Discrimination of temperature and strain with a single FBG based on the birefringence effect

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Abstract: We will demonstrate a new technique to discriminate the temperature and strain effects using a single fiber Bragg grating (FBG). The birefringence is typically induced during FBG inscription, and it is manifested as polarization-dependent loss (PDL), and it is defined as the maximum change in the transmitted power for polarizations. Two independent measurements of the resonance wavelength shift and the changes of PDL can discriminate those effects.

OCIS codes: (230.0230) Optical devices; (060.2370) Fiber optics sensors

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1. Introduction

Optical fiber grating based sensors provide a number of sensing techniques that can be applied to a range of structural sensing applications [1,2]. In addition to the usual desirable features of optical sensors, namely, immunity to electromagnetic interference, small size, and geometric flexibility [2], fiber gratings can be mass-produced [3].

One of the problems in using fiber grating for sensor heads is the single measurement of resonance wavelength shift cannot distinguish between the effects of temperature and strain. Thus several discriminating techniques have been proposed, like dual-wavelength superimposed gratings [4], hybrid Bragg grating/long period grating [5], Bragg grating inscribed in PANDA fiber [6], or two spliced gratings in different doping sections [7]. However all these schemes require two independent measurements with two gratings. In this paper, we will demonstrate a new technique for discrimination of the temperature and strain effects using a single fiber Bragg grating (FBG), measuring the resonance wavelength shifts and the PDL changes induced by the birefringence of the FBG.

The birefringence of optical fiber is typically induced during the process of laser beam exposure onto optical fiber. The photo-induced birefringence was reported to have two main origins: the polarization of the UV writing beam and the asymmetric index change in the transverse plane [8,9]. This birefringence causes the orthogonal polarization modes to experience different couplings through the fiber grating. Such dependence on the polarization modes is manifested as changes in the spectral characteristics like the resonance wavelength and the peak depth, and this effect can be measured in terms of the polarization-dependent loss (PDL) in the transmission spectrum [10]. Thus two different gratings for polarization eigen-modes are actually embedded in a single typical fiber grating, and the PDL change is more sensitive to external perturbations in FBG rather than in LPFG since FBG typically has a narrow bandwidth and a high peak depth compared with long-period fiber grating (LPFG). The measurements of PDL changes and resonance wavelength shifts in a single FBG can discriminate the temperature and strain effects.

2. Theory

The principle of FBG is interpreted by coupled mode theory between forward and backward propagating core modes. The derivations are in numerous articles [11]. The resonance wavelength of FBG is given by the phase-matching condition:

$$\lambda_B = 2 n_{\mathrm{co}} \Lambda \tag{1}$$

where λ_B is the resonance wavelength, Λ and n_{co} are respectively the grating period and the effective index of the core. The shift in the resonance wavelength with strain and temperature can be expressed using

$$\Delta\lambda_B = \lambda_B (K_T\, \Delta T + K_\varepsilon\, \Delta\varepsilon) \tag{2}$$

where ΔT and $\Delta\varepsilon$ are the changes in temperature and strain, respectively, and the coefficients K_T and K_ε are the temperature and strain sensitivities of the resonance wavelength shift ($\Delta\lambda_B$), respectively. Since the resonance wavelength shifts with the temperature or strain change and the peak depth has little change with these effects, single measurement cannot discriminate the temperature and strain effect. So, to overcome the problem of cross sensitivity, many alternative techniques based on two independent measurements with two fiber gratings were proposed.

The birefringence is induced in the optical fiber during the process of FBG inscription. Since optical fiber gratings are typically fabricated by irradiating UV laser beam onto a portion of the optical fiber from a single side, the resulting azimuthal asymmetry in the

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refractive index change of the fiber can be induced [8], and s-polarized UV beam for FBG writing can also make the birefringence of the fiber severe [9]. The photo-induced birefringence slightly separates the resonance conditions for two eigen polarization modes:

$$\Delta\lambda = 2\,\Delta n\,\Lambda\ , \tag{3}$$

where Δn is the index difference caused by the photo-induced birefringence. Thus two different gratings for polarization eigen-modes are actually embedded in a single typical fiber grating. The changes of the resonance wavelengths with strain or temperature changes can be represented by

$$\begin{pmatrix} \Delta\lambda_s \\ \Delta\lambda_p \end{pmatrix} = \begin{pmatrix} K_{sT} & K_{s\varepsilon} \\ K_{pT} & K_{p\varepsilon} \end{pmatrix} \begin{pmatrix} \Delta T \\ \Delta\varepsilon \end{pmatrix} \tag{4}$$

where ΔT and $\Delta\varepsilon$ are the changes in temperature and strain, respectively, and the coefficients K_{iT} and $K_{i\varepsilon}$ are the temperature and strain sensitivities. $\Delta\lambda_s$ and $\Delta\lambda_p$ are the changes of resonance wavelengths for two polarization eigen-modes. The birefringence is on the order of 10^{-6} [9, 12]. Considering the grating period (Λ) of FBG is around 500 nm, the separation ($\Delta\lambda$) of the resonance wavelengths is ~ 0.004 nm with the birefringence of 4×10^{-6}. This effect is hardly observable using unpolarized light source and optical spectrum analyzer (OSA). It can be clearly seen through PDL measurements. The PDL is defined as the maximum change in the transmitted power for all possible states of polarization:

$$PDL[dB] = 10\log_{10} T_{\max} - 10\log_{10} T_{\min} = 10\log_{10}(P_{\max}/P_{\min})\,, \tag{5}$$

and it dramatically increases as the resonance wavelengths for the eigen polarization modes become separated.

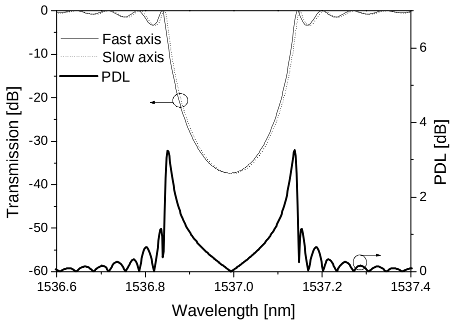

Fig. 1. Simulations of transmission spectra and PDL of FBG with the birefringence of 4×10^{-6}, the grating period (Λ) of 530 nm, and the length (L) of 1 cm.

These effects were analytically simulated and the results were shown in Fig. 1. The slightly separated transmission spectra of the two eigen polarization modes and the PDL curve were plotted. The transmission spectra were obtained analytically using the parameters L = 1 cm and Λ = 530 nm. The birefringence induced by UV exposure was taken to be 4×10^{-6}, and the coupling coefficient κ was 5×10^{-4}.

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The changes of resonance wavelength (λ) and maximum PDL (k_{max}) can be represented by

$$\begin{pmatrix} \Delta\lambda \\ \Delta k_{\max} \end{pmatrix} = \begin{pmatrix} (\Delta\lambda_s + \Delta\lambda_p)/2 \\ function(\Delta\lambda_s - \Delta\lambda_p) \end{pmatrix} = \begin{pmatrix} K'_{1T} & K'_{1\varepsilon} \\ K'_{2T} & K'_{2\varepsilon} \end{pmatrix} \begin{pmatrix} \Delta T \\ \Delta\varepsilon \end{pmatrix} \tag{6}$$

where the coefficients K'_{iT} and $K'_{i\varepsilon}$ are the temperature and strain sensitivities of Δλ and Δk_{max}, respectively. The inversion of the transfer matrix can discriminate the effects of temperature and strain with a single FBG.

3. Experiments

We fabricated the FBG using a phase mask with 1060-nm period and frequency-doubled (244 nm) CW Argon-ion laser with 100 mW power. A photosensitive optical fiber is placed in close to the phase mask, and the interference pattern through the mask photo-imprints a refractive index modulation in the core of the fiber. The photosensitivity fiber was made at K-JIST, which was treated with hydrogen loading under 90 bar for 4 days. The specifications of the fiber are: cutoff wavelength $\lambda_c = 940\ nm$, $\Delta = 1\%$, core and cladding diameters 3.2 μm and 122.1 μm, respectively. The UV writing beam was irradiated on a 1-cm section of the stripped fiber by a single-side exposure for 70 seconds. The measurement setup for the transmission spectrum and the PDL of FBG is shown in Fig. 2. The FBG was placed in a temperature-controlled oven and the temperature was varied in the range of 30 to 70 ºC. The fiber was suspended using two fiber holders, one of which was mounted on a translation stage for application of strain on the FBG.

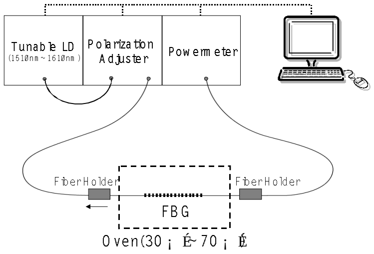

Fig. 2. The experimental setup.

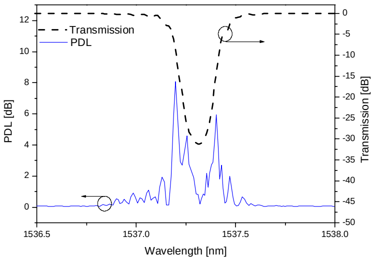

Fig. 3. Transmission spectra and PDL of the FBG.

The transmission spectrum and the PDL were measured using a PDL meter that consisted of a tunable LD, a liquid crystal-based polarization adjustor and a power-meter. The PDL

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measurement used the Mueller matrix method. The measurement results are shown in Fig. 3. The peak depth is 31 dB and the maximum PDL is ~8 dB near 1537.2 nm.

