Two-dimensional non-spatial filtering based on holographic Bragg gratings*

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The filter made up of two gratings performs as a two-dimensional non-spatial filtering. This paper reports that the volume Bragg gratings are fabricated by interfering two collimated coherent laser beams in photopolymer. Diffraction efficiency of a single grating is up to 78% in Bragg's condition, then a two-dimensional non-spatial filter, which consists of two volume Bragg gratings and a half-wave plate, enables the laser beam filtered in two dimensions with the diffraction efficiency of 54%. The Bragg's condition and effect of polarisation on performances of the two-dimension filter are also discussed.

Keywords: spatial filter, Bragg gratings, two-dimensional filtering, polarisation
PACC: 4280B, 4280F, 4240K, 4225J

1. Introduction

One of the most widespread used space filters is the so-called 'pinhole' filter,[1] which consists of a lens with a pinhole in the focal plane. The problem with this type of spatial filters is the requirement for matching spatially and angularly a tightly focused laser beam to a small target. Experimentally, the initial alignment of spatial filters is difficult and tedious and requires a manual search through three-dimensional position space in an attempt to maximize the throughput intensity. Furthermore, the focusing required for pinhole spatial filter is problematic when it is used with high-power lasers. If the pinhole position changes or if there is a slight misalignment, a high-power laser can damage the pinhole or its edge when the power is increased or even permanent damage due to heating.

Ludman *et al.* had developed non-spatial filtering[2−6] to solve the numerous problems inherent in spatial filters.

In contrast, non-spatial filtering, that is, a volume Bragg filter element is inserted in the laser beam path to selectively diffract light propagating at a particular on-axis angle, without a lens or a pinhole. It is operated directly on the laser beam propagation angle, makes use of the grating's angular sensitive selectivity, transmits the unwanted light without diffraction.[7] This is so-called 'Bragg's diffraction'.

In this paper, we analyse the properties of the two-dimensional (2D) filter by synthesizing theory of one-dimensional (1D) non-spatial filtering[8] and its experimental results. It is important to note that, to improve diffraction efficiency, the effects of polarisation[9,10] are also taken into account in the process of 2D filtering.

2. Principle of 2D non-spatial low passed filter

2.1. Filtering characteristic of volume Bragg grating

An incident laser beam considers arbitrary spatial variations in intensity as a linear combination of plane waves.

Assume that a volume Bragg grating is illuminated at the same incident angle by laser with different wavelengths, the diffracted beams with different wavelengths propagate at different exit angles (compare upper and lower group of beams in the left part of Fig. 1), in which, wavelength λ_2 satisfies the Bragg's

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condition. While assume that the same grating is illuminated at the same wavelength by laser with different incident angles, the diffracted beams propagate with different angles also at different exit angles (compare upper and lower group of beams in the right part of Fig. 1), in which, the one satisfied with the Bragg's condition propagates at a dramatically different angle.

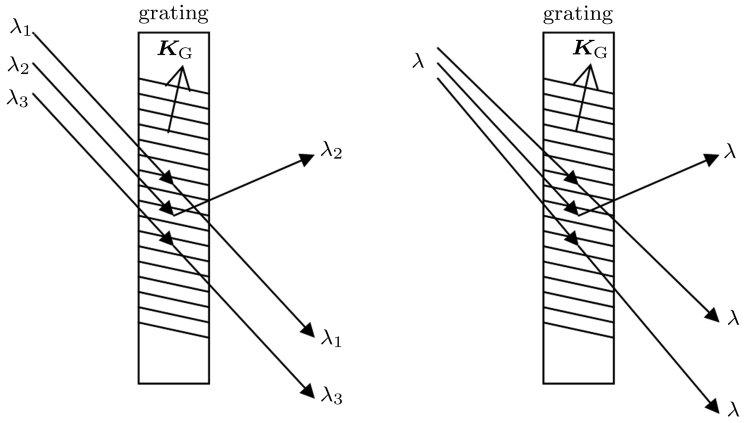


Fig. 1. Filtering process of volume Bragg gratings.

2.2. Bragg's diffraction of volume Bragg gratings

For volume Bragg gratings, diffraction of a plane monochromatic beam with a certain wavelength λ occurs for the only one certain angle which depends on grating spatial frequency according to Bragg's condition. Moreover, due to the diffractive characteristic of Bragg grating, the propagating vector of the beam has been changed.

