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Improving the spectral sharpness of an apodized fibre grating

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Abstract. We fabricate a steep skirt fibre Bragg grating (FBG) by employing an apodized phase mask. Gaussian UV beams with different FWHM are used on the mask to derive better spectral responses. The ratio of the FBG reflection bandwidth at −0.5 to −20 dB is improved from 0.35–0.55.

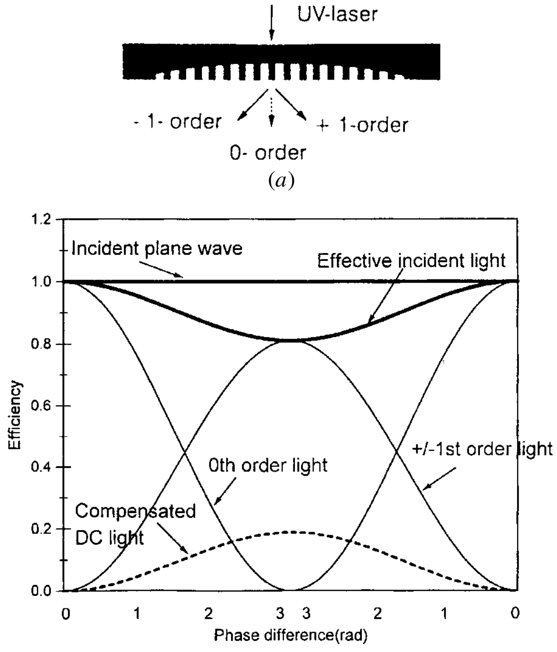
Keywords: Fibre Bragg grating, raised Gaussian apodization

1. Introduction

Dense wavelength division multiplexing (DWDM) communication systems require devices with high channel isolation. Fibre Bragg gratings (FBGs) are becoming strong candidates as wavelength-selective components due to their low insertion loss, low polarization-dependent loss (PDL), low polarization mode dispersion (PMD), and high wavelength selectivity. Sharp, well-defined filter amplitude responses are critical characteristics for passive devices in DWDM systems [1]. However, the limits on the bandwidth of the FBG are usually imposed by the side lobes of the spectral response [2]. A uniform FBG yields highly undesirable side lobes due to Fabry–Perot resonance at the sharp boundaries of the grating. A well-discussed method of reducing these side lobes is to apodize the coupling strength along the grating by gradually tapering the index modulation profile to zero at the two edges [3]. This helps to reduce the side lobes in the longer wavelength, but it still leads to resonance occurring in the shorter wavelength. Since the wavelength reflected at either end of the grating is smaller than that at the centre portion of the grating, this would induce bigger side lobes in the lower wavelength.

To further suppress these side lobes, it is necessary to keep the average refractive index constant along the grating. Various efforts have been reported in the literature [4–9]. Pan and Shi [4] used an apodized phase mask (APM) with variable diffraction efficiency to fabricate their steep skirt FBGs; Malo *et al* [5] demonstrated a double exposure method by using shadow masks to control the index variation along the grating; Singh and Zippin [6] fabricated an apodized fibre grating by use of a uniform phase mask and a single illumination process; while Cole *et al* [7] used a 'moving fibre/phase mask-scanning beam' technique for enhanced flexibility in producing fibre gratings.

In this paper, we photo-imprint the grating by use of an APM. However, the input Gaussian beam has been tailored to have a different FWHM when fabricating the FBG. A steep skirt spectral response has been obtained in order to meet the requirements of DWDM communication systems.



(*b*)

Figure 1. (*a*) Schematic diagram of an APM. (*b*) Diffraction efficiencies of an APM.

2. Principle

The APM has a constant duty cycle of 50%, the same as any uniform phase mask. However, it changes the phase difference from π in the middle to zero at the edges of the mask, as shown in figure 1(*a*). Since there are usually more

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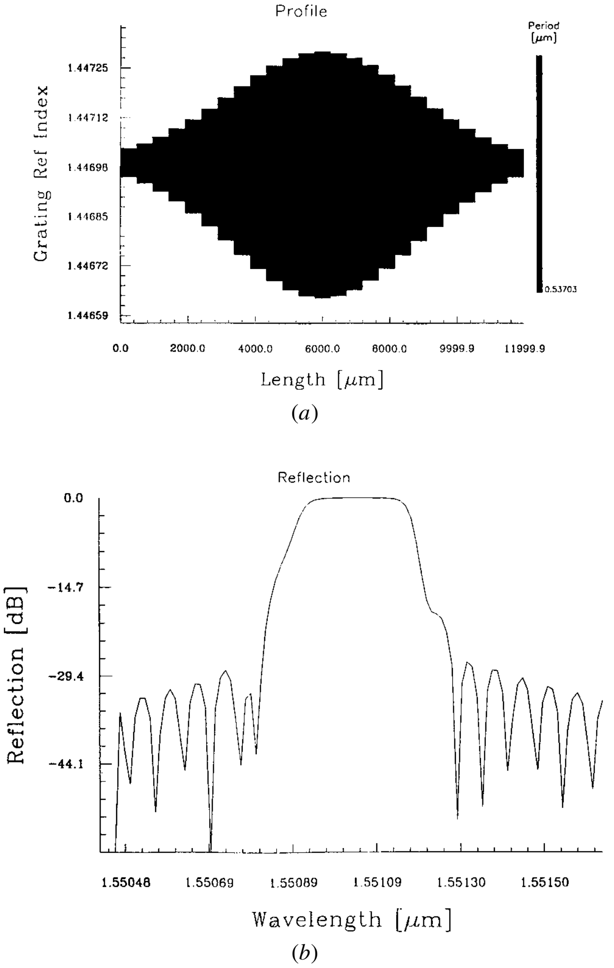


(*a*)

(*b*)

Figure 2. (*a*) An increased Gaussian apodization of index modulation at two wings of a fibre grating. (*b*) The calculated reflection spectrum of the grating.

than 10 000 periods in a phase mask, the phase variation is very small in these periods. We could express the intensity profile of the diffraction light in Fourier series as shown in the following:

$$E(x) = \sum_n a_n e^{j\frac{2n\pi}{L}x} \tag{1}$$

$$a_n = \frac{1}{L}\int_0^L e^{-j\frac{2n\pi}{L}x} E(x)\,dx \tag{2}$$

where

$$E(x) = \begin{cases} 1 \rightarrow 0 < x < \dfrac{L}{2} \\ e^{j\theta} \rightarrow \dfrac{L}{2} < x < L \end{cases}$$

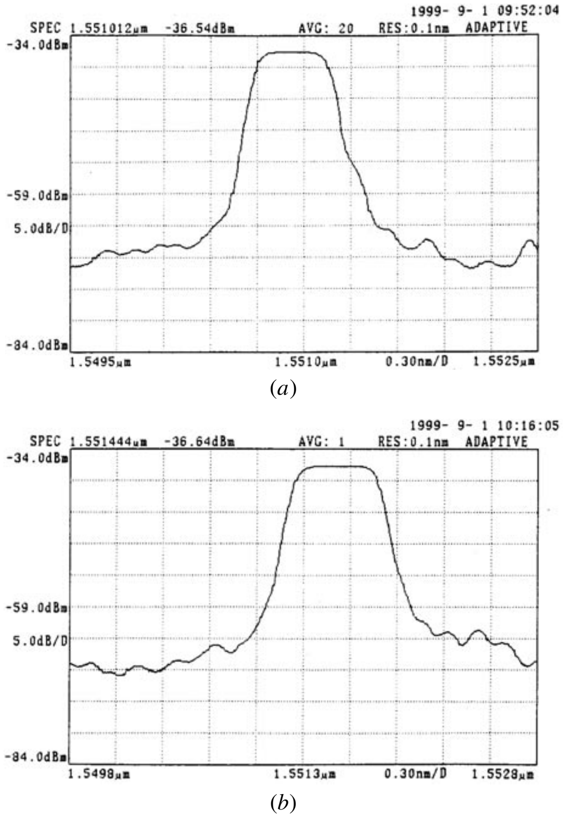
$$a_0 = \frac{1}{L}\left(\int_0^{\frac{L}{2}} 1\,dx + \int_{\frac{L}{2}}^{L} e^{j\theta}\,dx\right) = \frac{1}{2}(1 + e^{j\theta}) \tag{3}$$

