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Method for holographic femtosecond laser parallel processing using digital blazed grating and the divergent spherical wave

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Abstract. A method for holographic femtosecond laser parallel processing is proposed, which can suppress the interference of zero-order light effectively and improve the energy utilization rate. In order to blaze the target pattern to the peak position of zero-order interference, a phase-only hologram containing a digital blazed grating is designed and generated, and the energy of the target pattern can be increased by 3.793 times in theory. In addition, by subsequently increasing the phase of the divergent spherical wave, the focal plane of the target pattern and the plane of the multiorder diffraction beam resulting from the pixelated structure of the spatial light modulator (SLM) can be separated. Both a high-pass filter and aperture are used to simultaneously eliminate the influences of zero-order light and multiorder interferential patterns. A system based on the phase-only SLM (with resolution of 1920×1080) is set up to validate the proposed method. The experimental results indicate that the proposed method can achieve high-quality holographic femtosecond laser parallel processing with a significantly improved energy utilization rate. [DOI: 10.1117/1.OE.54.1.016109]

Keywords: femtosecond laser; holography; parallel processing; spatial light modulator; zero-order light suppression; digital blazed grating; divergent spherical wave; filtering.

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1 Introduction

Femtosecond laser processing is a powerful technique which enables microfabrication in transparent materials. The advantages of femtosecond laser processing include high-spatial resolution, reduced thermal destruction, and widespread application for various materials.[1] However, it is a drawback that such a device fabrication requires a huge number of processing points. Therefore, the throughput of femtosecond laser processing must be improved.

In recent years, with the development of spatial light modulator (SLM) technology, achieving parallel processing design by loading a computer-generated hologram (CGH) on the SLM can not only save the cost of a diffractive optical element in traditional parallel processing, but also flexibly generate the arbitrary patterns. Therefore, femtosecond laser holographic parallel processing based on SLM has attracted broad attention in research.[2–6] However, dynamic SLM holograms based on pixel structure still face many problems for achieve the target diffraction pattern, as the zero-order diffracted light and multiorder image reproduction caused by the characteristics of the SLM pixel structure have a large impact on the target image quality. A great number of studies aiming at addressing these issues was carried out by researchers in the holographic display fields all around the world.[7–11] For example, Palima and Daria[7] designed a CGH which can produce a desired phase and a corrective phase, and the beam with the corrective phase can destructively interfere with the zero-order beam. Christmas et al.[8] separated the reconstructed pattern from the zero-order light focus position and eliminated the zero-order light interference by filtering. Silvennoinen et al.[9,10] used a 500-mm Fresnel lens and beam blocker to remove the unwanted zero-order diffraction from the image plane. Zhang et al.[11] proposed a new technique to eliminate the zero-order light by adding both a linear phase and a divergent spherical phase to the precalculated phase distribution on the phase-only SLM.

In this paper, a novel method for holographic femtosecond laser parallel processing is proposed, which can not only suppress the interference of zero-order light effectively, but also improve the energy utilization rate. The paper is organized as follows. In Sec. 2, the reasons for the existence of zero-order light of SLM with a pixelated structure are demonstrated. In Sec. 3, an optimization method of hologram projection is illustrated. Finally, experimental results using the proposed method and discussions are given in Secs. 4 and 5, respectively.

2 Optical Characteristic of the Pixelated Phase-Only Spatial Light Modulator

Holographic femtosecond laser parallel processing in this paper is realized based on the pixelated structure of the SLM with a phase-only hologram. In this section, optical field characteristics of the phase-only SLM are investigated. Based on the study, the cause of zero-order light which disturbs the target pattern is explained.

Figure 1 shows the geometric schematic of an SLM pixelated structure (Holoeye, pluto NIR-2). The single pixel, whose pixel size is a, is square and the pixel space is d.

