Effects of design parameters of diffractive optical element on stray light

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Abstract: Diffractive optical elements (DOEs) have been widely applied to acquire different beam shapes in illumination systems. However, the experimental values of diffraction efficiency are greatly different from the ideal values because of stray light of high diffractive orders around the targeted spot. The reasons were theoretically discussed for the stray light and many DOEs with different design parameters were simulated. Through the simulation analysis, a new parameter, named relative period, was defined. It was proportional to the wavelength and inversely proportional to the far-field diffraction angle and the size of DOE cells. It is suggested that the diffraction efficiency, which is independent from the beam shapes, could be improved by increasing relative period. As a result, the stray light of high diffractive orders could be suppressed effectively by regulating the parameters of the far-field diffraction angle and the size of DOE cells. The new parameter has an important role in the design of DOE.

Key words: diffractive optical elements; beam shaping; dffraction efficiency; relative period

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衍射光学元件设计参数对杂散光的影响

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摘　要:衍射光学元件被广泛应用于激光光束整形领域中。然而,在实际测量中常常发现衍射效率实际的测量值与设计值存在较大的偏差,原因之一在于输出的焦斑主瓣以外会产生高级次衍射杂散光。文中从理论上推导了高级次衍射杂散光产生的原因并对具有不同设计参数的衍射光学元件进行了仿真分析。通过研究,定义了一个新的参数,相对周期。它与光波波长成正比,与衍射光学元件的采样单元尺寸以及远场衍射角成反比。结果表明,衍射光学元件的衍射效率只是关于相对周期的函数,而与焦斑主瓣的具体形状无关。随着相对周期的增加,衍射效率随之增大。所以可通过适当选取远场衍射角和采样单元尺寸的参数以调整相对周期的大小,有效抑制高级次衍射杂散光。该参数在衍射元件的设计中具有重要的指导意义。

关键词:衍射光学元件; 光束整形; 衍射效率; 相对周期

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0 Introduction

Laser beam shaping techniques have been applied to many applications. The multilevel phase-only diffractive optical element (DOE) is a good solution for most applications due to its high efficiency, light weight, small volume, and cheap fabrication. The common practice is shaping a laser beam to a circular or rectangular shape with flat-top intensity distribution. Up until now, several methods for beam shaping were developed[1-6]. The common methods for design DOE are iterative algorithms like Gerchberg-Saxton algorithm, the geometrical methods, the hybrid algorithms and so on. Although most of them could achieve ideal diffraction efficiency, the design results ar e greatly different from the measurement results because of stray light of high diffractive orders. For instance, Rong Wu from University of Science and Technology of China found the experimental diffraction efficiency was far less than ideal value because a lot of energy was diffracted to high orders[7]. So it is necessary to investigate how to suppress the stray light of high diffractive orders.

In this paper, the relationship between stray light of high diffractive orders and some design parameters will be shown. In section one, the reasons of this stray light are theoretically discussed. After analysis, the relative period is defined. It could be found that the diffraction efficiency is the function of this new parameter. In order to prove this theory, in section two, many diffractive optical elements with different design parameters are simulated.

1 Theories

Figure 1 schematically represents a beam shaping system which includes DOE. The laser beam is expanded and collimated by an optical system of telescope, and then redistributed by DOE to create a desired pattern on the image plane. By using a Fraunhofer diffraction integral, the complex light field

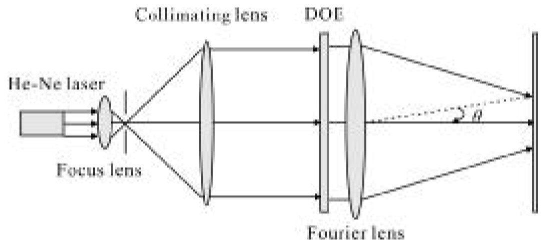

Fig.1 Schematic of beam shaping system including DOE

at distance f behind the Fourier lens is:

$$\mathbf{U_o}(\varepsilon_o,\eta_o)=\frac{1}{\lambda f}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\mathbf{U}_i(\mathbf{x}_i,\mathbf{y}_i)t(\mathbf{x}_i,\mathbf{y}_i)\exp[-j2\pi(\varepsilon_o\mathbf{x}_i,\eta_o\mathbf{y}_i)]d\mathbf{x}_i d\mathbf{y}_i \quad (1)$$

where $\mathbf{U_o}(\varepsilon_o,\eta_o)$ and $\mathbf{U}_i(\mathbf{x}_i,\mathbf{y}_i)$ are the distributions of complex amplitude in the focal plane and input plane, and f is the propagation distance. $t(\mathbf{x}_i,\mathbf{y}_i)$ is the transmittance of DOE at laser wavelength λ.

