Fast generation of controllable equal-intensity four beams based on isosceles triangle multilevel phase grating realized by liquid crystal spatial light modulator*

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Liquid crystal spatial light modulator (LCSLM) realizing equal-intensity multiple beams often has some features, i.e., phase valley between two adjacent pixels, flyback region when phase decreases immediately from 2π to 0, and inevitable backplane curvature, which are different from those of most conventional diffractive optical elements (DOEs), such as static DOEs. For optimal intensity uniformity, equal-intensity multi-beam generation must be considered for these artifacts. We present a tunable-grating method in which the intensity uniformity can be improved by considering the LCSLM artifacts. For instance, tuning phase modulation depth of the grating, called isosceles triangle multilevel phase grating (ITMPG), can be used not only to improve the intensity uniformity, but also to fast steer four beams with narrow beamwidths, determined by the same effective aperture of ITMPG. Improved intensity uniformity and high relative diffraction efficiency are demonstrated through experiments with phase-only LCSLM.

Keywords: liquid crystal spatial light modulator, phase grating, splitter

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1. Introduction

To improve throughput, equal-intensity multiple beams have been widely used in different areas, such as lithography,[1] femtosecond laser processing,[2] optical tweezers,[3,4] optical communication,[5] data storage[6] and so on. Many methods[7−19] has been proposed to generate equal-intensity multiple beams realized by controllable pixelated liquid crystal spatial light modulator (LCSLM).[20,21] One of them is a method in which the LCSLM is divided into different parts and each part is responsible for steering one beam, many parts results in many beams.[13] This method is simple, however, it makes beamwidth widened by decreasing the effective aperture, so it is rarely used. Logically, in the second category of methods the full LCSLM surface is used for forming each steered beam. The methods of this category can, in turn, be divided into quite a few groups. First, the most direct method individually forms the desired beams through computing the desired pattern by complex addition of the phase profiles.[14] Then each of relative phases for such phase profiles may be optimized to improve the diffraction efficiency and the uniformity through various iterative algorithms.[15,16,22] The algorithm of second group is called Gerchberg–Saxton (GS) algorithm,[23] the most popular method. It can be used to optimize the phase distribution of LCSLM, which is used to generate the far-field multiple beams with the desired arbitrary diffraction pattern. During theoretical calculation, the weighted method (also called weighted Gerchberg–Saxton algorithm) can increase the intensity uniformity.[17] But in reality, phase quantization,[24] phase valley,[25] flyback region,[24,26] backplane curvature[27,28] and so on, these LCSLM phase errors cause the actual phase distribution to deviate from the theoretical value, which deteriorates the intensity uniformity. In order to compensate for the phase errors, the direct search method[18,19,29] was proposed. Here, for each pixel, possible phase settings are tested and the optimal setting (determined by, e.g., the diffraction efficiency and the intensity uniformity among the spots) is kept. As

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a result, it suffers long computation time. Considering the fact that the response time of the nematic LCSLM is on the order of ms (ferroelectric LCSLM is faster), a technology to fast generate high-uniformity multiple beams is urgently needed. Wang *et al.*[30] did some theoretical research on the isosceles triangle phase grating (ITPG) used for a 1×4 splitter with an efficiency of 90.2% of four beams. In the present paper we propose a method, in which an isosceles triangle multilevel phase grating (ITMPG) is used to generate four beams (special example of multiple beams) with phase-only LCSLM, and which has such advantages as short computation time, narrow beam width, high relative diffraction efficiency, and improved intensity uniformity.

2. Isosceles triangle multilevel phase grating

As shown by the dash line in Fig. 1, during grating period T, the phase distribution of ITPG forms an isosceles triangle with phase modulation depth $\phi_{\rm h}$. Quantized ITPG is called isosceles triangle multilevel phase grating (ITMPG), which can be realized by phase-only LCSLM, and its phase profile with 4 stair levels is shown by the solid line in Fig. 1.

