# Fabrication of a $\pi$-phase-shifted fiber Bragg grating at twice the Bragg wavelength with the standard phase mask technique

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Received March 5, 2009; revised May 6, 2009; accepted May 13, 2009; posted June 2, 2009 (Doc. ID 108389); published June 26, 2009

A pair of reflection peaks/transmission dips, at twice the Bragg wavelength, were observed in spectra of a Type I fiber Bragg grating written with the standard phase mask technique. The occurrence of two peaks/dips, rather than one, is attributed to the interleaved refractive index modulations along the fiber core, with the periodicity of the phase mask that has been observed previously in images of gratings that cause destructive interference in a reflected wave at the Bragg condition owing to the $\pi$ phase difference between the grating phases. Thus the standard phase mask technique produced an alternative type of $\pi$-phase-shifted grating at twice the design Bragg wavelength. © 2009 Optical Society of America

*OCIS codes:* 060.3735, 050.2770, 230.1480.

The reflective and the transmissive properties of fiber Bragg gratings (FBGs) have been well studied and used in many applications [1]. The usual fabrication method is to direct a UV laser beam through a phase mask, of period $\Lambda_{pm}$, to generate an interference pattern that results in a refractive index variation along the fiber core [2,3]. The resultant Bragg wavelength, $\lambda_B$, is the first harmonic resonance (i.e., $m=1$) given by [1]

$$\lambda_B(m) = \frac{2}{m} n_{eff} \Lambda, \tag{1}$$

where $\lambda_B(m)$ is the reflected wavelength at the harmonics $m=1,2,3,\ldots$ and $\Lambda$ is the grating period along the fiber core. The effective index of the fundamental fiber mode, $n_{eff}$, can be approximated as the refractive index of the fiber core at $\lambda_B(m)$. Phase masks are designed to provide maximum contrast for the interference of the $\pm 1$ diffraction orders, through elimination of the zero and the higher orders. However, these undesired orders are not totally suppressed in a real phase mask, and simulations and experiments show that coexisting FBG periods of $\Lambda = \Lambda_{pm}/2$ and $\Lambda_{pm}$ are due to their presence in the interference field [4–7]. Indeed, a zeroth diffraction order of just 1% of the total power affected dramatically the interference pattern and the corresponding refractive index variations written into polymers [8]. Furthermore, the same coexisting FBG periodicities ($\Lambda_{pm}/2$ and $\Lambda_{pm}$) in a phase-mask-written FBG have been imaged using differential interference contrast (DIC) microscopy [9] and other techniques [10]. The formation of the complex refractive index structure observed in these DIC images has been verified by modeling based on the strengths of the phase mask's diffraction orders [11].

FBGs exhibit spectral features at shorter wavelengths, corresponding to higher (i.e., $m>1$) harmonic reflections in Eq. (1) [3,12–15]. For example, a 1060 nm pitch phase mask that had a Bragg wavelength at 1535 nm had a transmission dip at 770 nm [3], which is the $m=2$ order of a grating having a periodicity of half of that of the phase mask (i.e., $\Lambda = \Lambda_{pm}/2$), as expected. However, features [3] at 620 and 1030 nm can be explained only by the existence of a grating with the phase mask period (i.e., $\Lambda = \Lambda_{pm}$), in which these are the $m=5$ and 3 orders, respectively [12]. Clearly, from Eq. (1), the first-order spectral features of such a grating lie at twice the Bragg wavelength (denoted as $\lambda_{2B}$), i.e., near 3 $\mu$m. Such wavelengths are inaccessible with conventional optical fiber technology; the observation of features associated with $\lambda_{2B}$ requires a phase mask of much smaller pitch. Thus, in this Letter, a standard phase mask with a design wavelength of $\lambda_B = 785$ nm was used to investigate the spectral features at twice the Bragg wavelength.

