Effect of polarization on efficiency of volume Bragg grating filter

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Diffraction efficiency of volume Bragg grating, whose period is in the same order as the incident wavelength, is related to the polarization direction of the incident linear polarized beam. When two linearly polarized recording beams with the same polarization direction are used for recording volume Bragg gratings in a photopolymer with diffusion amplification, the azimuth of polarization of the reconstruction beam influences the diffraction efficiency of the grating. When the probe beam is linearly polarized and oriented orthogonally to the grating vectors, the ±1-order diffraction beams are also linearly polarized with polarization direction parallel to that of the probe beam. According to the results, a two-dimensional non-spatial optical filter consisting of the volume Bragg gratings would achieve significantly higher efficiency.

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Volume Bragg gratings (VBGs) are important in applications such as data storage, optical communications, and optical filtering. Non-spatial optical filters consist of two VBGs attached with optical cement. The overall efficiency of one-dimensional (1D) filter tested was 70%–85%, and the theoretical efficiency of two-dimensional (2D) filter was extrapolated as 56%–81%[1]. However, tested practical efficiency was half of the theoretical extrapolated results. Drawbacks that hinder popularizing and applying this type of non-spatial filter include expensive fabrication of the transparent optical cement and poor efficiency.

In this letter, we present a new non-spatial optical filter that considers the influence of polarization in the diffraction efficiency[2]. A half-wave plate (HWP) is placed between the two gratings to alter the polarization of the beam which has been output from the first one, incident upon the second one. Using this simple implementation, the efficiency of 2D filter is improved by approximately 30%.

In the case where the grating period approximates the incident wavelength, polarization strongly influenced the diffraction efficiency of the VBG[3−5]. When the probe beam was linearly polarized in this type of grating, the diffractive beam output was also linearly polarized in the same polarized direction. Nevertheless, the diffraction efficiencies of the two cases were not the same. When the polarization of the probe beam was oriented orthogonally to the grating vector, the diffraction efficiency achieved the maximum; when polarization was oriented parallel to the grating vector, the diffraction efficiency declined.

The individual efficiencies of the first orders were highly sensitive to polarization of the probe beam; thus, diffraction efficiency varied between 57% and 90%. This was achieved by modulating the polarization state of the incident light when grating period was approximate to the wavelength of incident probe beam. Thus, both highly polarization sensitive and polarization independent diffractions were achieved using polarization grating.

Assuming that the two recording beams (object beam and reference beam, labeled as 1 and 2, respectively, in Fig. 1(a)) have the same strength, and they are both s linearly polarized beams and incident upon the xoz plane (recording material plane) with a small angle θ[6]. Thus, the phase difference $\Delta\varphi$ between the two beams is expressed as

$$\Delta\varphi = 2kx\sin\theta, \tag{1}$$

where $k = 2\pi / \lambda$ and λ is the recording wavelength.

Assuming that the coordinate of Jones vector is (X, Y), and the included angle with the coordinate (x, y) is α; the Jones matrix of the two beams is expressed as

$$\begin{cases} O = a\begin{pmatrix}\cos\alpha \\ \sin\alpha\end{pmatrix}\mathrm{e}^{-\mathrm{i}\Delta\varphi/2} \\ R = a\begin{pmatrix}\cos\alpha \\ \sin\alpha\end{pmatrix}\mathrm{e}^{-\mathrm{i}\Delta\varphi/2} \end{cases}, \tag{2}$$

where a is the strength of the beam. If α is 90°, the two incident beams are both s polarized. When the two beams are compacted as one linearly polarized beam, which serves as the recording beam, the strength distributes cosine modulation in the x direction is

$$I = 2a^2\left(1 + \cos\Delta\varphi\right). \tag{3}$$

This makes the refraction index distribute cosine modulation within the light field. During the same period, the equation converts the index to become the grating. The refraction index is given by