The $\boldsymbol{k}_0$ is the wave vector of a readout beam of the first Bragg grating, and $\boldsymbol{k}_1$ is the wave vector of the diffracted beam of the first grating and simultaneously the wave vector of the readout beam of the second one, while $\boldsymbol{k}_2$ is the wave vector of the diffracted beam of the second grating. Grating vectors $\boldsymbol{K}_{\rm G1}$ and $\boldsymbol{K}_{\rm G2}$ are respectively vectors of the two gratings. In accordance with Kogelnik's theory, when the Bragg's condition is obeyed, the grating vector $\boldsymbol{K}_{\rm G}$ and the two wave propagating vectors $\boldsymbol{k}_{\rm R}$ and $\boldsymbol{k}_{\rm I}$ are coplanar and make up an isosceles triangle.

$$\boldsymbol{K}_{\rm G} = \boldsymbol{k}_{\rm R} - \boldsymbol{k}_{\rm I}. \tag{1}$$

So, the following expressions could be derived as:

$$\boldsymbol{K}_{\rm G1} = \boldsymbol{k}_0 - \boldsymbol{k}_1,$$

$$\boldsymbol{K}_{\rm G2} = \boldsymbol{k}_1 - \boldsymbol{k}_2, \tag{2}$$

where

$$|\boldsymbol{k}_0| = |\boldsymbol{k}_1| = |\boldsymbol{k}_2| = \frac{2\pi}{\lambda}. \tag{3}$$

In spatial rectangular coordinate system, the first grating whose grating vector $\boldsymbol{K}_{\rm G1}$ is oriented orthogonally to the y-axis is laid in the x–y plane; while for the second grating, whose grating vector $\boldsymbol{K}_{\rm G2}$ lies in the plane made up of $\boldsymbol{k}_1$ and y-axis, its orientation is decided by the Bragg's angle.

Assume Bragg's angle is γ, then the angle between $\boldsymbol{k}_2$ and y-axis relying on the various γ is

$$\begin{cases} \pi/2 - 2\gamma, & (0 < \gamma < \pi/4)\,, \\ 0, & (\gamma = \pi/4)\,, \\ 2\gamma - \pi/2, & (\pi/4 < \gamma < \pi/2)\,. \end{cases} \tag{4}$$

Hence, the three wave vectors could be expressed as follows:

$$\boldsymbol{k}_0 = |\boldsymbol{k}_0| \sin\gamma \cdot \hat{x} + 0 \cdot \hat{y} - |\boldsymbol{k}_0| \cos\gamma \cdot \hat{z}, \tag{5}$$

$$\boldsymbol{k}_1 = |\boldsymbol{k}_1| \sin\gamma \cdot \hat{x} + 0 \cdot \hat{y} + |\boldsymbol{k}_1| \cos\gamma \cdot \hat{z}, \tag{6}$$

$$\boldsymbol{k}_2 = \begin{cases} -|\boldsymbol{k}_2| \cos(2\gamma) \sin\gamma \cdot \hat{x} + |\boldsymbol{k}_2| \sin(2\gamma) \cdot \hat{y} - |\boldsymbol{k}_2| \cos(2\gamma) \cos\gamma \cdot \hat{z}, & (0 < \gamma < \pi/4)\,, \\ |\boldsymbol{k}_2| \cdot \hat{y}, & (\gamma = \pi/4)\,, \\ |\boldsymbol{k}_2| \cos(2\gamma) \sin\gamma \cdot \hat{x} + |\boldsymbol{k}_2| \sin(2\gamma) \cdot \hat{y} + |\boldsymbol{k}_2| \cos(2\gamma) \cos\gamma \cdot \hat{z}, & (\pi/4 < \gamma < \pi/2)\,. \end{cases} \tag{7}$$

Moreover, it is demonstrated that[9,10] grating performs its polarisation characteristics, when the grating periodicity has the same order magnitude as the wavelength of incident beam. In addition, each diffracted beam has the same polar orientation as that of the incident beam, only if the incident beam is linearly polarised. In order to achieve maximum diffraction efficiency, the polar orientation of incident beam should be input along with the grating lines.

3. Numerical simulation results

We set the Bragg's angle as $\theta = \pi/18$, the average refractive index of the medium as $n = 1.5$, the refractive index modulation as $\Delta n = 8\times10^{-3}$, and the wavelength in the air as $\lambda = 632.8$ nm. So the grating vector should be calculated as $K = 4\pi n \sin\theta/\lambda$, and the thickness of the grating as d, according to the equation of diffraction efficiency $\eta = \sin^2(\pi\Delta n d/\lambda\cos\theta)$, when $d = \lambda\cos\theta/2\Delta n \approx 40$ μm, the diffraction efficiency would reach the peak 100%.

