Diffraction properties of volume holographic grating with multi-structures

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ABSTRACT
The diffraction characteristics of the volume holographic gratings made by multi-exposures with angular multiplexing during its construction is investigated. Because of the reflection by the interface between the emulsion and the substrate or the air there is an extra unslanted periodic structure inside a slanted grating, it will affect properties of the slanted volume holographic gratings. When the angle between the surface of the substrate and the grating plane of the slanted grating is less than a certain value, an extra peak accompanying the main peak will appear in the diffraction spectrum. But, when the angle is larger than the certain value, one designed and expected main peak will disappeared while the extra peak is kept and observed. This phenomenon limits the capacity of the volume hologram for the application in wavelength-division multiplexing (WDM).

1. Introduction
In recent years, a hot research topic in wavelength-division multiplexing (WDM) is to operate 16 or more channels per fiber. To reach the challenge, new optical components are necessary that are capable of multiplexing and demultiplexing ever-greater numbers of channels with very minimum loss, cross-talk, and high reliability [1]. Hologram has been shown to produce narrowband optical filter [2~5]. A volume holographic wavelength demultiplexer based on rotation multiplexing in the 90° geometry had been reported [6]. To achieve multi-channel WDM wavelength and/or angular multiplexing is necessary. Thus, cross-talk is an important factor that must be considered so that the WDM with good quality can be obtained.

The effect of cross-talk of angular multiplexed volume hologram on optical interconnects has been widely discussed [7~12]. This kind of cross-talk is undesirable because it limits the capacity of hologram. Recently, the authors of this paper discussed the characteristics of volume hologram with multi-period by means of the angular or the wavelength multiplexing in holographic photonic crystals [13]. However, in our studies, another factor which affects the
properties of the volume hologram gratings, which we called as self-talk, is found. It is caused by the interference of the reference beam itself during recording the angular multiplexing volume hologram, and it is different from the common “cross-talk”. Sometimes, this effect may be shown off by the appearance of another extra peak accompanying the expected main peak in diffraction spectrum. But, in some case, the expected main peak will disappear while the extra peak exists still. In this paper, this phenomena is investigated theoretically and experimentally in detail.

2. Physical and theoretical considerations

For simplicity, it is assumed that the recording medium and the hologram grating are put in the air. Generally, this is the genuine case. Fig.1 shows the typical Lippman set-up geometry for recording reflection hologram gratings. What the recorded grating is slanted or unslanted depends on the angle $\theta_1$ in Fig.1. The two cases are analyzed as follows.

1) For unslanted grating, $\theta_1 = 0$. During its recording, the laser beam which was taken as the reference beam is normally incident on the surface of the recording medium, the beam reflected by the mirror is as the object beam. The recording wavelength is $\lambda_0$.

Then, the spacing of the interference fringes caused by the two beams is

$$\Lambda_0 = \frac{\lambda_0}{2} \quad (1)$$

If the reconstruction beam is also normally incident on the recorded grating, the wavelength of the diffracted beam will be $\lambda_0 = 2\Lambda_0$.

2) For slanted grating, during its recording, the incident angle of the laser beam to the surface of the medium is $\theta_1$. The recording wavelength is $\lambda_0$. Then, according to Fig.1, the spacing of the interference fringes caused by the two beams is also

$$\Lambda_1 = \frac{\lambda_0}{2} \quad (2)$$

Fig.1 Set-up geometry for recording reflection hologram gratings. When $\theta_1 = 0$ unslanted grating is recorded. When $\theta_1 \neq 0$ slanted grating is recorded.