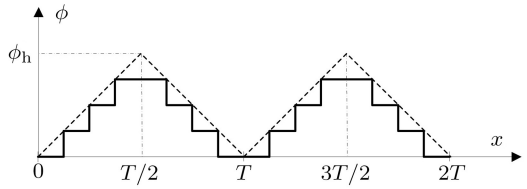


Fig. 1. Phase profile of phase grating. Dash line: ITPG. Solid line: ITMPG with $L=4$.

2.1. Principle

The ITMPG includes $2L$ phase modulation elements (pixels of LCSLM) in one grating period T, here $L\in N_+$, $L\geq3$, and its transmission function can be expressed as

$$u\left(x,\phi_{\rm h},L\right)=\sum_{n=-\infty}^{\infty}\delta\left(x-nT\right)*\sum_{K=0}^{L-1}{\rm e}^{{\rm i}\,\phi_{\rm h}K/L}\left[{\rm rect}\left(\frac{2Lx-\left(K+\frac{1}{2}\right)T}{T}\right)+{\rm rect}\left(\frac{2Lx+\left(K+\frac{1}{2}\right)T}{T}\right)\right],\quad(1)$$

where i defined as ${\rm i}^2=-1$ is known as the imaginary unit, and

$$\sum_{K=0}^{L-1}{\rm e}^{{\rm i}\,\phi_{\rm h}K/L}\Big[{\rm rect}\big((2Lx-\big(K+1/2\big)T)/T\big)+{\rm rect}\big((2Lx+\big(K+1/2\big)T)/T\big)\Big]$$

is the phase distribution during one grating period $[-T/2,T/2]$.

Supposing that monochromatic plane wave with wavelength λ is normally incident on the grating, governed by Eq. (1), and according to Fraunhofer diffraction, at distance z the far-field complex amplitude can be written as

$$\begin{aligned}U\left(\xi,\phi_{\rm h},L\right)=&\frac{C}{2}\exp\left[{\rm i}\,\phi_{\rm h}\left(L-1\right)/2L\right]\sum_{n=-\infty}^{\infty}\delta\left(\xi-\frac{n}{T}\right){\rm sinc}\left(\frac{\xi T}{2L}\right)\\&\times\left[\frac{{\rm sinc}\left(\dfrac{\phi_{\rm h}-\xi T\pi}{2\pi}\right)}{{\rm sinc}\left(\dfrac{\phi_{\rm h}-\xi T\pi}{2\pi L}\right)}{\rm e}^{-{\rm i}\,\xi T\pi/2}+\frac{{\rm sinc}\left(\dfrac{\phi_{\rm h}+\xi T\pi}{2\pi}\right)}{{\rm sinc}\left(\dfrac{\phi_{\rm h}+\xi T\pi}{2\pi L}\right)}{\rm e}^{{\rm i}\,\xi T\pi/2}\right],\end{aligned}\quad(2)$$

where C is a complex constant, $\xi=x/\lambda z$ the spatial frequency coordinate, and ${\rm sinc}\left(x\right)=\sin\left(\pi x\right)/\pi x$.

It can be known from the grating equation that the position of diffractive n-th order is n/T in the spatial frequency plane. Therefore the normalized intensity of diffractive n-th order ($\xi=n/T$) can be expressed as

$$I_n\left(\phi_{\rm h},L\right)=\frac{{\rm sinc}^2\left(\dfrac{n}{2L}\right)}{4}\left|\frac{{\rm sinc}\left(\dfrac{\phi_{\rm h}-n\pi}{2\pi}\right)}{{\rm sinc}\left(\dfrac{\phi_{\rm h}-n\pi}{2\pi L}\right)}{\rm e}^{-{\rm i}\,n\pi/2}+\frac{{\rm sinc}\left(\dfrac{\phi_{\rm h}+n\pi}{2\pi}\right)}{{\rm sinc}\left(\dfrac{\phi_{\rm h}+n\pi}{2\pi L}\right)}{\rm e}^{{\rm i}\,n\pi/2}\right|^2.\quad(3)$$

Equation $I_n(\phi_h, L) = I_{-n}(\phi_h, L)$ can be derived from Eq. (3), so far-field diffraction pattern is symmetric with respect to 0-th order. The second equation $I_n(-\phi_h, L) = I_n(\phi_h, L)$ can also be derived, and the normalized intensity is an even function of phase difference ϕ_h. Finally the third equation $I_n(\phi_h + 2L\pi, L) = I_n(\phi_h, L)$ can be derived, and the normalized intensity is a period function of phase difference ϕ_h with period $2L\pi$. Therefore, domain $n \geq 0$ and $\phi_h \in [0, L\pi)$ will be considered for analysing normalized intensity $I_n(\phi_h, L)$ symmetric with respect to the 0-th order. In the domain $\phi_h \in [0, L\pi)$, $I_L(\phi_h, L) = I_{-L}(\phi_h, L) = 0$, the effective scope of beam steering is limited to $(-L, L)$, namely the scope of beam steering is $\xi \in (-L/T, L/T)$ in the spatial frequency plane.

For convenience, in the most of the following discussion, the instance of ITMPG with stair-level number $L = 8$ is chosen for numerical calculation and experiment. In Fig. 2(a), for two adjacent diffractive orders such as first order and second order, second order and third order and so on, there is one intersection with maximal intensity, called the maximal-intensity intersection, the dark point attached with j. At the maximal-intensity intersection, the two diffractive orders j and $(j+1)$ (such as orders 1 and 2 for $j = 1$), where $j \in N_+$, have the same intensity. And then, it can be easily known from the zeroth-order symmetry of normalized intensity (3) that the opposite two adjacent negative diffractive orders $-j$ and $-(j+1)$ (such as orders -1 and -2 for $j = 1$) have the same intensity as orders j and $(j+1)$ at the same one maximal-intensity intersection (the same phase modulation depth and intensity). Therefore at the maximal-intensity intersection, the four diffractive orders $-j$, $-(j+1)$, j and $(j+1)$ (such as orders $-1, -2, 1$ and 2 for $j = 1$), have the same intensity, which is marked as case j listed in Table 1. And the phase difference $\phi_h(j)$ of the maximal-intensity intersection in Fig. 2(a) can be given by

$$I_j(\phi_h(j), 8) = I_{j+1}(\phi_h(j), 8), \tag{4}$$

where $\phi_h(j) \in (\varphi_{max}(j), \varphi_{max}(j+1))$, $j \in N_+$, and $\varphi_{max}(n)$ is the value of phase difference ϕ_h as the intensity of the n-th order is maximal.

It can be understood from Table 1 where numerical solutions of Eq. (4) are listed that four beams (orders) with an equal intensity can be generated by ITMPG with different values of phase difference $\phi_h(j)$, such as phase modulation depth $\phi_h = \phi_h(1)$ for $j = 1$, four orders of $-1, -2, 1$ and 2 have the same intensity as shown in Fig. 2(b), and the four beams can be symmetrically steered from the inside orders to outside orders or opposite by tuning the phase difference ϕ_h to different values of $\phi_h(j)$, the deflection resolution is related to the reciprocal of grating period, $1/T$, as shown in Fig. 2(b), where the spatial frequency coordinate ξ of diffractive order n is n/T.