It is well known that the DOE in beam shaping is multilevel phase plate, which results in phase delay for the propagating beam. The lithography process in combination with reactive ion etching in glass is a well-known technique for the production of multilevel phase DOEs. As a result, the transmittance of DOE should be further expressed in the form:

$$t(\mathbf{x}_i,\mathbf{y}_i)=\exp[j\varphi(\mathbf{x}_i,\mathbf{y}_i)]=$$

$$\sum_{\mathbf{m}=-\mathbf{N}/2}^{\mathbf{N}/2}\sum_{\mathbf{n}=-\mathbf{N}/2}^{\mathbf{N}/2}\exp[j\varphi(\mathbf{m},\mathbf{n})]\mathrm{rect}(\frac{\mathbf{x}_i-\mathbf{m}l}{l},\frac{\mathbf{y}_i-\mathbf{n}l}{l})=$$

$$\sum_{\mathbf{m}=-\mathbf{N}/2}^{\mathbf{N}/2}\sum_{\mathbf{n}=-\mathbf{N}/2}^{\mathbf{N}/2}\exp[j\varphi(\mathbf{m},\mathbf{n})]\delta(\mathbf{x}_i-\mathbf{m}l,\mathbf{y}_i-\mathbf{n}l)\mathrm{rect}(\frac{\mathbf{x}_i}{l},\frac{\mathbf{y}_i}{l}) \quad (2)$$

where $\varphi(\mathbf{m},\mathbf{n})$ are the phases of DOE, * denotes convolution operation and $\mathbf{N}$ is the total numbers of the DOE cells. The function rect denotes the rectangular function. The physical meaning of Eq.(2) is that the phase distribution of the DOE as a diffractive screen of the incident field, the size of each cell is l, and the distance between every two cells is also equal to l. Based on the Fourier transform of $\mathbf{U}_i(\mathbf{x}_i,\mathbf{y}_i)t(\mathbf{x}_i,\mathbf{y}_i)$ as shown in Eq.(1), the complex amplitude distribution of the transmitted light could be written as:

$$\mathbf{U_o}(\varepsilon_o,\eta_o)=\frac{1}{\lambda f}\mathbf{F}\{\mathbf{U}_i(\mathbf{x}_i,\mathbf{y}_i)\exp[j\varphi(\mathbf{x}_i,\mathbf{y}_i)]\}=\frac{1}{\lambda f}\mathbf{F}\{\mathbf{U}_i(\mathbf{x}_i,\mathbf{y}_i)\sum_{m=-\frac{N}{2}}^{N/2}\sum_{n=-\frac{N}{2}}^{N/2}\exp[j\varphi(\mathbf{m},\mathbf{n})]\delta(\mathbf{x}_i-\mathbf{m}l,\mathbf{y}_i-\mathbf{n}l)\mathrm{rect}(\frac{\mathbf{x}_i}{l},\frac{\mathbf{y}_i}{l}) =$$
$$\frac{1}{\lambda f}\mathbf{F}\{\mathbf{U}_i(\mathbf{x}_i,\mathbf{y}_i)\sum_{m=-\frac{N}{2}}^{N/2}\sum_{n=-\frac{N}{2}}^{N/2}\exp[j\varphi(\mathbf{m},\mathbf{n})]\delta(\mathbf{x}_i-\mathbf{m}l,\mathbf{y}_i-\mathbf{n}l)\mathbf{F}\{\mathrm{rect}(\frac{\mathbf{x}_i}{l},\frac{\mathbf{y}_i}{l})\}=$$
$$\frac{1}{\lambda f}\mathbf{F}\{\mathbf{U}_i(\mathbf{x}_i,\mathbf{y}_i)\sum_{m=-\frac{N}{2}}^{N/2}\sum_{n=-\frac{N}{2}}^{N/2}\exp[j\varphi(\mathbf{m},\mathbf{n})]\delta(\mathbf{x}_i-\mathbf{m}l,\mathbf{y}_i-\mathbf{n}l)[l^2\mathrm{sinc}(l\varepsilon_o,l\eta_o] \tag{3}$$