$$n = n_0 + \Delta n \cdot \cos\left(\Delta\varphi\right). \tag{4}$$

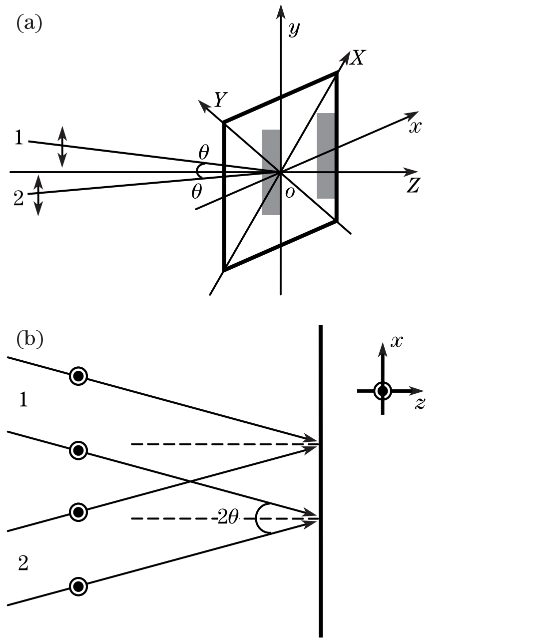

Fig. 1. Optical paths of (a) holograph recording and (b) polarized recording.

The optical properties of polarization can also be approximately derived using the Jones matrix method. The transmitting matrix T is

$$T = \mathrm{e}^{\phi_0} \begin{pmatrix} \mathrm{e}^{\mathrm{i}\Delta\phi\cos\varphi} & 0 \\ 0 & \mathrm{e}^{-\mathrm{i}\Delta\phi\cos\varphi} \end{pmatrix}, \quad (5)$$

where $\phi_0 = kn_0 d$, $\Delta\phi = k\Delta n d$, d is the thickness of the material, $n_0 = (n_\mathrm{e}+n_\mathrm{o})/2$ is the weak-field average index of refraction of the material, and $\Delta n = (n_\mathrm{e}-n_\mathrm{o})/2$ is the refractive index modulation.

The probe linearly polarized beam propagates parallel to the reference beam, where the azimuth is γ given by

$$C = \begin{pmatrix} \cos\gamma \\ \sin\gamma \end{pmatrix} \mathrm{e}^{-\mathrm{i}\Delta\varphi/2}. \quad (6)$$

Therefore, the diffraction light field is

$$D = TC = \mathrm{e}^{\mathrm{i}\phi_0}\cos(\Delta\phi) \begin{pmatrix} \cos\gamma\cdot\mathrm{e}^{-\mathrm{i}\Delta\varphi/2} \\ -\sin\gamma\cdot\mathrm{ie}^{-\mathrm{i}\Delta\varphi/2} \end{pmatrix} + \mathrm{ie}^{\mathrm{i}\phi_0}\sin(\Delta\phi) \begin{pmatrix} \cos\gamma\cdot\mathrm{e}^{\mathrm{i}\Delta\varphi/2} \\ \sin\gamma\cdot\mathrm{ie}^{\mathrm{i}\Delta\varphi/2} \end{pmatrix}, \quad (7)$$

As we anticipated, the variations of the diffraction efficiency were achieved by modulating the polarization state of the incident light. The first part of Eq. (7) is the 0-order diffraction of the grating (i.e., the transmitting light); the second part is either the +1-order or the −1-order diffraction of the grating. Polarization of output beam had the same value as that of input beam. Ideally, diffraction efficiency should be

$$\eta = \sin^2(\Delta\phi) = \sin^2(\pi/2) = 100\%. \quad (8)$$

The relative diffraction efficiency of the grating in experiment was defined as

$$\eta = \frac{P_{-1}}{P_{-1}+P_0}, \quad (9)$$

where P_{-1} is the strength of the diffractive beam and P_0 is the strength of the transmitting beam.

Serial experiments were performed to prove the relationship between diffraction efficiency and incident polarization. The experimental setup is shown in Fig. 2.

