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Vector flat-top beam with Higher-order

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Abstract

In this paper, we introduce a new kind of vector flat-top-laser beam; we call it higher-order vector flat-top beam. We generate such laser beam, by the incoherent superposition of two orthogonal modes in polarization (Horizontal and vertical polarizations). The two basic modes are; the fundamental-Gaussian beam (LG_{00}) and one Higher-order-Vortex-Laguerre-Gaussian beam ($LG_{0\ell}$) with different topological charges of ($\ell = 1, \ell = 2,$ and $\ell = 3$). The resulting beam has almost a uniform intensity, and it is invariant under propagation in lossless systems. We believe that the resulting laser beam will have applications in laser material processing and laser micromachining.

Keywords: Vector beams, Flat-top beams, Laguerre-Gaussian beams

1. Introduction

Recently, the possibility of structuring light, both in scalar and vector regimes, in its spatial degrees of freedom such as polarization, phase, and amplitude [1] has opened a new way towards the development of laser applications. A most common case is transforming the Gaussian beam that has a peak intensity into uniform irradiance known as flat-top beam. The latter offers many applications including optical data processing [2,3], optical trapping [4], gravitational-waves detectors [5], laser-driven acceleration of particles [6, 7], optical recording, medical surgery, laser material processing, laser coupling into fibres [2], and military use [8].

Thus, a range of generation methods for this beam has been introduced such as diffractive optical elements [9], aspherical refractive lenses [10], and micro-lens arrays [11]. The traditional flat-top beam alters its shape during the propagation in contrast to the higher-order-Gaussian beams, which are eigenmodes of free space [12]. Among which, are the well-known Laguerre-Gaussian beams, which are characterized by a radial and azimuthal index. Besides scalar beams, the light beams with spatially inhomogeneous states of polarization known as vector beams [2] have attracted lots of interest in various fields by offering new groundbreaking applications.

In this work, we present a higher-order flat-top beam with variant polarization, by superposing the fundamental-Gaussian beam LG_{00} and Laguerre-Gaussian-vortex beam $LG_{0\ell}$ with different topological charges $(\ell = 2;\ \ell = 3)$ that could exhibit a uniform intensity during the propagation. We use simulations, to emphasize the main characteristics of the obtained higher-order-vector flat-top beams.

2. Superposition of a Gaussian beam $(\boldsymbol{LG_{00}})$ with a first-order-vortex beam $(\boldsymbol{LG_{01}})$

Firstly, in this section, we present the principle of the generation of a Vector flat-top beam, as demonstrated by the authors of the paper [13]. In that paper, they used a weighting superposition of a Gaussian beam and the first-order-Vortex-Laguerre-Gaussian beam. The amplitude of the orthogonal superposition is given by

$$E(r,\varphi,z) = \sqrt{\alpha}\ LG_{00}(r,\varphi,z)\hat{e}_V + \sqrt{(1-\alpha)}LG_{01}(r,\varphi,z)\hat{e}_H \qquad (1)$$

With $\hat{e}_V$ and $\hat{e}_H$ are polarization vectors, they denote the horizontal and vertical components of the Jones matrix. α is a parameter that quantifies the vectorness degree of an optical beam given by $V = 2|\sqrt{(\alpha(1-\alpha))}|$, where, for a perfect flat-top beam $\alpha = 0{,}5$, and we expect a perfect vector state with $(V = 1)$. However, for $\alpha = 0$ or $\alpha = 1$ the beam becomes purely scalar.

From equation (1), the intensity of the resulting beam is

$$I(r,\varphi,z) = \alpha|\ LG_{00}(r,\varphi,z)|^2 + (1-\alpha)\ |LG_{01}(r,\varphi,z)|^2 \qquad (2)$$

Where $LG_{01}(r,\varphi,z)$ and $LG_{00}(r,\varphi,z)$ refer to Laguerre-Gaussian modes of a radial order $p = 0$ and azimuthal orders $\ell = 1$ and $\ell = 0$ respectively.