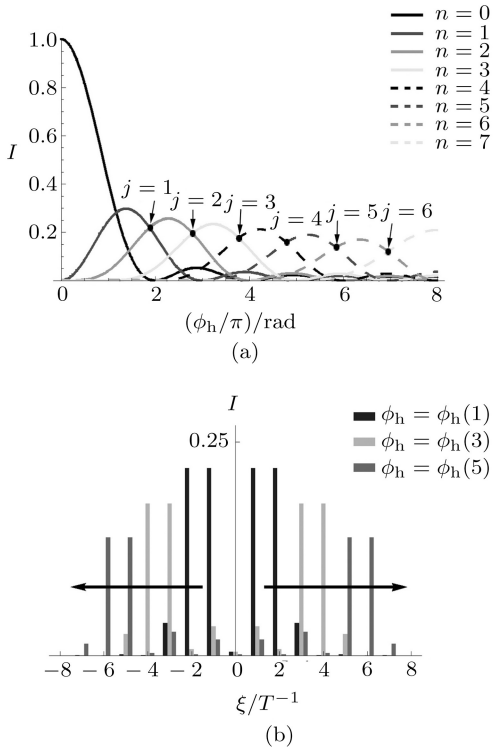


Fig. 2. ITMPG with $L = 8$. (a) Normalized intensity of different n orders. The dark point pointed from j is the maximal-intensity intersection of two adjacent diffractive orders. (b) Steering four beams.

Table 1. Parameters for whole 6 ITMPGs (j from 1 to 6) with $L = 8$. Values of diffraction efficiency of four beams (orders) η_4, relative diffraction efficiency η_{r4} and computation time for whole 6 ITMPGs t_c.

j	1	2	3	4	5	6
orders	$\pm1, \pm2$	$\pm2, \pm3$	$\pm3, \pm4$	$\pm4, \pm5$	$\pm5, \pm6$	$\pm6, \pm7$
ϕ_h/rad	5.9111	8.7811	11.862	15.055	18.359	21.855
η_4/%	87.67	78.52	71.10	63.36	55.32	48.65
η_{r4}/%	91.30	85.86	83.67	82.23	81.08	81.41
t_c/ms			203			

2.2. Beam width

Considering that a monochromatic plane wave is normally incident on the ITMPG with effective aperture $D = mT$, where $m \in N_+$ is the number of grating periods, and according to the diffraction grating theory, the half angular width of diffraction order is

$\Delta\theta_n \approx \lambda/(mT\cos\theta_n)$, where λ is the wavelength, and θ_n is the deflection angle of the n-th order relative to the 0-th order. So beam width of diffraction order is determined by the effective aperture of ITMPG.

The normalized complex amplitude of collimated Gaussian beam propagating along the z axis, which is widely used in experiment, can be expressed as

$$E(r,z) = \exp\left[\frac{-r^2}{\omega^2(z)}\right], \tag{5}$$

where r is the radial coordinate, and $\omega(z)$ is the ($1/e^2$ intensity) beam radius at a distance z from the minimum beam waist of a Gaussian beam.

Considering that a collimated Gaussian beam is normally incident on the ITMPG with an aperture more than 3 times Gaussian beam diameter, where over 99% laser energy passes through the ITMPG, the far-field complex amplitude can be written as

$$U_{\mathrm{G}}(\xi) = \frac{1}{2}\sum_{n=-\infty}^{\infty}\exp\left[-\pi^2\omega^2(d)\left(\xi-\frac{n}{T}\right)^2\right]\mathrm{sinc}\left(\frac{n}{2L}\right)\exp\left[-\mathrm{i}\,\phi_h(1-L)/2L\right] \times\left[\frac{\mathrm{sinc}\left(\dfrac{n\pi-\phi_h}{2\pi}\right)}{\mathrm{sinc}\left(\dfrac{n\pi-\phi_h}{2\pi L}\right)}\times\mathrm{e}^{-\mathrm{i}\,n\pi/2}+\frac{\mathrm{sinc}\left(\dfrac{n\pi+\phi_h}{2\pi}\right)}{\mathrm{sinc}\left(\dfrac{n\pi+\phi_h}{2\pi L}\right)}\mathrm{e}^{\mathrm{i}\,n\pi/2}\right], \tag{6}$$

where $\omega(d)$ is the beam radius at the ITMPG on the x axis.

