Characteristics of fork fringes formed by two obliquely-incident vortex beams with different topological charge number

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Abstract. Optical vortex is a mode of light whose phase distribution varies as $\exp(il\phi)$, where l is called the topological charge of the vortex and ϕ is an azimuthal angle in the plane perpendicular to the propagating direction. The vortex beam of charge l carries an orbital angular momentum of $l\hbar$ and has its application in manipulating micrometer-sized particles. A common method to detect topological charges of optical vortices is interference with a tilted Gaussian beam. In this work, we study the interference pattern of two obliquely-incident vortex beam with different topological charges, created by spatial light modulators (SLMs). We find fork-like fringes similar to those observed from the interference between a vortex and Gaussian beam. The fringe difference between the top and the bottom of the fork equals the difference the topological charges of the two vortices, as predicted by the theory. When the topological charges are the same and the fork pattern disappears. The tilted angle between the vortex beam affects the fringe spacing: the larger the tilt angle the smaller the fringe spacing. When the tilt angle radial from the defect canter. We suggest the result can be used to detect a topological charge of a vortex beam.

1. Introduction

The phase distribution φ of an optical vortex (OV) on the plane perpendicular to the propagation axis changes linearly with the azimuthal angle ϕ and can be written as $\varphi = l\phi$, where l is typically an integer and usually called the topological charge of the vortex. Such phase distribution causes the wavefront to be helical and the vortex inherits an orbital angular momentum of $l\hbar$. The orbital angular momentum of optical vortices has been first studied by Allen et al. [1] and can be applied in several topics, such as classical and quantum communications [2–4], trapping and manipulating micrometer-sized particles [5], and plasmonics [6–10]. Various techniques have been used to determine topological charges of optical vortices. The most common technique is interfering with tilted Gaussian beam [11]. Other techniques include investigating Talbot patterns of optical vortex's diffraction through gratings [12], using Stokes polarimetry and a Shack–Hartmann wavefront sensor [13], an ultracompact array of elliptical nanoholes [14], single-slit diffraction of an optical beam with phase singularity [15], an annular triangle aperture [16], interference intensity analysis [17], a diamond-shaped aperture [18], and a hole wheel [19].

The interference patterns of two vortex beams with different topological charges have only been studies for the case of composite optical vortices, where two collinear beams of optical vortices with different topological charges have been superimposed to form new composite vortices [20-21]. In this paper, we study the interference pattern of two obliquely-incident vortex beam with different topological charges, created by spatial light modulators (SLMs). We suggest the result can be used as an active method to detect topological charges of vortex beams.

2. Theoretical Simulation

We use Laguerre-Gaussian beams to represent optical vortices. A Laguerre-Gaussian beam to topological charge l propagating along the z-axis can be expressed as [22]

$$E\left(LG_p^l\right)\alpha\left[\frac{r\sqrt{2}}{w(z)}\right]^{|l|} L_p^{|l|}\left[\frac{2r^2}{w^2(z)}\right]\cdot e^{\left(\frac{-r^2}{w^2(z)}\right)}\cdot e^{\left(\frac{-ikr^2}{2\left(z^2+z_R^2\right)}\right)}\cdot e^{(-il\phi)}\cdot e^{-i\left(2p+|l|+1\right)\tan^{-1}\frac{z}{z_R}} \tag{1}$$

Where $\phi=\tan^{-1}(y/x)$ is the azimuthal angle in the plane perpendicular to the z-axis. $L_p^{|l|}$ is generalized associated Laguerre polynomial. $w(z)$ is the laser beam waist at the position z, and z_R is Rayleigh range. To generate off-axis interference patterns we rotate both beams about the x-axis for an angle $\pm\phi$ using the rotation matrix

$$\begin{pmatrix}X'\\Y'\\Z'\end{pmatrix}=\begin{pmatrix}1 & 0 & 0\\0 & \cos\phi & \sin\phi\\0 & -\sin\phi & \cos\phi\end{pmatrix}\cdot\begin{pmatrix}X\\Y\\Y\end{pmatrix} \tag{2}$$

The first optical vortex beam with topological charge l_1 is rotated for an angle $+\phi$ (counterclockwise) and superimposed with the second vortex beam with topological charge l_2 that is rotated clockwise an angle $-\phi$ (clockwise), as shown in figure 1. The interference intensity is observed on the plane z = 0.

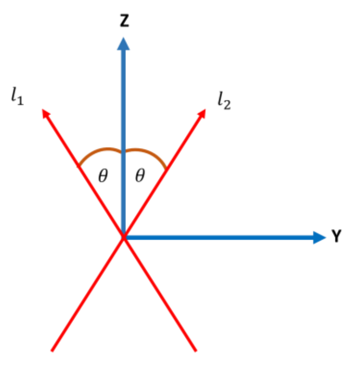

Figure 1. Shows the pathway of light used to create the optical vortex, first vortex (l_1), and the second vortex (l_2).