$$\begin{aligned} a_{\pm1} &= \frac{1}{L}\left(\int_0^{\frac{L}{2}} e^{\mp j\frac{2\pi}{L}x}\,dx + \int_{\frac{L}{2}}^{L} e^{j\theta}e^{\mp j\frac{2\pi}{L}x}\,dx\right) \\ &= \pm\frac{1}{\pi}(-1 + e^{j\theta}) \end{aligned} \tag{4}$$

where $E(x)$ is the summation of the total diffraction light, a_0 and $a_{\pm1}$ are the amplitudes of the 0th and ±1st order light, θ is the phase difference on the phase mask, and L is the mask period. Since the incident light is split to orders of diffraction light when passing through the APM, the 0th order light would introduce a dc index change with a nearly inverse Gaussian profile along the grating, due to the phase change on the APM as calculated in equation (3). By calculating equation (4), we also know that the power of the ±1st order light is only about 81% that of the total diffraction light at the mask centre. Since the fringes of the grating are formed by the interference of the ±1st order light, the ac index modulation would be less than that required to achieve a constant average index at the grating centre. The 0th order light would raise the index above the average at two wings of the FBG when exposing a plane wave on the APM, as shown in figure 1(*b*). In this case, the wavelength reflected at either end of the grating is longer than that at the centre, which would lead to some side lobes in the longer wavelength. We use an IFO grating simulation tool to calculate the corresponding reflection spectrum and find a small kink at the longer wavelength in the case when the grating reflectivity increases to 99%: this is shown in figure 2. In order to acquire a constant average index along the grating, it is necessary to change either the background light or the ±1st order diffraction light in magnitude. In the following, we demonstrate the methods used to accomplish the desired index modulation by using an appropriate Gaussian beam on the APM to write the apodized fibre grating.

3. Experiment and discussion

We fabricate the FBG by using an APM in this experiment. The mask has a FWHM of 5.3 mm and the total grating length is about 12 mm. The pulsed UV light coming from an excimer laser of Lamda Physik compex 205 has a wavelength of 248 nm. The beam profile of the laser in the vertical direction can be characterized as a top hat distribution, which is nearly a plane wave within a 15 mm region of the beam centre, while in the horizontal direction, the distribution is nearly Gaussian. The output spot size is 12×24 mm^2, and could be tailored by a pair of cylindrical lenses. We use Fibrecore photosensitive fibres in this experiment; the fibres have a numerical aperture of 0.12. At first, the fibre in contact with the mask is exposed by the plane wave for 1500 shots and the reflectivity of the grating formed increases to 99%. The reflection spectrum of the fabricated grating is shown in figure 3(*a*). There appear to be some side lobes in the longer wavelength, as we predicted. The skirt steepness, which is the ratio of the reflection bandwidth at −0.5 to −20 dB, is 0.35. After the first exposure, we remove the mask and expose a Gaussian beam with a 30 mm FWHM directly onto the fabricated grating to change the dc index along the grating. This would compensate the average refractive index at the centre of the grating as shown in figure 1(*b*). We post-UV trimmed the grating by 100 shots. The kink in the longer wavelength has disappeared, and the skirt steepness increases to 0.4 as shown in figure 3(*b*). We could see that the total linewidth at both −0.5 and −20 dB also increases. This might be because the post-UV trimming does not completely compensate the average index to be constant along the grating. Since the post-UV trimming would raise the average index, the reflection spectrum also moves toward the longer wavelength.



(*a*)

(*b*)

Figure 3. (*a*) Reflection spectrum of a FBG fabricated by exposing a plane wave on an APM. (*b*) Reflection spectrum of the same FBG but which has been post-UV trimmed by a Gaussian beam.

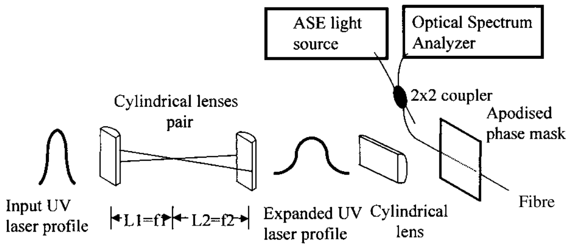


Figure 4. Experimental setup for fabricating the apodized FBG by using a beam expanding apparatus.

