Real-time phase measurement of optical vortices based on pixelated micropolarizer array

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Abstract: The special spiral phase structure of an optical vortex leads to an intriguing study in modern singular optics. This paper proposes a real-time phase measurement method of vortex beam based on pixelated micropolarizer array (PMA). Four phase-shifting fringe images can be obtained from a single interference image, thus the vortex beam phase can be obtained in real-time. The proposed method can achieve full-field phase measurement of the vortex beam with the advantages of lower computation and vibration resistance. In the experiments, the typical phases of vortex with different topological charges are loaded on a spatial light modulator (SLM) to generate diffraction vortex beam, and the phase distribution of vortex beam is obtained in real-time, which confirm the robustness of this method. This method is of great significance in promoting the study of optical vortices.

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1. Introduction

The dislocations in wave trains were first investigated by Nye and Berry in 1974 [1]. This phenomenon was later defined by Coullet et al. as “Optical vortices” [2]. Among various studies on optical vortex, phase distribution is of particular interest in this paper. Allen et al. [3, 4] proved that the vortex beam with phase factor of $\exp(-i\ell \theta)$ had orbital angular momentum of $\ell \hbar$ ($\ell$ is the topological charge, and $\hbar$ is the Planck constant) under the conditions of paraxial and nonparaxial propagations, which drew attention of researchers to the phase distributions of special optical vortices. Swartzlander [5] first observed the optical vortex solitons in Kerr nonlinear media, which created a precedent of studying the optical vortex propagation in nonlinear media and the interaction of the optical vortex and the nonlinear media. Kuga et al. [6] constructed an optical vortex to trap neutral atoms. He et al. [7] observed the transfer of angular momentum to absorptive particles from a laser beam with a phase singularity. Simpson et al. [8] achieved rotating operation of the particles by optical vortex and called this technique optical spinner. Mair et al. [9] achieved the experimental demonstration of transfer of angular momentum to parametric down-converted photons. In addition, the optical vortices can also be applied as an information carrier in free space optical communication [10, 11]. There are many kinds of way to generate vortex beams, such as mode transformation method [12, 13], computer-generated hologram [14, 15], spiral phase plate [16–18], and liquid crystal spatial light modulator (SLM) [19, 20].

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The acquisition of phase distribution of vortex beam is of significance to the study of the orbital angular momentum. For the regular vortex beam, the phase distribution can be predicted, but for the irregular vortex beam, such as the interference field of multiple vortex beams, the phase distribution is hard to predict. Moreover, the predicted phase distribution is not identical with the actual phase. Thus, the experimental phase measurement of the vortex beam is necessary. Guo [21] proposed a linear scanning pinhole sampling array to reconstruct the wavefront. The phase and the amplitude of the wavefront passing through a pinhole sampling array plate can be directly extracted from the inverse Fourier transform of the far-field diffraction intensity pattern. However, scanning the whole surface is time-consuming, and only the phase of sampled point can be measured. The measured phase image quality can be increased with smaller scanning period at a cost of longer scanning time. Dudley [22] used SLM and polarization grating to replace quarter wave plate and beam splitter to measure the wavefront of propagating light field based on the Stokes parameters. However, the change of SLM phase in the measurement halved the frame rate of phase measurement, and the pixel level position match is required as the two images are recorded in the different positions of the detector.

An excellent candidate for phase measurement is the phase-shifting technique. However, the phase is unavailable without precise vibration isolation, thus traditional phase-shifting method has not been used in the phase measurement of the vortex beam. The appearance of pixelated micropolarizer array [23, 24] promotes the real-time polarization measurement [25, 26] and phase-shifting digital hologram [27–29]. In this paper, the pixelated micropolarizer array fabricated by electron beam lithography is applied to real-time full-filled phase measurement of vortex beam which reduces the requirements of vibration isolation, and the experimental results confirm the robustness of this method.

