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Propagation property of the non-paraxial vector Lissajous singularity beams in free space

Haitao Chen [a,b,*], Zenghui Gao [b]

[a] College of Physics and Engineering, Chengdu Normal University, Chengdu 611130, China
[b] Key Laboratory of Computational Physics, Yibin University, Yibin 644000, Sichuan, China

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ABSTRACT

The analytic expressions for the free-space propagation of paraxial and non-paraxial vector Lissajous singularity beams are derived, and used to compare the propagation property of a Lissajous singularity carried by paraxial and non-paraxial vector beams in free space. It is found that the creation of a single Lissajous singularity, the creation and annihilation of pairs Lissajous singularities may take place for the both cases. However, after the annihilation of a pair of singularities, no Lissajous singularities appear in the output field for non-paraxial vector Lissajous singularity beams, which is different from the paraxial vector Lissajous singularity beams.

1. Introduction

Since Kessler and Freund studied polarization singularities in polychromatic vector wave fields, much interest has been exhibited in the singular phenomena of polychromatic vector beams [1–15]. The Lissajous singularities can be created by second-hormonic generation with commensurate frequencies or can emerge from the incoherent addition of two incommensurate vector beams [1,4,10–12]. It is well known that there exist Lissajous figures with definite shapes after an enough large number of optical cycles whether the frequencies of polychromatic vector beams are coherent or incoherent [1,4,14,15].

The propagation properties of laser beams have been studied extensively within the framework of the paraxial approximation which is valid for beams with small divergence angle and spot size much larger than the wavelength. However, the paraxial approximation is no longer valid for beams with large divergence angle or small spot size comparable with the wavelength. Nonparaxial beams, such as tightly focused beams and diode laser beams with large divergence angle, are applied in practice [16]. Luo et al. derived the analytical expression of the nonparaxial Gaussian vortex beams propagating in free space and discovered that the variation of the beam parameters and propagation distance results in a shift of polarization singularities, but their position relation remains unchanged [17]. It is interesting to ask what will happen when non-paraxial vector Lissajous singularity beams propagate in free space? The purpose of this paper is to deal with such subject by comparing propagation of the paraxial and non-paraxial polychromatic vector beams carrying a Lissajous singularity at the input fields. In Section 2 the analytical expressions for the two cases are derived by using the Fresnel diffraction integrals and the Rayleigh–Sommerfeld diffraction integrals, respectively. Section 3 illustrates the evolution of Lissajous singularities for the both cases in free space with numerical examples. Finally, Section 4 summarizes the main results obtained in this paper, and compares the results obtained with previous work.

2. Theoretical expression of the free-space propagation

Consider a polychromatic vector beam $\boldsymbol{E}$ at the plane $z=0$ formed in two incoherent components $\boldsymbol{E_1}$ and $\boldsymbol{E_2}$ with different angular frequencies $\omega_{1,2}$, i. e.,

$$E_1(0, t) = \left[E_{1x}(0)\vec{i} + E_{1y}(0)\vec{j} \right]\exp(-i\omega_1 t), \tag{1a}$$

$$E_2(0, t) = \left[E_{2x}(0)\vec{i} + E_{2y}(0)\vec{j} \right]\exp(-i\omega_2 t), \tag{1b}$$

with

* Corresponding author at: Key Laboratory of Computational Physics, Yibin University, Yibin 644000, Sichuan, China
E-mail address: chqcht@sina.com (H. Chen).

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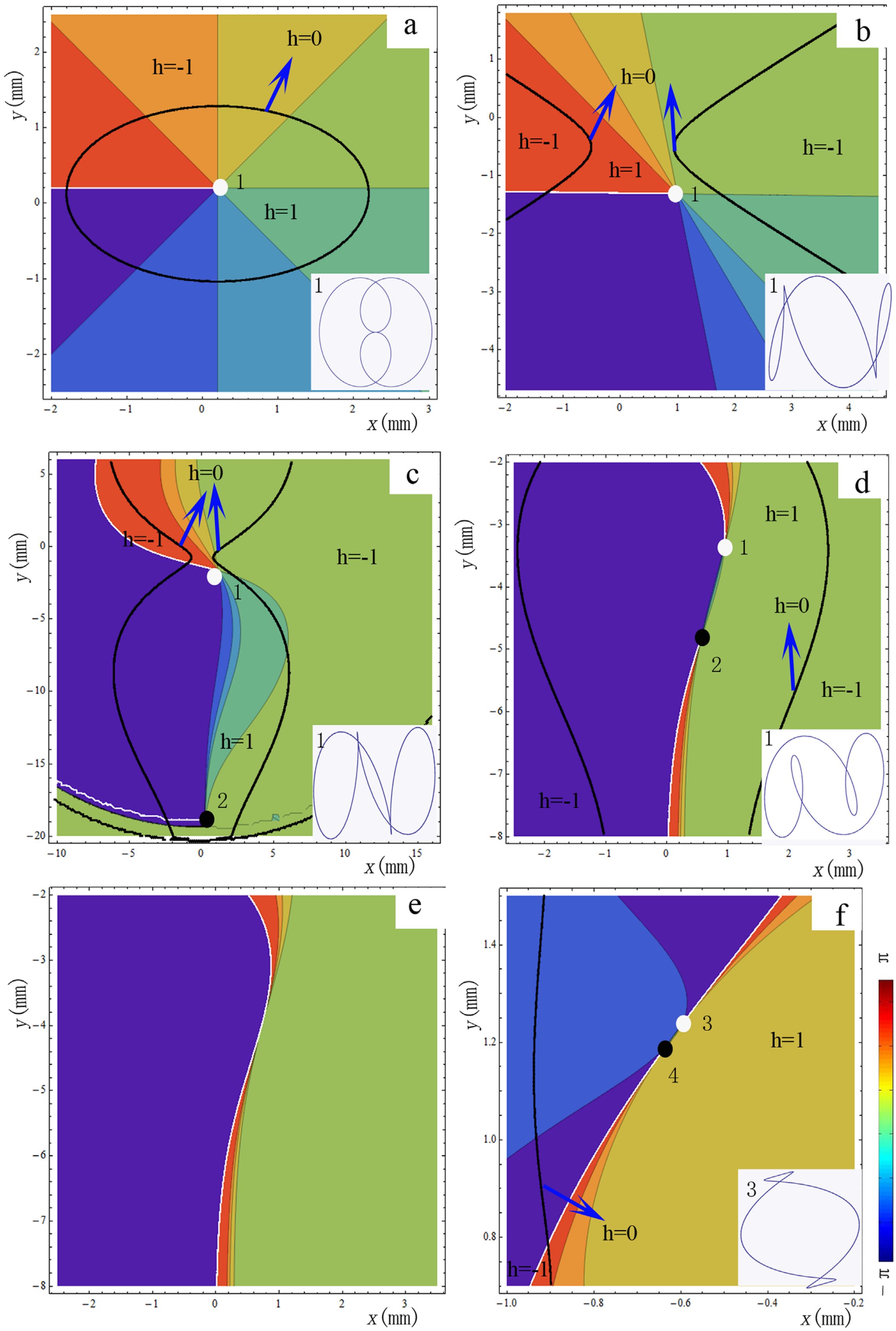

Fig. 1. Free-space propagation property of the paraxial beams carried a Lissajous singularity at the input fields (a) $z=0$, (b) $z=0.005z_{R2}$, (c) $z=0.032z_{R2}$, (d) $z=0.08z_{R2}$, (e) $z=0.083z_{R2}$, (f) $z=0.576z_{R2}$.