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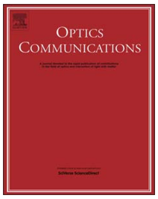

Shaping perfect optical vortex with amplitude modulated using a digital micro-mirror device

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ABSTRACT

We propose a technique to generate of perfect optical vortex (POV) via Fourier transformation of Bessel-Gauss (BG) beams through encoding of the amplitude of the optical field with binary amplitude digital micro-mirrors device (DMD). Furthermore, we confirm the correct phase patterns of the POV with the method of Mach–Zehnder interferometer. Our approach to generate the POV has the advantages that rapidly switch among the different modes, wide spectral regions and high energy tolerance. Since the POV possess propagation properties that not shape-invariant, we therefore suppose that our proposed approach will find potential applications in optical microscopy, optical fabrication, and optical communication.

1. Introduction

An optical vortex (OV) has a spiral phase and a donut-shaped intensity distribution, which attracts wide spread interest and contributes to various applications, such as stimulated mission depletion microscopy [1], optical trapping of nanoparticles [2], free-space optical communication [3] and quantum communication [4]. However, some applications of optical vortex beam are limited by its unfixed ring diameter depending on topological charge l (the number of twist in a wave-front per unit wavelength). This property may cause problems in applications of optical vortexes, such as optical tweezers and orbital angular momentum (OAM) communications, which are desired to provide a large topological charge and a fixed dark hollow simultaneously.

To overcome the limitation of optical vortex beam, Ostrovsky and co-workers [5,6] firstly introduced the concept of a perfect optical vortex (POV) beam: one having bright ring radius independent of topological charge. They used a special phase mask, generated from a complex equation, to approximately generate the POV. Compared to an ordinary optical vortex whose radius of main bright intensity ring is proportional to the vortex's topological charge [7], the radius of the bright ring of POV does not change with the topological charge and only has one bright ring. The study of POV has recently attracted wide attentions [8,9], and its application in optical tweezers has been demonstrated. However, almost all of these reports were realized by using spatial light modulators (SLM) to modulate phase, the disadvantages of SLM are their lack of tolerance to a high-density laser, and their switching frequency is limited to tens level.

The digital micro-mirrors device (DMD) endures significantly higher illumination power, supporting several spectral regions from 350 to 2000 nm, and high switching frequency about 4–32 KHz, thus has already been employed in various research areas [10], such as high-resolution television, rapid generation of Laguerre-Gaussian beam [11] and vortex orbital-angular-momentum (OAM) modes [12], meta-q-plat direct writing [13], liquid crystal fork gratings direct writing [14], fabricating micro-lens arrays [15], multiple-aperture confocal imaging [16], variable fiber optic attenuators [17], optical neural networks [18], optical spectrometers [19], and wave-front correction [20].

In this letter, we encode amplitude information by modulating the position and the width of a binary amplitude grating, respectively, then realize such amplitude mask on a DMD to successfully generate POV, and we also can be arbitrarily tune radius and topological charge of POV. Furthermore, we confirm the correct phase patterns of the POV with the method of Mach–Zehnder interferometer. Our method has the ability to generate stable POV with high accuracy, rapid switching among the different modes due to high frame rates (32 kHz binary switching) and high tolerance power (2 W/cm^2 visible light). Due to the propagation properties that shape-invariant of POV, our proposed approach could have potential applications in optical microscopy, optical fabrication, and optical communication.

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2. Theoretical

To introduce our technique, we first studied the design of a two-dimensional computer-generated hologram of phase profile to generate the POV [9]. Since we intend to modify the amplitude binary grating as well as the phase profile of the wave-fronts to create POV, a mean of create a binary computer-generated hologram that represents the amplitude grating, this can be realized through Lee method [21] in which the normalized transmittance of the amplitude pattern can be written as

$$h(x,y) = \frac{1}{2} + \frac{1}{2}\mathrm{sgn}[\cos\left(2\pi\left(\mu_0 x + \nu_0 y\right) - 2\pi p(x,y)\right) - \cos(\pi w(x,y))] \quad (1)$$

Here, sgn(x,y) is the sign function. It is easy to check that in the limit where $w(x,y)$ and $p(x,y)$ are slowly varying. We can find the corresponding $w(x,y)$ and $p(x,y)$ functions for a general complex scalar field $A(x,y)\exp(i\varphi(x,y))$ according to the relations

$$w(x,y) = \frac{1}{\pi}\arcsin\left[A(x,y)\right] \quad (2)$$

$$p(x,y) = \frac{1}{\pi}\varphi(x,y) \quad (3)$$

where $A(x,y)$ is the intensity distribution of Gauss's functions, $\varphi(x, y)$ is phase parameter formed by an argument of function *exp* $(i\eta r + il\theta + ix/x_0)$, here η is the axicon parameter, l is the spiral phase parameter, x_0 is grating constant which determined the desired pattern into a specific direction. Ordinary Gauss beam combining an axicon and a spiral phase factors through diffraction to form a Bessel-Gauss (BG) beam [9], such BG beam is then optical Fourier-transformed through a simple lens to get a POV beam. We can adjust the radius of the bright ring of POV through modifying axicon parameter, change the POV's topological charge with spiral phase parameter, and also adjust the width of the bright ring of POV through modifying the beam's waist or the focal distance of lens. If only intensity modulation instead of phase modulation using Lee method, and the resulting POV still has a little radial side lobe. Since the radial side lobe of optical vortexes mainly come from the helical phase structure of the central part of the beam diffraction [22], so we add a filter function $f(r,\theta)$ simply as follows to describe the space filter function.