According to the 3σ probability of Gaussian distribution $P\{|\xi - n/T| \le 3\sigma\} = 99.73\%$, where $\sigma = 1/\left(\sqrt{2}\pi w(d)\right)$, at the maximal-intensity intersection, in the domain $T \le 1/6\sigma$ and $\xi \in [(n/T-3\sigma),\,(n/T+3\sigma)]$, amplitude distribution of concerned diffraction n-th order, such as $n = -j$, $-(j+1)$, j, or $(j+1)$, approximately obeys the Gaussian function $\mathrm{e}^{-\pi^2\omega^2(d)}$, and the normalized intensity of concerned diffraction n-th order is approximately governed by Eq. (3). For setup with $w(d) = 1.5$ mm and $T = 2L\times 18 = 288$ μm in the following experiment, where $T < 1/6\sigma$, the following discussion and results of concerned diffractive orders ($\xi \in [(n/T-3\sigma),\,(n/T+3\sigma)]$) about diffraction efficiency and intensity uniformity are suitable not only for monochromatic plane wave incident on ITMPG, but also for collimated Gaussian beam. For the collimated Gaussian beam incident on ITMPG, the beam radius at far field is $\lambda f/\pi\omega(d)$, without considering the aperture shape factor, where the Fourier transform lens of focal length f is used to generate the far-field diffractive pattern. The beam width of diffraction order is determined by the beam width of laser incident on LCSLM, which is considered as the effective aperture of ITMPG.

The beam widths of four beams generated by ITMPG are determined by the same effective aperture. Therefore the four beams generated have the same narrow beamwidth approximately.

2.3. Relative diffraction efficiency

It can be seen from Table 1 that diffraction efficiency η_4 of the four orders can reach 87.67%, and for different j values the diffraction efficiency can be expressed by

$$\begin{aligned}\eta_4(j) =& I_{-j}(\phi_{\mathrm{h}}(j),L) + I_{-(j+1)}(\phi_{\mathrm{h}}(j),L)\\ &+ I_j(\phi_{\mathrm{h}}(j),L) + I_{j+1}(\phi_{\mathrm{h}}(j),L),\end{aligned} \tag{7}$$

where $L = 8$ listed in Table 1. However the diffraction efficiency is less than 90.2%[30] of ITPG, and it is inevitably caused by quantization factor $\mathrm{sinc}^2(n/2L)$ in Eq. (3). From Subsection 2.1, it can be known that the four orders for different j values have the same intensity, so at the maximal-intensity intersection equation (7) is changed into

$$\eta_4(j) = 4I_j(\phi_{\mathrm{h}}(j),L), \tag{8}$$

where $I_j(\phi_{\mathrm{h}}(j),L)$ is the normalized intensity of the j-th order at the maximal-intensity intersection.

As shown in Fig. 2(a), the intensity of the j-th order at the maximal-intensity intersection (dark point) decreases with j value increasing, therefore the diffraction efficiency η_4 decreases with j value increasing in Table 1.

In this paper, diffraction patterns are concerned mainly in the effective scope $(-L/T, L/T)$ of beam steering, therefore the relative diffraction efficiency $\eta_{r4}(j,L)$ is defined as the ratio of the sum of intensities of four diffractive orders $-j$, $-(j+1)$, j and $(j+1)$ to the whole intensity in the effective scope of beam

steering, when four beams with an equal intensity are generated by ITMPG with phase difference $\phi_{\rm h}$ equal to $\phi_{\rm h}(j)$. Relative diffraction efficiency $\eta_{r4}(j,L)$ can be written as

$$\eta_{r4}(j,L)=\frac{I_{-j}(\phi_{\rm h}(j),L)+I_{-(j+1)}(\phi_{\rm h}(j),L)+I_{j}(\phi_{\rm h}(j),L)+I_{j+1}(\phi_{\rm h}(j),L)}{\sum\limits_{k=-L}^{L}I_{k}(\phi_{\rm h}(j),L)}. \tag{9}$$

The maximal relative diffraction efficiency of ITMPG with 8 stair levels listed in Table 1 is 91.30%. It can be seen in Table 1 that relative diffraction efficiency η_{r4} decreases more slowly with j value increasing than diffraction efficiency η_4 due to the decreasing of the whole intensity in the effective scope of beam steering denoted by the denominator in Eq. (9).

