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Simulation of self-healing of polarization singularities

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ABSTRACT

The generation and propagation of polarization singularities have been researched for years. In this article, we explored self-healing of polarization singularity generated from Bessel beams when encountering obstacles during propagation. The topological structure can be reconstructed due to the self-healing of Bessel beams, and we found that the reconstruction of the topological structure is much faster than the healing of the broken amplitudes.

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1. Introduction

Singular optics is a new branch of modern physical optics dealing with singularities [1,2]. In scalar fields, the singularities in the transverse plane are known as "wave dislocations" or "optical vortices" where the amplitude of the field vanishes and the phase can't be defined [1,3]. The phase around the singularity varies continuously with topological charge, defined by the phase change in units of 2π along a closed loop surrounding the singularity, positive for anticlockwise while negative for clockwise. As for vectorial field, the attention moves to the singularities reside in the polarization states of the field [4–11]. In the transverse plane of a paraxial beam, the polarization ellipses are defined by the ellipticity and the azimuth. When one of the two parameters is undefined, the singularities in the vector-field emerge. They are the so-called C-points or *L*-lines. These are low-order polarization singularities, where the topological charge of the structure is $\pm 1/2$. In addition, there exist integral value [10] and high-order value of topological charges [12–14].

The generations to observe polarization singularities have been raised in many ways [15–23]. The common method is utilizing two orthogonal circularly polarized components to generate Poincaré beam [24,25]. Based on this, Bessel-Poincaré beams [26] and Mathieu-Poincaré beams [27] are also been proposed. Here we focus on the Bessel beams for its property of self-healing [28–32]. The generation and self-healing of vector Bessel-Gauss beams with variant state of polarizations upon propagation have been studied in [33]. But when the polarization structure contains singularity, something interesting will arise.

In this article, we conducted the simulation of generation of polarization singularities based on two orthogonal circularly polarized Bessel beams, and explored the polarization states upon propagation after encountering obstacles. We found that the topological structure could indeed self-heal, and the reconstruction of the topological structure is faster than the self-healing of the amplitudes.

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Fig. 1. Bessel beam intensity patterns of (a) a zeroth-order beam and (b) a first-order beam.

2. Generation of polarization singularity with bessel beams

An ideal Bessel beam can be expressed in cylindrical coordinate system as [34]:

$$E(r,\phi,z) = A_0 \exp(ik_z z) J_1(k_r r) \exp(\pm il\phi), \tag{1}$$

where J_l is the *l*th-order Bessel function, k_z and k_r are the longitudinal and radial wavevectors, with $k = \sqrt{k_z^2 + k_r^2} = 2\pi/\lambda$, where λ is the wavelength. We can take k_z as $k \cdot \cos \alpha$ and k_r as $k \cdot \sin \alpha$, where α is the angle between the propagation direction and the *z* axis. To meet the condition of paraxial approximation, α must take a very small value. The two components we used here are $E_0 = A_0 \exp(ik_z z)J_0(k_r r)$ and $E_1 = A_0 \exp(ik_z z)J_1(k_r r)\exp(-i\phi)$ respectively. We set $A_0 = 1$, $\lambda = 632.8nm$ and $\alpha = \pi/50000$. The intensity pattern of the two components in the initial plane (z = 0)are shown as Fig. 1. Here we should notice the difference of the max value of the colorbar in each figures.

To generate polarization singularity with these two components, we should put them into a vectorial system, just like in [24]. Here for simplification, we do not take the amplitude ratio of the two components into consideration. The synthetic field can be described as:

$$\mathbf{E} = E_0 \cdot \mathbf{e}_{\mathbf{L}} + E_1 \cdot \mathbf{e}_{\mathbf{R}},\tag{2}$$

where $\mathbf{e}_{\mathbf{L}}$ and $\mathbf{e}_{\mathbf{R}}$ are two circular basis vectors, defined as:

$$\mathbf{e}_{\mathbf{L}} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1\\ -i \end{pmatrix}, \tag{3a}$$

$$\mathbf{e}_{\mathbf{R}} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1\\ i \end{pmatrix}. \tag{3b}$$

With Eq. (2), we could calculate the Stokes parameters of the field to generate the polarization states. The Stokes parameters in such a system are calculated as [9]:

$$\begin{cases}
S_0 = |E_1|^2 + |E_0|^2, \\
S_1 = 2Re\left(E_1^* \cdot E_0\right), \\
S_2 = 2Im\left(E_1^* \cdot E_0\right), \\
S_3 = |E_1|^2 - |E_0|^2.
\end{cases}$$
(4)

where $Re(\cdot)$ denotes taking the real part of the item in the bracket, while $Im(\cdot)$ meaning the imaginary part, and the superscript * is the symbol of conjugate. Then we can get the ellipticity and azimuth of the polarization ellipses as:

$$e = \tan\left[\frac{1}{2} \arcsin\left(\frac{S_3}{S_0}\right)\right],$$

$$\psi = \frac{1}{2} \arctan\left(\frac{S_2}{S_1}\right).$$
(5a)
(5b)

With the parameters of the polarization ellipses, we can illustrate the polarization states of the field, shown as Fig. 2(a). The background denotes the intensity of the synthetic field. The red ellipses represent left-handed polarized while the green ones represent right-handed. We can see in the center of the field there exists a Lemon. When we exchange E_0 and E_1 in

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