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Influence of light incident angle on fiber grating fabrication

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Abstract: Phase mask writing method is a common method for fiber grating fabrication. According to the near-field diffraction theory, the influence of incident angle on the diffraction field is analyzed when the UV laser light is obliquely incident on the phase mask. Based on the coupled-mode theory of inclined grating, the transmission matrix method is used to analyze the influence of incident angle of UV laser light on the spectral characteristics of the grating. The calculation results show that the incident angle increases and the center reflection wavelength of the gratings shifts to the longer wavelength, meanwhile the reflectivity decreases. To ensure that the grating wavelength drift less than 0.2nm, the incident angle should be controlled less than 0.92 degrees.

1. Introduction

With its small size, high sensitivity, anti-electromagnetic interference and other advantages, fiber Bragg gratings has broad application prospects in temperature, stress and acoustic sensing[1]. UV exposure phase mask method is widely used in optical fiber grating fabrication because of its advantages of easy mass production, good product consistency and stable product performance. During the grating fabrication process, the optical fiber is usually exposed by the interference fringes formed by the ±first-order diffracted light of the phase mask. Therefore, it is required that the ultraviolet laser light source be incident on the phase mask as vertically as possible to sufficiently suppress the 0th-order diffracted light. However, there are usually some complicated beam adjusting devices between the UV light source and the phase mask. It is very difficult to ensure that the UV laser can completely perpendicularly enter the phase mask.

Therefore, in this paper, we study the effect of the UV light incidence angle to the phase mask on the diffraction field characteristics and the grating spectral characteristics in order to obtain the influence of the beam alignment error on the quality of the optical fiber grating so that to provides a theoretical basis on the beam alignment accuracy control.

2. The influence of incident angle on the diffraction field

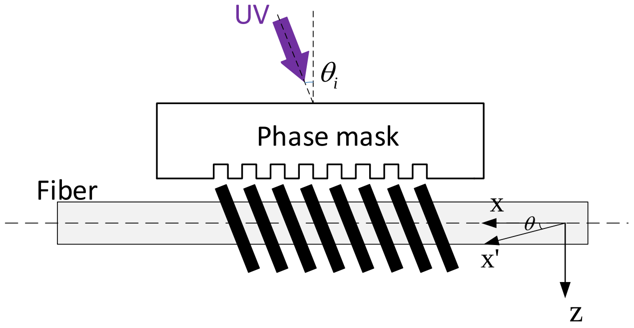


Figure 1 The schematic diagram of the UV obliquely incident on the phase mask

The phase mask used in the ultraviolet laser exposure phase mask method is usually a normal incidence phase mask having a uniform grating pitch. The width of the teeth and the groove portions in the mask is equal. On the front surface of the phase mask, let the light field be a plane wave with unit amplitude and zero phase. The absorption of light intensity by the phase mask is negligible. The transmittance function of the phase mask can be expressed as:

$$F(z)=\begin{cases}\exp(i\varphi_1) & \left(\left|x-(2J+1)\dfrac{\Lambda}{2}\right|<\dfrac{\Lambda_{PM}}{2}\right)\\ \exp(i\varphi_2) & \left(\left|x-J\Lambda\right|<\dfrac{\Lambda_{PM}}{2}\right)\end{cases} \quad (1)$$

Λ_{PM} is the period of the phase mask, φ_1,φ_2 is the phase delay produced by the lightwave through the phase mask's teeth and troughs, which can be expressed as

$$\begin{cases}\varphi_1=\dfrac{2\pi}{\lambda}n_g(d+h)\cos\theta_i^{'}\\ \varphi_2=\dfrac{2\pi}{\lambda}n_g d\cos\theta_i^{'}+\dfrac{2\pi}{\lambda}h\cos\theta_i\end{cases} \quad (2)$$

n_g is the phase mask material refractive index; θ_i is the incident angle; $\theta_i^{'}$ is the angle of refraction; d is the mask thickness; h is the tooth height.

At the back surface of the phase mask, the optical wavefield can be expressed as

$$E(x)=\exp\left(i\frac{2\pi}{\lambda_{UV}}x\sin\theta_i\right)F(x) \quad (3)$$

Fourier series expanded

$$E(x)=\exp\left(i\frac{2\pi}{\lambda_{UV}}x\sin\theta_i\right)\sum_{-\infty}^{\infty}c_m\exp\left(i\frac{2m\pi}{\Lambda_{PM}}x\right) \quad (4)$$

Among them, the expansion coefficient is

$$c_m=\frac{1}{\Lambda_{PM}}\int_{-\Lambda_{PM}/2}^{\Lambda_{PM}/2}F(x)\exp\left(-i\frac{2m\pi}{\Lambda_{PM}}x\right)dx \quad (5)$$