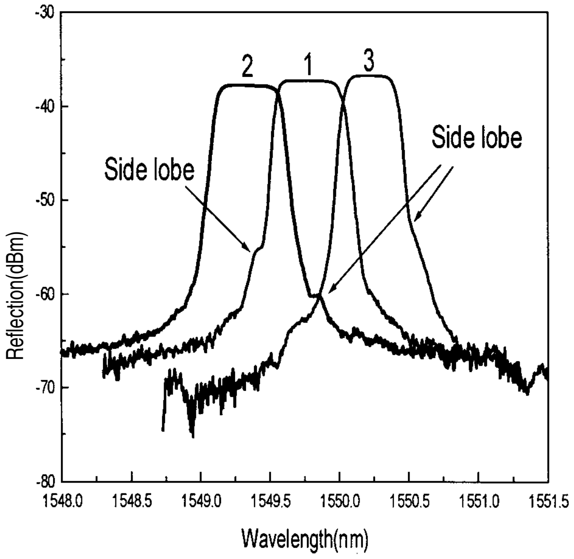


Figure 5. Reflection spectra of three FBGs fabricated by different laser beams. The numbers on the spectra are expressed below: (1) by a laser beam of 6 mm FWHM, (2) by a laser beam of 20 mm FWHM and (3) by a laser beam of 30 mm FWHM.

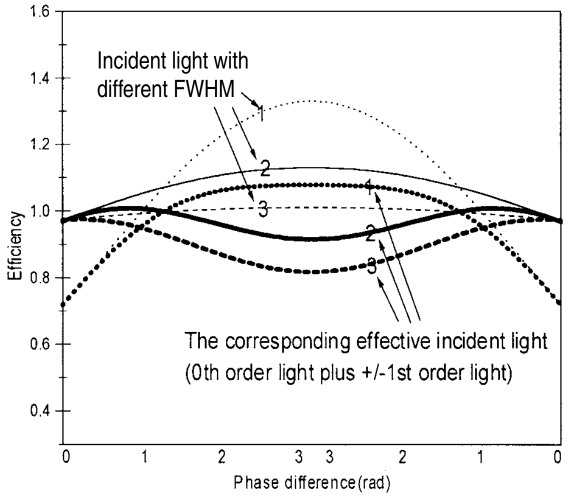


Figure 6. Corresponding effective incident light of three different input laser beams. The numbers in the figure are also in accordance with those in figure 5.

If the APM is illuminated by a Gaussian beam instead of a plane wave, the ±1st order diffraction light and the 0th order transmission light would change their efficiencies simultaneously. By choosing a Gaussian beam with an appropriate FWHM, the drawback of fabricating an apodized FBG by using a plane wave could be reduced. We expand the input Gaussian beam by a pair of cylindrical lenses as shown in figure 4. Since the two cylindrical lenses are confocal, the beam width will be enlarged by a factor of $f2/f1$, where $f2$ and $f1$ are the focal lengths of the first and second cylindrical lens, respectively. In this paper, the input laser beam initially has a FWHM of about 6 mm. We expand the laser beam to 20 and 30 mm, and then use these three beams to fabricate the FBGs. Reflection spectra of these gratings are compared in figure 5. Some side lobes appear in the shorter wavelength when exposed to the 6 mm wide beam, and side lobes in the longer wavelength when exposed to the 30 mm wide beam. However, the skirt steepness of the FBG has been improved to 0.55 when exposed to the 20 mm wide beam. Since the Gaussian beam has higher intensity at the centre, the situation of raising the index above the average at two ends when exposing a plane wave could be reduced. In figure 6, we demonstrate the corresponding effective incident light when exposing Gaussian beams with different FWHM on the APM. The average index of the FBG is raised at two edges when exposing beam 3 with a larger beam width, and is lowered at two edges when exposing beam 1 with a smaller beam width, while the average index of the FBG exposed to beam 2 with a medium beam width acquires better uniformity, and therefore a better spectral response.

4. Conclusion

Although an APM could fabricate a steep skirt FGB, a tailored input laser beam would further enhance the apodization. In this paper, we demonstrate the drawback when fabricating the FBG by launching a plane wave on an APM. Then we illustrate that the skirt steepness could be improved from 0.35–0.55 by employing a Gaussian beam with an appropriate FWHM. This method provides the flexibility to manufacture gratings as critical wavelength-selective devices for optical communications.

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