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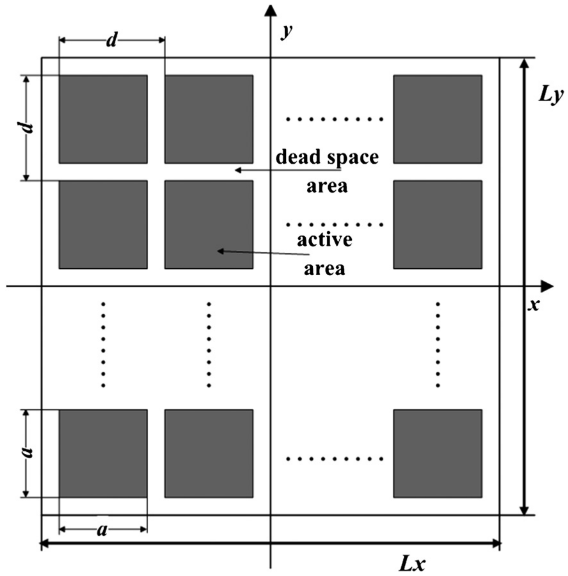

Fig. 1 Geometry schematic of pixelated phase-only spatial light modulator (SLM).

L_x and L_y represent the width and length of the SLM, respectively. The origin of the XOY coordinate system is in the center of the phase-only SLM.

The transmittance function of the SLM pixelated structure can be described as

$$t(x,y) = \mathrm{rect}\left(\frac{x}{L_x},\frac{y}{L_y}\right)[t_{\mathrm{ac}}(x,y)+t_{\mathrm{ds}}(x,y)], \tag{1}$$

where rect is the rectangular function.

The transmittance function of coding phase hologram areas (active areas) in SLM is expressed as

$$t_{\mathrm{ac}}(x,y) = \mathrm{rect}\left(\frac{x}{a},\frac{y}{a}\right)\otimes\left\{\frac{1}{d^2}\mathrm{comb}\left(\frac{x}{d},\frac{y}{d}\right)\exp[i\varnothing_{\mathrm{ac}}(x,y)]\right\}. \tag{2}$$

$\varnothing_{\mathrm{ac}}(x,y)$ is the hologram coding phase information computed by the Gerchberg–Saxton algorithm,[12] which is loaded on the active areas; $\otimes$ is the convolution operation; and $\mathrm{rect}(x/L_x, y/L_y)$ is the aperture function of the SLM.

The transmittance function of noncoding areas (dead space areas) in SLM is expressed as

$$t_{\mathrm{ds}}(x,y) = \left\{\left[\mathrm{rect}\left(\frac{x}{d},\frac{y}{d}\right)-\mathrm{rect}\left(\frac{x}{a},\frac{y}{a}\right)\right]\otimes\frac{1}{d^2}\mathrm{comb}\left(\frac{x}{d},\frac{y}{d}\right)\right\}A_{\mathrm{ds}}(x,y)\exp[i\varnothing_{\mathrm{ds}}(x,y)]\}, \tag{3}$$

where $A_{\mathrm{ds}}(x,y)$ and $\varnothing_{\mathrm{ds}}(x,y)$ denote the amplitude and the phase modulation of the dead space areas, respectively.

The complex amplitude distribution $T(f_x,f_y)$ in the reconstruction plane is the Fourier transform of $t(x,y)$, i.e., $T(f_x,f_y)=\mathfrak{F}[t(x,y)]$, where $\mathfrak{F}$ denotes the Fourier transform.

Further, $T(f_x,f_y)$ can be expressed as

$$T(f_x,f_y) = L_xL_y\mathrm{sinc}(f_xL_x,f_yL_y)\otimes[T_{\mathrm{ac}}(f_x,f_y)+T_{\mathrm{ds}}(f_x,f_y)]. \tag{4}$$

The contribution to the complex amplitude from the active areas is

$$T_{\mathrm{ac}}(f_x,f_y) = a^2\mathrm{sinc}(f_xa,f_ya)[\mathrm{comb}(f_xd,f_yd)\otimes E(f_x,f_y)], \tag{5}$$

where

$$E(f_x,f_y) = \mathfrak{F}\{\exp[i\varnothing_{\mathrm{ac}}(x,y)]\}. \tag{6}$$

The above equations indicate that the shape of pixels forms the sinc envelope and the comb function describes the replication of the reconstruction pattern $E(f_x,f_y)$ in the output plane.

The contribution to the complex amplitude from the dead space areas is

$$T_{\mathrm{ds}}(f_x,f_y) = \{[d^2\mathrm{sinc}(f_xd,f_yd) - a^2\mathrm{sinc}(f_xa,f_ya)]\mathrm{comb}(f_xd,f_yd)\}\otimes F(f_x,f_y), \tag{7}$$

where

$$F(f_x,f_y) = \mathfrak{F}\{A_{\mathrm{ds}}(x,y)\exp[i\phi_{\mathrm{ds}}(x,y)]\}. \tag{8}$$

As L_x and L_y are large enough, the scanning function $L_xL_y\mathrm{sinc}(f_xL_x,f_yL_y)$ here approximately equals the δ function.