After integral

$$\begin{cases}c_0=\dfrac{1}{2}\left[\exp(i\varphi_1)+\exp(i\varphi_2)\right]\\ c_m=\dfrac{\sin(m\pi/2)}{m\pi}\left[\exp(i\varphi_2)-\exp(i\varphi_1)\right] \quad (m=\pm1,\pm2,\cdots)\end{cases} \quad (6)$$

The relative intensity of diffracted light of each level is respectively:

$$\begin{cases}I_0=\left|c_0\right|^2=\dfrac{1}{2}\left[1+\cos(\varphi_1-\varphi_2)\right]\\ I_m=\left|c_m\right|^2=\dfrac{2\sin^2(m\pi/2)}{m^2\pi^2}\left[1-\cos(\varphi_1-\varphi_2)\right] \quad (m=\pm1,\pm2,\cdots)\end{cases} \quad (7)$$

For the ideal mask case, the 0 order diffracted light is completely suppressed. In this case, it is necessary to ensure that the phase mask plate has the same tooth width and troughs width ,and the tooth height $h=\lambda_{UV}/2(\mathrm{n}_g-1)$. The wavelength of the incident UV laser light source is 248 nm, the phase mask mask refractive index is 1.5, the tooth height is 248 nm, the phase mask period is 1.06 μm and the mask thickness is 2 mm.

The relative intensity of diffracted light of level 0 and level is calculated as a function of angle of incidence. As shown in Figure 2, it can be seen from the figure that at small incident angles (less than 10 degrees) The influence of the intensity is negligible. As the angle continues to increase, the diffraction efficiency of the 0 order diffracted light increases, and the order diffracted light decreases.

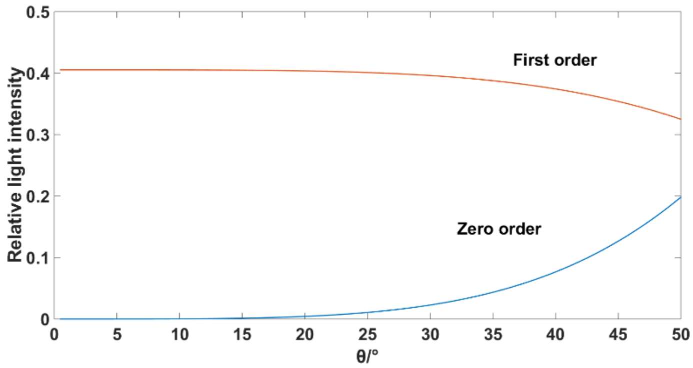


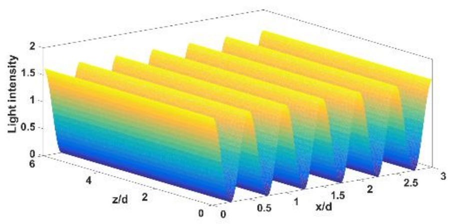
Figure 2 The relative light intensity of zero order and first order under different incident angle

The diffraction field after the mask can be expressed as:

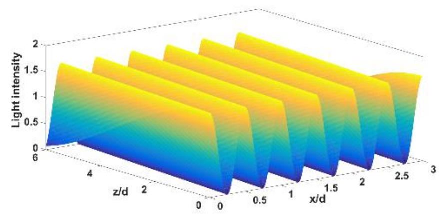
$$E(x,z)=\sum_{-\infty}^{\infty}c_m\exp\left(i\left(k\sin\theta_i+\frac{2m\pi}{\Lambda_{PM}}\right)x\right)\cdot\exp\left(i\sqrt{k^2-\left(k\sin\theta_i+\frac{2m\pi}{\Lambda_{PM}}\right)^2}z\right) \quad (8)$$

According to the calculation results in Fig. 2, the influence of the incident angle on the 0th-order diffracted light is neglected at a small incident angle, only the ± 1st order diffracted light is considered. Can be obtained at different angles of incidence under the mask after the light intensity distribution[2]:

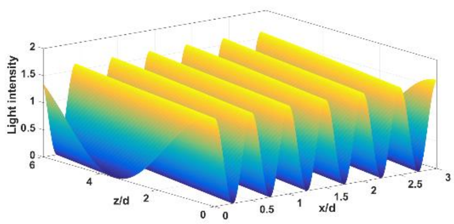
$$I(x,z)=\left|E(x,z)\right|^2=2\left\{1+\cos\left[\frac{2\pi}{\Lambda_{PM}/2}\left(x-\frac{\theta_i\cdot z}{\sqrt{1-(\lambda_{UV}/\Lambda_{PM})^2}}\right)\right]\right\} \quad (9)$$