In Step 1, the photo-detector (PD) measured the strength of the beam directly from the He-Ne laser at approximately 930 μW. In Step 2, a HWP was placed into the path of the beam between the source (He-Ne laser) and the PD. The indications varied from 820 to 900 μW while rotating the HWP. In other words, the polarization had a slight effect on the opto-electric sensor. In Step 3, the strength of the light was measured and charted after placing one of the gratings behind the HWP. Indications varied from 335 to 682 μW, while the indication was 620 μW without the HWP. In the case where the maximum strength of the beam was achieved in Step 3, another HWP and the second grating were placed. The strength of the beam was measured in Step 4 while rotating the second HWP. Despite incorporating all sources of loss from the HWP including reflection, absorption, scattering, and other Fresnel losses, the maximum strength of the beam increased from 153 to 178 μW with the placement of the HWP.

The relationship was obtained through placing a HWP into the propagating He-Ne laser beam by turning the azimuth of the HWP from 0° to 180°. The beam was a linearly polarized beam with the wavelength of 632.8 nm pointing toward the grating. The strength graph of the ±1-order diffraction beam was acquired from the light detector, as shown in Fig. 3(a).

Next, at the azimuth that enabled the diffraction efficiency of the first grating to reach the maximum, the second HWP was rotated from 0° to 180°. Strength graph of the ±1-order diffraction beam was acquired

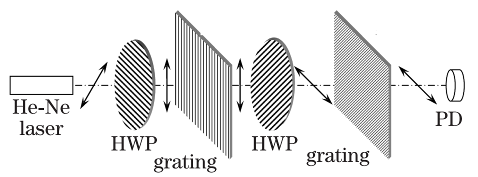

Fig. 2. Illustration of experimental setup.

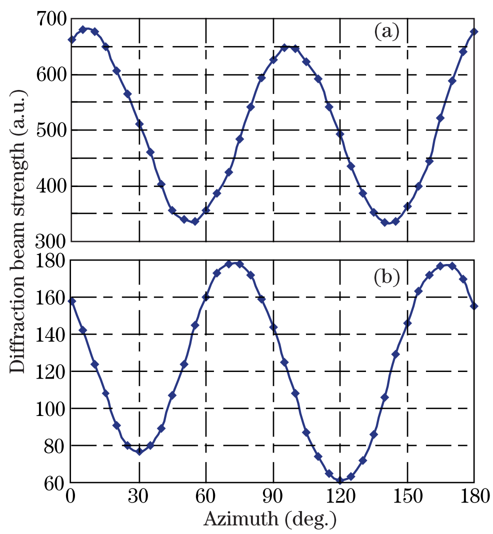

Fig. 3. Strength graphs of the beams. (a) 1D output; (b) 2D output.

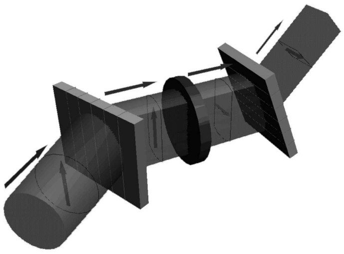

Fig. 4. Experimental optical path of new 2D non-spatial filtering.

from the light detector, as illustrated in Fig. 3(b).

Apparently, from the above steps, the fluctuating strength of the diffractive beam is caused by the polarization. If this is used in 2D optical filtering, the overall efficiency of the filter should be enhanced.

Experimental optical path of the 2D filtering was achieved by placing a HWP between the two gratings. The next step was to justify the orientation of the linear polarization of the beams towards the two gratings, and enable both input beams to orient orthogonally to their grating vectors respectively. These are likewise oriented orthogonally to the grating vector of the second grating.

These results have useful applications. We accomplished the 2D filter in this implementation, as shown Fig. 4[7]. The overall efficiency of the filter was enhanced due to the polarized direction.

In conclusion, we have shown a VBG whose grating period is in the same order of the wavelength of the incident probe beam. The grating has several unique properties, one of which is variation in diffraction efficiency achieved by modulating the polarization state of the incident light. Another property is the production of cosine modulation on the peak diffraction efficiency by the azimuth of polarization of the probe beam. To achieve the highest overall efficiency of the 2D filter, we can simply insert a piece of HWP into the two gratings of the filter, then justify the azimuth of the polarization of the incident beam propagating into the second grating. Thus, the linearly polarized beam is oriented orthogonally to the grating vector. The experimental results are in good agreement with the theoretical expectation based on Jones matrix. Using the simple implementation, the overall efficiency of the 2D filter is increased to approximately 70% at its peak.

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