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Generation of optical vortex based on computer-generated holographic gratings by photolithography

Shaoxiang Li and Zhenwei Wang[a)]
Department of Physics, College of Science, National University of Defense Technology, Changsha, Hunan Province, 410073, China

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The Laguerre-Gaussian beam is a typical example of the optical vortices, which can be generated by computer-generated holograms (CGHs) with the topological charge controlled. Here, we fabricated transmission-amplitude CGH gratings (up to 100 lines per millimeter) on metal film by photolithography technique. Such CGH grating grooves feature high resolution and fine smoothness, so that the gratings can be used to generate Laguerre-Gaussian beam with perfect mode. They are also applicable for the generation of femtosecond optical vortices due to the high damage threshold of the metal film. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4823596]

For decades, the optical vortices (OV) attracted great interests because of their important applications in optical tweezers,[1] optical spanners,[2] quantum communication,[3] and atom cooling.[4] Most recently, theoretical calculations indicated that vortex configuration can guide high power ultrashort pulses over a long distance in the atmosphere before they break up into filaments initiated by Kerr-lens self-focusing, which suggests OV can be used as a powerful tool for the remote atmosphere sensing,[5] therefore, the femtosecond OV generation becomes an important research topic.[6,7] A typical example of the OV is Laguerre-Gaussian (LG_p^l) beam with a helical phase structure. In the intensity profile, LG_p^l mode has the characteristics of $p+1$ radial nodes (or $p+1$ concentric rings) and an independent azimuthal mode l, also known as topological charge of the beam.[8] When $p=l=0$ (LG_0^0), the beam is Gaussian mode TEM_{00}. Generally, people are interested in LG_0^l mode (also called donut-mode), which displays a single annular ring. The electric field expression for the LG_0^l mode contains a phase term $exp(il\varphi)$ (φ is the azimuthal angle), which makes each photon of such beams carry an orbital angular momentum[9] of $l\hbar$.

Since laser output is commonly Hermite-Gaussian mode, for obtaining Laguerre-Gaussian (LG) beams, mode conversion is needed. Currently, the main conversion methods include spiral phase plates (SPPs),[10,11] cylindrical lens mode-conversion,[12,13] and computer-generated holograms (CGH).[14–16] Although SPPs have a high conversion efficiency near 100%, they are not suitable for femtosecond LG pulses generation because of the chromaticity problem.[17] Cylindrical lens mode converter can, in principle, produce pure Laguerre-Gaussian modes, but the setup is difficult to align.[12] In comparison, CGH is a preferred method because of its simple structure and easy operation. So far, people fabricated CGH gratings mostly through holographic imaging[7] or micromachining based on laser burning.[6] The CGH grating based on holographic plate features high resolution, but it is not applicable for high power femtosecond laser pulses because of the limited damage threshold of the emulsion.[7,18] The CGH gratings fabricated by laser micromachining have a high damage threshold[6] (up to 10^{12} W/cm^2); however, such gratings suffer from low resolution and the grating grooves are quite rough, which leads to LG beam conversion with poor mode. In this work, by photolithography technique, we fabricated CGH gratings with different topological charges on metal film. Such gratings feature high resolution and high damage threshold, which can be used to generate high power femtosecond LG beams.

In order to obtain the CGH grating pattern, we simply consider a vortex beam propagating along z direction with helical phase character as $\exp[i(kz+l\varphi+\phi_0)]$, and a plane wave $\exp[i(k_z z+k_x x)]$ propagating along the direction with an angle θ relative to z direction. In the plane $z=0$, the interference of the two beams gives the CGH grating pattern

$$I(x,y)=\frac{1}{2}\left\{1+\cos\left[l\left(\arctan\frac{y}{x}+n\pi\right)-kx\sin\theta+\phi_0\right]\right\}, \tag{1}$$

where $l=1, 2, 3,\ldots$ is the topological charge of the LG beam, ϕ_0 is an arbitrary phase factor, $\varphi=\arctan\frac{y}{x}+n\pi$ is the azimuthal angle, and n takes the value as following for keeping $0\le\varphi\le 2\pi$:

$$n=\begin{cases}0, & 0\le\varphi\le\pi/2\ (x\ge 0\,\&\,y\ge 0);\\ 1, & \pi/2\le\varphi\le 3\pi/2\ (x<0);\\ 2, & 3\pi/2\le\varphi\le 2\pi\ (x\ge 0\,\&\,y<0).\end{cases} \tag{2}$$