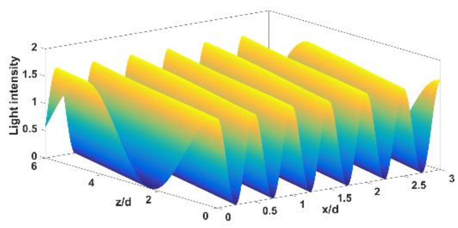
(a)0 degree



(b)2 degree



(c)4 degree



(d)6 degree

Figure 3. The light field after the phase mask under different incident angle

It can be seen from the formula that the interference fringe period is independent of the incident angle and is half of the mask period. Fig. 3 shows the ± 1storder interference fringes intensity distribution under different incident angles. It can be seen from the figure that the angle between the interference fringes and the z-axis increases with the incident angle. The size of the interference fringes increases with the incidence of UV laser light source Angular approximation.

3. Grating reflection spectrum analysis

3.1 Theoretical model

It can be seen from the above analysis that when analyzing the effect of UV laser light source entering the phase mask with a smaller incidence angle on the grating, the impact of the interference fringe deflection angle on the grating spectrum can be considered. When the grating is engraved, the optical fiber is usually kept parallel to the phase mask and perpendicular to the grating on the mask. In this case, the inclination of the grating to be engraved will be the same as that of the interference fringes, and the loss of the optical fiber to the ultraviolet laser light source is ignored in the calculation , Set the UV laser light intensity in the optical fiber core before and after the same.

Core refractive index change distribution can be expressed as

$$\delta n_{co}\left(x,z\right)=\overline{\delta n_{co}}\left\{1+\nu\cos\left[\frac{2\pi}{\Lambda_g}x^{'}+\phi\left(x^{'}\right)\right]\right\} \tag{10}$$

In the formula, it is the average variation of the refractive index of the core. It defines and determines the grating period along the x-axis (fiber) of the resonant wavelength as the axis grating period, which can be regarded as the same as the ± 1st-order interference fringe period and half the mask period ; For the interference fringe tilt angle can be approximately equal to the incident angle UV laser light source for the refractive index change stripes visibility is the phase change of refractive index.

For a uniform fiber Bragg grating, the mode coupling mainly occurs between the positive and negative propagating core guide modes. Coupled mode equations can be written as:

$$\frac{dR}{dx}=i\hat{\sigma}R(x)+i\kappa S(x) \tag{11}$$

$$\frac{dS}{dx}=-i\hat{\sigma}S(x)-i\kappa R(x) \tag{12}$$

In the formula $R(x)=A(x)\exp[i\Delta\beta x-\phi/2]$, $S(x)=B(x)\exp[-i\Delta\beta x+\phi/2]$, $\hat{\sigma}$ is the DC self-coupling coefficient, $\hat{\sigma}=\Delta\beta+\sigma$ $\sigma=\frac{2\pi}{\lambda}\overline{\delta n_{eff}}$,the detuning $\Delta\beta=2\pi n_{eff}(\frac{1}{\lambda}-\frac{1}{\lambda_D})$, $\lambda_D=2n_{eff}\Lambda$ is the grating design Bragg wavelength, κ is the AC coupling coefficient $\kappa=\frac{\pi}{\lambda}\nu\overline{\delta n_{eff}}$.

The influence of tilt angle on the grating can be translated into the effect on the visibility v of the stripe[3]:

$$\frac{\nu_{\mp\pm}(\theta)}{\nu}=\frac{\iint_{core}dxdy\exp(\pm i\frac{2\pi}{\Lambda}x\tan\theta)\vec{e}_{\mp t}(\mathrm{x,y})\cdot\vec{e}^{\,*}_{\pm t}(\mathrm{x,y})}{\iint_{core}dxdy\vec{e}_{\mp t}(\mathrm{x,y})\cdot\vec{e}^{\,*}_{\pm t}(\mathrm{x,y})} \tag{13}$$

Equivalent fringe visibility, with the following parameters: core radius 2.5um, grating period 530nm, calculate the normalized equivalent streak visibility with angle changes, as shown in Figure 4.