3. Experiment

A 4-mw diode laser (λ=633nm) is used in our experiment as a coherent source for the interference of two vortex beams. The laser source is expanded by an optical telescope to a diameter of about 15 mm in order to cover the whole polarizer beam splitter (PBS), (THORLABS,CCM1-PBS252M 620-1000nm). The PBS splits the laser into two equally-intended beam, one goes to the first SLM (LC2012,Holoeye Photonics AG with resolution of 1024x768 pixels, transmitive) and the other goes to the second SLM (PLUTO, Holoeye Photonics AG with resolution of 1920x1080 pixels, reflective). A series of gray-level images are loaded and displayed onto SLM1 and SLM2 screen, varying the spatial phases on the SLM screens, producing the optical vortices with integer-valued topological charges. The optical vortices from both SLMs are superimposed at the CCD camera screen after being translated through a mirror2, and then the second BS (THORLABS<CM1-BS252M 700-1100nm)

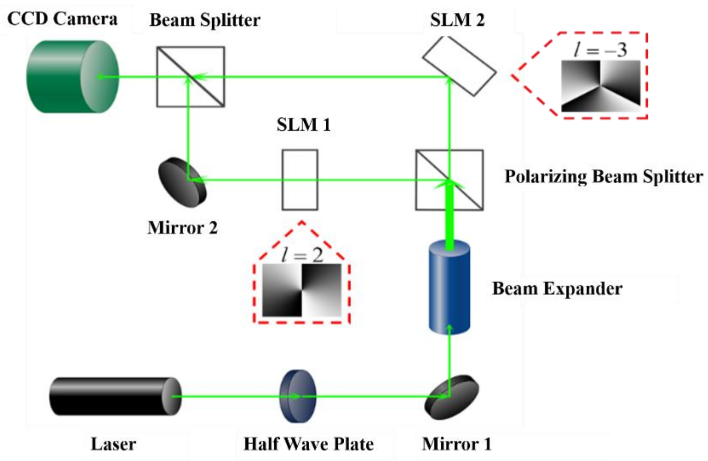

Figure 2. The setup for interference of two optical vortex beams. SLM1 and SLM2 are used to generate integer-valued topological defect charges. See text for more details.

4. Results and Discussions

We find fork-like fringes similar to those observed from the interference between a vortex and a Gaussian beam. The fringe difference between both ends of the fork equals the difference between the topological charges of the two vortices

Figure 3. shows comparisons between experimental and stimulation results. The interference patterns in Figure 3a and 3b are from the topological charges of l_1 = 2 and l_2 = –3. The results show similar fork-like patterns with the number of bright fringes on the left (N_L) of the fork is 3 and the right (N_R) is 8. This result shows that the difference between the fringes at the right side and the left side of the fork yields the relation $N_R – N_L = l_1 – l_2$. In Figure. 3c and 3d, with the topological charges of l_1 = –5 and l_2 = –4, the number of fringes on the left is 7 and on the right is 6, yielding $N_R – N_L = l_1 – l_2 = –1$. In Figure 3e and 3f, with the topological charges of l_1 = –5 and l_2 = –5, the number of fringes on the left is equal to the right, yielding $N_R – N_R = l_1 – l_2 = 0$.

Our simulation also reveals that, when the rotated beams are on the y-z plane, as shown in Figure 1., the interference fringes are along the x-axis (perpendicular to the plane of the rotated beams). When the tlited angle ϕ is small the spacing between the fringes is wider. In Figure 3b, 3d, and 3f, we adjust the tilted angle ϕ such that the fringe spacing matches our experimental results.

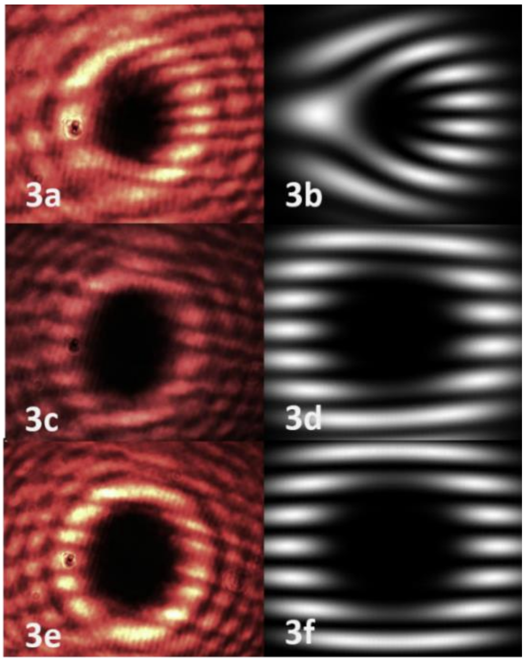

Figure 3. Off-axis interference patterns between two optical vortices produced by our SLMs with the topological charges of $l_1 = 2$ and $l_2 = -3$ (3a), $l_1 = -5$ and $l_2 = -4$ (3c), $l_1 = -5$ and $l_2 = -5$ (3e). Fig. 3b, 3d and 3f are corresponding simulation results using the same topological charges as fig. 3a, 3c and 3e respectively.

5. Summary

we have studied the interference pattern of two vortex beams with different topological charges, created by spatial light modulators (SLMs). We find fork-like fringes similar to those observed from the interference between a vortex and a Gaussian beam. The fringe difference between the two sides of the fork equals the difference between the topological charges of the two vortices, as predicted by the theory. When the topological charges are the same and the fork pattern disappears. We suggest the result can be used as an alternate method to detect a topological charge of an unknown vortex beam. The conventional method, which use a Gaussian beam as a reference beam may be disadvantage when detecting large topological defect charges because the fringe difference is large and may be hard to observe. Our method has an advantage of adjusting the topological charges of the reference beam to match that of the unknown vortex charges until the fork pattern disappears.

Acknowledgments

We would like to thank the Research Fund for DPST Graduate with First Placement, Grant # 024/2555.

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