According to Eq. (8), the light distribution in the center of the reconstruction plane ($f_x=0, f_y=0$) can be described as

$$T(0{,}0) = \left(\frac{a}{d}\right)^2E(0{,}0)+\left[1-\left(\frac{a}{d}\right)^2\right]F(0{,}0) = \mu E(0{,}0)+(1-\mu)F(0{,}0), \tag{9}$$

where $\mu=(a/d)^2$ represents the fill factor of the SLM ($\mu < 100\%$). The first term in $T(0{,}0)$ is the zero-frequency part of the reconstructed image of the hologram and the second term is the zero-order distortion caused by dead space areas on the SLM pixelated structure.

3 Optimization Method of Hologram

3.1 *Loading Digital Blazed Grating*

Multiorder image reproduction exists during the processes of applying an SLM pixelated structure to achieve reproduction of the target pattern. It is located between the adjacent maximum positions of interferences with a central position of $\pm k/2d$, $k=1{,}3{,}5\ldots$. The image reproduction is modulated by a single-slit diffraction pattern. As for the two-dimensional (2-D) case, first-order image reproduction can be obtained around the zero-order with higher energy compared with the four other diffractions. However, the efficiency of optical energy utilization is low. As in holographic parallel processing, it is only desired to get a target pattern with high energy. To realize this target, combining the former work by Tan et al.[13] and Yu et al.,[14] in this paper, we present a method to blaze the reproduction image to the maximum point of zero-order interface by using a digital blazed grating. In theory, the energy of the target pattern can be improved by 279.3% using the proposed method (Holoeye, pluto NIR-2).

The 2-D digital blazed grating can be characterized as

$$\varnothing_{\mathrm{bg}}(i,j)=\frac{2\pi}{T}\mathrm{mod}\,(bi+cj,T), \tag{10}$$

where mod is the remainder operation; $-L_x/2d \le i \le L_x/2d-1$, $-L_y/2d \le j \le L_y/2d-1$; T is the period of the digital blazed grating, and a digital blazed grating with different blazing angles can be obtained by varying the values of T; digital blazed gratings with different directions can be obtained by varying the values of b and c. As the phase modulation range of SLM is $0\sim 2\pi$, the phase distribution loaded on SLM is

$$\phi=\mathrm{mod}(\phi_{\mathrm{ac}}+\phi_{\mathrm{bg}},2\pi). \tag{11}$$

3.2 *Loading Divergent Spherical Phase*

After the target pattern is blazed to the maximum point of the zero-order interface, it is necessary to eliminate the disturbance of the zero-order light beam spot caused by the SLM pixel structure in lens L Fourier plane before leading to the microscope processing system. Otherwise, the quality of the processing pattern will suffer a severe degradation. In order to separate the focal plane of the target pattern from the multiorder diffraction beam plane, phase information of the spherical wave $\phi_s=-k/2r(x^2+y^2)$ is added to the precalculated phase distribution of the hologram plane, which is equivalent to adding a negative lens to the target pattern imaging procedure. Here, $k=2\pi/\lambda$ is the wave number in free space; λ is the wavelength; and r is the distance from the SLM to the center of the divergent spherical wave. By doing so, a reconstruction pattern can be shifted from the focal plane of the Fourier lens along the optical axis, while the zero-order illumination will remain unchanged. As shown in Fig. 2, f is the focal length of the Fourier lens.

The total phase loaded on the SLM can be expressed as

$$\phi_{\mathrm{SLM}}=\phi_{\mathrm{ac}}+\phi_s. \tag{12}$$

The distance between the focal plane of the Fourier lens and the reconstruction plane can be expressed as

$$\Delta d=\frac{rf}{r-f}. \tag{13}$$

When $r>f$, a real image of the reconstruction pattern can be obtained. The zero-order light can be blocked by adding a high-pass filter in the focal plane of the Fourier lens. In consequence, a high-quality target pattern without interference can be exported and led into the microscope processing system to achieve high-quality holographic femtosecond laser parallel processing.

