Use of first-order diffraction wavelengths corresponding to dual-grating periodicities in a single fiber Bragg grating for simultaneous temperature and strain measurement

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ABSTRACT

A fiber Bragg grating sensor fabricated by a phase mask with 536 nm uniform pitch is presented. Two peaks/dips occur, at 785 and 1552 nm, due to reflection/transmission at the Bragg wavelength and at double the Bragg wavelength, and arising from FBG periodicities associated with half the phase mask periodicity and the phase mask periodicity, respectively. It provides simultaneous measurement of temperature and longitudinal strain, with similar intensities in both wavelengths making it better suited for long-distance operation and multiplexing compared with similar schemes.

Keywords: Fiber Bragg grating (FBG), Bragg wavelength, peaks at double the Bragg wavelength

1. INTRODUCTION

Fiber Bragg gratings (FBGs) have been utilized in sensing physical parameters, particularly temperature and strain, owing to the observable changes in the Bragg wavelength in response to these measurands. Furthermore they can be multiplexed and, due to the low optical attenuation near 1550 nm (< 0.2 dB/km), suitable FBGs may be located at large distances from the instrumentation unit. However, the temperature and strain cross-sensitivity must be addressed, which is often achieved by the use of a free-standing FBG (i.e. its Bragg wavelength responds to temperature variations only). Another method of addressing this problem, involving the use of both the first- and second-order diffraction wavelengths of a single FBG fabricated with a phase mask, was first reported by Brady et al. and avoids the complication of having FBGs in pairs. In this situation, the reflected wavelength of a FBG at the $m^{th}$ harmonic (i.e. order) is given by

$$\lambda_{m(\Lambda)} = \frac{2}{m} n_{eff} \Lambda$$

where $\lambda_{m(\Lambda)}$ is the reflected wavelength of order $m = 1, 2, 3, \ldots$, $n_{eff}$ is the effective refractive index of the fiber core at $\lambda_{m(\Lambda)}$, and $\Lambda$ is the FBG period. This technique requires the inversion of a $2 \times 2$ matrix so that temperature and strain may be deduced simultaneously from the measurement of both wavelength shifts. Some years later Echevarría et al. optimized the FBG fabrication process, using a phase mask with periodicity $\Lambda_{pm}$ of ~ 1 $\mu$m and thus $\Lambda$ of ~ 0.5 $\mu$m, giving 1$^{st}$ and 2$^{nd}$-order diffraction wavelengths at 1535.85 and 767.94 nm, respectively (denoted here as $\lambda_{1(\Lambda_{pm}/2)}$ and $\lambda_{2(\Lambda_{pm}/2)}$, respectively), and consistent with Equation (1). In this sensor scheme the secondary diffraction order ($\lambda_{2(\Lambda_{pm}/2)}$) is located at a wavelength where the attenuation is considerably higher compared with the 1.5 $\mu$m region, exceeding 2.5 dB/km. Indeed optical power considerations of such two-wavelength FBGs suggest further practical disadvantages as at the secondary diffraction order the reflected power is significantly smaller compared with the first-order, and the available light sources have lower power, whereas numerous sources exist for 1.5 $\mu$m operation for communications applications. This increases the systematic error in determining the second-order wavelength for simultaneous temperature-strain measurement. Furthermore, this limits the possibilities for multiplexing many 1$^{st}$- and 2$^{nd}$-order FBGs.

Differential interference contrast imaging and other imaging methodology have revealed that FBGs fabricated by the standard phase mask technique have a complex structure within, exhibiting two separate grating periodicities, namely half of phase mask period, i.e. $\Lambda = \Lambda_{pm}/2$ as expected, and also the phase mask period, i.e. $\Lambda = \Lambda_{pm}$. Modelling has

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shown that the latter periodicity is due to higher phase mask diffraction orders. FBG effects due to \( \Lambda_{pm} \) are not observable in FBGs having a Bragg wavelength (i.e. associated with \( \Lambda_{pm}/2 \)) near 1550 nm. However, if a FBG were to be fabricated so that \( \Lambda_{pm} \) was associated with 1550 nm then at the standard FBG wavelength, i.e. near 785 nm, the reflective power should be much greater compared with FBGs for which operation near 785 nm involves \( m = 2 \) in Equation (1).

This paper reports a dual-wavelength FBG sensor suitable for the simultaneous measurement of temperature and strain operating at wavelengths near 785 and 1550 nm through the use of a phase mask having a 536 nm uniform pitch. The sensor involves a novel combination of the Bragg wavelength (\( \lambda_{1}(\Lambda_{pm}/2) \)) and twice the Bragg wavelength (\( \lambda_{2}(\Lambda_{pm}) \)), which are due to the first harmonic (\( m = 1 \)) of grating structures with period equal to \( \Lambda_{pm}/2 \) and \( \Lambda_{pm} \), respectively, and which are located in the region of 0.75 and 1.5 \( \mu \)m, respectively. This provided considerably greater signal power near the 785 nm wavelength compared with dual wavelength sensors involving a FBG fabricated for normal operation near 1550 nm (i.e. involving \( \lambda_{1}(\Lambda_{pm}/2) \) and \( \lambda_{2}(\Lambda_{pm}/2) \)).

2. METHODOLOGY

A collimated 130 mW UV laser beam (244 nm wavelength) confined within a 5 mm circular aperture was used to fabricate the FBGs in SMF-28 fiber through a phase mask with 536 nm uniform pitch, which was manufactured by Ibsen. The average relative strengths of the diffraction order of the phase mask, as measured, were for 0, ±1 and ±2 order, 9.8%, 34.6% and 7.2%, respectively. The fiber was exposed to 92 atm of hydrogen at 65 \( ^\circ \)C for 3 days to increase the photosensitivity prior to irradiation. The hydrogenated fiber was located within hundreds of micrometers from the phase mask to ensure exposure of the fiber to the interference pattern generated by all diffraction orders.

The sensor was placed in a heat-stabilized chamber with 1 \( ^\circ \)C temperature accuracy. The temperature was varied from 20 to 100 \( ^\circ \)C in 5 \( ^\circ \)C intervals, and measured with a calibrated thermocouple of 0.1 \( ^\circ \)C precision located adjacent to the FBG. FBG spectra were measured once the temperature had stabilized at each step. For longitudinal strain evaluation, the FBG was mounted in a high precision single-axial stage that could be adjusted manually up to 0.01 mm precision along a longitudinal axis at a fixed 25 \( ^\circ \)C temperature. Transmission and reflectance spectra near 1.5 \( \mu \)m (\( \lambda_{1}(\Lambda_{pm}/2) \)) were monitored by an optical spectrum analyzer (OSA) having 0.1 nm resolution, using illumination by an Er\textsuperscript{3+} broadband source. A 780 nm centre wavelength superluminescent laser diode of FWHM = 45 nm was used to obtain reflection and transmission spectra in the region of \( \lambda_{1}(\Lambda_{pm}) \) (i.e. near 780 nm) with the same OSA with a setting of 0.05 nm resolution.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 Reflection and Transmission Spectra at \( \lambda_{1}(\Lambda_{pm}/2) \)

The transmittance and reflectance at \( \lambda_{1}(\Lambda_{pm}/2) \) are shown in Fig. 1(a) and (b), respectively. A clear single transmission dip is observed at 784.9 nm, and the corresponding single peak reflectance at the same wavelength is greater than 75% of the incident power, corresponding to 0.1 \( \mu \)W peak power. The slight energy loss in the reflection spectrum may be due to cladding mode scattering from the FBG. This dominant reflectance/transmission at \( \lambda_{1}(\Lambda_{pm}/2) \) is due a FBG of periodicity equal to \( \Lambda_{pm}/2 \), which arises from exposure to the UV interference of the +1 and -1 diffraction orders of the phase mask. The response at \( \lambda_{1}(\Lambda_{pm}/2) \) is consistent with the theoretical value (i.e. 781.5 nm), as calculated using Equation (1) in conjunction with a Sellmeier equation that gives the effective refractive index for silica fiber of 1.458 at 785 nm.
3.2 Reflection and Transmission Spectrum at $\lambda_{1(\Lambda_{pm})}$

Fig 2(a) shows the reflectance located at $\lambda_{1(\Lambda_{pm})}$ of the FBG and the two transmission dips are reflected in 1552.2 and 1552.5 nm, respectively, as shown in Fig 2(b). The reflectances of the two peaks are over 0.22, corresponding to 0.01 µW peak power, with about 3 nm separation and less than 6% variation. These reflection/transmission spectra are attributed to the fringe pattern created by the interference of the 0, +1 and -1 diffraction beams and which are generated with an interference pattern period equal to the phase mask ($\Lambda_{pm}$), as explained previously \(^8\)-\(^11\). The relatively weak reflection peaks are due to the lower refractive index contrast formation in the FBG with grating periodicity equal to $\Lambda_{pm}$.

3.3 Variation of Temperature against $\lambda_{1(\Lambda_{pm}/2)}$ and $\lambda_{1(\Lambda_{pm})}$

The wavelength variations at $\lambda_{1(\Lambda_{pm}/2)}$ (solid line) and at $\lambda_{1(\Lambda_{pm})}$ (dotted line) for temperatures between 20 and 100 °C in the FBG are presented in Fig. 3. The peaks/dips at $\lambda_{1(\Lambda_{pm}/2)}$ and $\lambda_{1(\Lambda_{pm})}$ shift from 784.9 to 785.4 nm, and from 1552.5 nm to 1553.3 nm, respectively. In each case the response, as expected, is linear, and the temperature coefficients of the peak/dips at $\lambda_{1(\Lambda_{pm}/2)}$ and $\lambda_{1(\Lambda_{pm})}$ are calculated to be 6.0 and 10.9 pm/°C, respectively, determined from the gradient of the fitted straight lines.

3.4 Variation of Longitudinal Strain against $\lambda_{1(\Lambda_{pm}/2)}$ and $\lambda_{1(\Lambda_{pm})}$

The variation of longitudinal strain against $\lambda_{1(\Lambda_{pm}/2)}$ (solid line) and at $\lambda_{1(\Lambda_{pm})}$ (dotted line) are illustrated in Fig. 4. The strain was varied from 235 to 2118 µε at 235 µm intervals, which caused the wavelengths at $\lambda_{1(\Lambda_{pm}/2)}$ and $\lambda_{1(\Lambda_{pm})}$ to vary
from 785 to 785.8 nm and 1552.5 to 1554.2 nm, respectively. As anticipated, the response is linear in each case, and the gradient of each of the fitted straight lines provided longitudinal strain coefficients of 0.5 and 0.9 pm/µε, respectively.

4. CONCLUSION

FBGs having dual-grating periodicities generated by the first-order diffraction wavelengths at \( \lambda_{1/2} \) and \( \lambda_1 \) were fabricated using a phase mask with uniform pitch (536 nm) using standard FBG writing technology. These features are attributed to the first harmonic \( m = 1 \) of a grating with having two periodicities, namely \( \Lambda_{pm}/2 \) and \( \Lambda_{pm} \), and changes in the wavelength due to temperature changes and longitudinal strain exhibit good linearity. Although this approach to simultaneous temperature and longitudinal strain measurement is similar to work reported previously\(^2\),\(^5\), our scheme provides the significant improvement of providing similar reflective power at the two wavelengths. This is particularly useful, since the greater intensity at the first-diffraction wavelength (i.e. 785 nm) compared to the second-diffraction wavelength (i.e. 1553 nm) overcomes the relatively higher fiber attenuation at the shorter wavelength. This makes the sensor suitable for multiplexing or for practical long-range simultaneous temperature and strain measurements.

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6. REFERENCES