Equation (1) is commonly used to simulate the sinusoidal interference pattern. For fabricating gratings, we need to binarize the interference pattern as

$$I(x,y)=\begin{cases}1, & I(x,y)\ge 1/2;\\ 0, & I(x,y)<1/2.\end{cases} \tag{3}$$

Figure 1 shows the binary grating patterns with different topological charges ($l=1, 2, 3$) calculated according to the above equations by MATLAB software (The MathWorks, Inc). We can observe intuitively that the middle fringe of charge-l grating is divided into l forks.

a)zwwang@nudt.edu.cn

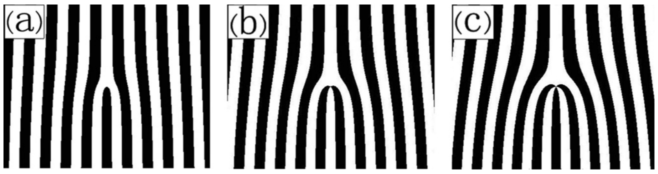

FIG. 1. Binary CGH grating patterns: (a) $l=1$; (b) $l=2$; and (c) $l=3$. The fork reveals the phase singularity.

By photolithography technique, we transferred the grating patterns obtained above onto metal film to get CGH gratings. The manufacture procedures are displayed in Fig. 2. We selected a commercial photomask plate (Mask-Blank-3015, OMNISUN Information Materials Corp.) for grating fabrication, which consists of a glass substrate with 1.5 mm thickness, a Chrome (Cr) layer with 100 nm thickness and a photoresist layer with 500 nm thickness (AZ1500 positive photoresist, Shipely Corp.) from bottom to top. First, we transferred the fork-shaped gating patterns in Fig. 1 onto the photoresist layer by photolithography ($MP80^{+}$ Photomask Writer, Micronic Corp.). In this process, a focused X-ray beam was projected onto the photoresist to scan the desired patterns (Fig. 1), which is so-called exposure. After developing with AZ1500-matched developer, the exposed photoresist was removed and the grating pattern appeared. Consequently, parts of the Cr layer were exposed in air. Then the exposed Cr film was wet-etched by using Ammonium-Ceric-Nitrate ($(NH_4)_2Ce(NO_3)_6$) solution. At last, the residual photoresist was cleaned off with Acetone (C_3H_6O) solution, and then we get the CGH patterns on Cr film with glass substrate.

By photolithographic method stated as above, we fabricated three CGH gratings with different topological charges ($l=1, 2, 3$), and the density of grooves is about 100 lines per millimeter. Figure 3 displays the microscope images of the gratings. The black strips correspond to the Cr film, while the bright strips correspond to the glass substrate. Since photolithography technique features high resolution, we can see the grooves of CGH gratings are very smooth (with submicrometer roughness). Such gratings are much better than those fabricated by laser micromachining,[6] in which the groove roughness is about 10 μm due to the difficulty of laser burning control.

Since the strips of Cr film blocks the light from the ultraviolet to the infrared, while the glass substrate is transparent, our gratings are transmission-amplitude type. To get OV

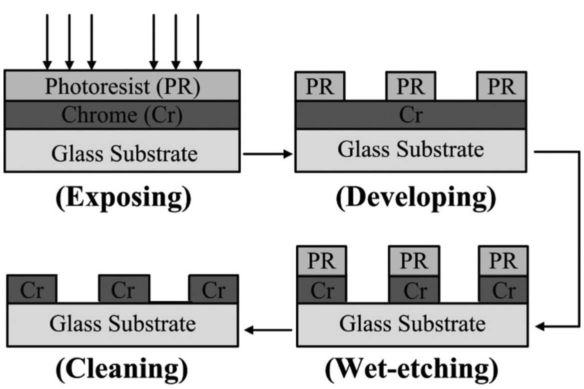

FIG. 2. The CGH grating fabrication by photolithography.