4 Experimental Setup

The experimental setup is shown in Fig. 3. The laser source is a mode-locked Ti:sapphire ultrafast oscillator (Coherent, Chamleon Vision-S) with a central wavelength at 800 nm, pulse duration of 75 fs, and repetition rate at 80 MHz.[15] The power of the femtosecond laser (about 3 W) is modulated with a half-wave plate and a Glan Laser beam splitter. After passing through a shutter and beam expander, the laser beam illuminates a liquid crystal SLM to ensure the modulation effect. The SLM (Holoeye, pluto NIR-2) has 1920×1080 pixels, each with a pitch of 8 μm. In this work, the central 1080×1080 pixels are used. A high-pass filter and aperture are placed at the focal plane of Lens 1 to block the zero-order light. The remainder of the modulated beam is collected by Lens 2 and focused through a microscope object (100, 0.9 NA) into the sample plane. In this work, the photoresist is SZ-2080 (provided by IESL-FORTH, Greece).

5 Result and Discussion

To validate the feasibility of the proposed method, four experiments are conducted for comparison. A Chinese character shown in Fig. 4 is selected as the target pattern to be processed. The dimension of the total pattern is 1080×1080 pixels, and the dimension of the target pattern is 50×50 pixels. The phase holograms in the experiments are computed by the GS algorithm. In order to eliminate random error, the hologram is loaded using the time-domain averaging method,[16] which loads a hologram every 150 ms for a total number of 10. The target pattern is fabricated with a single exposure of 30 s and outgoing power of the SLM is about 290 MW.

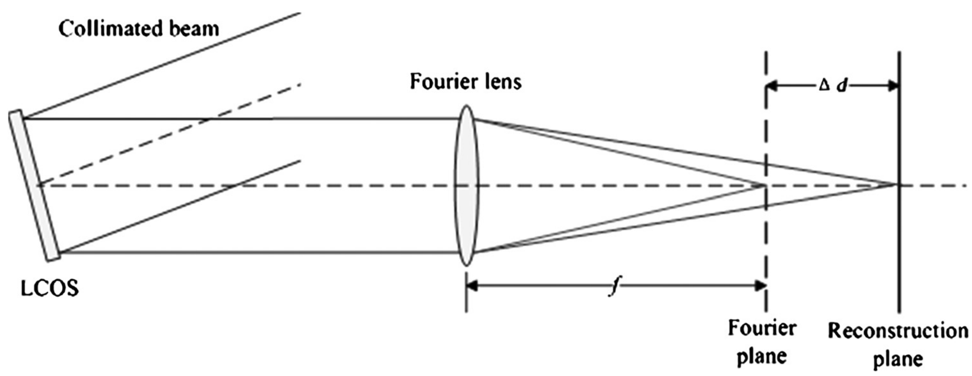

Fig. 2 Optical system design for separating the zero-order beam from the reconstruction pattern using optimized phase with additional divergent spherical wave.

