Analysis and Simulation of Talbot Interferometer Used for Fabrication of Fiber Bragg Grating*

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Abstract A Talbot interferometer used for fabrication of fiber Bragg grating is analyzed in this paper. As the light ray tracing method can not give the actual intensity distribution of interference field when spatial coherence and temporal coherence of excimer laser are taken into account, electromagnetic theory is used for the detail description of the near interference field and far interference field, and a computation model is established, which considering the turning angle of mirrors as a model parameter for the first time. With the model, a series of simulations are carried out. From the results of calculations, we obtained a more actual status of interference field. The results showed that spatial coherence had a large influence on fringe visibility of both near and far field interference, and the far field was stricter with spatial coherence. The effect of turning angles of mirrors on far field interference cannot be negligible.

Keywords Talbot interferometer; Fiber Bragg grating; Interference; Spatial coherence
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0 Introduction

In 1993 Hill proposed phase mask technique, which enabled fiber Bragg grating (FBG) fabricated with a low-cost excimer laser and the high efficiency of grating formation and became a popular fabrication technique of FBG[1]. But there exist two major problems in this technique. Generally the photosensitive optical fiber is fixed in the position immediate behind the phase mask, which may result in the damage to the surface of expensive phase mask after some time. Another problem of proximity-printing mode is that the period of FBG is half of the period of phase mask, i. e. the period of FBG is only dependent of the period of phase mask, thus we need to change the phase mask when we want to write a FBG with a different Bragg wavelength. The problems can be resolved through the use of Talbot interferometer[2,3] or its variants[4]. There are several mathematical models about Talbot interferometer, but those models mainly deal with the near field interference or the far field without considering the effect of turning angle of mirrors.

In this paper we report our research on the development of a Talbot interferometer. Both near interference field and far interference field of Talbot interferometer under KrF excimer laser irradiation are analyzed, and a more complete computation model, which incorporates turning angles of mirrors as computation parameter for the first time, is established.

1 Theory of Talbot interferometer used for writing FBG

1.1 Analysis of the wave field behind phase mask

The illustration of the Talbot interferometer used for writing FBG is showed in Fig. 1. The light beam through the phase mask is diffracted to different directions and the main energy is concentrated on the ±1 diffraction orders. The ±1 order diffraction light beams are recombined after being reflected by two mirrors. The light-recombining angle, which leads to the change of period of interference fringe, will vary with rotation of the two mirrors. Because FBG is inscribed with the interference fringe, the period of FBG changed correspondingly. Since the spatial coherence and temporal coherence of excimer laser will affect the actual intensity distribution , which can not

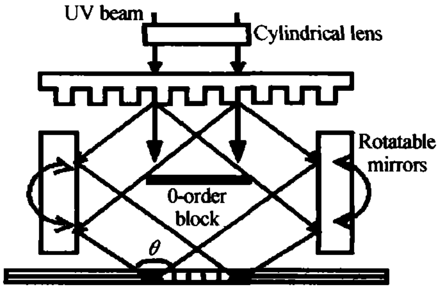

Fig. 1 Schematic diagram of Talbot interferometer

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be described by geometric optics in detail, it is necessary to study the interference field with the electromagnetic theory of light.

The geometry of the phase mask is shown as Fig. 2.

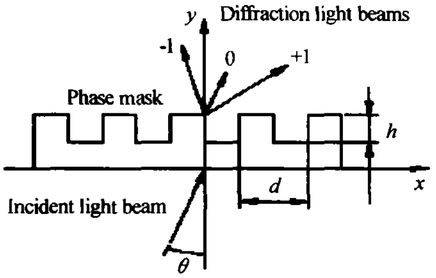


Fig. 2 Diffraction geometry of incident light through phase mask

The period is d and the phase function in a period of phase mask is expressed as

$$t(x) = \begin{cases} \exp(i\varphi_1) & 0 < x < d/2 \\ \exp(i\varphi_2) & d/2 \leqslant x \leqslant d \end{cases} \tag{1}$$

where φ_1 and φ_2 are the phase retardations in different x positions.