The amplitude expression of the normalized $LG_{0\ell}\ (r,\varphi,z)$ mode is expressed by

$$LG_{0\ell}\ (r,\varphi,z) = \sqrt{\frac{2}{\pi\, w(z)|\ell|!}}\left(\frac{\sqrt{2}r}{w(z)}\right)^{|\ell|} exp\left(-\frac{r^2}{w(z)^2} + ik\frac{r^2}{2R(z)}\right) \times \exp\big(i(1+|\ell|)\eta(z)\big) \qquad (3)$$

Here; $w(z) = w_0\sqrt{1 + \left(\frac{z}{z_r}\right)^2}$, $R(z) = z\left(1 + \left(\frac{z_r}{z}\right)^2\right)$, $z_r = \pi w_0^2/\lambda$, $\eta(z) = \arctan\left(\frac{z}{z_r}\right)$, $\theta_0 = (\lambda/\pi w_0)$, are, the beam width, the ray of wavefront curvature, the Rayleigh length, the Gouy phase shift, and the divergence angle, respectively. In addition, w_0 is the Gaussian beam waist, λ is the wavelength of the used laser.

As a first example, we show in Figure 1, the 3D intensities representation of the fundamental-LG beam (Fig1. a), as well as the first-order-vortex-LG beam (Fig1.b). The incoherent superposition of the cited beams gives us the first-order-vector flat-top beam (Fig1.c). In subfigure (Fig1.d) we present the propagated flat-top Vector beam in 3D. The main conclusion is, the invariant property of the obtained beam during propagation. It is worth recalling the different numerical values used in the different simulations; the beam waist is w_0=1mm, and the laser wavelength is λ=532 nm.

3. Superposition of Gaussian beam (LG_{00}) with a higher-order-vortex $(LG_{0\ell})$ beam

Following the same principle presented above, we demonstrate in this section the generation of higher-order vector flat-top beam, by the superposition of one higher-order-LG beam with fundamental-Gaussian beam. We have the same equation of the resulted intensity, it is given by

$$I(r,\varphi,z) = \alpha|\ LG_{00}(r,\varphi,z)|^2 + (1-\alpha)\ |LG_{0\ell}(r,\varphi,z)|^2 \quad (4)$$

In the following, we use subsections to present results of each superposition order.

3.1 Superposition of a fundamental-Gaussian Beam (LG_{00}) with a Higher-order-vortex (LG_{02}) Beam

Let's consider at first stage the superposition of the second-order-Vortex-LG beam with the fundamental-Gaussian beam, the profiles as well as 3D presentation of the different beams are presented in Figure 2

3.2 Superposition of a fundamental-Gaussian Beam (LG_{00}) with a Higher-order-vortex (LG_{03}) Beam

Let's now consider the superposition of the third-order-vortex-LG beam with the fundamental-Gaussian beam, the profiles as well as 3D presentation of the different beams are presented in Figure 3

4. Results

In this section, we simulate intensities of the generated vector flat-top beams using equations (1- 4)

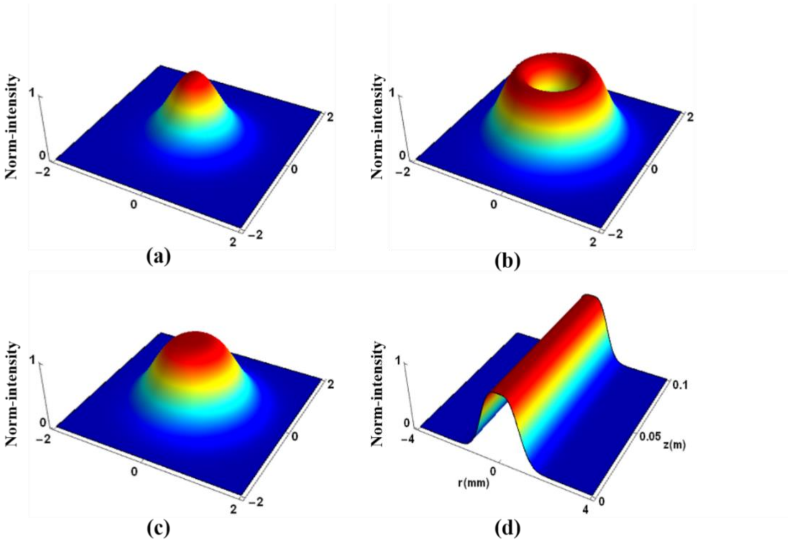

Figure 1. Intensity profiles 3D view; (a) fundamental-Gaussian beam with a peak at the center, (b) first-order-Laguerre-Gaussian-Vortex beam, (c) superposition of fundamental-Gaussian beam (a) and first-order of Laguerre-Vortex beam (b), (d) propagation of first-order-flat-top beam.