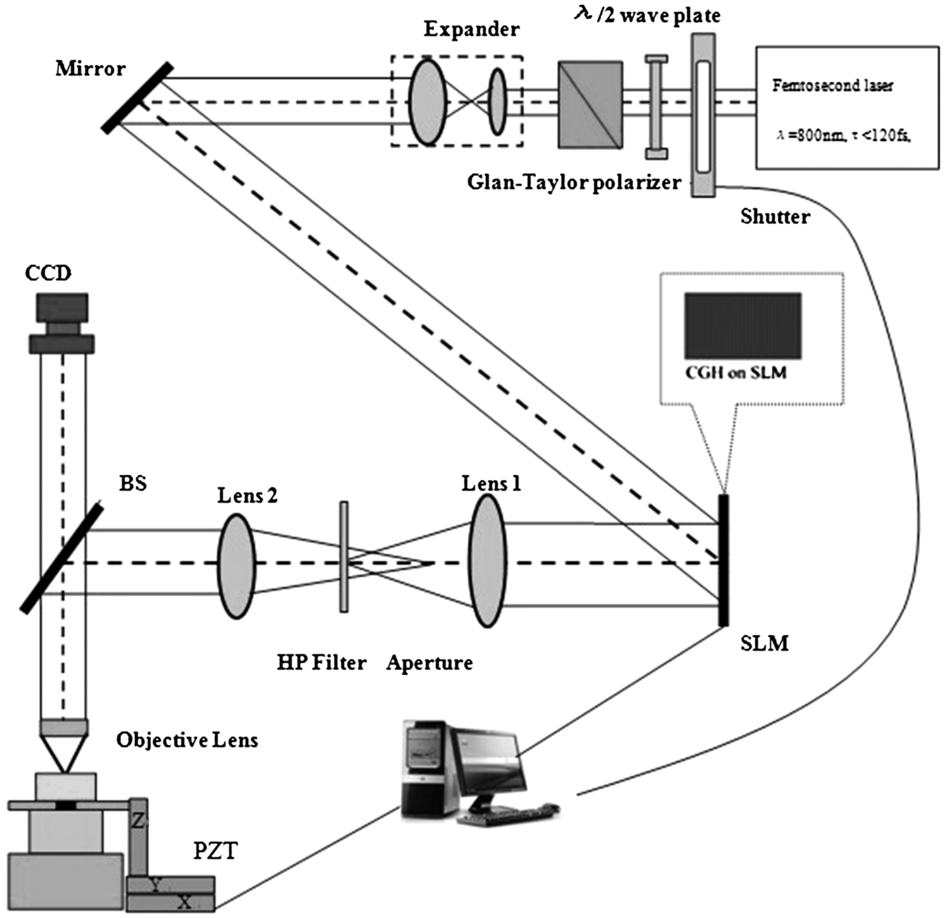

Fig. 3 Diagram of the laser system.

In the first experiment, we first load a group of holograms on SLM without a digital blazed grating and divergent spherical wave, and the processing result is shown in Fig. 5(a). It is clear that a strong zero-order light spot exists in the center of the pattern. Processing of the pattern exhibits a gradient, in which the part close to the zero-order light spot is entirely exposed while the part away from the zero-order light spot is partly exposed. The phenomenon is in accordance with the physical characteristics.

Fig. 4 Chinese character.

In order to improve the energy utilization rate, in the second experiment we load a group of holograms on SLM with a digital blazed grating, and the processing result is illustrated in Fig. 5(b). Although the entire Chinese character pattern has been exposed, there is a zero-order light spot in the center of the character. The reason is that the energy of the zero-order light is too high.

In the third experiment, we also load a group of holograms on SLM with a digital blazed grating, but this time a high-pass filter located in the focal plane of Fourier lens is utilized to block the zero-order light. As shown in Fig. 5(c), the zero-order light is successfully suppressed. However, this method reduces the energy efficiency of the central beam and leads to the failure of the entire explosion in the center of the character pattern.

In the last experiment, a group of holograms on SLM with a digital blazed grating and divergent spherical wave are utilized. The results indicate that this method can not only improve the energy utilization rate, but also, by using the high-pass filter and aperture, separate the focus focal plane of the target pattern and the plane of the multi-order diffraction beam resulting from the SLM pixelated structure. As shown in Fig. 6, it can be seen that the zero-order light is suppressed and the character pattern can be entirely exposed.

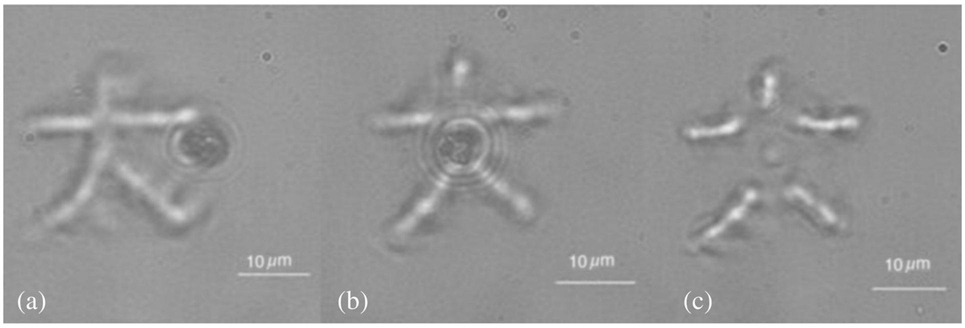

Fig. 5 Processing results detected by a CCD camera for optimized phase (a) without digital blazed grating and divergent spherical wave; (b) with digital blazed grating; and (c) with digital blazed grating and a high-pass filter located in the focal plane of Fourier lens.

