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Generation of optical vortices with tunable intensity modulation

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Abstract

We analyze vortex properties of the optical beams generated by a spiral phase plate (SPP) which cannot modulate the phase of the incident beam range from 0 to 2π nicely, and find that the vortices have intensity modulation (IM) with central bright speckle. We construct an improved SPP to produce high quality optical vortices with definite IM. Theoretical analysis and real experiments show that this improved SPP can be used to produce optical vortices with configurable intensity modulation degree and without central bright spot.

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Keywords: Phase modulation; Intensity modulation; Spatial light modulator; Optical vortex; Spiral phase plate

Optical vortices are intriguing special optical fields with helical wave-fronts and well-defined orbital angular momentum [1,2]. This kind of optical fields has been widely applied in many fields, such as trapping of atoms or mesoscopic particles [3–5], processing quantum information [6] and so on. Researchers have already grasped many ways to produce optical vortices with a fixed topological charge (TC), such as by use of computer-generated holograms (CGHs) [7,8], spiral phase plates (SPP) [9,10], spatial light modulators (SLM) [11,12] and so on. Recently, some researchers have attempted to produce composite optical vortices with intensity modulation and different TCs. In 2005, Lin [13] introduced an algorithm to construct a diffractive optic element for producing this special field. Davis [14], Guo [15] and Lee [16] observed that the optical vortex generated by SLM has intensity modulation (IM) on the main annulus. They analyzed the phenomenon and found that it is the interference of two optical vortices with reverse TCs. In 2006, Schmitz [17] introduced a way to produce optical vortices with reverse TCs by a phase mask of two interfering collinear vortex beams. The experimental results show that the optical vortices have periodic IM on the main annulus. It can be used to construct optically-driven micromachines or facilitate in-parallel molecular and cell assays. Here, we introduce a simple way to produce optical vortices with definite IM by an improved SPP.

The complex transmittance (CT) of an ideal SPP can be written as

$$T_1(r,\theta) = \mathrm{Circ}\left(\frac{r}{R}\right)\exp\left[\mathrm{j}\mathrm{Rem}\left(\frac{l\theta}{2\pi}\right)\right], \tag{1}$$

where (r,θ) are the polar coordinates in the input plane and l is an integer indicating the TC of the SPP. Rem is the remainder of $l\theta$ divided by 2π. $\mathrm{Circ}(r/R)$ is the circular aperture function with the radius of R.

We can get a new SPP by introducing a new parameter, that is

$$T_2(r,\theta) = \exp\left[\mathrm{j}S\mathrm{Rem}\left(\frac{l\theta}{2\pi}\right)\right]. \tag{2}$$

Here we define S as the phase modulation parameter (PMP). It means that the SPP can modulate the phase of the incident beam from 0 to $2S\pi$. When $S = 1$, the Eq. (2) describes a conventional SPP. When S is not an integer, the azimuthal phase of the field transmitted through the SPP is discontinuous with a period of $2\pi/l$. Eq. (2) can be rewritten as a Fourier series as below [18]

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$$T_2(r,\theta) = \sum_{N=-\infty}^{+\infty} c_N \exp\left(\mathrm{j}\frac{Nl\theta}{2\pi}\right), \tag{3}$$

where N is integer and c_N is the complex amplitude of the component $\exp[\mathrm{jRem}(Nl\theta/2\pi)]$, which can be written as

$$c_N = \exp[\mathrm{j}(S-N)\pi]\mathrm{sinc}(S-N). \tag{4}$$

From Eqs. (3) and (4), we can see that the field transmitted through the new SPP includes vortex components with TC of Nl. The relative intensity of each component is equal to

$$I_N = |c_N|^2 = \mathrm{sinc}^2(S-N). \tag{5}$$

The components with TC equal to 0, $\pm l$ are the dominant components. The interference of the components with $\mathrm{TC} = \pm l$ forms a modulated vortex. The zero order component with $\mathrm{TC} = 0$ forms a bright spot in the center of the modulated vortex. This spot affects the vortex's quality. Fig. 1 has a size of 2 mm × 2 mm, it shows the simulation results of the optical vortices produced by the SPP with $l = 40$, $S = 0.9$ and $R = 2.56$ mm. In this simulation, a laser beam with the wavelength of $\lambda = 632.8$ nm and a Fourier lens with the focal length of $f = 240$ mm are used. From Fig. 1 we can see that the optical vortex has IM and a bright spot in the center, which coincides with the analysis described above.