$$f(r,\theta) = \begin{cases} 0 & r < R_1 \\ 1 & R_1 < r < R_2 \\ 0 & r > R_2 \end{cases} \quad (4)$$

Here, R_1 and R_2 are radial parameters for filter function obtained by the trial-and-error method, mainly modulate the ratio of R_1 and R_2 which approximately equal to the spot size. The total amplitude mask for the DMD is formed by plotting an argument of function can be written as

$$T(x,y) = h * f \quad (5)$$

So the amplitude mask like a doughnut with special patterns. The DMD utilized is a 1920 × 1080 elements device with a 10.8 μm pixel pitch. In our experimental setup, light reflected from mirror in the "on" state is projected to the optical system, and the pixel on the DMD appears bright, while the "off" state mirror, resulting in a dark pixel. Intensity shaping of spatial modes can be achieved by switching the micro-mirrors on/off rapidly. However, the modes created using this process are not temporally stable and have the desired intensity profile only when averaged by a slow detector. Alternatively, a pseudo-random pixel dithering has been used by previous workers to achieve continuous amplitude modulation [23]. Fig. 1 shows the amplitude mask designed for generation of POV, in which we choose the spiral phase parameter $l=3$ and different axicon parameter $\eta=6.9$ or 8.8 μm^{-1}, the optimized ratio of R_1 and R_2 is 1/3.

3. Experiment

The experimental setup is schematically shown in Fig. 2. A He–Ne laser with wavelength 633 nm is utilized as the light source. A beam expander expands the laser to approximately 10 mm in

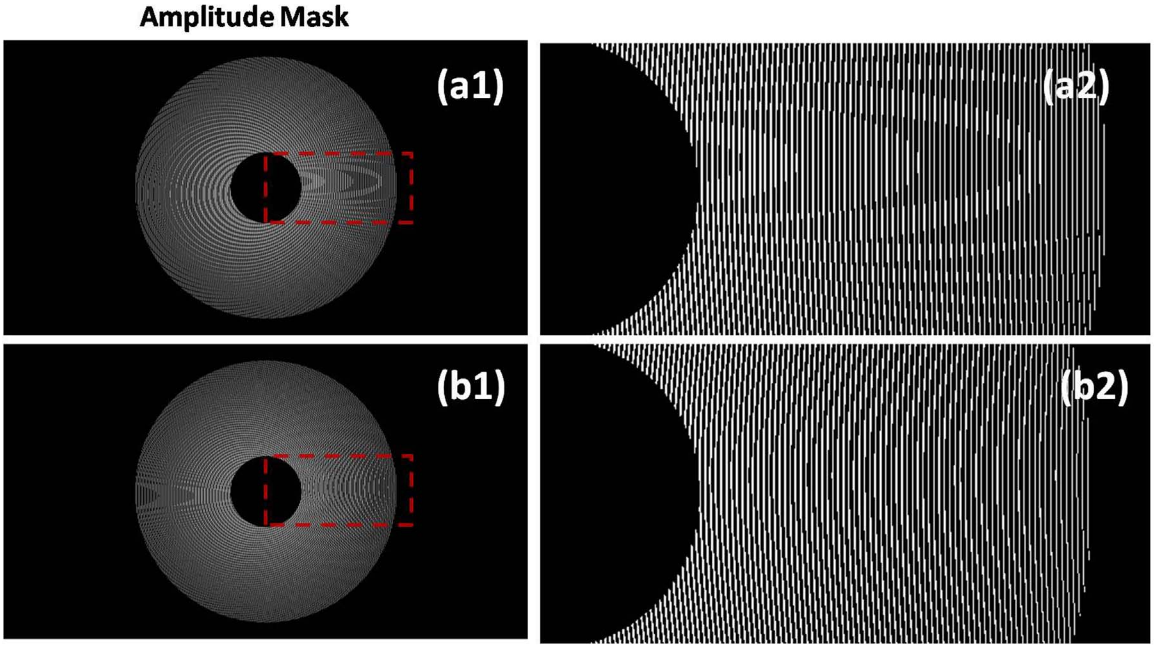

Fig. 1. Amplitude mask on DMD with topological charge $l=3$, but with different axicon parameter $\eta=6.9\ \mu m^{-1}$(a1), $\eta=8.8\ \mu m^{-1}$(a1); (a2,b2) is partially enlarged view of the red dots block in a1 and b1 respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)