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Sidelobe suppression of spectral response in holographic optical filter

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Abstract

In order to suppress sidelobes of holographic filter's spectral response we propose to use weighting of grating intensity distribution along light propagation. This can be realized in photorefractive material (for example in $LiNbO_3$:Fe) by using spatial selective decaying of conventional uniform grating by illumination of light through some transparent mask. Experimental results show that it is able to obtain 8 dB improvement of sidelobe level compared to uniform grating. But it is accompanied by 1.7 times expansion of main lobe and two times decrease of diffraction efficiency.

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1. Introduction

Optical spectral filters have been widely used in the fields of spectroscopy, astronomy observations and recently in dense wavelength division multiplexing (DWDM) communication. Last one becomes very popular and makes new application and requirements for optical elements.

DWDM technology uses spectral compression of different communication channels in one fiber [1]. The less spectral separation between neighbor channels the more number of channels and more information capacity can be realized. Narrow spectral optical filters those are used to separate one channel from others should have negligible interchannel cross-talk. Thus it is important to develop a spectral filter that has not only narrow spectral response but also with low sidelobe level.

2. Basic principle

The main characteristic of a filter is its spectral response. Conventional holographic optical filter is a thick grating that uses Bragg selectivity of diffraction [2–6]. This means that among all broad optical spectrum incident onto a grating only spectral components lying in narrow spectral range cause a noticeable diffraction. By separating a diffracted light one can perform a filtration.

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Holographic grating of a phase kind has an advantage that it could be realized with a very high diffraction efficiency (close to 100%). This is very good for a filter as for passive element. Usually, holographic phase grating can be made by two beam interference in photorefractive materials or in photopolymers. In this case distribution of grating intensity is uniform. It is known that spectral response of uniform grating has a shape like sinc^2 function. The main parameters of a filter are the sidelobe level and the wavelength passband $\delta\lambda$.

It is known that wavelength passband determines the spectral resolution of a filter. As for sidelobe level, it determines the dynamic range of optical spectral devise. They are very important parameters especially in DWDM systems because if some weak signal is observed on the filter output it is unknown whether this signal is useful but weak or it is caused by hitting of strong signal of neighbor channel inside sidelobe.

It is also known that in the case of diffraction of light on thick transparent grating with low modulation of refractive index (up to 30% of efficiency) the diffraction efficiency is proportional to a square of spatial Fourier transform on amplitude distribution of grating along light propagation [4,5]. In the case of uniform grating, diffraction efficiency can be written as

$$\eta \propto L^2 \mathrm{sinc}^2\left(\frac{\Delta\beta L}{2}\right), \tag{1}$$

where $\Delta\beta$ is the phase mismatch and L is the thickness of the grating. Phase mismatch means deviation from the Bragg condition and can be caused by two factors: changing the incident light angle and changing the light wavelength. If phase mismatch is caused only by spectral deviation $\Delta\lambda$, for the isotropic diffraction it can be written as

$$\Delta\beta = \frac{\pi\Delta\lambda}{n_o \Lambda^2 \cos\Theta_i}, \tag{2}$$

where Λ is the grating spacing and n_o is the refractive index.

In this case we have an optical filter with a wavelength passband $\delta\lambda$ at -3 dB level of Eq. (1) that is equal numerically

$$\delta\lambda = \frac{\lambda^2 \cos\Theta_i}{2Ln_o \sin^2\Theta_i}, \tag{3}$$

where Θ_i is the incident angle, λ is the optical wavelength. The sidelobe level of a uniform grating response is equal to -13 dB that is not good.

From linear theory it is known that in order to get a response with small sidelobes it can be achieved through some weighting (or apodization) of signal distribution in aperture. The weighting function may be different. It is important to know that all of weighting functions besides the decrease of sidelobe level give some expansion of main lobe (that means decrease of spectral resolution).

The weighted function may be chosen to be fitted for a particular situation. It is known that Hamming function can provide a minimum of sidelobe level at acceptable decreasing of spectral resolution [7]. Other weighting functions usually give different relationships between sidelobe level and passband expansion. Let us consider Hamming weighting function

$$W(x) = \begin{cases} \alpha + (1-\alpha)\cos\left(\frac{2\pi}{L}x - \pi\right), & 0 \leqslant x \leqslant L, \\ 0, & \text{other } x, \end{cases} \tag{4}$$

where $\alpha = 0.54$ – Hamming constant, L is device's aperture and x is a direction crossed to K-vector of a grating. Applying a spatial Fourier transform on Eq. (4) along x direction we have obtained analytically the dependence of diffraction efficiency as

$$\eta \propto \left[\alpha \mathrm{sinc}\left(\frac{\Delta\beta L}{2}\right) + \frac{1-\alpha}{2}\mathrm{sinc}\left(\frac{\Delta\beta L}{2} - \pi\right) + \frac{1-\alpha}{2}\mathrm{sinc}\left(\frac{\Delta\beta L}{2} + \pi\right)\right]^2 L^2. \tag{5}$$

Mathematical formulas (4) and (5) means following. If it would be possible to realize a grating intensity distribution like Eq. (4) (Fig. 1) so we would obtain a spectral response as Eq. (5) (Fig. 2, solid line). Fig. 2 also shows the spectral response of a conventional uniform grating (dot line) with the same thickness and spacing.

It can be seen that characteristic of grating with weighting could have extremely low sidelobe level (up to -42 dB). But it is accompanied by some

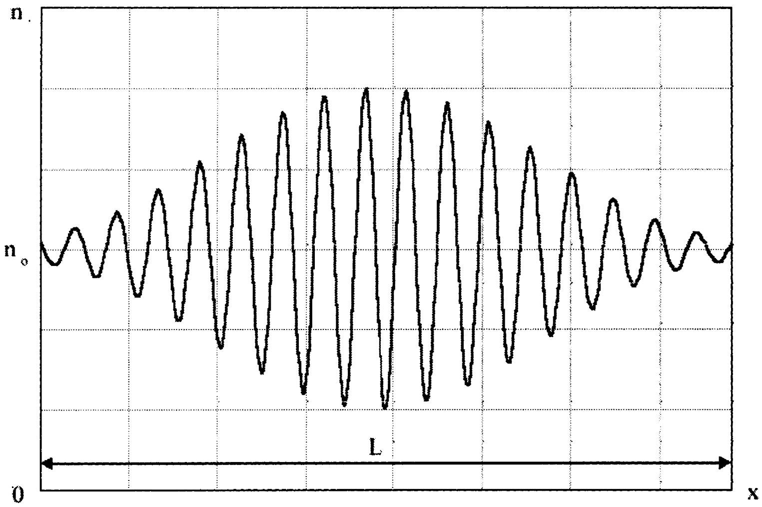

Fig. 1. Grating weighted by Hamming function.

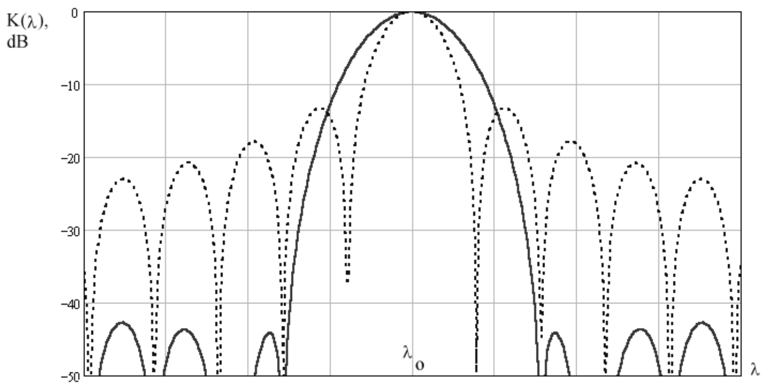

Fig. 2. Spectral response of weighted grating (—) compared with standard one (···).

expansion of the main lobe (up to 50% or in 1.5 times at −3 dB level). That means decreasing of spectral resolution.

Analysis shows that grating that has maximum intensity in the center and falls in the sides should have an improvement in sidelobe level.

3. Experimental results

Firstly we created a uniform grating by traditional method of two beam interference in photorefractive medium [8,9]. Fig. 3 shows the basic idea of hologram creation by mixing of two plane waves. The distance between interference fringes Λ (or grating spacing) depends on wavelength of beams λ_{rec} and angle between them α

$$\sin\left(\frac{\alpha}{2}\right) = \frac{\lambda_{rec}}{2n_o\Lambda}, \tag{6}$$

where α is measured inside of medium. As for grating thickness L and optical aperture D, usually they are determined by crystal's and beam's sizes.

To record a grating we used argon laser in single mode (514 nm). The schematic diagram is shown in Fig. 4. Experimental parameters for recorded grating are summarized in Table 1.