According to the Ref. [5], when a plane wave is projected on the phase grating, the diffraction wave in transmission can be expressed as

$$E(x,y) = \sum_m T_m \exp[i(k_{mx}x + k_{my}y)] \tag{2}$$

$$k_{mx} = 2\pi m/d + k_0 \sin\theta \tag{3}$$

$$k_{my} = \sqrt{k_0^2 - k_{mx}^2} \quad (m = 0, \pm 1, \pm 2 \cdots) \tag{4}$$

where T_m is the complex amplitude, θ is the incident angle, and k_0 is the wave number of central wavelength. Normalized to the total energy of the incident wave, the diffraction efficiency can be obtained by

$$\eta_m = \frac{|T_m|^2 k_{my}}{k_0 \cos\theta} \tag{5}$$

The maximum diffraction order should fulfill the condition $m < d/\lambda$ in order to be a forward diffraction wave. Eq. (2) means the light wave field can be seen as the synthesis of a series plane waves, which is helpful for the further analysis.

1.2 Analysis of far interference field of Talbot interferometer

In the far interference field of Talbot interferometer, the turning angles of mirrors are important, the models of literatures published before only considered the situation where the turning angles of mirrors are zero or only deal with the near interference field. In this paper we will incorporate the turning angles of mirrors as parameters into the computation model for the first time.

Assuming that a plane wave incident in the phase mask with an angle θ and a unit intensity, and what we concerned is the intensity distribution of Talbot interferometer. The mirrors are rotated by angle α_r and α_l respectively. As mentioned above, the transmission wave behind the phase mask is made up of a series of plane waves having different propagation angles. It is hard to get the analysis formula of interference field when the turning angles of mirrors are included, but it can be obtained through numeric integral. In order to simplify the numeric model and make the model easy to be implemented by Matlab software, the propagation of wave through Talbot interferometer is analyzed in the following.

The diffraction plane waves reflected by the mirrors can be regarded as the plane waves coming from O_1 and O_2 respectively, as showed in Fig. 3. In the each coordinates, such as $x'o_1y'$, the correspondent diffractive light waves have the same formula expression of propagation. We can get the expression of far interference field just to add each diffraction order light with a series of coordinates transfers. In the situation as shown in Fig. 3, the coordinates transfers are given by

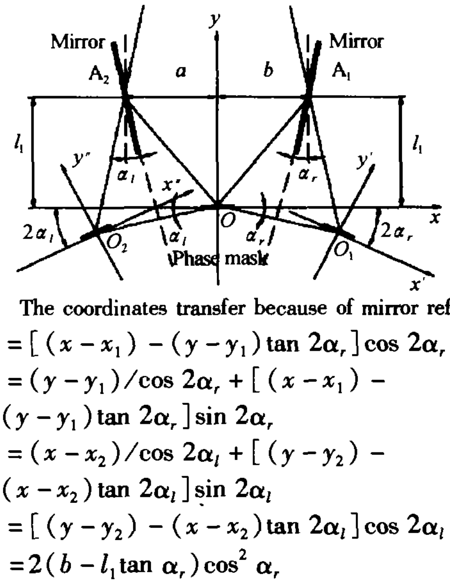


Fig. 3 The coordinates transfer because of mirror reflection

$$x' = [(x - x_1) - (y - y_1)\tan 2\alpha_r]\cos 2\alpha_r \tag{6}$$

$$y' = (y - y_1)/\cos 2\alpha_r + [(x - x_1) - (y - y_1)\tan 2\alpha_r]\sin 2\alpha_r \tag{7}$$

$$x'' = (x - x_2)/\cos 2\alpha_l + [(y - y_2) - (x - x_2)\tan 2\alpha_l]\sin 2\alpha_l \tag{8}$$