With the software Mathematica, 92.3% of computation time 203 ms of the 6 gratings is used to calculate the definition domain of $\phi_{\rm h}(j)$ in Eq. (4). The computation time is possible to be shortened through decreasing the resolution to solve definition domain. And according to the calculation of ITMPG with quantization stair-level number L in domain $[8,100]$, the relative diffraction efficiency of four beams generated by ITMPG is more than 80.32%.

2.4. Intensity uniformity

As shown in Fig. 2(a), the normalized intensity of the n-th order is a monotonically decreasing function in domain $\phi_{\rm h}\in(\varphi_{\max}(n),\,\varphi_{\max}(n+1))$, and is a monotonically increasing function in domain $\phi_{\rm h}\in(\varphi_{\max}(n-1),\,\varphi_{\max}(n))$. Therefore, the ratio between intensities for two adjacent diffractive orders $I_{n+1}(\phi_{\rm h},8)/I_n(\phi_{\rm h},8)$ is a monotonically increasing function in domain $\phi_{\rm h}\in(\varphi_{\max}(n),\,\varphi_{\max}(n+1))$ as shown in Fig. 3. According to the further calculation of ITMPG with quantization stair-level number L in domain $[3,100]$, the monotonicity of the ratio still exists. With the monotonicity, the decreased four-beam intensity uniformity caused by LCSLM phase errors should be increased. According to the research of the intensity loss during changing pattern,[31] the smaller the average difference in phase setting of the LCSLM pixel during changing patterns, the less will the energy loss of beams be. During adjusting intensity, the method proposed in this paper can make the four beams more stable through using a small tuning of phase difference $\phi_{\rm h}$.

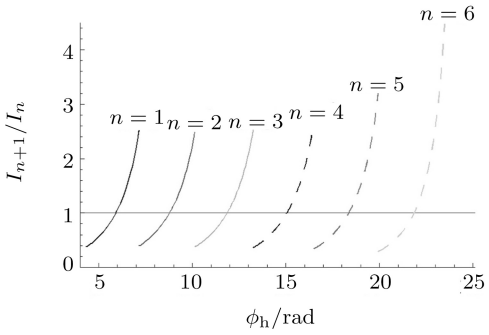


Fig. 3. Ratio between intensities for two adjacent diffraction orders, n and $(n+1)$.

ITMPG can generate two pairs of beams (four beams), which are symmetric with respect to the 0-th order and have the same intensity. In the spatial frequency plane, the spacing between two beams in one pair is $1/T$. The four beams generated each have not only a short computation time of about 34 ms per grating, but also a minimal beamwidth determined by the same effective aperture of LCSLM. The relative diffraction efficiency is more than 80.32% with $L=8$. Tuning phase difference $\phi_{\rm h}$ to a different value of $\phi_{\rm h}(j)$, the two pairs of beams can be symmetrically steered from the inside orders to outside orders or opposite, the deflection resolution is related to the reciprocal of grating period, $1/T$. With the monotonicity of the ratio between intensities for two adjacent diffractive orders, the intensity ratio can be adjusted by tuning phase difference $\phi_{\rm h}$.

3. Experiment

3.1. Setup

Two-dimensional (2D) LCSLM obtained from Boulder Nonlinear Systems is used as the phase-only LCSLM to test ITMPG as shown in Fig. 4. In LCSLM, the pitch of phase modulation element is 18 μm, and the number of phase modulation elements is 256×256. The intensity of 632.8-nm HeNe laser with frequency stabilization is adjusted preliminarily

by attenuator 1, then by rotating polarizer 3 and 4. To modulate light wave in the form of phase only, the polarization direction of polarizer 4 must be parallel to the liquid crystal director of LCSLM. Collimated Gaussian beam is generated by zoom beam expender 2, and its beam diameter is 1.5 mm, which is less than 1/3 the aperture of LCSLM. The charge-coupled device (CCD) is placed in the focal plane of lens to capture the far-field diffraction patterns.