The platform of Matlab is utilized to realize some numerical simulation:

A plane monochromatic wave has been used as the reconstructed beam. In addition, we assume that the light incident upon the Bragg grating has a small angular deviation from Bragg's angle both on horizontal and on vertical.

On the first step, deviation from Bragg's angle on horizontal has been simulated. In Fig. 2, for volume Bragg's gratings, an ideal diffraction efficiency of a beam with a certain wavelength (assumed 632.8 nm) occurs for the only one certain angle which depends on grating spatial frequency according to Bragg's condition. The diffraction efficiency depends on detuning from Bragg's angle, so it would decline sharply when the reconstructed beam occurs on the angular deviation. One can see a well-known central maximum and a number of side lobes with gradually decreasing magnitude. In this figure, the decline slope has been decided by the refractive index modulation and the thickness of the grating.

As shown in Fig. 2, curve a (solid line) corresponds to a 40-μm-thick volume Bragg grating with 8×10^{-3} refractive index modulation, which provides 100% diffraction efficiency at an assumed wavelength of 632.8 nm, curve b (dashed line) shows decrease of diffraction efficiency resulted from decrease of refractive index modulation down to 4×10^{-3} at the same grating thickness, this decrease of diffraction efficiency at the total shape down to about 50%, the second minimum moves to the position of the first minimum for refractive index modulation of 8×10^{-3} gratings, curve c (dash-dot line) shows decrease of diffraction efficiency resulted from decrease of the thickness down to 20 μm when refractive index modulation equals to 8×10^{-3}, this also provides diffraction efficiency of 50% but positions of minima and maxima of the side lobes are not changed practically.

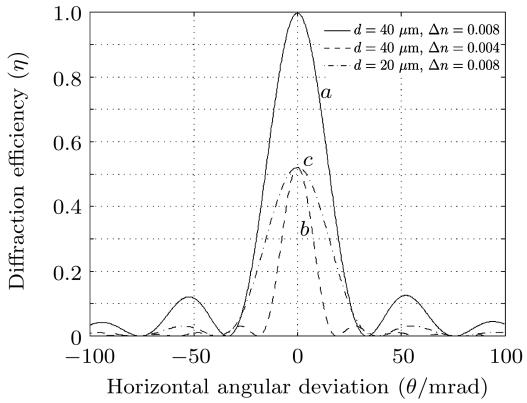
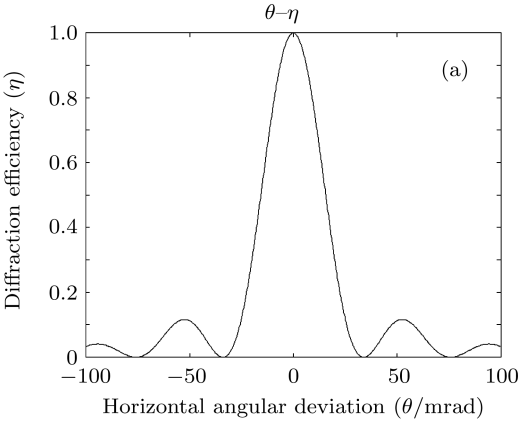


Fig. 2. Diffraction efficiency versus horizontal angular deviation.

The angular deviation on vertical also has an effect on the diffraction efficiency of the grating.

On the second step, the result of diffraction efficiency has been calculated and illustrated. It is obvious in Fig. 3(b) that the shape of vertical angular deviation is something similar to the one of horizontal, see Fig. 3(a). It may also reach minimum diffraction efficiency of zero, but its decline rate is much slower than that of horizontal. It is clearly showed that the diffraction efficiency is near its 100% limit on vertical angular deviation in a wider range. In other words, vertical angular selectivity is not as good as horizontal angular selectivity.



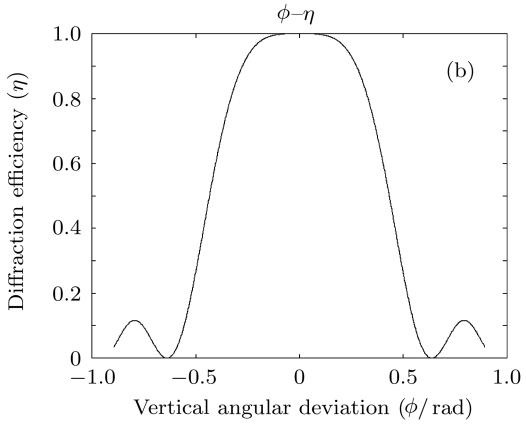


Fig. 3. Comparison of vertical angular deviation with horizontal angular deviation. (a) Diffraction efficiency versus horizontal angular deviation. (b) Diffraction efficiency versus vertical angular deviation.