2. Experimental method

Fig. 1. Microscopic images of PMA recorded by (a) SEM and (b) optical microscope

Metal grating is a grid of periodic and parallel metallic wires. When the metal grating period is larger than the light wavelength, the grating is used as diffraction grating due to the diffraction effect of the grating; when the metal grating period is smaller than the light wavelength, the grating is used as linear polarizer due to the polarization and non-diffraction effect. The metallic nanowires transmit parallel polarized light and reflect cross polarized light. Our group used electron beam lithography (EBL) to fabricate a $320 \times 240$ aluminum pixelated micropolarizer array based on the polarization effect of the metallic nanowires. The nanowires with $140\text{nm}$ period and $100\text{nm}$ height are etched on high light-transmissive glass substrate, and the pitch of the units is $7.4\mu\text{m}$, and the polarization directions of each $2 \times 2$ units are $0^\circ$, $135^\circ$, $90^\circ$, and $45^\circ$, see the scanning electron microscope (SEM) image in Fig. 1(a). The polarization performance of the PMA is observed by an optical microscope. The PMA is placed on the object stage and the observation light is linearly polarized and rotatable. The units are bright when their polarization direction are parallel to the observation light’s.
and the units are dark when their polarization direction are perpendicular to the observation light’s, see Fig. 1(b). The intensities of optical microscope images change with the linear polarization direction of observation light. The PMA is integrated with a charge coupled device (CCD) of same pitch.

To measure the phase of the vortex beam, we used an experimental setup as shown in Fig. 2. The measured vortex beam is generated by loading a special phase mask on the SLM. A 532nm laser beam is split into two mutually perpendicular linear polarization beams by the first polarization beam splitter (PBS1): the P-polarized beam is transmitted to the SLM and the S-polarized beam is reflected and used as the reference beam. The half wave plate (HWP) is used to adjust the intensity ratio of two beams. After recombining in the PBS2, the two light beams transmit through the QWP and PMA, thus the interferogram is acquired by the CCD. The lens 1 in Fig. 2 is used to adjust the size of the object wave diffracted by the SLM. Four images can be obtained from a single frame image, which represent the images of polarization directions of 0°, 135°, 90°, and 45°, and the gray value can be expressed as I(0), I(135), I(90), and I(45).

![Fig. 2. Schematic of the experimental phase sensing setup. HWP: half wave plate; PBS: polarization beam splitter; BS: beam splitter; SLM: spatial light modulator; QWP: quarter wave plate; PMA: pixelated micropolarizer array; Lens 1 is used to adjust the size of the object wave and its focal length is 210mm.](image)

The complex amplitudes of the object beam and reference beam when the beams recombine in the PBS2 are shown as follows:

\[
U_s = \sqrt{I_s} \exp(i\phi_s) \quad \text{(1)}
\]

\[
U_r = \sqrt{I_r} \exp(i\phi_r) \quad \text{(2)}
\]

Here the \(I_s\) and \(\phi_s\) are the intensity and phase of the object beam, and \(I_r\) and \(\phi_r\) are the intensity and phase of the reference beam. As the reference beam is a plane wave, the values of the \(\phi_r\) in the cross section are equivalent.

The interference light intensities when the combined beams received by the CCD are related with the polarization angle \(\alpha\) of the PMA unit

\[
I(\alpha) = \frac{1}{2} \left[ I_s + I_r + 2\sqrt{I_s I_r} \cos(\phi + 2\alpha) \right] \quad \text{(3)}
\]

where \(\phi = \phi_s - \phi_r\). When the wave front increase or decrease an equal constant phase, the propagation characteristic in not changed. As the values of the \(\phi\) in the cross section are equivalent, \(\phi\) is equivalent to the \(\phi_s\).
Thus, the phase $\phi$ can be calculated by

$$\phi = \arctan\left(\frac{I(135) - I(45)}{I(0) - I(90)}\right)$$  \hspace{1cm} (4)$$

The phase of each $2 \times 2$ units can be calculated by their four intensity values, but this method sacrifices the resolution, and the resolution of phase image is only a quarter of the original image. Usually linear interpolation method is used to obtain the same resolution as the original image [30]. The use of the PMA in the phase-shifting interferometry achieves real-time phase measurement, and overcomes the disadvantages of traditional phase-shifting techniques: the traditional time phase-shifting (TPS) requires precise vibration control and is limited to the measurement of the static or quasi-static objects [31], and the traditional space phase-shifting (SPS) can be used in the dynamic measurement, but requires pixel-level position match and fringe intensity correction [32].

3. Experimental results

![Fig. 3. Application of PMA on phase measurement of the vortex with topological charge $l = 2$.](image)

(a) Phase loaded on the SLM; (b) Interference image acquired by the CCD; (c) Four fringe patterns generated from (a) by linear interpolation method; (d) The calculated wrapped phase image; (e) The calculated wrapped phase filtered by WFT; (f) Unwrapped phase of the spherical phase component; (g) Unwrapped phase of the vortex phase component; (h) and (i) are the unwrapped phase of (e) in two-dimensional display and three-dimensional display, respectively.