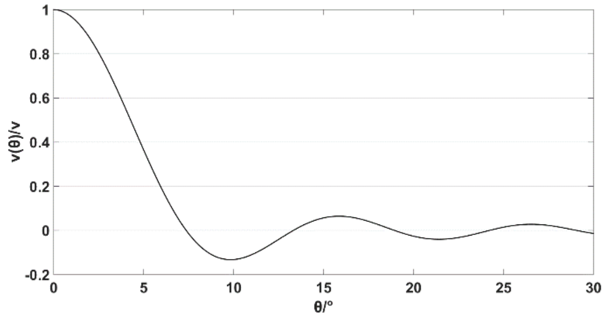


Figure 4 The normalized visibility varies with incident angle

As can be seen from the figure, the visibility of the equivalent fringes decreases rapidly with the increase of the inclination angle, and the visibility of the equivalent fringes approaches 0 when the inclination angle is about 7.5 degrees, and between the front and the back of the fiber core The coupling efficiency is close to 0, the core energy is mainly dissipated to the cladding mode and radiation touch. By multiplying the visibility of the stripe by the normalized equivalent stripe visibility in Eq. 14, the visibility of the equivalent stripe can be obtained. The visibility distribution of the stripe can reflect the inclination of the interference fringe caused by the oblique incident phase mask of the ultraviolet laser light source Raster effect.

3.2 Numerical calculation

Using the transfer matrix method, the following parameters are introduced: the grating length is 0.01m, the effective refractive index of the core is 1.456, 0.0001, the visibility of the stripe is 1 and the grating period is 530nm, the grating reflection spectra under different incident angles are calculated as shown in FIG. 5

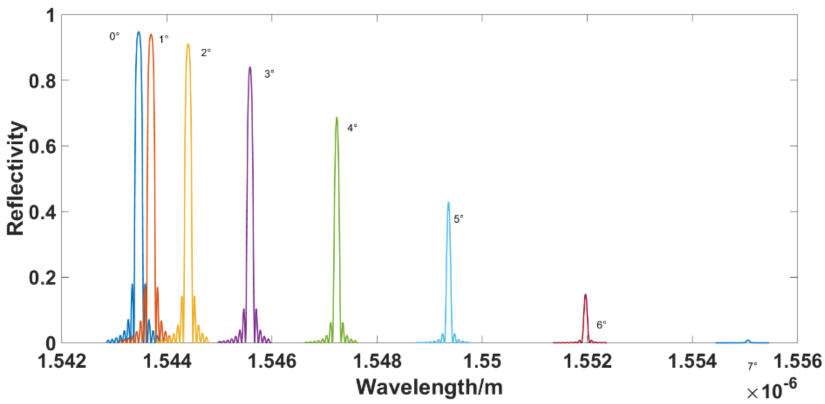


Figure 5. Grating Reflectance Spectrum at Different Incidence Angle

As can be seen from Figure 5, the oblique incidence of UV laser light source mainly causes two changes: one is the center wavelength of the reflection spectrum drifts to the long wavelength; the other is the decrease of the maximum reflectivity of the grating. The former is the existence of tilt angle, making the grating x-axis period becomes larger, according to the Bragg equation shows that the grating period becomes larger will result in larger Bragg wavelength; the latter is due to the grating tilt angle increases, resulting in equivalent streak visibility decreases, causing AC coupling According to the calculation formula of the maximum reflectance of the uniform grating, it can be seen that the decrease of the AC coupling coefficient will cause the decrease of the grating reflectivity.

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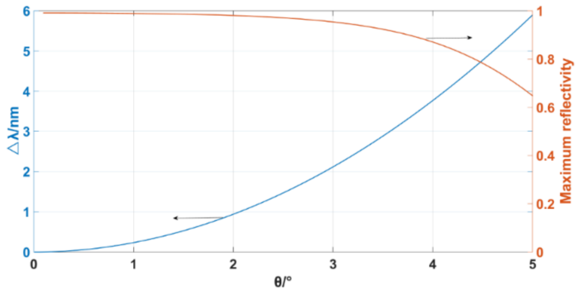

Figure6. Grating wavelength shift and maximum reflectance at different incident angles

For sensing grating, to meet the requirements of large-scale wavelength division multiplexing, it is usually necessary to precisely control the wavelength of the grating to be engraved. Fig. 6 shows the wavelength drift and maximum reflectance with incident angle caused by oblique incidence of UV laser source (calculated as above). If the wavelength drift is less than 0.2nm, the incidence angle of UV laser light source should be less than 0.92 degrees.

4. Conclusion

In this paper, the diffraction characteristics of the oblique incident phase mask of UV laser source and the influence of grating spectra were studied. The calculated results show that the influence of the incident light intensity on the diffraction light intensity is negligible when the incidence angle is less than 10 degrees. The influence of the interference angle on the tilt angle of the interference fringes is only considered. The tilt angle of ± 1 order diffraction light interference fringes can be approximately equal to the incident angle of the light source. Inclination will cause the center of the grating grating reflection wavelength shift to the long wavelength, the grating reflectivity decreases, to ensure that the grating wavelength drift is less than 0.2nm, to control the incidence angle is less than 0.92 degrees. This study has some guidance on the fabrication of high-precision fiber grating.

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