According to Eq. (3), the complex amplitude distribution of the output light field consists of two parts. The first part is the Fourier transform of the incident field and the phase distribution of the DOE. The result of Fourier transform, which is evaluated by the numerical technique according to the Whittaker -Shannon sampling theorem [8], is that Output complex amplitude will show cycle distribution and easy to obtain the cycle is equal to $\lambda f/l$. Other cycles of light which does not belong to the targeted illumination region is called stray light of high diffraction orders. Consequently, the energy could be diffused. The other part is the sinc function which could modulate the complex amplitude distribution over the entire image plane. The dark points happen to be at $\mathbf{x_o}=\mathbf{m}(\lambda f/l)$, $\mathbf{y_o}=\mathbf{n}(\lambda f/l)$ ($\mathbf{m},\mathbf{n}=1,2,3\cdots$). In order to calculate the distribution of this stray light in simulation, according to Eq. (4), we adopt 5×5 points in computer to replace one phase cell of DOE. The intensity distribution in the focal plane is shown in Fig. 3.

$$\begin{cases}\varepsilon_o=\dfrac{\Delta \mathbf{x_o}}{\lambda f}=\dfrac{1}{\mathbf{N}\Delta \mathbf{x}_i}\\[2ex] \eta_o=\dfrac{\Delta \mathbf{y_o}}{\lambda f}=\dfrac{1}{\mathbf{N}\Delta \mathbf{y}_i}\end{cases} \tag{4}$$

As a result, this modulation has ability to suppress stray light of high diffraction orders and concentrate most of energy to the targeted illumination region. However, this stray light could not be completely eliminated. The most important purpose of this paper is regulation design parameters to suppress this stray light as possible as we could.

In order to evaluate stray light, diffraction efficiency is defined as:

$$\eta=\sum_{x_o,y_o\in D}I(x_o,y_o)/\sum_{x_o,y_o}I(x_o,y_o) \tag{5}$$

where $\mathbf{D}$ is the targeted illumination region, and $\mathbf{I}$ is the intensity of diffraction field.

A new parameter, named relative period, is defined as:

$$\mathbf{T_{rp}}=\frac{\mathbf{P}}{\mathbf{r}}=\frac{\lambda f}{l\mathbf{r}}\approx\frac{\lambda}{\theta l} \tag{6}$$

where $\mathbf{P}$ is the cycle of the intensity distribution, $\mathbf{r}$ is half of the targeted illumination region along $\mathbf{x}$ or $\mathbf{y}$ direction, and θ denotes the far-field diffraction angle (see Fig.1).

In order to simplify the calculation, the relationship between diffraction efficiency and relative period is discussed over the lateral dimension. According to discussion of Eq. (3), the output intensity will show cycle distribution and flat top illumination (the value could be seen as a constant under ideal conditions). The Integration regions are the areas of spots in each cycle. As a result, the first part of Eq.(3) could be counteracted in Eq. (7).

$$\eta=\frac{\sum_{x\in D}I(x_o)}{\sum_{x_o}I(x_o)}=\frac{\int_{-r/\lambda f}^{r/\lambda f}[l\mathrm{sin}\mathbf{c}(l\varepsilon_0)]^2 d\varepsilon_0}{\sum_{\mathbf{m}=-\mathbf{N}}^{\mathbf{N}}\int_{(-r/\lambda f)+(\mathbf{m}/l)}^{(r/\lambda f)+(\mathbf{m}/l)}[l\mathrm{sin}\mathbf{c}(l\varepsilon_0)]^2 d\varepsilon_0} \tag{7}$$

where $\mathbf{N}$ is the order of diffraction light. The result is sufficiently accurate when calculations take $\mathbf{N}=3$ because of the modulation of sinc function in focal plane. Assuming $t=l\varepsilon_0$, the Eq.(7) could be written as:

$$\eta(\mathbf{T_{rp}})=\frac{\int_{-(1/\mathbf{T_{rp}})}^{1/\mathbf{T_{rp}}}\mathrm{sin}\mathbf{c}^2(t)dt}{\sum_{\mathbf{m}=-3}^{3}\int_{(-(1/\mathbf{T_{rp}}))+\mathbf{m}}^{(1/\mathbf{T_{rp}})+\mathbf{m}}\mathrm{sin}\mathbf{c}^2(t)dt} \tag{8}$$

According to Eq.(8), it is suggested that the diffraction efficiency, which is independent from the beam shapes, is the function of relative period. The relationship between theoretical maximum diffraction efficiency and relative period is calculated in MATLAB, and the consequences are shown in Fig.2.