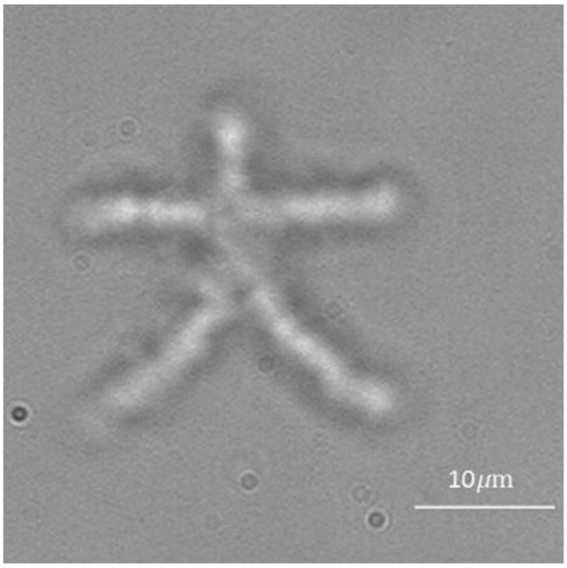

Fig. 6 Processing result detected by a CCD camera for optimized phase with digital blazed grating and divergent spherical wave.

6 Conclusion

In order to improve the energy utilization rate in holographic femtosecond laser parallel processing, this paper first analyzes the impact of SLM pixelated structure on phase-only hologram encoding, and a phase-only hologram containing a digital blazed grating and divergent spherical wave are designed and generated to improve the energy utilization rate and suppress the zero-order light. The experimental results indicate that the proposed method can achieve high-quality holographic femtosecond laser parallel processing with a significantly improved energy utilization rate. The proposed method can also be used to eliminate the zero-order interruption in optical systems using an SLM pixelated structure.

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References

1. X. Dong et al., "Femtosecond laser two-photon micro-/nano-fabrication and its applications," *Chin. Sci. Bull.* **53**(1), 2–13 (2008) (in Chinese).
2. Y. Hayasaki et al., "Variable holographic femtosecond laser processing by use of a spatial light modulator," *Appl. Phys. Lett.* **87**(3), 031101 (2005).
3. H. Lin, B. Jia, and M. Gu, "Dynamic generation of Debye diffraction-limited multifocal arrays for direct laser printing nanofabrication," *Opt. Lett.* **36**(3), 406–408 (2011).
4. Y. Hayasaki et al., "Experimental investigation of the closest parallel pulses in holographic femtosecond laser processing," *Appl. Phys. A* **107**(2), 357–362 (2012).
5. S. Hasegawa and Y. Hayasaki, "Adaptive optimization of a hologram in holographic femtosecond laser processing system," *Opt. Lett.* **34**(1), 22–24 (2009).
6. S. Hasegawa and Y. Hayasaki, "Holographic vector wave femtosecond laser processing," *Int. J. Optomechatron.* **8**(2), 73–88 (2014).
7. D. Palima and V. R. Daria, "Holographic projection of arbitrary light patterns with a suppressed zero-order beam," *Appl. Opt.* **46**(20), 4197–4201 (2007).
8. J. Christmas, N. Collings, and A. Georgiou, "Blocking zero-order in phase shift hologram generation," UK Patent GB2438458 (2007).
9. M. Silvennoinen et al., "Parallel femtosecond laser ablation with individually controlled intensity," *Opt. Express* **22**(3), 2603–2608 (2014).
10. E. H. Waller and G. von Freymann, "Multi foci with diffraction limited resolution," *Opt. Express* **21**(18), 21708–21713 (2013).
11. H. Zhang et al., "Elimination of a zero-order beam induced by a pixelated spatial light modulator for holographic projection," *Appl. Opt.* **48**(30), 5834–5841 (2009).
12. R. W. Gerchberg and W. O. Saxton, "A practical algorithm for the determination of phase from image and diffraction plane pictures," *Optik* **35**, 237–246 (1972).
13. K. L. Tan et al., "Dynamic holography for optical interconnections. II. Routing holograms with predictable location and intensity of each diffraction order," *J. Opt. Soc. Am. A* **18**(1), 205–215 (2001).
14. Y. Yu, T. Wang, and H. Zheng, "Optimization of optoelectronic reconstruction of phase hologram by use of digital blazed grating," *Acta Phys. Sin.* **58**(5), 3154–3160 (2009) (in Chinese).
15. C. Zhang et al., "A rapid two-photon fabrication of tube array using an annular Fresnel lens," *Opt. Express* **22**(4), 3983–3990 (2014).
16. N. J. Jenness et al., "A versatile diffractive maskless lithography for single-shot and serial microfabrication," *Opt. Express* **18**(11), 11754–11762 (2010).

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