Characteristics of the diffraction field and the topological charge judging of the bended vortex beams through a double slit

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The isophase line will be bended when a vortex beam propagation a certain distance, and the topological charge of this vortex beam cannot be got exactly as usually because of the interference fringe distortion by a double slit. The characteristics of the diffraction field of the bended vortex beams through a double slit are discussed. The bending phenomenon causes the interference fringe distortion at both ends of the stripe. A new improved method to judge the topological charge accurately and easily by counting the number of bright spots is proposed here.Thesimulating results show that the topological number is equal to the number of the bright spots plus one.

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1. Introduction

Young's double-slit [1] is one of the most classic experimentsin the history of physics, it demonstrates the wave nature of light. As known to all, light can carry both spin angular momentum (SAM) and orbital angular momentum (OAM) [2,3]. SAMisassociated with the polarization of the beam, and OAM is associated with the angle to the complex amplitudedistribution of the light field, it makes the light wave-frontcarrythespiral phase distribution [4]. In recent years, the research for the beam of spiral wave-front with phase factor $\exp(im\varphi)$ is a hot topic, where φ is the azimuthal coordinate and m is an integer number which characterizes the strength or topological charge of the phase circulation. Laguerre-Gaussian (LG) beams belong to the class [3].

A lot of research have made on diffraction characteristics of vortex beam, including Young's double-slit [5], a triangle aperture [6], hexagonal aperture [7], annular aperture [8], multi points interferometer [9,10], a single slit [11] and so on. But most consider that vortex light can be transmitted steadily by default, not considering the bending of isophase line [12].

In this paper, we simulated Young's double slit phenomenon of vortex beam with considering the bending isophase line. In order to overcome the inaccuracy caused by the bending isophase line, we propose a new improved method to judge topological charge accurately .The simulating result provides certain guiding significance.

2. Theoretical Analysis

Laguerre-Gaussian vortex beam is representative of the vortex beam whichhas the complex field amplitude given by [13]

$$E_1(\boldsymbol{\rho}, z=0) = \left(\frac{\rho}{\sigma}\right)^{|m|} exp\left(\frac{-\rho^2}{\sigma^2}\right) exp(im\varphi)\, E_0 \quad (1)$$

where σ is the spot size parameter, m is the topological charge, and E_0 is an constant. As illustrated in Fig.1, in the source plane of z=0,the isophase point distribution in the line of radial direction. After transmitting a distance in the space, in the observation of $z=z_0$, the complex filed amplitude given by [12]

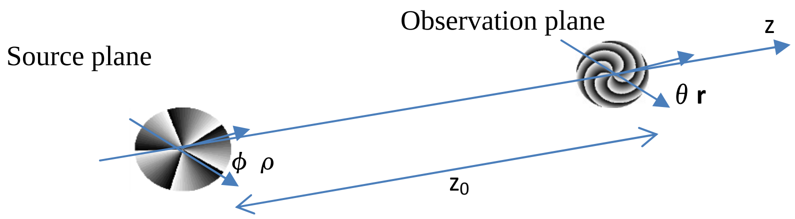


Fig.1. Schematic of source plane and observation plane

when m>0, and

$$E_2(\boldsymbol{r}, z = z_0) =$$
$$(-i)^{m+1}\left(\frac{\sigma'}{\sigma}\right)^m \left(\frac{r}{\sigma'}\right)^m exp\left(-\frac{r^2}{\sigma'^2}\right) exp(im\theta)\, exp\left(ikz_0 +\right.$$

i2z0kσ2r2σ′2E0 (2)

when m<0,

$$E_3(\boldsymbol{r}, z = z_0) =$$
$$(-i)^{m+1}\left(\frac{\sigma'}{\sigma}\right)^{|m|} \left(\frac{r}{\sigma'}\right)^{|m|} exp\left(-\frac{r^2}{\sigma'^2}\right) exp(i|m|\theta)\, exp\left(ikz_0 +\right.$$

i2z0kσ2r2σ′2E0 (3)

where $\sigma'^2 = \sigma^2\left(1 + \frac{4{z_0}^2}{k^2\sigma^4}\right)$, σ' *is the spot size parameter in the observation plane.*