Fig.2 Geometric structure of reconstruction of the slanted grating.
The set-up geometry for reconstruction of the grating is illustrated schematically in Fig.2. If the reconstruction beam incidents normally on the surface of the medium (but not the plan of the reflection grating), because Bragg’s law must be satisfied, the wavelength of the diffracted beam should be \(2\lambda_1 \cos \theta_1' = \lambda_1\), where \(\theta_1'\) is the refractive angle determined by Snell’s law, and we have
\[
\lambda_1 = \frac{\lambda_0}{n} \sqrt{n^2 - \sin^2 \theta_1}
\]
where, \(n\) is the refractive index of the medium. This peak wavelength is expected for the recorded grating. From Fig.2, The angle between the diffracted beam and the surface of the medium is \(2\theta_1'\), and the diffracted beam of the grating emits in an angle \(\theta_2\) with respect to the surface of the medium. They satisfy the relation \(n \sin 2\theta_1' = \sin \theta_2\). The grating is generally placed in the air, then
\[
\sin \theta_2 = \frac{n \sin \theta_1'}{n} \sqrt{n^2 - \sin^2 \theta_1}
\]

Since the value of the refractive index of the medium is larger than that of the air, the total internal reflection may happen when the diffracted beam refracts our from the surface of the volume holographic gating. The critical condition of total internal reflection is determined by \(n \sin 2\theta_1' = 1\), by using \(\sin \theta_1 = n \sin \theta_1'\) and Eq.(3), we have
\[
4 \sin^4 \theta_1 - 4 \sin^2 \theta_1 + n^2 = 0.
\]
By solving the equation, the critical angle of total internal reflection in Fig.2 is
\[
\theta_{1c} = \sin^{-1}\left[\frac{n^2 \pm n\sqrt{n^2 - 1}}{2}\right]^{1/2}.
\]

3) During recording a slanted reflection holographic grating, another extra grating may be constructed, Fig.3 shows the case. The beam refracted by the front surface of the medium could be partially reflected by the rear interface of the recording medium and the substrate (or the air), and forms the beams \(1'', 2'', 3''\ldots\) and \(2', 3', 3'\ldots\). As the recording beam is a laser beam with long coherent length which is much larger than the thickness of the recording medium, inside the medium, there should be the
interference caused by beams 1' and 2'', 2' and 3'', and so on. It builds an extra unslanted grating. We call this kind of interference as “self-talk”. The fringe spacing of the extra grating is

\[ \Lambda' = \frac{\lambda_0}{2 \sin[(\pi - 2\theta_i)/2]} = \frac{\lambda_0}{2 \cos \theta_i} \]  

(7)

The Bragg’s law for the extra grating is \[ 2\Lambda' = \lambda_0' \], so, the wavelength of its diffracted beam is

\[ \lambda_0' = \frac{\lambda_0}{\cos \theta_i} = \frac{n\lambda_0}{\sqrt{n^2 - \sin^2 \theta_i}} \]  

(8)

According to the above analysis, the angular multiplexed reflection grating is practically more complicated. As an example, a double exposed grating is considered as follows, and it is assumed that the reference beam has the angle of 180° with respect to the object beam.

The first grating recorded by \( \theta_i = 0 \) is an unslanted, its Bragg’s law is expressed by Eq.(1), and the wavelength of the diffracted beam is \( \lambda_0 \). The second grating is recorded by \( \theta_i \neq 0 \). However, according to the above analysis in 2) and 3), we know that there still are two gratings in it. One recorded by \( \theta_i \neq 0 \) is a slanted, which is designed and expected, the other is an unslanted extra grating caused by ‘self-talk”. Their Bragg’s law are expressed by Eq.(2) and (7) respectively, and the wavelengths of the diffracted beams are determined by Eq.(3) and (8) respectively. Fig.4 shows the structure of the double exposed grating. When the angular multiplexed grating is illuminated by a collimated white light beam, three diffracted wavelengths will be observed. \( \lambda_0 \) and \( \lambda_i \) are expected, but \( \lambda_i' \) is unexpected. We can find that \( \lambda_1' > \lambda_0 \).

From Eq.(6), during the construction of the grating, if the angle \( \theta_i \) is equal to or larger than \( \theta_{ic} \), the diffracted beam by the slanted grating will have total internal reflection at the interface of the medium and the air, the beam can not emit from the hologram. Thus, in the diffraction spectrum of the grating, the corresponding peak with the wavelength \( \lambda_i \) will disappear, and only the peaks with the wavelengths \( \lambda_0 \) and \( \lambda_i' \) will be observed. It should be noted that the wavelength \( \lambda_i' \) is not designed and not expected. On the other hand, the diffraction efficiency of the extra unslanted grating is not high since the intensity of the reflected beams 1”, 2”, 3”… is

![Fig.4 Structure of the double exposed volume holographic grating. There are three sub-gratings inside the hologram. The solid line represents the two designed and expected gratings. The dashed line represents the extra grating caused by “self-talk”.

