Apodisation of photo-induced waveguide gratings using double-exposure with complementary duty cycles

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Abstract: We present a novel apodisation scheme for photo-induced waveguide gratings. The apodisation is implemented with double exposures that have reversely varying duty cycles. We have successfully applied the proposed scheme to remove the sidelobes of long period gratings (LPGs). We also observed for the first time super strong sidelobes in LPGs when creating them with only a single varying-duty-cycle exposure. The strong sidelobes can be well explained with a Mach-Zehnder interference model.

OCIS codes: (060.2340) Fiber optics components; (060.3735) Fiber Bragg gratings

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1. Introduction

Since the first discovery of photosensitivity of optical fiber, photo-induced grating devices have found extensive applications in optical communications and sensing [1]. Photo-induced gratings can be created in different forms, for example, in different waveguides such as planar waveguides and optical fiber, also in different period scale ranges such as short period (Bragg gratings) and long period (long period gratings). Both short period gratings and long period gratings (LPG) with normal uniform coupling profile have strong sidelobes near the main reflection/transmission band, which are not desirable for most applications, such as add/drop filtering in wavelength-division multiplexing systems andoptical amplifier gain equalizing with cascaded gratings [2]. There have been several apodisation schemes reported to remove the undesirable sidelobes, such as using variable-diffraction-efficiency phase mask [3,4], the fiber/phase mask dithering method [5], the pre-exposure compensation method [6], the symmetric stretching method [7] and the phase mask method with polarization control [8,9]. In this paper, we report a novel apodisation technique based on double exposure of two reversely tailored profiles in the pitch duty cycle. In principle, the technique can be implemented in both Bragg grating and long period grating fabrication. We demonstrated here that it is particular suitable for fabricating apodised long period gratings.

2. Principle

The principle of apodisation by tailoring duty cycles has been used in surface-corrugated grating fabrication [10]. However, the variations of the duty cycles can cause resonance wavelength changes due to the corresponding variations of the effective refractive index averaged over each grating period. Wiesmann *et al.* addressed this problem by adjusting the grating period accordingly [10]. Although a similar method may be applied, in principle, to photo-induced grating fabrication, the compensation scheme is complex and difficult since the required grating-period variation profile depends on the photo-induced index change amplitude. For example, gratings with the same apodisation profiles but different strengths will require quite different grating-period profiles, and this problem is further complicated when one considers the decay of the photo-induced index change and gratings with chirp. The new scheme that we propose below is much simpler and can readily be implemented in the photo-induced grating fabrication process.

The principle of the proposed method is schematically shown in Fig.1. The apodisation process is performed using double exposure. In the first exposure, the duty cycle of each period along the grating length varies between 0 and 0.5 with a bell-shaped profile, which results in correspondingly bell-shaped profiles for both the coupling strength (k_1) and the averaged effective refractive index ($\overline{\Delta n_1}$). In the second exposure, the duty cycle is varied between 1 and 0.5 with an inverted bell-shaped profile, which results in reversal of the bell-shaped profile for the averaged effective refractive index ($\overline{\Delta n_2}$), but retains the same (non-

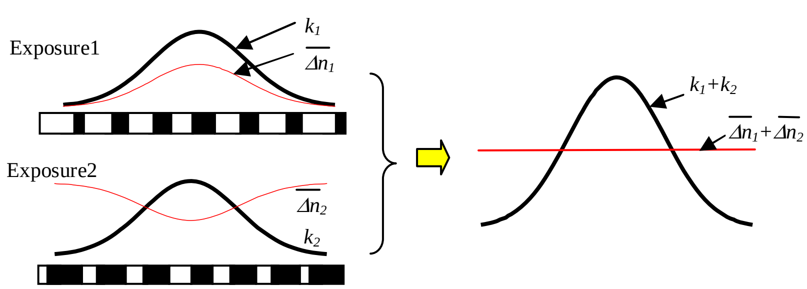

Fig.1. Schematic of the proposed apodisation method with double exposure and varying duty cycle.

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inverted) bell-shaped profile for the coupling strength (k_2). With the second exposure, the variation of the effective index due to the first exposure is compensated while the coupling strength is simultaneously enhanced.