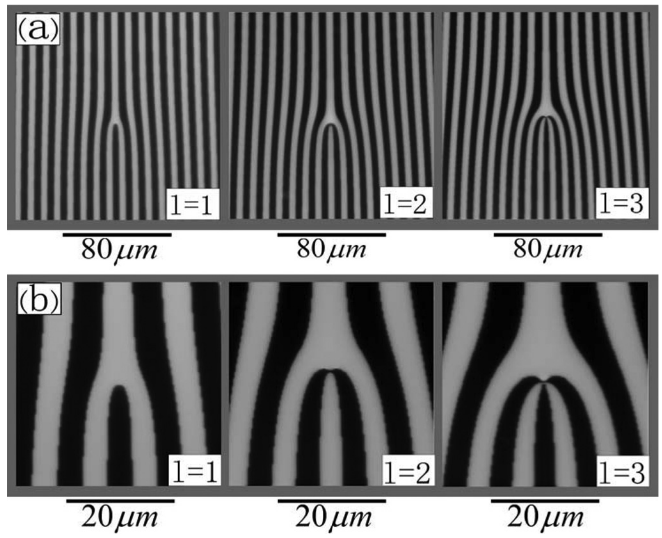

FIG. 3. The structures of CGH gratings with charges of $l=1$, 2, 3 observed under microscope. (a) and (b) display the central forks observed under different magnifications.

mode (LG_0^l), we irradiated the grating surface normally with He-Ne laser mode LG_0^0. Then a series of LG beams were reconstructed in the different order diffractions. The 0 order diffraction remains the incident LG_0^0 mode, and the +1 order diffraction is the LG_0^{+l} beam, which is our target OV mode. Its far field diffraction patterns were recorded by CCD camera, and the images are shown in Fig. 4(a). We can see LG_0^l mode generated by such gratings is perfect. Figure 4(b) shows the normalized transverse intensity distribution. With the topological charge increasing, the dark region becomes bigger and the donut ring becomes thinner, which is the feature of the LG_0^l mode.

To confirm the above LG_0^l beams have helical phase structures, we made them to interfere with the same reference He-Ne laser beam (LG_0^0). The interference patterns are displayed in Fig. 4(c). The central fringe of the interference pattern is obviously divided into l forks, which is consistent with the theoretical simulations (Fig. 1). Because the intensity of reference Gaussian beam peaks at the center, and it gradually weakens from center to edge, while the center of LG_0^l beam presents a dark region, the fringe contrast of interference is smallest in the center. Therefore, we can see that the central interference patterns are blurring. In literatures, some groups exposed holographic plate by such interference pattern to get high resolution CGH gratings,[18] however, because of the obvious defection of the central interference pattern, it is difficult to fabricate high-quality CGH gratings by such holographic method.

Since the gratings are fabricated by metal Cr film which features high damage threshold, they can be used for the high power femtosecond OV generation. By illuminating the gratings with femtosecond pulses at intensity of about 110 GW/cm^2 (1.6 mJ per pulse, 50 fs duration, 800 nm center wavelength), we generated femtosecond LG pulses (140 μJ per pulse) with intensity of about 10 GW/cm^2. If we want to get higher energy femtosecond OV pulses, we need to increase the incident pulses energy. However, metal Cr strongly absorbs the photons from the ultraviolet to the infrared, therefore such gratings cannot be applicable for the