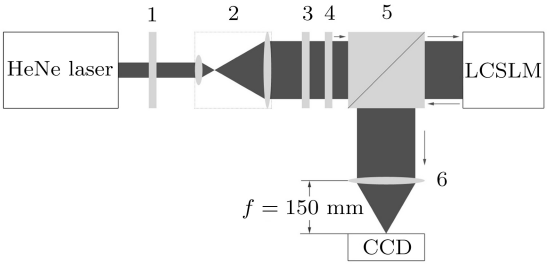


Fig. 4. Experiment set up. 1: attenuator, 2: zoom beam expender, 3 and 4: polarizer, 5: beam splitter, 6: lens.

3.2. Results of four beams

As listed in Table 1, the ITMPGs moduled by 2π are written into the LCSLM. The captured far-field diffraction patterns are shown in Fig. 5(a). Four beams are generated and they are symmetric with respect to the 0-th order (the centre spot), which is consistent with the above theory. However, due to the LCSLM phase errors, the intensity uniformity of four beams is lower within a range from 0.4 to 0.82 as shown in Fig. 5(b). Here, the intensity uniformity is defined as $U = I_{\min}/I_{\max}$, where $I_{\min}$ and $I_{\max}$ are the minimum and maximum peak intensities, respectively.[32] With the monotonicity of ratio $I_{n+1}(\phi_{\rm h}, 8)/I_n(\phi_{\rm h}, 8)$, the intensity ratio can be adjusted by the fine tuning of phase difference $\phi_{\rm h}$. After optimizing the phase difference $\phi_{\rm h}$ as shown in Fig. 6, among the four beams the intensity uniformity of two adjacent beams (on the left or right in Fig. 5(a)) is more than 0.8, and the maximal value

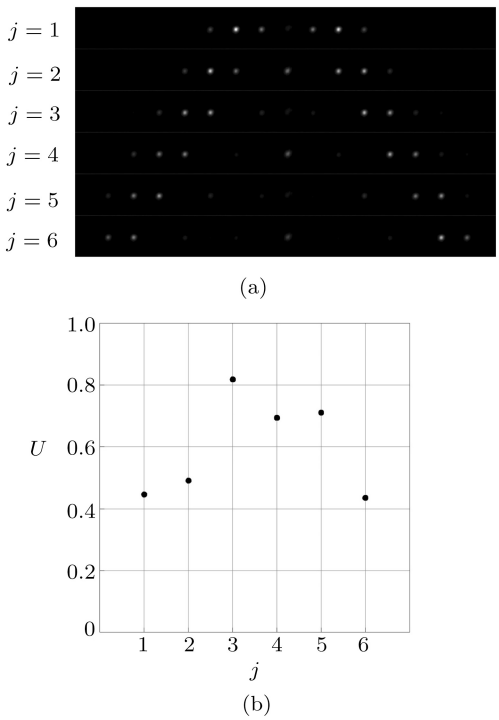


Fig. 5. Measurement results for ITMPG with theoretical phase difference, with the power of laser incident on LCSLM kept unchanged. Panel (a) shows far-field pattern of ITMPG, and panel (b) displays intensity uniformity.

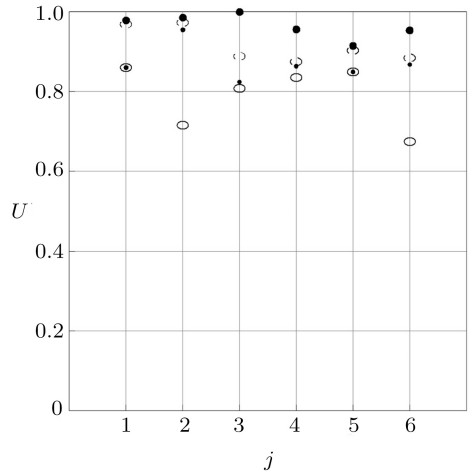
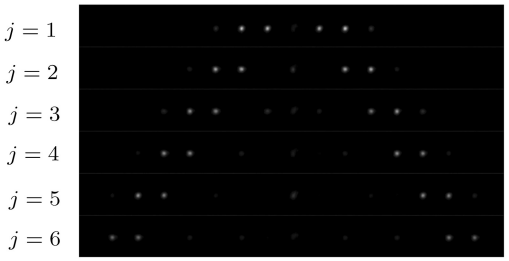