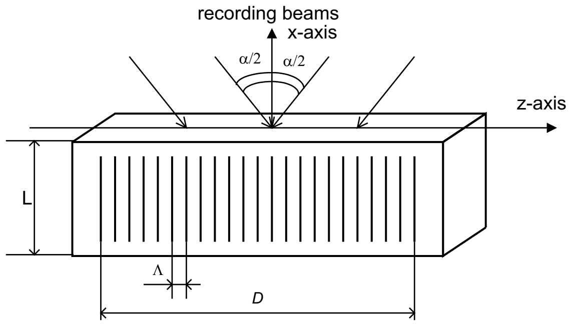

Fig. 3. Creation of conventional uniform grating in lithium niobate.

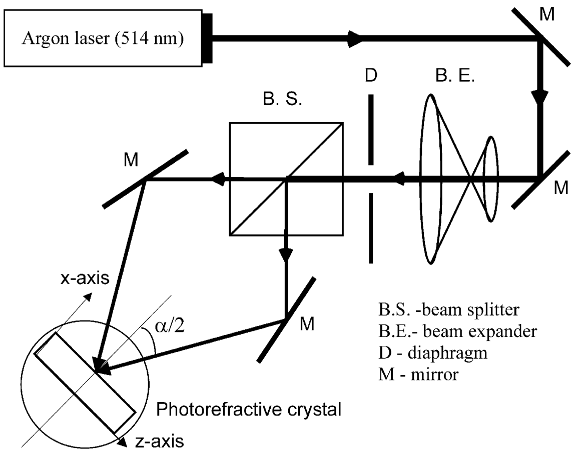

Fig. 4. Schematic diagram of recording.

Table 1
Experimental parameters of recording grating

Media	$LiNbO_3$:Fe
Record wavelength λ_{rec}	514 nm
Mixing angle α (inside)	4.52°
Grating spacing Λ	2.78 μm
Optical aperture D	15 mm
Thickness L	10 mm
Diffraction efficiency (at 514 nm)	60%

After recording we measured diffraction efficiency of the grating using by wavelength tunable laser (LEXEL 479). It should be mentioned that because of the spectral mismatch of Bragg condition we had to retune the incident angle in accordance with central point ($\lambda = 788.6$ nm) of the

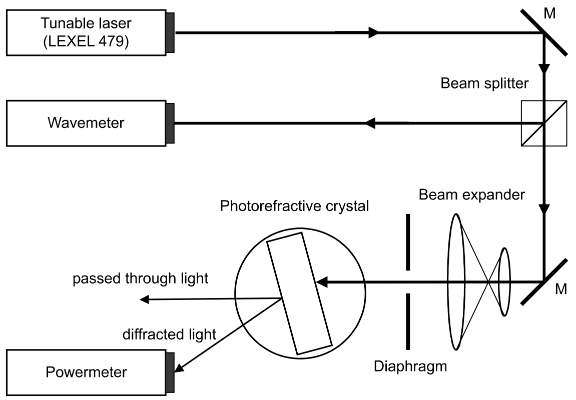

Fig. 5. Schematic diagram of testing.

laser tuning range. The incident angle can be derived as

$$\sin\Theta_{\mathrm{i}} = \frac{\lambda}{2n_{\mathrm{o}}\Lambda}. \tag{7}$$

For our example, $\Theta_{\mathrm{i}} = 3.6°$ corresponds $\lambda = 788.6$ nm. Then we probed the diffraction efficiency of the grating by changing wavelength in the range 773–805 nm. The schematic diagram of testing is shown in Fig. 5. The results in relative log scale are shown in Fig. 6 (solid line). Theoretical curve using by formulas (1) and (2) for the same conditions of grating is shown by dot line in the same figure.

It can be seen that the experimental curve is very close to the theoretical one. The main parameters of this holographic filter are included in Table 2.

To perform the weighting of uniform grating we used a phenomena of hologram decaying by light illumination. We made a transparency which darkening density (along x-direction) is inverse to weighting function (4), attached it in the grating surface and then illuminated the grating through it by using argon laser. Fig. 7 shows the schematic diagram. The light passing through the transparency has a nonuniform intensity (along x-direction). Thus the parts of a holographic grating those are illuminated by larger intensity are decayed with higher amount. By using this principle we weighted a grating by function (4).