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pretty low. It makes the amplitude of the unexpected peak with the wavelength \( \lambda_i' \) is much smaller than the other two expected peaks in the diffraction spectrum.

3. Experimental observations

The recording layout of gratings was as same as that shown in Fig.1. The recording medium used was dichromated gelatin (DCG) with the thickness of \( 36 \mu m \) and the refractive index of 1.52. An argon ion laser (Spectra-Physics 2020) was employed. A spectrophotometer (Shimazu UV-365) was used to measure the transmission spectra of the gratings. The measured results were normalized automatically by the spectrophotometer.

Because DCG swells after processing, the grating constant will be larger than that before processing. The swelling factor was shown to be about 1.06 by lots of experiments. So, the calculated values of \( \lambda_0 \), \( \lambda_i \) and \( \lambda_i' \) should be multiplied by 1.06 to match the measured results for all verifications.

For DCG, the critical angle of the total internal reflection at the interface of the medium and the air expressed by Eq.(6) is \( \theta_{ic} = 32^\circ42' \). The following are the experimental results (\( \lambda_r \) is the recording wavelength).

1) Single exposed unslanted grating (\( \theta_i = 0 \), \( \lambda_r = 514 nm \))

The transmission spectrum is shown in Fig.5. There is only one peak in the spectrum which is positioned at 548.3nm.

2) Single exposed slanted grating (\( \theta_i = 30^\circ \), \( \lambda_r = 514 nm \))

The transmission spectrum is shown in Fig.6. Two peaks in the spectrum positioned at 489nm and 595nm respectively are observed. The calculated wavelengths are 514.8nm and 577.7nm respectively. The relative errors are 5.0% and 2.9% respectively.

3) Single exposed slanted grating (\( \theta_i = 35^\circ \), \( \lambda_r = 514 nm \))

The transmission spectrum is shown in Fig.7. It can be found that only one peak corresponding to Eq.(8) is observed as \( \theta_i \) is larger than \( \theta_{ic} = 32^\circ42' \), and the total internal reflection makes that the expected diffracted beam can not emit out from the surface of the hologram. The position of the unexpected peak is at 600nm, and the calculated value is 589.2nm, the relative error is 1.8%.

4) Double exposed grating (\( \theta_i = 0 \) and 30° respectively, \( \lambda_r = 488nm \))

The transmission spectrum is shown in Fig.8. Three peaks are observed in the spectrum. They are positioned at 512nm, 490nm and 563nm respectively. The calculated wavelengths of the three peaks are 517.3nm, 498.3nm and 548nm respectively. The relative errors are 1%, 0.1% and 2.7% respectively.
Double exposed grating ($\theta_1 = 0^\circ$ and $35^\circ$ respectively, $\lambda_R = 488nm$)

The transmission spectrum is shown in Fig.9. There are only two peaks in the spectrum. The peak with the wavelength corresponding to Eq.(3) cannot emit from the hologram because of the total internal reflection as $\theta_1$ is larger than $\theta_{ic} = 32^\circ 42'$. The two peaks are positioned at 525nm and 581nm respectively while the calculated values are 517.2nm and 572.4nm respectively. The relative errors are both 1.5%.
In all transmission spectra, the amplitudes of the unexpected peaks corresponding to Eq.(8) are much lower than expected peaks.

4. Conclusion

There is an extra unslanted grating in an slanted volume holographic grating, and a lower unexpected diffracted peak is always accompany the designed and expected peaks. Also, one designed and expected peak will disappear if incident angle during recording is larger than a critical value. It limits the channel capacity of the angular multiplexing volume hologram as being used for WDM and DWDM.

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References: