Impact on Diffraction Efficiency of Binary Optical Elements for Spot Exposure Superposing Ratio

J Liu, J B Tan, C G Zhao, M G Shan, D F Wang

Institute of Ultra-precision Optoelectronic Instrument Engineering, Harbin Institute of Technology, Harbin 150001, CHINA

E-mail: liujian@hit.edu.cn

Abstract. In fabrication of free form optical surfaces, spot exposure is a typical mode in laser photolithography. Proper selection of spot exposure superposing ratio is the key to optimize etching quality and writing speed. In this paper, a new composite diffractive grating structure is modeled for the influence on diffraction efficiency of binary optical elements caused by spot-exposure superposing ratio. Composite grating can be transformed into one simple rectangular grating and two triangular gratings. Angular spectrum theory is used to describe the mathematical expression of the composite diffractive grating. Through simulation analysis, the relationships between diffraction efficiency and the other three items as grating depth, spot radius, and blaze wavelength, has been shown. Simulation results indicate that shape error caused by spot exposure ratio impact the diffraction efficiency greatly in deep etching, and the transmittance will reach maximal point approximately while spot exposure ratio is over 60%. This conclusion can be taken as the theoretical foundation for exposure frequency selection in laser photolithography figure generation.

1. Introduction

Laser photolithography is one of the important modes in diffractive optical elements fabrication. In order to fabricate form pattern freely, in laser photolithography, high intensive spot exposure is usually used to realize complex pattern writing [1]. In spot exposure mode, approximate lines or curve patterns can be etched by properly adjacent spot superposing. Generally, there are adequate spots in unit length and the spots are tiny enough, so the pattern errors can always be neglected.

In some cases, large size spot exposure by defocus writing or a small aperture objective has to be used to accelerate writing speed, so it is necessary to consider the proper selection of spot exposure superposing ratio. Since the laser writing spot exposure modulating frequency is restricted by AOM (acoustic optical modulator) and the highest frequency of serial AOM used in photolithography is usually less than 10MHz, too high spot superposing ratio will slow the writing speed, however, too low superposing ratio may increase shape errors. If those shape characters can be kept after exposure and subsequent handing, it will be necessary to analyze the influence regularity between diffraction efficiency and superposing ratio so as to select proper spot exposure modulating frequency and improve the quality of the composition pattern. In this paper, phase grating is taken as an example to analyze the influence of the spot-superposing ratio on diffraction efficiency.

2. Mathematics model
In spot exposure mode, approximate lines or curve patterns can be etched properly by adjacent spot superposing. \(dotp = \left( 1 - \frac{d}{2R} \right) \times 100\%\) defined as spot exposure superposing ratio, \(d\) equals to the distance between two adjacent spot centers, \(R\) represents the radius of exposure spot. According to the definition of variable \(dotp\), it is obvious that \(dotp = 0\) means adjacent spots separated totally, and \(dotp = 1\) means adjacent spots superposed totally. Generally speaking, in writing process, \(0 < dotp < 1\), so arc \(AB\), \(BC\) and line \(AB\) will enclose an unexposed area in Fig. 1. In order to simplify the analysing model, \(\Delta ACB\) is defined to represent this area, then the bottom margin \(AB = 2R(1 - dotp)\) and the distance \(h\) from vertex \(C\) in \(\Delta ACB\) to line \(AB\) equals \(R - \sqrt{R^2 - (R(1 - dotp))^2}\).

To explain the influence of the superposing ratio on diffraction efficiency, a one-dimensional phase grating is taken as an example to analyze it. Fig. 2 shows the mathematical model structure of the diffractive grating. Under the influence of the spot exposure superposing ratio, grating transfers not only in X direction but also in Y direction. \(T_x, T_y\) are the grating coefficients, respectively in X and Y direction. Then this grating can be taken as the special grating which is composited by two triangular gratings in Y direction and one rectangular grating in X direction.

![Figure 1. Variable Definition in Spot Superposing Exposure](image)

![Figure 2. Mathematics Model Structure of Diffractive Grating](image)

According to the analysis of an equivalent mathematical model about etching error in spot exposure, the grating transparency function \(t(x, y)\) can be expressed as following:

\[
t(x, y) = \sum_{n} \sum_{m} \delta(x - mT_x, y - nT_y) \cdot \left( \frac{x + (R-h/2)}{h} \right) \cdot \left( \frac{y-d/2}{d/2} \right)
\]

\[
\text{rect} \left( \frac{x-(R-h/2)}{h} \right) \cdot \Lambda \left( \frac{y+d/2}{d/2} \right) + \text{rect} \left( \frac{x}{T_y - 2R} \right) \cdot e^{i2\pi f_y} \]

In function (1), \(\text{rect}(x, y), \Lambda (x, y)\) respectively represent rectangular function and triangular function. To simplify the calculation of diffraction efficiency simply, phase constant has been ignored, so that angular spectrum function of \(t(x, y)\) can be written as function (2). \(f_x, f_y\) are angular spectrums. \(f_o = \frac{(n-1)d}{\lambda T_x}\), \(m, n\) means diffractive order in X and Y direction. \(F \{t(x, y)\} = \sum_{n} \sum_{m} \delta \left( f_x - \frac{m}{T_x}, f_y - \frac{n}{T_y} \right) \cdot \left( \frac{\pi d}{2} \right) \cdot \sin c \left( \frac{\pi h}{2} \right) \cdot e^{i2\pi f_x} \)

\[
\cdot \sin c \left( \frac{\pi f_y d}{2} \right) \cdot e^{-i2\pi f_y} + \left( \frac{\pi d}{2} \right) \cdot \sin c \left( \pi h \left( f_x - f_o \right) \right) \cdot e^{-i2\pi \left( f_x - f_o \right)} \]
\[ \sin^2 \left( \frac{\pi f_x d}{2} \right) e^{i2\pi f_x d + \left| T_x - 2R \right| \sin c \left( \pi (f_x - f_{0})(T_x - 2R) \right)} \cdot e^{-i2\pi f_x} \] \hspace{1cm} (2)

3. Diffraction efficiency analysis

While the first order diffractive wave is discussed, \( m=n=1 \), \( f_x = \frac{1}{T_x}, f_y = \frac{1}{T_y} \), \(+1\) order diffraction efficiency \( \eta = a_i^2 |a_i|^2 \) [2][3],

\[
a_i = \sin c \left( \pi h(f_x - f_{0}) \right) e^{i2\pi f_x d},
+ \sin c \left( \pi h(f_y - f_{0}) \right) e^{-i2\pi f_y d},
\]

\[
+ \sin c \left( \pi (f_x - f_{0})(T_x - 2R) \right) \cdot e^{-i2\pi f_x} \quad \text{(3)}
\]

If grating coefficient \( T_x \), spot radius \( R \) and grating depth \( h_d \) are decided, the relationship between \( \text{dOpt} \) and \( \eta \) will be determined. Fig. 3 and 4 show the transmittance curve with different value of \( h_d \), \( \lambda \) and \( \text{dOpt} \).

![Figure 3. Diffraction Efficiency Curve (h_d=5\mu m)](image)

(a) Consider Shape Errors Caused by Superposing Ratio

(b) Neglect Shape Errors Caused by Superposing Ratio

![Figure 4. Diffraction Efficiency Curve (h_d=10\mu m)](image)

(a) Consider Shape Errors Caused by Superposing Ratio

(b) Neglect Shape Errors Caused by Superposing Ratio

According to Fig. 3 and 4 simulation results, ordinarily in a deep etching process, diffraction efficiency increases with superposing ratio. But this rule can be interfered with by a blaze wave. There is no absolute function relationship between superposing ratio and diffraction efficiency towards different waves with different grating blazes. This rule is a consistent result with reference [4].
A monotone function has been found in this calculation to exist for the relationship between superposing ratio and transmittance. As far as blaze wave, superposing ratio usually decreases transmittance.

(a) Consider Shape Errors Caused by Superposing Ratio  
(b) Neglect Shape Errors Caused by Superposing Ratio

Figure 5. Diffraction Efficiency Curve( $h_d=1\mu m$, $\lambda=0.6328\mu m$ )

(a) Consider Shape Errors Caused by Superposing Ratio  
(b) Neglect Shape Errors Caused by Superposing Ratio

Figure 6. Diffraction Efficiency Curve( $h_d=5\mu m$, $\lambda=0.6328\mu m$ )

Curves shown in Fig. 5 and 6 are about grating diffraction efficiency changing with spot radius and superposing ratio. In thin photosensitive resist etching, superposing ratio impact diffraction weakly. However, this effect will be strengthened if the depth of resist is increased. While the spot superposing ratio reaches 60%, the diffraction efficiency approaches maximum.

4. Conclusion
According to analyses at different depths, and different spot radius, the relationship between the diffraction efficiency and the superposing ratio shows that the influence of the superposing ratio can be neglected in thin etching. But in deep etching, it is really necessary to consider the influence of spot superposing ratio. In general, in both of these two cases that mentioned above, spot exposure error will decrease transmittance of blaze wave.

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