$$y'' = [(y - y_2) - (x - x_2)\tan 2\alpha_l]\cos 2\alpha_l \tag{9}$$

$$x_1 = 2(b - l_1 \tan\alpha_r)\cos^2\alpha_r \tag{10}$$

$$y_1 = -(b - l_1 \tan\alpha_r)\sin 2\alpha_r \tag{11}$$

$$x_2 = -2(a - l_1 \tan\alpha_l)\cos^2\alpha_l \tag{12}$$

$$y_2 = -(a - l_1 \tan\alpha_l)\sin 2\alpha_l \tag{13}$$

And the light wave field is then expressed simply as

$$E = E_0 \exp(ik_0 y\cos\theta) + \sum_{p=-1}^{-N} E_p \exp[i(-k_{px}x'' + k_{py}y'')] + \sum_{q=1}^{N} E_q \exp[i(-k_{qx}x' + k_{qy}y')] \tag{14}$$

Where N is the maximum diffraction order, which decided by the ratio of d/λ. Through the equation $I = EE^*$ the far interference field of Talbot interferometer can be obtained. When the spatial coherence and temporal coherence of excimer laser are taken into account, it is needed to do some assumptions. One assumption is the intensity of excimer laser is homogeneous within the beam divergence angle ϕ and is 0 beside of the beam divergence angle, another is the interference fields with different wavelengths can be added incoherently[7]. Then through the numeric integral with the expression

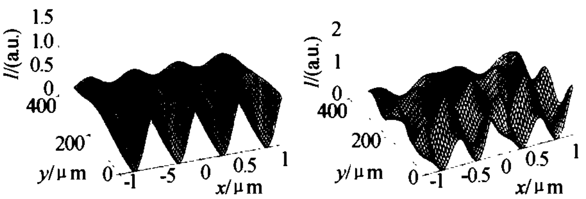
$$I_{\text{total}} = \int_{\lambda_1}^{\lambda_2} \int_{-\frac{\phi}{2}}^{\frac{\phi}{2}} I(\lambda, \theta) \, d\theta d\lambda \tag{15}$$

we get the actual interference field . If the parameter a, b and rotation angle α_l, α_r are set to 0, the above equations are also suited for the calculation of near interference field.

2 Result of calculations

In order to investigate the interference field, the equations are implemented with Matlab software and the calculation conditions are chosen as the following: a phase mask with a period $d = 1084$ nm, 248 nm KrF excimer laser having a beam divergence of 2 mrad and line width of 1 nm, the mechanical parameters $a = b = 15$ mm and l_1 is 63 mm. Because the producer of phase mask only provides the range of diffraction efficiencies instead of accurate values, the diffraction efficiencies are assumed within the range. In the following calculations, only the diffraction efficiencies .and rotation angle of mirror are changed.

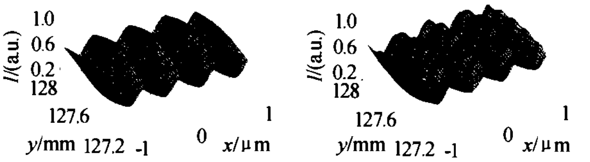
Fig. 4 shows the near interference fields. Obviously, spatial coherence limited the coherence depth in y coordinate. Because of the symmetry of Talbot interferometer, the effect of the temporal coherence on the interference of the same diffraction order is little. Fig. 4(b) changes η_0 to 0.05, it can be seen the zero order diffraction has a large influence on the intensity distribution, resulting from the interference between zero order diffraction and ± 1 order diffraction.