For producing high quality optical vortex with IM, we should eliminate the central bright spot. We add a new phase function $\exp[-\mathrm{jRem}(l\theta/4\pi)]$ to Eq. (2) for constructing an improved SPP. For $\exp[-\mathrm{jRem}(l\theta/4\pi)]$ to be a periodic function, l must be an even number. This improved SPP can be expressed as

$$\begin{aligned} T_3(r,\theta) &= \exp\left[\mathrm{j}S\mathrm{Rem}\left(\frac{l\theta}{2\pi}\right)\right]\exp\left[-\mathrm{jRem}\left(\frac{l\theta}{4\pi}\right)\right] \\ &= \sum_{N=-\infty}^{+\infty} c_N \exp\left\{\mathrm{j}\left[\frac{(N-1/2)^{l\theta}}{2\pi}\right]\right\}. \end{aligned} \tag{6}$$

When a plane wave transmits the improved SPP, the transmitted field can be written as

$$\begin{aligned} u_2(r,\theta) = \mathrm{Circ}\left(\frac{r}{R}\right) \sum_{N=-\infty}^{+\infty} \exp[\mathrm{j}(S-N)\pi] \\ \times \mathrm{sinc}(S-N)\exp\left[\mathrm{j}(N-\frac{1}{2})l\theta\right]. \end{aligned} \tag{7}$$

The optical field in Eq. (7) includes vortex components with TC of $(N-1/2)l$. Here the components whose TC is equal to $\pm l/2$ are the dominant components.

Fig. 2 shows the radial intensity distribution of the optical vortices with $l = 40$, in which the solid and dash dot line correspond to $\mathrm{TC} = 20$ and $\mathrm{TC} = 60$, respectively, for the same incident beam. From Fig. 2 we can see that the optical vortex with $\mathrm{TC} = 3l/2$ has no influence on the main annular intensity of the optical vortex with $\mathrm{TC} = l/2$. The intensity modulation degree (IMD) of the optical vortex was only controlled by the components with $\mathrm{TC} = \pm l/2$. The max and min intensity of the optical vortex on the main annulus can be simply expressed as

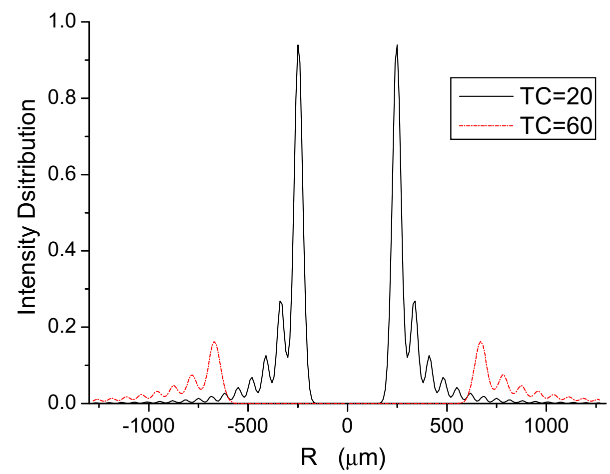

Fig. 2. Radial intensity distribution of ideal optical vortex. The solid line and dash dot line correspond to TC = 20 and TC = 60, respectively.

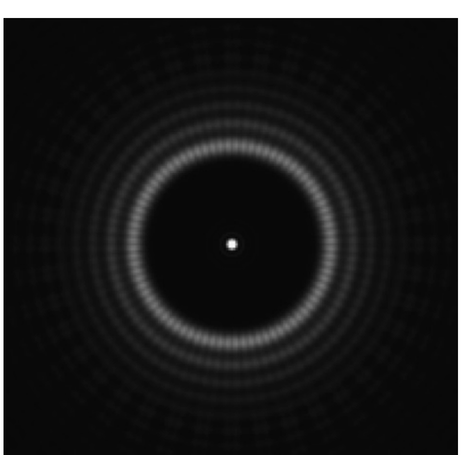

Fig. 1. Simulation result of the output optical vortex produced by using the SPP based on Eq. (2).

Fig. 3. Simulation result of the output optical vortex produced by using the improved SPP based on Eq. (6).