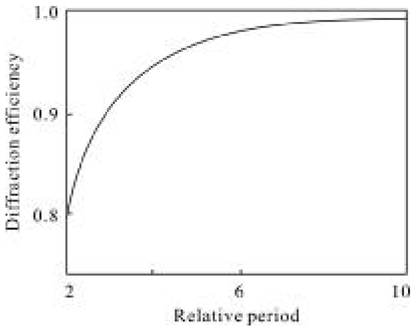

Fig.2 Relationship between diffraction efficiency and relative period

It is suggested that the diffraction efficiency could be improved by increasing relative period and the slope of the curve decreases gradually. If relative period could be more than 5, energy loss which is caused by the stray light of high diffraction orders could be controlled less than 4%. The diffraction efficiency in the two-dimensional direction should be obeyed $\eta=\eta_{T_{rpx}}=\eta_{T_{rpy}}$. However, the value of relative period is not the more the better. Beam uniformity and diffraction efficiency could be influenced when the size of the focused profile is reduced toward the diffraction limited and the size of the DOE cells is decreased to wavelength magnitude[9-10].

2 Simulation results and discussion

A 16 level phase DOE has been designed through a hybrid algorithm. The full calculate area of DOE and the targeted illumination region are set to be 20 mm×20 mm and 2.5 mm×5 mm. The incident wavelength, propagation distance, and the size of DOE cells are 632.8 nm, 1 000 mm, and 0.1 mm. Consequently, θ_x=1.25 mard, θ_y=2.5 mard, and T_{rpx}=5.06, T_{rpy}=2.53. The design results are shown in Fig.3, and the diffraction efficiency is equal to 80.02%.

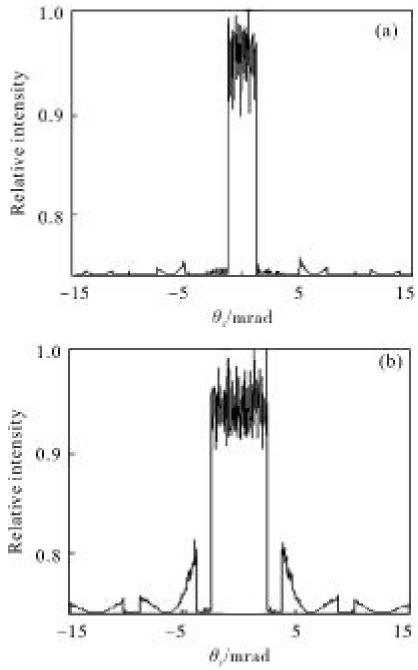

Fig.3 Intensity distribution in focal plane

Reducing the far-field diffraction angle of DOE could increase the value of relative period and suppress the stray light of high diffraction orders. In orde r to reduce the far-field diffraction angle, propagation distance is increased to 1 500 mm, and other parameters are invariable. Consequently, θ_x=0.83 mrad, θ_y=1.67 mrad, T_{rpx}=7.59 and T_{rpy}=3.80. The diffraction efficiency is improved to 87.12% and the intensity distribution in the focal plane is shown in Fig.4.

Comparing the results of Fig.3 and Fig.4, the relative intensity of stray light is decreased obviously. As a result, the stray light of high diffraction orders could be suppressed by reducing far-field diffraction angle.

Reducing the size of DOE cells could also increase the value of relative period and suppress the stray light. The size of DOE cells is decreased to 0.05 mm, and other parameters are invariable. Consequently, θ_x=1.25 mrad, θ_y=2.5 mrad, T_{rpx}=10.12 and T_{rpy}=5.06. The diffraction efficiency is improved to 92.22% and the intensity distribution in the focal plane is shown in Fig.5.

