_r \) component for a focused cylindrically vortex polarized THz beam on the planes of \( z = -10 \), \(-5 \), 0, 5, and 10 mm. (c) Measured and (d) simulated longitudinal amplitude distributions of the \( E_r \) component on the x-z plane. (e) Measured and (f) simulated transverse wrapped phase maps. (g) Measured and (h) simulated longitudinal phase distribution.

With a Si lens, the cylindrically vortex polarized THz beam is focused. The \( E_x \) and \( E_y \) components of the focused cylindrically vortex polarized THz beam are coherently measured, respectively. To observe the vortex phase distribution conveniently, the \( E_r \) component are calculated by combining \( E_x \) and \( E_y \). The complex field of \( E_r \) can be expressed as

\[
E_r = E_x \cos \phi + E_y \sin \phi.
\]
The transverse and longitudinal amplitude distributions of $E_z$ for 0.7 THz are shown in Figs. 8(a) and 8(c), which manifest a main spot surrounded by an annular lobe around the focal plane. On the focal plane, the diameter of the main spot is 0.96 mm and the inner and outer diameters of the annular lobe are 1.9 mm and 3.5 mm, respectively. The NA of the THz system is only 0.2 due to the size limitation of the TWRP. The focal depth of $E_z$ is 16 mm.

The corresponding transverse and longitudinal wrapped phase maps of $E_z$ are shown in Figs. 8(e) and 8(g), respectively, which show a vortex variation with a topological charge 1. Passing through the focal plane, the rotation direction of the vortex phase is counterclockwise and its twist direction reverses. On the focal plane, the phase distribution has two vortex variations in the regions of the main spot and the annular lobe, respectively. In addition, there is a $\pi$ phase jump on their boundary. Utilizing the modified Richards-Wolf formula, the complex field of focused $E_z$ can be written as [33]

$$E_z = -jA\exp\left(j\phi\int_0^\alpha \sqrt{\cos \theta \sin \theta} \cos \theta \left[J_0(kr \sin \theta) - J_1(kr \sin \theta)\right] \exp(jkz \cos \theta) d\theta\right),$$

where $J_0(kr \sin \theta)$ and $J_1(kr \sin \theta)$ are the zero and second order Bessel functions of the first kind. Here $\alpha$ is set as 12° due to the lower NA. The corresponding simulated amplitude and phase distributions of $E_z$ are presented in Figs. 8(b), 8(d), 8(f), and 8(h), respectively, which are completely consistent with the experimental results.

Fig. 9. Measured and simulated amplitude and phase distributions of $E_z$ for a focused cylindrically vortex polarized THz beam. (a) shows the measured transverse amplitude distributions of the $E_z$ component on the planes of $z = -10$ mm, $-5$ mm, 0 mm, 5 mm, and 10 mm. (c) is the longitudinal amplitude distribution of the $E_z$ component on the x-z plane. (e) and (g) are the corresponding transverse and longitudinal wrapped phase maps. (b), (d), (f), and (h) are the corresponding simulation results of the amplitude and phase by using the modified Richards-Wolf formula.
Finally, the $E_z$ component of the focused cylindrically vortex polarized THz beam is measured. The measured transverse and longitudinal amplitude distributions of $E_z$ for 0.7 THz are shown in Figs. 9(a) and 9(c), and the corresponding transverse and longitudinal wrapped phase maps are given in Figs. 9(e) and 9(g), respectively. Properties of $E_z$ are very similar to those of the circularly polarized light. The beam exhibits an annular amplitude and a vortex phase. The diameter of the dark region of $E_z$ is about 0.27 mm and its focal depth is 16 mm. The distribution of $E_z$ is also simulated by using the modified Richards-Wolf formula [33]. Around the focal point, the complex field of $E_z$ can be expressed as

$$E_z = -2A \exp(j\phi) \int_{0}^{\theta_0} \sqrt{\cos^2 \theta \sin^2 \theta} J_1(kr \sin \theta) \exp(jkz \cos \theta) d\theta.$$  (5)

The corresponding simulated amplitude and phase distributions of $E_z$ are shown in Figs. 9(b), 9(d), 9(f), and 9(h), which reproduce the experimental phenomena very well.

4. Conclusions

In conclusion, the vector diffraction properties of converging THz beams with linear, circular, and cylindrical vortex polarization are systematically measured by using the THz digital holographic imaging system. Specially, the distributions of the $E_z$ components of the focused beams with different polarization are intuitively presented. The $E_z$ component for the linearly polarized radiation has the dipole distribution, while $E_z$ for the circularly and cylindrically vortex polarized beams show the annular amplitude and vortex phase distributions. In addition, the theoretical expectations have also been given utilizing the Richards-Wolf formulas. The simulation results accurately reproduce the experimental phenomena for different cases. This work provides a solid experimental investigation of the diffraction properties of the electro-magnetic waves and demonstrates the ability of the THz digital holographic imaging system.

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