A π-phase-shifted Fiber Bragg Grating Fabricated using a Single Phase Mask

S. P. Yam[1], Z. Brodzeli[1], B. P. Kouskousis[1], C. M. Rollinson[1], S. A. Wade[2], G. W. Baxter[1] and S. F. Collins[1]

[1]Optical Technology Research Laboratory, Centre for Telecommunications and Microelectronics, Victoria University,
PO Box 14428, Melbourne, VIC 8001, Australia
Phone: +(613)99194283, Fax: +(613)99194698, Email: stephen.collins@vu.edu.au
([2]Department of Mechanical and Aerospace Engineering, Monash University, Clayton, VIC 3800, Australia)

Abstract

A fiber Bragg grating at twice the Bragg wavelength was fabricated by a standard phase mask technique and its two peaks/dips are attributed to the interleaved refractive index modulations along the fiber core that produced a π-phase-shifted grating.

Introduction

Phase shifted gratings have found application in distributed feedback lasers [1] and wavelength division multiplexing [2]. Several methods for the fabrication of π-phase-shifted gratings have been reported [3], each requiring an elaborate set-up, and in which the resultant fiber Bragg grating (FBG) has two grating sections along the fiber core which are phase shifted with respect to each other. This paper reports a simple and effective method for creating π-phase-shifted gratings without modification of the standard phase mask technique.

The usual method for the fabrication of FBGs is to direct a CW or pulsed UV laser beam through a phase mask, of period Λ_{pm}, to generate an interference pattern so that the required refractive index variation may be induced along the fiber core [4,5]. The resultant Bragg wavelength, λ_B, is the first harmonic resonance (i.e. m = 1) given by the well-known Bragg formula

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

where $\lambda_B(m)$ is the reflected wavelength at the harmonics m = 1, 2, 3, ···, and Λ 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 $\lambda_B(m)$. Simulations and experiments with phase mask properties show that co-existing periods of $\Lambda = \Lambda_{pm}/2$ and Λ_{pm} in a FBG are due to the interference of the non-suppressed zeroth and higher diffraction orders of the phase mask [6-9]. The same co-existing FBG periodicities ($\Lambda_{pm}/2$ and Λ_{pm}) in a phase-mask-written FBG have been reported [10-12] and imaged using differential interference contrast (DIC) microscopy [13] and other techniques [14]. The formation of the complex refractive index structure observed in these DIC images was verified by modeling based on the known strengths of the diffraction orders of the phase mask used [15].

Clearly, from Eq. (1), the first order (m = 1) spectral features of a grating having Λ_{pm} would lie at twice the Bragg wavelength (denoted as λ_{2B}), i.e. near 3 µm. As such wavelengths are inaccessible with conventional optical fiber technology, observation of features associated with λ_{2B} requires a phase mask of much smaller pitch. Thus, in this work, a standard phase mask with a design wavelength of λ_B = 785 nm has been used to investigate the properties of spectral features at twice the Bragg wavelength.

Experimental Setup

FBGs were fabricated in Corning 1060 nm fiber (numerical aperture 0.14, cutoff wavelength 920 nm) so that features at twice the Bragg wavelength could be studied under singlemode propagation. The fiber was exposed to 92 atm of hydrogen at 65 °C for 3 days to increase photosensitivity prior to irradiation and placed within tens of micrometers from the phase mask to ensure exposure to the interference pattern generated by all diffraction orders [14]. A collimated 130 mW laser beam (244 nm wavelength) confined within a 5 mm circular aperture was incident normally on the phase mask (manufactured by Ibsen) that had a uniform pitch of Λ_{pm} = 536 nm. The average relative strengths of the diffraction orders were measured for the 0th, ±1st and ±2nd orders as 9.8%, 34.6% and 7.2%, respectively. An optical spectrum analyzer (OSA) was used to monitor transmission and reflectance spectra. To study spectra near 1550 nm (i.e. λ_{2B}) illumination was provided by an Er^{3+} broadband source and the OSA resolution was 0.1 nm. A 780 nm centre wavelength superluminescent diode of FWHM = 45 nm was used as the source in the region of λ_B, with an OSA resolution of 0.05 nm.
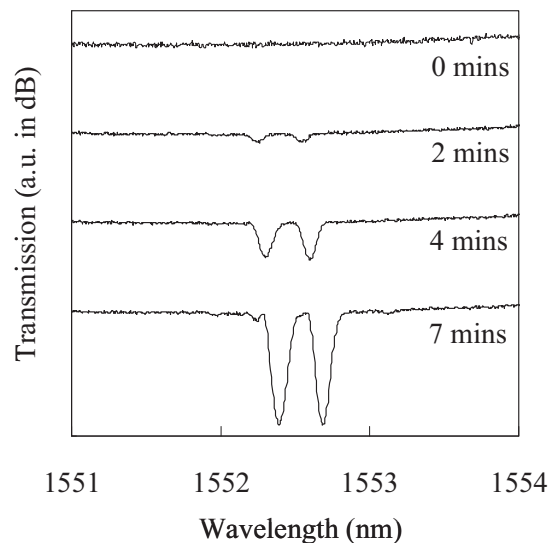

Fig. 1. Spectra near 1550 nm, showing the growth of a FBG in a 7-minute exposure through a phase mask of periodicity 536 nm.