4. Experiments

4.1. Fabrication of volume Bragg gratings

A volume hologram can be fabricated by interfering two coherent laser beams on a piece of holographic recording medium; then some follow-up treatment is necessary to preserve the image on the hologram.

In laboratory, at the recording stage, a He–Ne laser (wavelength 632.8 nm) was used to record the image on a 40 μm thickness RSP-II photopolymer with diffusion amplification (PDA) with the average refractive index of the medium as $n = 1.5$. A polarised beam splitter (PBS) is placed in the primary route geometry to divide the input laser into two beams, a half waveplate (HWP) is inserted before the PBS to justify the intensity ratio of the two beams, another HWP in one of its branches is to set the state of polarisation. To calculate easily, we have made the two beams interference on the PDA symmetrical. Then, at the reconstruction stage, a diode-pumped, frequency-doubled Nd:YAG laser with central wavelength of 532 nm was used for testing.

We set the incident angle as $\theta = \pi/18$ at the wavelength $\lambda = 632.8$ nm. The refractive index modulation is controlled by exposure time and post treatments approximating at $\Delta n = 8 \times 10^{-3}$. The diffraction efficiency reaches about 95% on Bragg's condition.

The dependence of diffraction efficiency of volume Bragg grating on the testing incident angle is shown in Fig. 4. There are also a central maximum and a number of side lobes with gradually decreasing magnitude. When Bragg's condition is obeyed, diffraction efficiency reaches the peak, while diffraction efficiency would decline sharply for a deviation on incident angle.

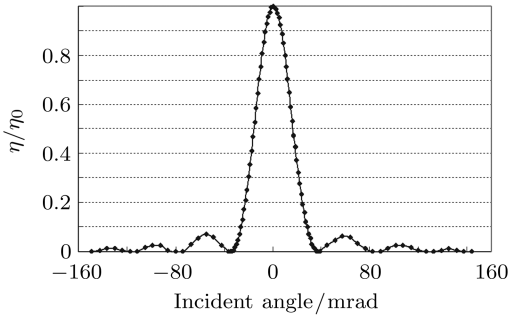


Fig. 4. Normalized diffraction efficiency of volume Bragg grating versus incident angle.

Thus, comparison of calculated data with experimental results shows very good correspondence.

4.2. The 2D non-spatial low pass filter

In Ref. [11], we had cleaned a laser beam in one dimension used one Bragg grating. Clearly, for most practical applications, it is expected to clean the input laser beam in two dimensions symmetrically as a conventional spatial filter. To achieve the object above, we insert two gratings in the route of the laser beam, whose grating vectors are orthogonal mutually in the laser beam path in series as a 2D non-spatial low pass filter, to clean the laser beam in two dimensions.

It is proved by experiment that diffraction efficiency relies strongly on the polar orientation of the linearly polarised incident beam. A higher diffraction efficiency would be achieved if the polar orientation of the incident polarised beam is parallel to the grating lines as theoretically described. Otherwise, losses would be brought on in varying degrees during the process of propagation, since the refractive index of grating is various, thus, diffraction efficiency decline. According to the conclusion, we have adopted some relevant adjustments on the 2D non-spatial filter.

The linearly polarised beam is incident upon the first grating, whose polarisation is designed to be parallel with the grating lines. In view of the theory above, the diffracted beam is also linearly polarised, oriented parallel to the grating lines. Then, an HWP is inserted between two gratings to alter the polar orientation of the diffracted beam. The fast axis of HWP orients 45° to the diffracted beam so that the output beam rotates 90° from the diffracted beam. Therefore, the polar orientation is parallel to the second

grating during incidence, the optical path of experiment is shown in Fig. 5.

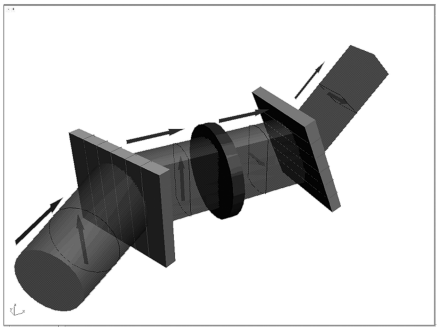


Fig. 5. Experimental optical path of 2D non-spatial filtering based on volume Bragg gratings.