To confirm the robustness of proposed method, experiments are conducted to measure the phase of vortex beam. Phase of the vortex with topological charge $l = 2$ is loaded on the SLM, see Fig. 3(a). The reflected diffraction beam is hollow vortex beam which has significant applications on trapping and manipulating micro-particles, trapping neutral atoms, and so on. This hollow vortex beam is easily generated and representative, and has expected $4\pi$ phase transition, making it suitable to be used to confirm the robustness of proposed method. The interference image is acquired by the CCD, see Fig. 3(b), and the adjacent $2 \times 2$ units gray values represent the intensities when the polarization directions are $0^\circ$, $135^\circ$, $90^\circ$, and $45^\circ$, respectively. Some black spots are observed, which are caused by dusts in the air adhered to the focal plane of the CCD introduced in the integration process. They can be eliminated.
when the integration is carried out in the clean room in our future work. Then the gray values of same polarization directions are extracted respectively to generate four images with same resolution by linear interpolation method [31], see Fig. 3(c). Therefore, four fringe patterns of different polarization directions are obtained from a single frame image. The wrapped phase distribution of vortex beam is calculated by Eq. (4), which is a spiral phase distribution, see Fig. 3(d). As the black spots are not completely opaque, the influence of the black spot is weak. The noise in the interferometry is inevitable, thus we used windowed Fourier transform (WFT) [33] to filter the noises, and then the filtered wrapped phase is obtained, see Fig. 3(e). As the central hollow area of the hollow vortex beam is dark and hasn’t any intensity and phase information, the calculated phase in the central hollow area is unnecessary and meaningless. The phase distribution in Fig. 3(e) includes two components: one is the spherical wave caused by the lens, the other is the phase of the vortex with topological charge $l = 2$ caused by the SLM.

Generally, phase unwrapping is conducted to see the three dimensional phase more clearly and directly. However, the wrapped phase with phase singularity in Fig. 3(e) is hard to be directly unwrapped, thus the two components are unwrapped respectively, and then superposed to obtain the unwrapped phase of Fig. 3(e). As the light path in the experiment is not changed, the spherical phase can be calibrated by loading a uniform phase on the SLM in the beginning, and then spherical phase is calculated by the proposed method. The unwrapped spherical phase is show in three-dimensional display in Fig. 3(f). The second part is calculated by subtracting the wrapped spherical phase from the Fig. 3(e), and then the unwrapped phase of the second part is obtained, see the three-dimensional display in Fig. 3(g). The superposition of Fig. 3(f) and (g) is the unwrapped phase of Fig. 3(e), which is shown in two-dimensional display in Fig. 3(h) and three-dimensional display in Fig. 3(i). It can be easily see that $4\pi$ phase transition is existed in Fig. 3(i), which is consistent with the expected result.
More experiments are conducted to confirm the robustness of proposed method by loading vortex phase with topological charge $l = 1$ and 6 on the SLM which has expected $2\pi$ (or $12\pi$) phase transition. The interference images are acquired by the CCD, see Fig. 4(a). Linear interpolation method [30] is used to generate four fringe patterns of different polarization directions from one single frame. The fringe patterns of one polarization direction are shown in Fig. 4(b). The filtered phase distributions calculated by Eq. (4) are shown in Fig. 4(c), including the spherical wave and the phase of the vortex with topological charge $l = 1$ (or $l = 6$). The vortex phase is calculated by subtracting the calibrated spherical phase from the Fig. 4(c), see Fig. 4(d). The superposition of Fig. 4(d) and calibrated unwrapped spherical phase is the unwrapped phase of Fig. 4(c), which is shown in two-dimensional display in Fig. 4(e) and three-dimensional display in Fig. 4(f). It can be easily see that $2\pi$ (or $12\pi$) phase transition is existed in Fig. 4(f) when $l = 1$ (or $l = 6$), which is consistent with the expected result.

**Conclusion**

In this paper, PMA is applied to phase-shifting interferometry to measure the phase of vortex. Typical hollow vortex beams are generated by loading the phase of vortex with topological charge $l = 1$, 2, and 6 on the SLM, and the phase of diffracted hollow beam with phase...
transition is obtained by the proposed method successfully, which is consistent with the expected results. Only one frame image is used to obtain the phase, thus real-time phase measurement of optical vortices is achieved base on the PMA. The proposed method is of great significance in promoting the vortex beam study, and also can be applied to the phase measurement of other special light field, such as Bessel, Airy and speckle fields.

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