FBGs were fabricated in Corning 1060 nm fiber (NA of 0.14, cutoff wavelength of 920 nm) so that features at $\lambda_{2B}$ could be studied under single mode propagation. The fiber was exposed to 92 atm of hydrogen at 65°C for 3 days to increase photosensitivity and placed within tens of micrometers from the phase mask to ensure exposure to the interference pattern generated by all diffraction orders [10]. A collimated 130 mW laser beam (244 nm wavelength), confined within a 5 mm diameter circular aperture, was focused via a cylindrical lens onto the phase mask (manufactured by Ibsen) having a pitch of $\Lambda_{pm} = 536$ nm, resulting in a FBG length of 5 mm. The average relative measured strengths of the 0th, the ±1st, and the ±2nd diffraction orders were 9.8%, 34.6%, and 7.2%, respectively. An optical spectrum analyzer (OSA) monitored transmission and reflectance spectra. Illumination near 1550 nm (i.e., $\lambda_{2B}$) was provided by an $Er^{3+}$ broadband source and the OSA resolution was 0.1 nm, while a 780 nm center wavelength superluminescent diode of FWHM 45 nm was used in the region of $\lambda_B$, with an OSA resolution of 0.05 nm.

The transmission and the reflection spectra measured near 785 nm are shown in Fig. 1 and show a clear single transmission dip at 784.9 nm and a single peak reflectance of greater than 75%. The FWHM is 0.36 nm. The slight energy loss in the transmission spectrum is due to scattering into cladding modes by the FBG. This dominant reflection/transmission corresponds to the design Bragg wavelength of the phase mask and arises from the $m=1$ and 2 harmonics in Eq. (1) of grating periods $\Lambda = \Lambda_{pm}/2$ and $\Lambda_{pm}$, respectively.

The time evolution of FBG transmission features near 1550 nm, i.e., at $\lambda_{2B}$, is shown in Fig. 2. There are two transmission dips, even though the fiber is single moded at this wavelength; a similar effect was observed at 2/3 of the Bragg wavelength [15]. These grow at the same rate; both shifted by 0.15 nm to longer wavelengths as expected for Type I FBGs, owing to the refractive index increasing by $\sim 1.4 \times 10^{-4}$ according to coupled mode theory [16]. This growth is similar to that observed for the design Bragg wavelength of 785 nm. The transmission and the reflection spectra in Fig. 3 that were recorded after 7 min of UV exposure have two FBG features at 1552.2 and 1552.5 nm. The reflectances of the two peaks of 0.22 are equal to within 6% and their separation is $\sim$3 nm. Both peaks are very narrow, each having a FWHM of $\sim$0.13 nm, while the combined width is $\sim$0.41 nm. These spectral features are attributed to the interference of all diffraction orders of the phase mask, which possesses interleaving planes with a period equal to that of the phase mask ($\Lambda_{pm}$). Indeed, when this phase mask was used in an arrangement in which only the $\pm 1$ diffraction orders were present, grating features near 1550 nm could not be obtained via UV exposure [17]. It is noted that as the strain and the temperature variation of spectral features near 1550 nm of a FBG fabricated with the same phase mask [18] are consistent with those for standard gratings having $\lambda_B$ near 1550 nm, the observed spectral features are indeed owing to the existence of a grating (with $\Lambda = \Lambda_{pm}$).

If the features near 1550 nm were due to a simple grating structure, a single peak/dip possessing a similar or larger width compared with features at 785 nm would be expected, depending on the grating strength [16]. The fact that these dual reflection peak/transmission dips near 1550 nm are narrow with a combined width that is not much greater than the width of the 785 nm peak suggests that the complex grating structure is the cause. DIC images of FBGs with $\lambda_B$ near 1550 nm [9,11] reveal, along the fiber core, two different phases of grating planes at the phase mask periodicity that is perfectly interleaved. In this Letter, involving $\lambda_B$ near 785 nm, the distance over which the interference pattern from the phase mask repeats itself, known as the Talbot

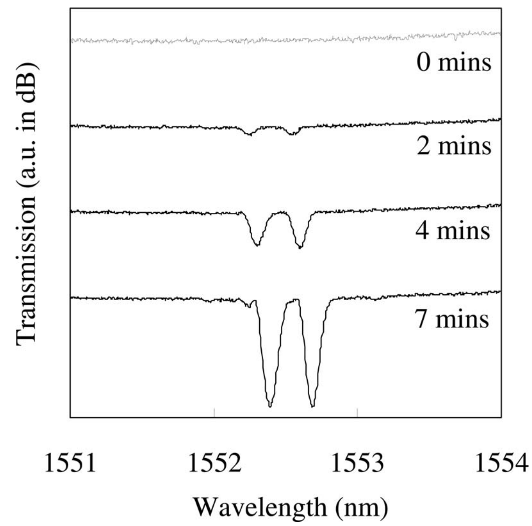


Fig. 2. Spectra near 1550 nm, showing the growth of a FBG in a 7 min exposure to 130 mW of CW UV laser light through a phase mask of periodicity 536 nm.