We assume the duty cycle in first exposure varies with the bell-shape function $\delta(x)$, here $\delta(x)$ varying between 0 and 0.5. Then the coupling strength and averaged effective refractive index can be described as [11]

$$k_1 = k_0 \sin[\pi \times \delta(x)] \tag{1}$$

$$\overline{\Delta n_1} = \overline{\Delta n_0} \delta(x) \tag{2}$$

Where k_0 and $\overline{\Delta n_0}$ are the amplitudes of the coupling strength and the refractive index change at the grating centre, respectively. In the second exposure, the duty cycle varies with the reversed bell-shape function, i.e. 1-$\delta(x)$, we have

$$k_2 = k_0 \sin[\pi \times (1 - \delta(x))] \tag{3}$$

$$\overline{\Delta n_1} = \overline{\Delta n_0} (1 - \delta(x)) \tag{4}$$

The combined coupling strength and effective index for the two exposures is thus

$$k_1 + k_2 = 2k_0 \sin[\pi \times \delta(x)] \tag{5}$$

$$\overline{\Delta n_1} + \overline{\Delta n_2} = \overline{\Delta n_0} \tag{6}$$

It is clear seen from eqn.(5) and (6) that the combined coupling strength is effectively apodised while the combined effective averaged refractive index is constant.

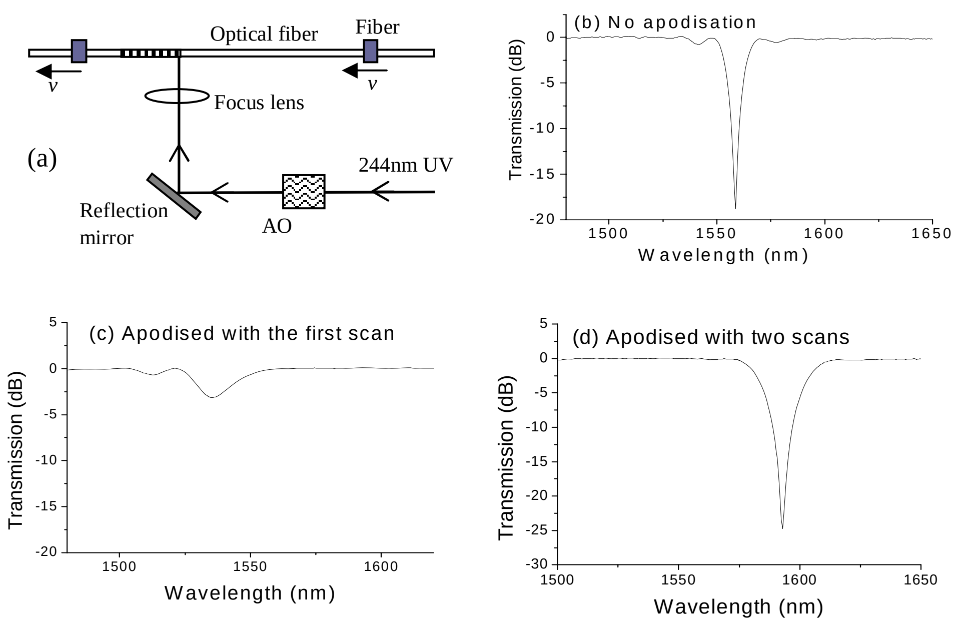

Fig. 2. (a) Schematic of the set up for LPG fabrication. (b)Transmission spectrum of a LPG without apodisation. (c) Transmission spectrum of an apodised LPG after the first exposure. (c) Transmission spectrum of the apodised LPG after two exposures.

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3. Experiment and discussion

The fabrication setup is schematically shown in Fig.2a, in which the UV writing beam (λ=244nm) was output from a frequency doubled argon ion laser and its beam size was reduced by a cylindrical focus lens before radiating to an optical fiber. The fiber was mounted on an air-bearing translation stage moving at constant speed with good stability and accuracy, which allow the grating to be created pitch-by-pitch. The periodic exposure and the varying duty cycle were realized by switching on/off an acousto-optic (AO) modulator, which was automatically controlled by a computer. The gratings were fabricated on hydrogen-loaded standard single mode fiber. For comparison, we first fabricated a long period grating without apodisation. It had a constant duty cycle of 0.5, a period of 400μm and a length of 50mm. Its transmission spectrum is shown in Fig.2b. It is seen that the unapodised LPG had sidelobes that result in an out of band loss of about 0.8dB. Then we fabricated an apodised long period grating with the proposed apodisation method. The apodised grating has a period of 395μm and a length of ~50mm. In the first exposure, the duty cycle varied with the function $\delta(x)=0.5cos[\pi(0.5\text{-}z/Lg)]$. The transmission spectrum after the first exposure is shown in Fig.2c, in which one note that the grating just has sidelobes on the short wavelength side. It should be pointed out that we have to make the grating relatively weak with the first exposure, otherwise the final grating will be too strong (over coupling) after the second exposure. Then we make the second exposure with its reversed duty cycle function $\delta(x)=1\text{-}0.5cos[\pi(0.5\text{-}z/Lg)]$. The transmission spectrum of the final grating after two exposures is shown in Fig.2d. It is clearly seen in Fig.2d that the sidelobes of the final grating is almost completely removed (<0.1dB). The experimental results prove the effectiveness of the proposed apodisation technique.