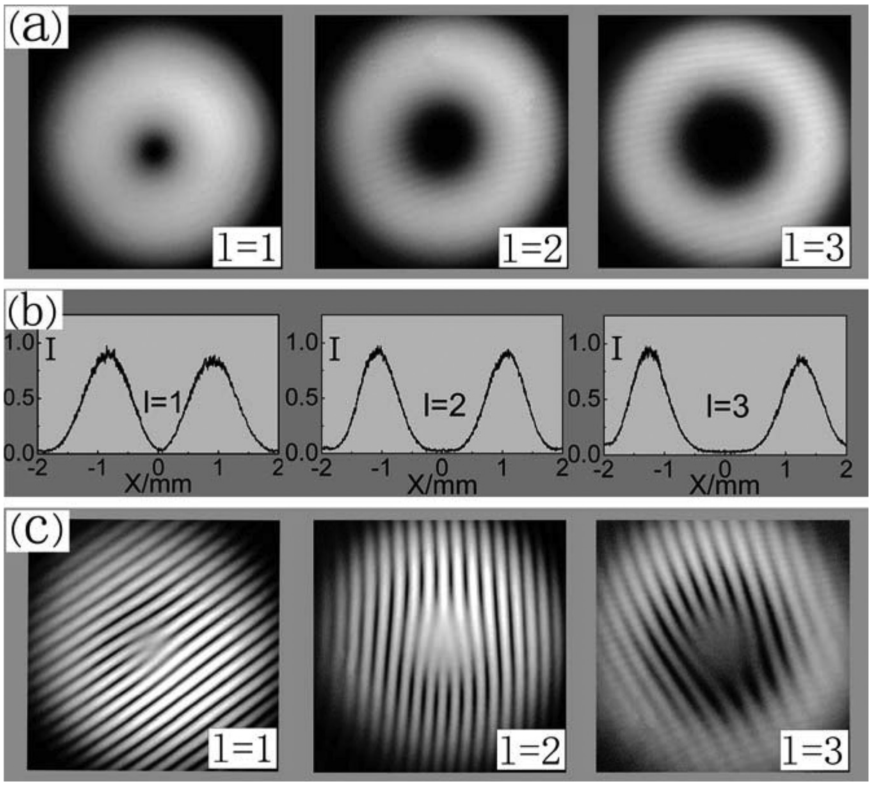

FIG. 4. (a) The LG_0^l mode obtained from the +1 order diffraction of the CGH gratings with different charges ($l = 1, 2, 3$); (b) the normalized transverse intensity distribution of LG_0^l beams corresponding to (a); (c) the interference patterns of the LG_0^l beams and the reference Gaussian beam.

hundreds GW or even TW OV pulses generation. For that purpose, we can use gold[19] or silver[20] film instead of Cr to fabricate reflection type gratings, and then we can expect to obtain the high power OV pulses at intensity up to TW/cm^2 (see Ref. 6).

For such amplitude gratings, half of the incident light power is blocked by metal Cr, and, also, the rest light is partly diffracted into the target first order, consequently, the efficiency of the LG_0^l mode conversion is as low as only about 8% in our experiment, which is consistent with the literatures.[7,18] Theoretical and experimental investigations demonstrated that volume phase type gratings are superior to amplitude type gratings, and the mode conversion efficiency can be up to 33.8% (see Ref. 7). In order to fabricate such phase type CGH grating by photolithography method, based on the above Cr film grating fabrication, we can continue to wet-etch the exposed glass substrate by hydrofluoric acid (HF) solution with the etching depth controlling (i.e., phase modulation controlling), and then remove the Cr film completely by Ammonium-Ceric-Nitrate ($(NH_4)_2Ce(NO_3)_6$) solution. Finally, we can get transmission-phase type CGH gratings with higher efficiency, which is our following research work.

In conclusion, we experimentally demonstrated that, the high quality CGH gratings applicable for high power femtosecond OV generation can be fabricated through photolithography technique. By using these gratings, we generated LG_0^l beams with perfect mode. Our work suggests such photolithographic CGH gratings will provide a powerful tool for the application of the high power femtosecond OV beams.

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