After weighting being performed we measured the diffraction efficiency of the grating by changing wavelength in the range 765–808 nm. The results

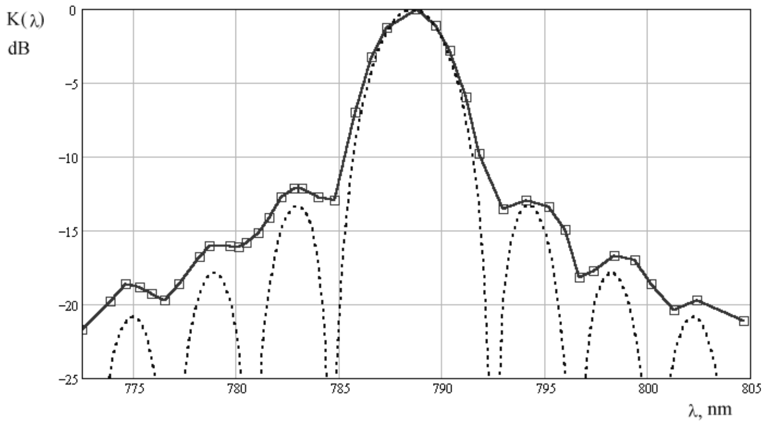

Fig. 6. Relative diffraction efficiency of uniform holographic grating in $LiNbO_3$ ((···) – theoretical curve, (—) – experimental data).

Table 2
Theoretical and experimental parameters for the filters with and without weighting

	Diffraction efficiency at maximum ($\lambda = 788.6$ nm) (%)	Sidelobe level (dB)		Spectral resolution (nm) (3 dB width)	
		Theory	Experiment	Theory	Experiment
Uniform grating	30	−13.3	−12	3.5	3.7
Weighted grating	15	−42	−20	5.2	6.6

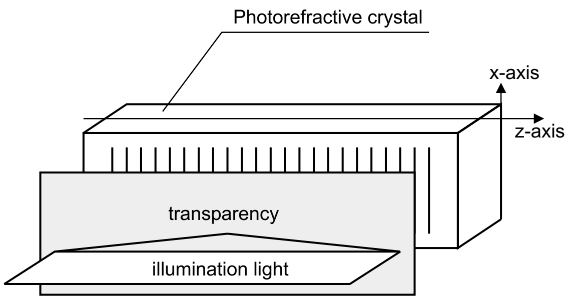

Fig. 7. Spatial selective decaying of hologram by light.

in relative log scale are shown in Fig. 8 (solid line). Theoretical curve by using formulas (2) and (5) is shown by dot line in the same figure.

The shape of characteristic has changed in good agreement with theoretic prediction. The difference between the expected prediction (−42 dB) and the experimental data (−20 dB) could be explained by the difference between the real intensity distribution of the grating and that of mathematical model shown in Fig. 1. Second important factor that limits our measurement was the background radiation. The parameters of filter with weighting are also summarized in Table 2.

4. Conclusion

Theoretical possibility of sidelobe suppression in spectral response of holographic filter by creation of nonuniform grating is proposed. It is based on the well known theory of weighting functions. Theoretical calculations show that it is possible to have −42 dB sidelobe level by using Hamming weighting function. Experimental setup based on spatial-selective decaying of hologram in photorefractive media by extra light illumination is offered also. Experimental results show that one can suppress sidelobes in 8 dB using the offered method. The main reason of difference between theoretical prediction (−42 dB) and experimental data (−20 dB) is a deviation in the real weighting distribution from the theoretical model (Fig. 1). But it should be noted that improvement in sidelobes is accompanied by expansion of main lobe

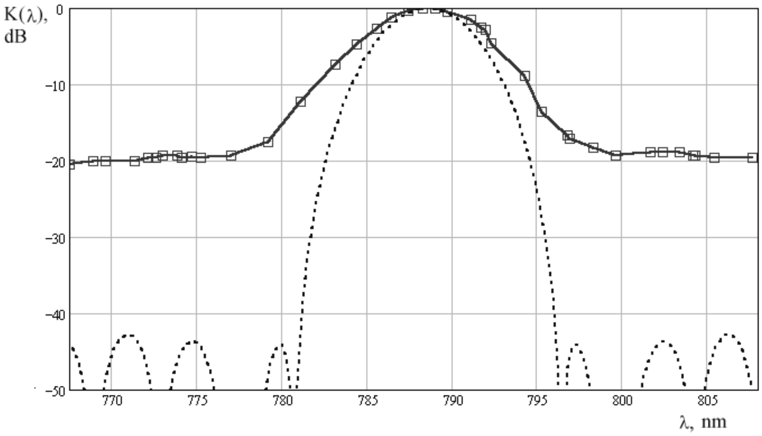

Fig. 8. Relative diffraction efficiency of weighted holographic grating ((· · ·) – theoretical curve, (—) – experiment data).

(in 1.7 times) and decreasing of diffraction efficiency (in two times).

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