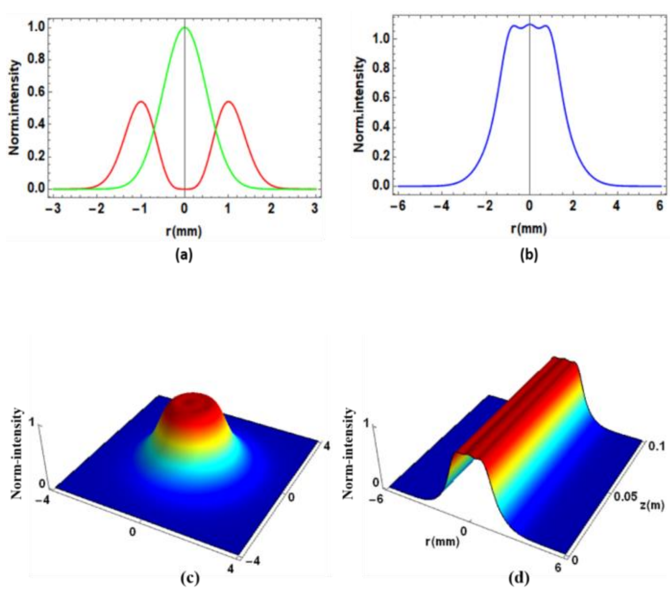

Figure 2. Intensity distribution. (a) The fundamental-Gaussian beam (LG_{00}) shown in green and second-order-vortex-Laguerre-Gaussian beam (LG_{02}) shown in red; (b) The total intensity distribution of the superposition of (LG_{00}) with (LG_{02}) . (c) 3D view of the Intensity distribution of the obtained flat-top beam (d) The propagation of a flat-top beam produced by superposition of (LG_{00}) with (LG_{02}).

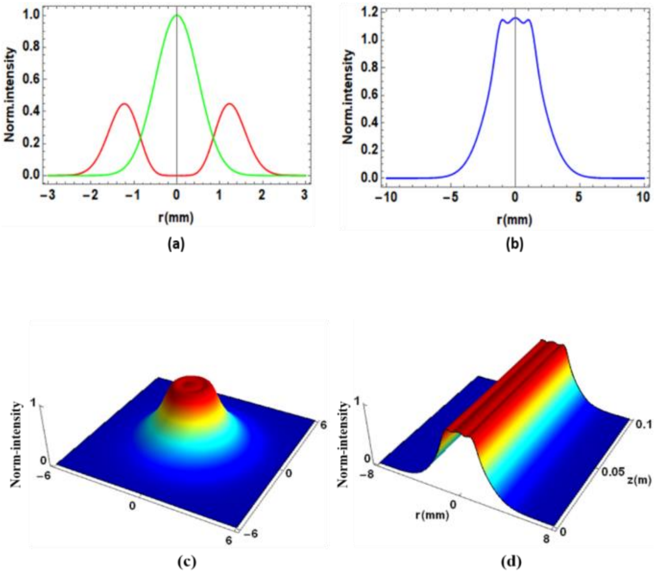

Figure 3. Intensity distribution. (a) The fundamental-Gaussian beam (LG_{00}) shown in green and third-order-vortex-Laguerre-Gaussian beam (LG_{03}) shown in red; (b) The total intensity distribution of the superposition of (LG_{00}) with (LG_{03}) . (c) 3D view of the Intensity distribution of the obtained flat-top beam (d) The propagation of a flat-top beam produced by superposition of (LG_{00}) with (LG_{03}).

5. Discussion

From the obtained results and figures (1-3), it is clear that the superposition of a Vortex-LG beam having a doughnut shape, with a Gaussian beam having a pic shape, the created beams are of a flat shape. The quality of the flat shape depends strongly on the LG beam order. The bigger is the LG beam order; the better is the quality of the beam flatness. It is worth to mention, that using higher-order-LG beams, requires the modification of the fundamental-Gaussian beam waist.

6. Conclusion

In summary, we have demonstrated a technique to create a vector flat-top beam using the superposition of, one higher-order-Vortex-LG beam and a fundamental-Gaussian beam. The two beams are orthogonal in polarization. By changing the order of the LG-vortex beam, as well as the width of the Gaussian beam, one can change the flatness of the obtained beams. Consequently, we can provide a multiple Vector flat-top beams with different characteristics, which can be used in many applications, such as High-resolution microscopy, micromachining and optical tweezing.

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