It should pointed out here that it is also possible to use the computer controlled AO modulator to directly write optimized index profiles to suppress sidelobes, which has been demonstrated by Grubsky et al. [12]. In their scheme, the nonlinear photosensitivity of the glass was measured first and then was implemented to keep the average index of the refraction constant during the fabrication.

In Fig.2b, we have noted that the sidelobes for the varying-duty-cycle LPG with only a single exposure are located on the short wavelength side of the main peak. We found that such sidelobes can be much stronger than those of a normal LPG. Fig.3a and 3b show two such examples, in which the sidelobe peaks are about 9.5dB and 15.2dB, respectively. It is also interesting to note in Fig.3b that, for a strong enough grating, the sidelobe magnitude can even exceed that of the main resonant peak. We would point out that the multiple resonant peaks in Fig.3a and 3b derive from the coupling of the core mode to the same cladding mode, which is different from the typical separated peaks due to the coupling of the core mode to the different cladding modes in a normal LPG [2]. The origin of the sidelobe is due to the variation of the effective refractive index. Similar sidelobes have also been observed in Bragg gratings and have been explained as a Fabry-Perot resonance effect [13]. For the LPG, however, the interpretation of the sidelobes is different. As shown in Fig.3c, the low-duty-cycle pitches at the input end can couple light to a certain cladding mode at a much lower wavelength than that due to the central pitches, and such light can only be coupled back to the fiber core towards the output end where similarly low-duty-cycle pitches exist. When the light is coupled back to the core, it can then interfere with the light propagating within the core. So, such an LPG forms a Mach-Zehnder interferometer [14] and results in oscillations on the short wavelength side. Since the path difference depends on the distance away from the center, the shorter wavelength resonance has a small free spectral range (FSR), which can be clearly seen in Fig.3a and 3b. It should be pointed out that if one makes an LPG with a reversed duty cycle (*ie*, just the second exposure), the oscillations will take place on long wavelength side, which can also be explained similarly.

It is also worth noting that the strong side peaks may be used to measure some physical parameters [15], which might also be combined with the main peak to realize simultaneous

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multiple-parameter measurement [16]. Although we have just demonstrated a simple apodisation profile, the technique is widely and readily applicable to any complex apodisation profile.

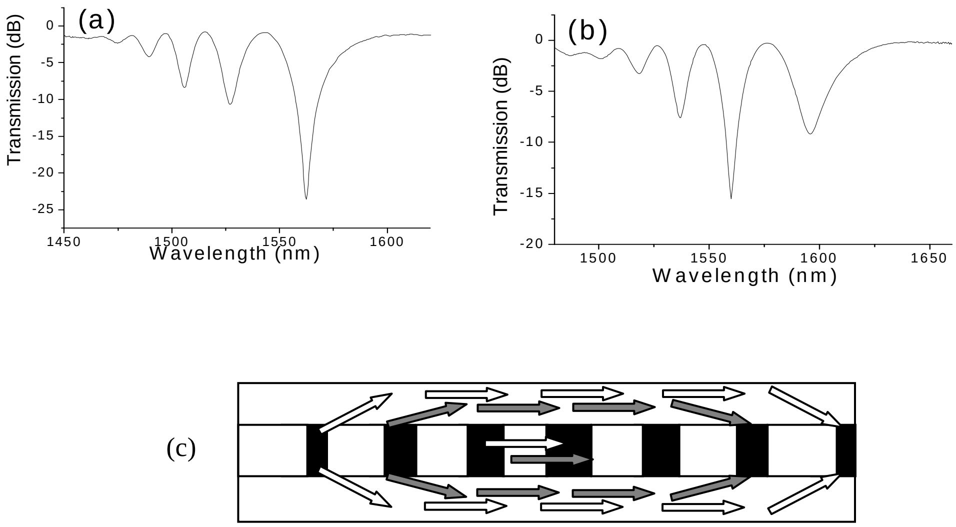

Fig. 3. (a) and (b) Two examples of the varying-duty-cycle LPG with only a single exposure. (c) Schematic of Mach-Zehnder interference formed in such a LPG.

4. Conclusions

We have proposed a novel apodisation scheme for photo-induced waveguide gratings. The apodisation is realized by two exposures with complementary duty cycles. The proposed method has been successfully applied to fabricate apodised long period gratings with significantly improved out-of-band performance. We also observed strong oscillations on the short wavelength side of those varied-duty-cycle- LPGs fabricated with only single exposure. We found that such oscillations can be well explained by Mach-Zehnder interference formed by the grating itself.

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