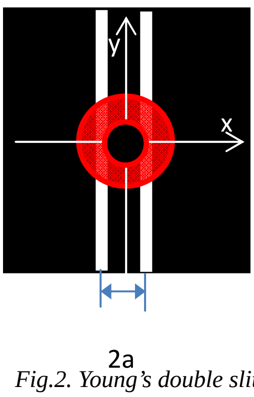


Fig.2. Young's double slit

Comparing Eq.(1) with Eq.(2), we can easily find that the spot size is broadened because of diffraction, and the degree being broadened is related to the distance. On the other hand, the Eq. (2) and Eq.(3) still retain the vortex factor $\exp(\mathrm{i}m\theta)$, but also cause the bending of the isophase line.

In general, when simulating Young's double-slitphenomenon of vortex beamwhich is shown in Fig.2, we used Eq.(1) as an the initial incident beam, so the intensity variation $I_1(x)$ due to the interference between the paths along the horizontal axis can be written as [14]

$$I_1(x) = I_0 cos^2\left(\frac{2\pi xa}{\lambda D} + 2m\tan^{-1}\left(\frac{a}{y}\right)\right) \quad (4)$$

where 2a is the slit distance, it should be higher than vortex size but smaller than the beam size, D is the diffraction distance, *m* is the topological charge.

In the experiment, the phase lineof vortex beam willbendafter propagating a certain distance because of this distortion, and the interference fringes will have different degrees of torsionaccording to Eq.(2), Eq.(3) and Eq.(4). The interference beam intensity of vortex beam with phase transition can be depicted as:

$$I_2(x) = I_0 cos^2\left(\frac{2\pi xa}{\lambda D} \pm 2|m|\tan^{-1}\left(\frac{a}{y}\right) + i\frac{2z_0}{k\sigma^2}\frac{r^2}{\sigma'^2}\right) \quad (5)$$

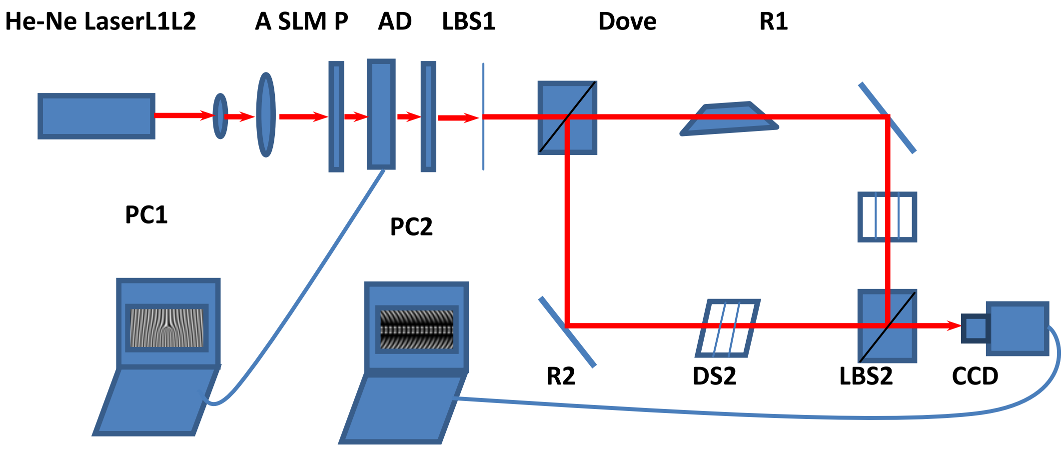


Fig.3. Schematic of experimental setup to measure the topological charge of vortexbeams. L1,L2,L3: lenses; A,P: polarizer; AD: aperture diaphragm; R1,R2: reflection mirror; DS1,DS2: Young's double slit; LBS1,LSB2: light beam splitter

In order to overcome the inaccuracy caused by the bending isophase line, we propose a new improved method to measure topological charge accurately. The schematic diagram is shown in Fig.3. A 632.8nm laser beam passing through the beam expander (L1) and collimating lens (L2) illuminates a transmission twist nematic liquid crystal SLM (Spatial Light Modulator LC-2002) with 800×600 pixels (each pixel size is 32 μ m × 32 μ m), the designed holographic grating displayed at the SLM diffracts the incoming beam into different diffraction orders. Only 1st-order vortex beam is allowed to pass through the aperture diaphragm. The vortex beam is divided into two beams that carry the same topological charge with LBS1, one passes through the Young' double slit (DS2) directly, and the other passing through a Dove prism first, with making the beam carry the opposite topological charge, getsthrough the Young' double slit (DS1). Then the two beams of diffraction synthesisea composite beam by LBS2.The diffraction pattern of the composite beam will be detected with a CCD. The complex amplitude expression of the composite beam can be described as Eq.(6).We can judge topological charge accuratelywith this method.

$$E_4 = E_0 cos\left(\frac{2\pi xa}{\lambda D} + 2|m|tan^{-1}\left(\frac{a}{y}\right) + i\frac{2z_0}{k\sigma^2}\frac{r^2}{\sigma'^2}\right)$$

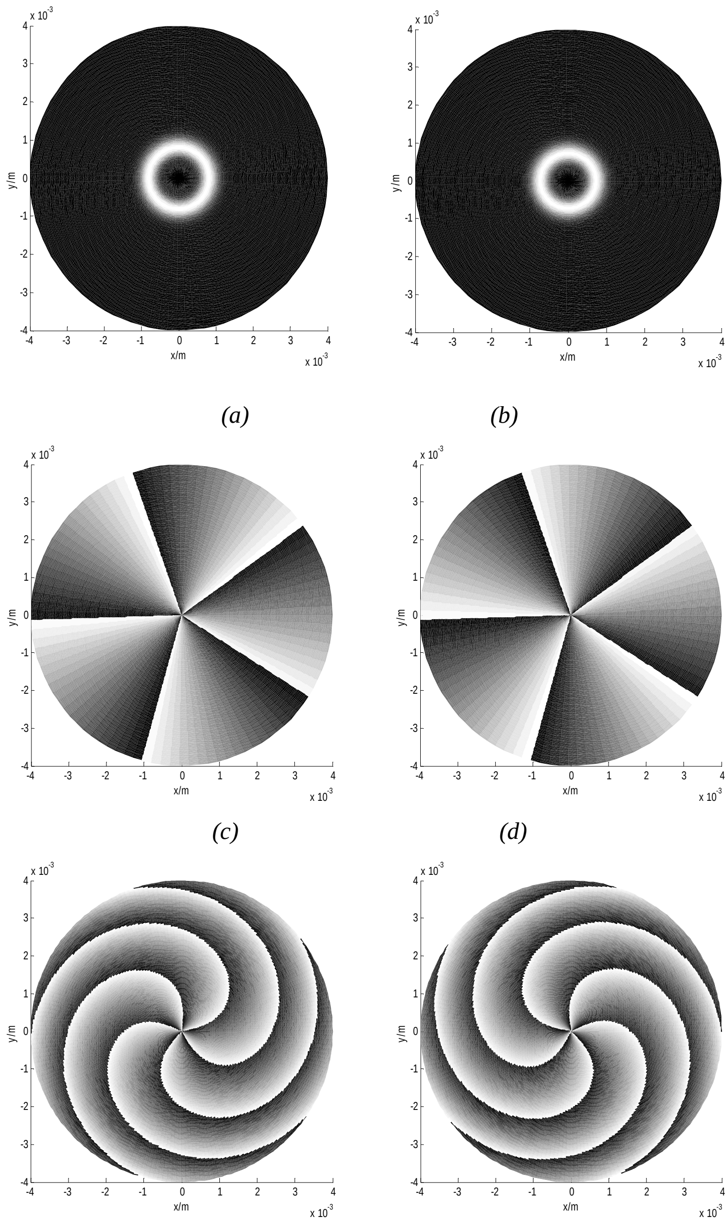
$$+E_0 cos\left(\frac{2\pi xa}{\lambda D} - 2|m|tan^{-1}\left(\frac{a}{y}\right) + i\frac{2z_0}{k\sigma^2}\frac{r^2}{\sigma'^2}\right) \qquad (6)$$

$$I_3 = {E_4}^2$$

$$= I_0\begin{pmatrix} cos\left(\frac{2\pi xa}{\lambda D} + 2|m|\,tan^{-1}\left(\frac{a}{y}\right) + i\frac{2z_0}{k\sigma^2}\frac{r^2}{\sigma'^2}\right) + \\ cos\left(\frac{2\pi xa}{\lambda D} - 2|m|\,tan^{-1}\left(\frac{a}{y}\right) + i\frac{2z_0}{k\sigma^2}\frac{r^2}{\sigma'^2}\right)\end{pmatrix}^2 \qquad (7)$$

3. Simulation Result

Without special instructions, we make λ=632.8nm, σ=0.5mm, D=4m, a=0.15mm, and z_0=1m in the process of simulation. According to Eq.(1) we can obtain the simulated intensity and phase distribution on the original plane as shown in Fig.4(a)(c)(d).The beam broadening effect is induced by diffraction with propagation, and also the phasedistribution exhibits special change in the plane of z=z_0, according to Eq.(2). The simulation diagrams of the intensity and phase are shown in Fig.4(b)(e)(f), which the isophase line changes from radial to arc. If the topological charge is positive, the isophase line will bend clockwise, and anticlockwise on the contrary.



(a) (b) (c) (d) (e) (f)

Fig.4. The intensty and phase distribution of the original plane (a)(c)(d)and observation plane(b)(e)(f), the topological charge of (c)(e) is m=5, the topological charge of (d)(f) is m=-5.

In genral, we can get the intensity distribution of the Young' double slit interference through Eq.(4) with non phase distortion, and as shown in the Fig.5(a)-(f), the dislocation of the interference fringes will produce |*m*| fringes for |m|=1,3,4. But the isophase line will be bended inevitably causedby the turbulence and inhomogeneous medium after propagation. Alsowe can get the distortion intensity distribution according to Eq.(5). The bending phenomenon causes the interference fringe distortion at the ends of the up and down, as shown in the Fig.5(g)-(l), it is not conducive for judging the topological charge exactly. So, we propose a new method, which the interference fringes will be intervened again. The superposition intensity of two beams is described as Eq(7) and is illustrated in Fig.5(m)-(o).We can find that each fringes appear fracture, and the number of bright spots in the middle increased as the increasing of the topological charge, whichthe rule is m=n+1, where n is the number of bright spots . Such as , the number of bright spot is equal to zero for m=1, the number of bright spot is equal to two for m=3, the number of bright spot is equal to three for m=4, and so on.

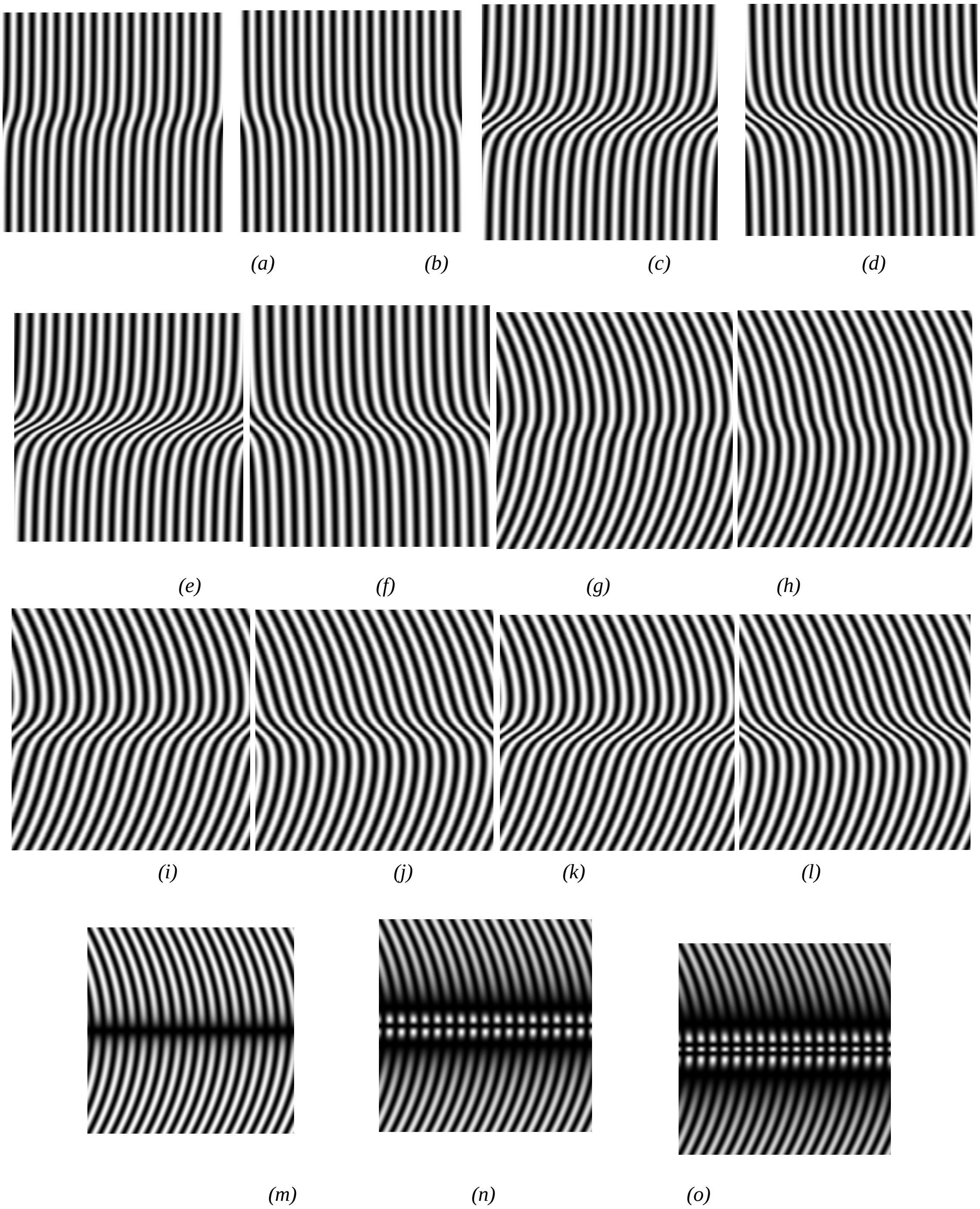


Fig.5. The superposition intensity distribution of two beams.(a)-(f)the intensity distribution of the Young' double slit interference for =1,-1,3,-3,4,-4, (g)-(l) the intensity distribution according to Eq.(5) for m=1,-1,3,-3,4,-4, (m)-(o) The superposition intensity distribution according to Eq.(7) for |m|=1,3,4.

4. Conclusions

The isophase line will bend inevitably caused by turbulence and inhomogeneous medium after propagation. The bending of the interference fringes is discussed in this paper. We deduced the bending diffraction intensity of vortex beam through the Young' double slit, and proposed an improved method which can overcome the impact of this error for judging the topological number accurately and easily by counting the number of bright spots.With theoretical analysis and derivation of the diffracted light field, we obtained the simulation pattern of diffracted light field. The simulating results show that the topological number is equal to the number of the bright spots plus one.

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