4. Results and discussion

Figure 4 shows the change in the transmission spectrum of the FBG under application of strain in the range of 0 to 0.438 %ε. The spectra were measured while increasing the strain at a step of 0.063 %ε. It is seen that the resonance wavelength shifts almost linearly with the strain and that there is very little change in the peak depth. Measurement of the spectral changes with different temperature showed similar results. For this reason, discrimination of the temperature and strain effects is not possible with measurements of the resonance wavelength shift alone.

In order to discriminate the temperature and strain effects using a single FBG, we measured the maximum PDL of the transmission spectrum in addition to the resonance wavelength shift as the temperature and strain were varied. Figure 5 shows the measurement results of the resonance wavelength shift and the maximum PDL as the strain is varied. The measurements were made in the room temperature (~ 22 ºC). It is seen that the resonance wavelength shifts to the long wavelength with the increase of the strain, which is due to increase of the grating periodicity. Increase of the PDL with strain can be explained by considering the uneven distribution of the stress in the core region. The birefringence induced by the single-side UV exposure causes uneven densification in the cross section of the core region [7]. With application of the strain on the fiber, the stress-optic effect will therefore be non-uniform, and the measurement results in Fig. 5 indicate that the stress-optic effect is larger in the region where the index change was larger. Application of strain will thus enhance the birefringence and the PDL will increase. Linear fitting of the graphs in Fig. 5 gives

$$\begin{aligned} \lambda_B[\text{nm}] &= 1537.4 + 11.1\,\varepsilon[\%], \\ k_{\max}[\text{dB}] &= 8.47 + 38.6\,\varepsilon[\%], \end{aligned} \tag{6}$$

where $k_{\max}$ is the maximum PDL.

The measurement results of the resonance wavelength shift and the PDL for the temperature in the range of 30 to 70 ºC are shown in Fig. 6. As the temperature is increased, the resonance wavelength shifts to the long wavelength and the PDL also increases. As in the case of the strain effect, the results indicate that the non-uniform change of the refractive index due to the enhanced birefringence as the temperature is increased. Linear fitting of the graphs in Fig. 6 gives

$$\begin{aligned} \lambda_B[\text{nm}] &= 1537.0 + 0.011\,T[^\circ\text{C}], \\ k_{\max}[\text{dB}] &= 5.84 + 0.13\,T[^\circ\text{C}]. \end{aligned} \tag{7}$$

Combining Eq. (6) and (7), we can write the results in vector form, and by inverting the sensitivity matrix, we finally obtain

$$\begin{pmatrix} T[^\circ\text{C}] \\ \varepsilon[\%] \end{pmatrix} = \begin{pmatrix} -37.9 & 10.9 \\ 0.128 & -0.0108 \end{pmatrix} \begin{pmatrix} \lambda_B[\text{nm}] - 1537.0 \\ k_{\max}[\text{dB}] - 5.84 \end{pmatrix}. \tag{8}$$

The deviations of the λ_B and $k_{\max}$ from linearity as shown in Figs. 5 and 6 are approximately 0.02 nm and 0.5 dB, respectively. From Eq. (8), the error estimates for measurements of temperature and strain are 6 ºC and 0.006 %, respectively.

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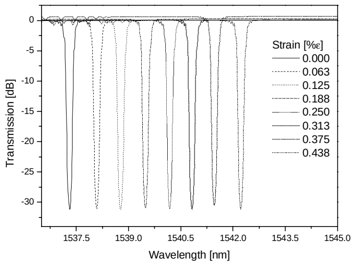

Fig. 4. Shift of the transmission spectrum with application of strain.

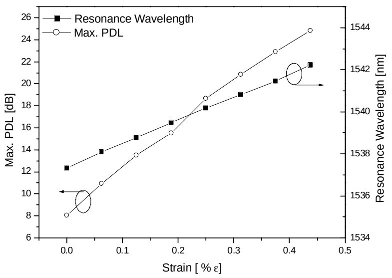

Fig. 5. Resonance wavelength shift and maximum PDL change with strain.

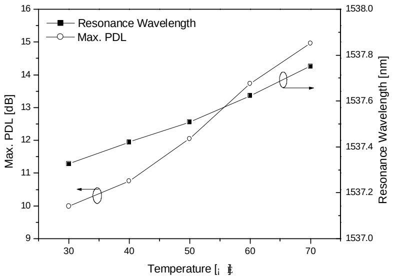

Fig. 6. Resonance wavelength shift and maximum PDL change with temperature.

5. Summary

A new method for discrimination of the temperature and strain effects using a single FBG fabricated by the single-side exposure of the UV beam has been proposed and experimentally demonstrated. The birefringence introduced in the FBG by the asymmetric exposure of the UV beam results in PDL in the transmission spectrum. The PDL was found to be rather sensitive to the temperature and strain changes, and we were able to discriminate the effects by measuring the resonance wavelength shift and the PDL changes. The experimental results indicate that the error estimates for measurements of temperature and strain are 6 ºC and 0.006 %, respectively. This method can easily improve the feasibility of optical sensor systems using a single FBG at each sensing point.