Results and Discussions

The time evolution of FBG transmission features near 1550 nm, i.e. at λ_{2B}, is shown in Fig. 1. Surprisingly, there are two transmission dips. These grow at the same rate, with both shifting by 0.15 nm to longer wavelengths as expected for type I FBGs, due to an induced refractive index increase of $\sim 1.4 \times 10^{-4}$ according to coupled mode theory [16]. This growth is similar to that observed near
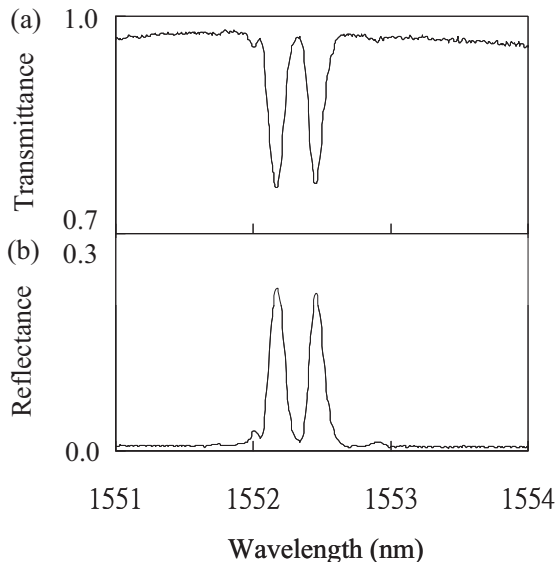

Fig. 2. The measured FBG (a) transmission and (b) corresponding reflection spectra at 1550 nm.

the design Bragg wavelength of 785 nm.

The spectra in Fig. 2 were recorded near 1550 nm after 7 minutes of UV exposure, with Fig. 2(a) showing two transmission dips at 1552.2 and 1552.5 nm and Fig. 2(b) showing the corresponding FBG reflection peaks. The reflectances of the two peaks of 0.22 are equal to within 6% and their separation is ~ 0.3 nm. Both peaks are very narrow, each having a FWHM of ~ 0.13 nm, while the combined width is ~ 0.41 nm. These reflection and transmission features are attributed to the fringe pattern created by the interference of all diffraction orders from the phase mask which possesses interleaving planes with a period equal to that of the phase mask (Λ_{pm}). Indeed, when this phase mask was used in an arrangement in which only the ± 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 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 λ_B near 1550 nm, the observed spectral features are indeed due to the existence of a grating (with $\Lambda = \Lambda_{pm}$).

If the features near 1550 nm were due to a standard grating structure, a single peak/dip possessing a similar or larger width compared to features at 785 nm would be expected, depending upon the grating strength [16]. Instead dual reflection peaks/transmission dips occur near 1550 nm that are narrower; together they have a width which is not much greater than the width of the 785-nm peak. This suggests that the complex grating structure is

the cause, and inspection of published DIC images of FBGs with λ_B near 1550 nm [13,15] reveals that along the fiber core there are two different phases of grating planes at the phase mask periodicity, which are perfectly interleaved. In this experiment, involving λ_B near 785 nm, the distance over which the interference pattern from the phase mask repeats itself, known as the Talbot length [13], was ~ 3.5 μm (for the combination of 0 and ± 1 diffraction orders) and, as this is smaller than the ~ 4 μm fiber diameter, both phases will be present in the fiber core. For light propagation in the fiber core at the Bragg condition near 1550 nm, the coupled forward and backward propagating modes reflected from each of the gratings are out of phase by π leading to destructive interference. FBGs having such properties are known as π-phase-shifted gratings and exhibit a notch in the middle of the transmission dip, the width of which depends upon the grating index variation [3]. In particular, there is close resemblance between a spectrum modeled for a grating index modulation of 10^{-4} consisting of two narrow peaks [3], and the spectrum shown in Fig. 2 for which the grating index modulation was determined [16] to be 1.3×10^{-4}.

Conclusions

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 π-phase-shifted grating at twice the Bragg wavelength, and was created without the need for any modifications of the standard phase mask arrangement.

References

[1] K. Sekartedjo et al, Electron. Lett. 20 (1984) p.80
[2] G. Agrawal et al, IEEE Photon. Technol. Lett. 6 (1994) p.995
[3] C. Martinez et al, Appl. Opt. 38 (1999) p.3223
[4] K. Hill et al, Appl. Phys. Lett. 62 (1993) p.1035
[5] B. Malo et al, Opt. Lett. 18 (1993) p.1277
[6] P. Dyer et al, Appl. Phys. Lett. 64 (1994) p.3389
[7] P. Dyer et al, Opt. Commun. 115 (1995) p.327
[8] P. Dyer et al, Opt. Commun. 129 (1996) p.98
[9] J. Mills et al, Appl. Opt. 39 (2000) p.6128
[10] C. Rollinson et al, Opt. Commun. 256 (2005) p.310
[11] W. Xie et al, Opt. Commun. 101 (1993) p.85
[12] S. Yam et al, J. Opt. A: Pure Appl. Opt. 10 (2008) 055307
[13] N. Dragomir et al, Opt. Lett. 28 (2003) p.789
[14] C. Smelser et al, Opt. Lett. 29 (2004) p.1458
[15] B. Kouskousis et al, Opt. Expr. 14 (2006) 10332
[16] T. Erdogan, J. Lightwave Technol. 15 (1997) p.1277
[17] S. Yam et al, J. of Electron. Sci. and Technol. of China 6 (2008) p.458
[18] S. Yam et al, Meas. Sci. Technol. 20 (2009) 034008