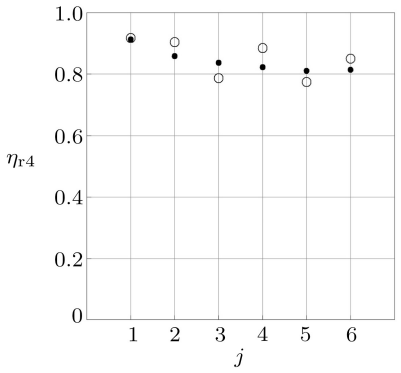
Fig. 6. Intensity uniformity of ITMPG with optimized phase difference. Dash ellipse is determined by uniforming two adjacent beams on the left. Big spot is determined by uniforming two adjacent beams on the right. Solid ellipse spot is determined by uniforming all the four beams. Small spot is determined by uniforming all the four beams after compensating for the backplane curvature of LCSLM.

is 0.999 (the first one achieved with LCSLM to the best of author's knowledge), limited by the number of linear levels for 2π phase difference with the LCSLM. At the same time, the intensity uniformity of the four beams can be improved to the range from 0.675 to 0.860. The symmetry of isosceles triangle is destroyed by the LCSLM phase error, especially backplane curvature, which makes the two pairs (left pair and right pair) of beams asymmetrical as described above. Compensating for the backplane curvature of LCSLM thus can further improve the intensity uniformity to the range from 0.824 to 0.954 as shown in Fig. 6, and its far-field diffraction patterns captured are shown in Fig. 7(a). With j value increasing

from 1 to 6, four beams with an equal intensity (the brightest 4 spots for each j in Fig. 7(a)) are generated and steered from the inside to outside order-by-order,



(a)



(b)

Fig. 7. Measurement results for ITMPG with optimized phase difference, with the power of laser incident on LCSLM kept unchanged. Panel (a) shows far-field pattern of ITMPG, and panel (b) displays relative diffraction efficiency. Spot denotes theoretical value, and open circle represents experimental value.

namely the deflection resolution is related to the reciprocal of grating period, $1/T$. And the relative diffraction efficiency with a maximal value of 91.7% accords well with the theoretical value as shown in Fig. 7(b). Improved by the fine tuning of phase difference $\phi_{\rm h}$ with compensating for the backplane curvature, the intensity uniformity of the four beams generated by ITMPG can be increased by 55.1% on average compared with that without improvement. Therefore with the monotonicity of the intensity ratio for two adjacent diffractive orders, the influence on beam energy, caused by LCSLM phase error, can be partially compensated by the fine tuning of phase difference $\phi_{\rm h}$.

4. Conclusion

It can be seen from the above theory and experiment that four beams can be symmetrically generated by ITMPG. The four beams can be symmetrically steered with a large tuning ITMPG phase modulation depth, and the intensity uniformity can be improved to partially compensate for the loss of beam energy resulting from LCSLM phase errors with little tuning that. Experimental results indicate that high intensity uniformity and high relative diffraction efficiency both can be achieved at the same time by a fine tuning phase modulation depth after compensating for the backplane curvature of LCSLM. The ITMPG is simple, and has such advantages as short computation time, narrow beam width, high relative diffraction efficiency and high intensity uniformity. However, the grating period of ITMPG limits the deflection resolution of the four beams, and the grating symmetry restricts its further application, our future work will focus on improving deflection resolution and steering asymmetrically. Now, it still has some potential applications in switching four beams to different input ports in laser communication, in increasing acquisition probability in laser detection and ranging (LADAR), in enhancing the reliability of laser security monitoring system and so on.

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