(a) η_0=0 and $\eta_{\pm1}$=0.3 (b) η_0=0.05 and $\eta_{\pm1}$=0.3

Fig. 4 Near interference field of Talbot interferometer with different diffraction efficiencies

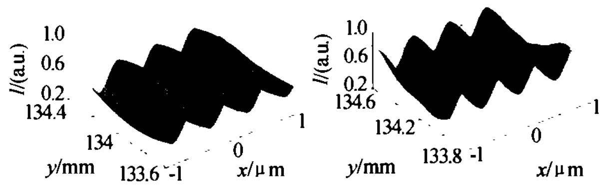
Fig. 5 discussed the far interference field when rotation angle $\alpha_l = \alpha_r = 0$. From Fig. 5(a), it can be seen that the position in y-axis direction where the inference fringe has the maximum visibility and the period of 542 nm coincided with the expectation made with light ray tracing. The far field has a similar intensity distribution at the x-axis direction as showed in the Fig. 4(a), but the maximum visibility decreased to about 0.5. That means a laser with better spatial coherence is preferred if we want to inscribe FBG in the far field. As the optical path differences are increased in the far interference field of Talbot interferometer, the interference between 0 order and 1 order is weakened with the same limit of laser temporal coherence and the periodicity in y-axis direction is not as evident as the Fig. 4(b).



(a) η_0=0, $\eta_{\pm1}$=0.3, other is zero (b) η_0=0.05, $\eta_{\pm1}$=0.3, other is zero

Fig. 5 Far interference field of Talbot interferometer at different diffraction efficiencies

Fig. 6 illustrated the situations with mirrors rotated. The mirrors rotated the same angle $\alpha_l = \alpha_r = 0.01$ rad in the Fig. 6(a), the period of interference fringe is 600 nm and visibility is about 0.46. Fig. 6 (b) discussed the situation that two mirror have different rotation angles, which related to the precision of adjusting mechanical device. The interference field tilted and the periodicity kept , here the period was 593 nm in x-axis direction, but visibility decreased to 0.388, which will deteriorate the fabrication of FBG, so it is necessary to improve the consistency and stability of mirror rotation.



(a) $\alpha_r = \alpha_l$=0.01 rad (b) α_r=0.01 rad and α_l=0.011 rad

Fig. 6 Far interference field of Talbot interferometer with different rotation angle of mirrors α and the main diffraction efficiencies $\eta_{\pm1} = 0.3$

3 Conclusions

In this paper, we analyzed the interference field of Talbot interferometer used for writing fiber Bragg grating. Geometry light ray tracing is useful in qualitative analysis, but when spatial coherence and temporal coherence are taken account, electromagnetic theory is needed in order to give a more detail information. Here we establish a computation model based on electromagnetic theory to solve the problem and the turning angles of mirrors are considered for the first time. The model is implemented with Matlab software and a series of simulations are carried out. From the results, the actual interference field and the effects of spatial coherence, temporal coherence and turning angles of mirrors are showed. It is inferred that a KrF excimer laser with improved spatial coherence is preferred if the FBG is written in far field and the position used to fix fiber is need to keep accuracy. The effect of rotation of mirrors on the visibility of interference fringe can be ignored when the two mirrors have the same rotation angle, but when there exists difference between the rotation angles of two mirrors, the effect should be treated carefully.

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用于制作光纤光栅的 Talbot 干涉仪的分析与建模

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摘　要　对用于制作光纤光栅的 Talbot 干涉仪进行了分析. 当考虑准分子激光器的空间相干性和时间相干性时,几何光学中的光线法并不能给出 Talbot 干涉仪干涉场的真实强度分布情况,而通过光的电磁理论,则可以提供对干涉场的详细描述. 基于电磁理论,建立了一个 Talbot 干涉仪干涉场计算模型,并首次将 Talbot 干涉仪的反射镜转角作为模型计算参数加以考虑,随后进行了一系列的计算. 计算结果显示了干涉场的分布,同时表明空间相干性对 Talbot 干涉仪的近场干涉和远场干涉影响都很大,其中远场干涉对空间相干性的要求更严格,且对于远场干涉,反射镜转角的影响不可忽视.

关键词　Talbot 干涉仪;布喇格光纤光栅;干涉;空间相干

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