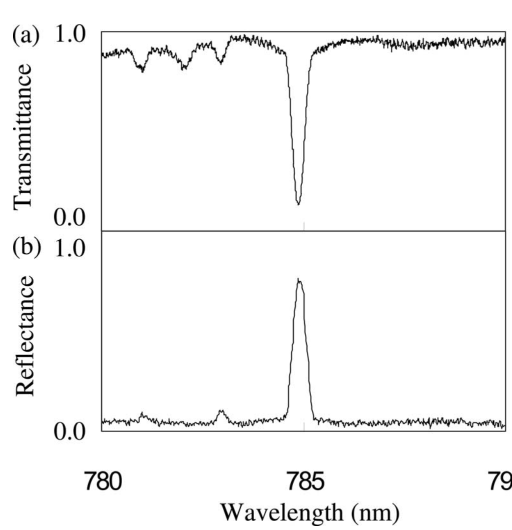


Fig. 1. Measured FBG (a) transmission and (b) corresponding reflection spectra at 785 nm.

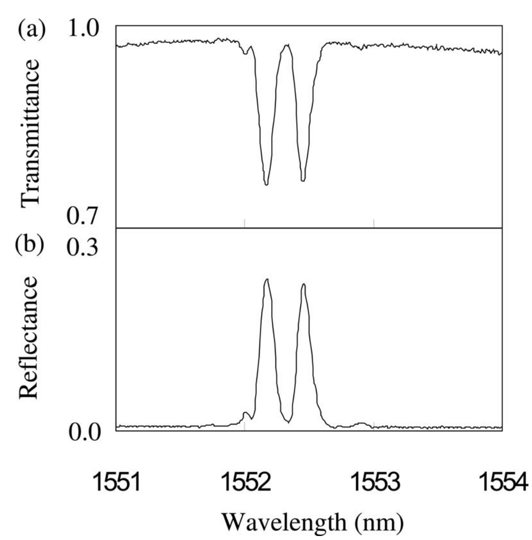


Fig. 3. Measured FBG (a) transmission and (b) corresponding reflection spectra at 1550 nm.

length [7], was ~3.5 $\mu$m (for the combination of 0 and $\pm$1 orders) and, as this is smaller than the ~4 $\mu$m core diameter, both grating phases will be present in the fiber core. For light propagating at the Bragg condition near 1550 nm in the fiber core, containing this complex structure, the two backward propagating modes reflected from each of the two gratings phases will be out of phase by $\pi$, leading to destructive interference. Such behavior occurs in $\pi$-phase-shifted gratings; those reported contain two grating sections along the fiber core that are shifted in phase with respect to each other [19–21]. Spectra of $\pi$-phase-shifted FBGs exhibit a notch in the middle of the transmission dip, the width of which depends on the grating index variation [19]. In particular, there is a close resemblance between a spectrum modeled for a 4 mm FBG (i.e., similar length) having a grating index modulation of $10^{-4}$ consisting of two narrow peaks [19] and that shown in Fig. 3 for which the grating index modulation was determined [16] to be $1.3\times10^{-4}$. Furthermore, such phase differences will exist for the odd harmonic reflections from $\Lambda_{pm}$, but not for the even harmonics, which is why there is a single peak at 785 nm (i.e., $m=2$) but two peaks occurred in single-mode fiber at 1040 nm for $\Lambda_{pm}=1060$ nm (i.e., $m=3$) [15]. Although phase-shifted gratings have found application in distributed feedback lasers [20] and wavelength division multiplexing [21], their fabrication involves an elaborate setup [19].

The expected existence of FBG reflection and transmission features at twice the Bragg wavelength, in a FBG fabricated with the standard phase mask technique, has been studied. Importantly, the resultant FBG has the properties of a $\pi$-phase-shifted grating at twice the Bragg wavelength and was created without the need for any modifications of the standard phase mask arrangement. Unlike $\pi$-phase-shifted FBGs reported previously, DIC images indicate that this FBG has the two grating phases arranged in parallel within the one section of the fiber core. Experimental and theoretical works are in progress to understand how the properties of these $\pi$-phase-shifted FBGs depend on writing conditions and thereby could be tailored for specific applications.

The authors acknowledge the financial support of the Australian Research Council. S. P. Yam, B. P. Kouskousis, and C. M. Rollinson acknowledge Victoria University for postgraduate scholarships.

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