A propagating laser beam is filtered by a 2D non-spatial filter made of two gratings whose grating vectors are orthogonal. The incident beam has a cone-shape, diffused slightly during propagation, as the big arrows illustrated outside the beams. In addition, the polar orientations are parallel with the grating lines as the arrows illustrated on cross sections of each phase in the optical path. Propagated throughout the first grating, the beam whose angle deviated from Bragg's angle passes over directly on 0-order. For the sake of simplicity, the transmitted beam has not been drawn. Whereas the diffracted beam is exactly the wanted result of spatial filtering, which can be obtained from +1-order of Bragg's diffraction, diffraction efficiency is up to 78%. It is obvious that both sides of the beam are chopped by the first grating as Fig. 5 indicated. In the same way, the beam diffracted by the first grating is filtered by the second grating again, thus, the cross section of the final output beam can be altered from sphere into square with the entire diffraction efficiency being nearly 54%.

The light spots of the laser beam filtered by the non-spatial filter are shown on the photos as Figs. 6 and 7. The left photo shows the remnant spot directly transmitted from the grating, while the right photo shows the diffractive spot of the grating. That is the 1D filtering result. Figure 7 shows the diffractive spot filtered by the second grating, i.e. the 2D filtering result.

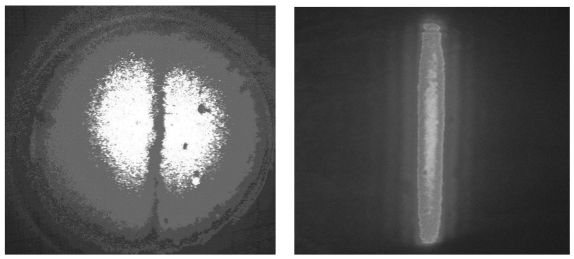


Fig. 6. Light spots of 1D filtering result.

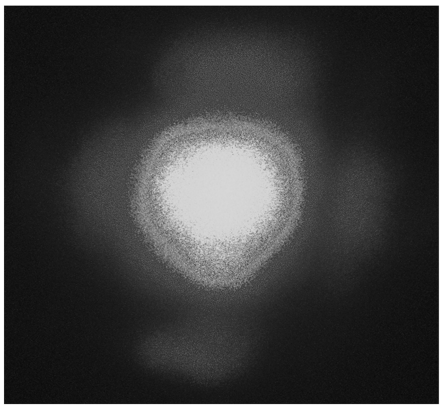


Fig. 7. Light spot of 2D filtering result.

5. Conclusions

5.1. Performance of experimental setup and filter effects

1) A practical mathematical model based on Kogelnik's coupled wave theory is developed for the diffraction of laser beams with angular deviation.

2) A theoretical model is compared with and found very close to experimental data.

3) The cross section is square. It is assumed that the two filters are on the same condition, the result of the procession should be square suited for some special application requirements.

4) The intensity of diffraction is uniform. The filter is operated directly on the propagation angle of the laser beam; the beam whose angle mismatches Bragg's angle would be filtered. Therefore, if the incident beam is a monochord-plain wave, the final image should appear as a uniform spot.

5) The parallel level is enhanced. A beam whose angle is matching Bragg's angle can be diffracted, while others are discarded. Thus, the output beam of the filter has only one direction, and that is exactly the diffracted vector's direction.

6) Diffracted polarisation is linearly polarised. To achieve the maximum diffraction efficiency, polarisation of the output beam would be linear, as the same as, but orthogonal with polarisation of the input beam.

5.2. Discussions

Both theory and experiments demonstrate that it is feasible to achieve 2D low pass filter by volume Bragg grating.

A 2D non-spatial filter, which consisted of two Bragg gratings in series, produces a clean uniform and collimated beam, which can be utilized in the optical system.

In contrast with the conventional filter, the advantage of our experimental equipment is that it can bear high-power laser not to be permanent damaged due to heating, in addition, it is much easier to be installed.

The cross section of the laser beam is altered from sphere to square by the Bragg's filter, which has an outstanding advantage in the environment of rectangular gain medium.

From the expression of $\boldsymbol{k}_2$ in Eq. (7), it is obvious that the output beam is not coplanar with the input beam, so that there would be a little trouble brought into practical optical research. For the sake of the following study, we simply lay a reflector or a prism in an appropriate position, which depends on the practical situation, to adjust the direction of the beam. Besides, the efficiency of the entire system is to be promoted.

In this paper, geometrical optics are simulated for the sake of convenience. That is, we assume that the incident laser beam is a standard plain monochromatic wave. In the next paper, we shall report that a normal Gaussian beam will be utilized for simulation in the optical system.

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