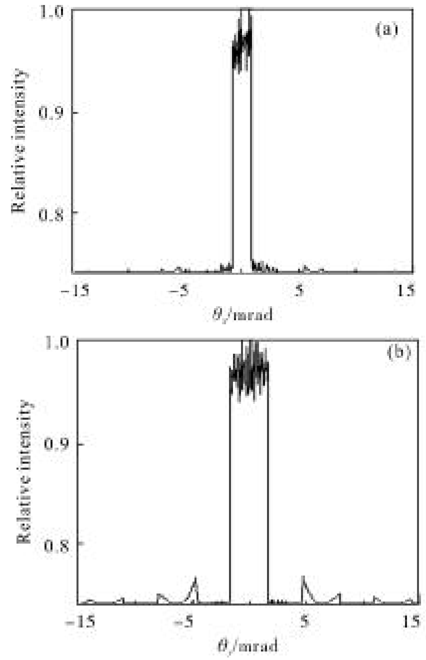

Fig.4 Intensity distribution in focal plane if θ is reduced

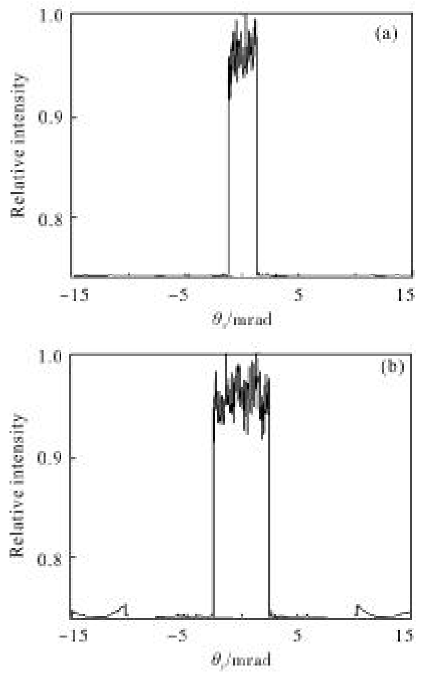

Fig.5 Intensity distribution in focal plane if l is reduced

Comparing the results of Fig.3 and Fig.5, the relative intensity of stray light is also decreased obviously. As a result, the stray light of high diffraction orders could be suppressed by reducing the size of DOE cells.

The relationship between diffraction efficiency and relative period is shown in Fig.6 by repeatedly adjusting the design parameters.

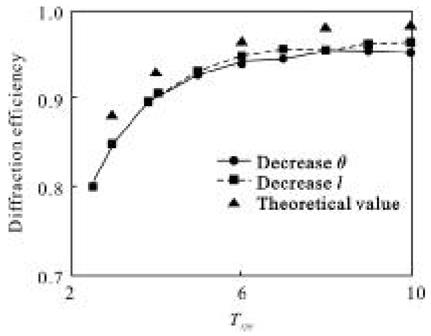

Fig.6 Relationship between diffraction efficiency and relative period after repeatedly adjusting design parameters

It is suggested that the diffraction efficiency is less than theoretical value ($\eta_{max}=\eta_{T_{rpx}}\eta_{T_{rpy}}$) because of some faint stray light around the targeted illumination region. This situation could be improved by optimizing algorithm and increasing phase levels. In addition, curves are almost overlapped through the different two methods (decrease θ and decrease l). So they have the same ability to suppress the stray light. Furthermore, when the minimum value of $\mathbf{T}_{rpx}$ and $\mathbf{T}_{rpy}$ is more than 6, diffraction efficiency, which is independent from the profile of output beam, could be stable approximately. Consequently, in order to avoid obvious reduction of diffraction efficiency, θ and l should be optimized to make sure the relative period is more than 6.

3 Conclusion

The intensity distribution in the focal plane of multilevel phase DOE is theoretically discussed. Because of fabrication restriction, there will be stray light of high diffraction orders around targeted illumination region. After analyzing, a new parameter, relative period, is defined to evaluate values of this stray light in the focal plane. It is proportional to the wavelength and inversely proportional to the far-field diffraction angle and the size of DOE cells. The diffraction efficiency could be improved by increasing relative period. In our numerical simulations, we observe that relative period should be maintained more than 6 in order to avoid obvious reduction of diffraction efficiency. This new parameter has an important role in the design of multilevel phase DOEs in beam shaping.

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