Resolving cross sensitivity of fiber Bragg gratings with different polymeric coatings

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An approach to resolve the cross sensitivity of fiber Bragg gratings (FBGs) is proposed by the adoption of different polymers as the coating materials for gratings. From the different optical responses resulted from the gratings of different polymeric coatings, sensitivity to individual parameter can be exactly revealed. As an application of this approach, simultaneous discrimination of axial strain and temperature with two FBGs of different polymeric coatings is demonstrated with the axial strain and temperature sensitivities of 1.228 pm/$\mu\varepsilon$ and 11.433 pm/°C for the acrylate-coated FBG, and 1.170 pm/$\mu\varepsilon$ and 11.333 pm/°C for the polyimide-coated FBG, respectively. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2919796]

Fiber Bragg gratings (FBGs) have received great attention for applications in modern telecommunication and optical sensor networks.[1] FBG sensors exhibit unique advantages such as immunity to electromagnetic interference, compact size, potential low cost, and the possibility of distributed measurement over a long distance, which have been reported as sensors for many measurands including temperature,[2] strain,[3] vacuum,[4] and refractive index.[5] However, cross-sensitivity effects, i.e., force, displacement, or pressure effects tangled with temperature effect, make it impossible to separately determine the temperature and other parameters by measurement of the wavelength shift of single FBG sensor. In order to realize practical applications of FBG sensors, discrimination techniques must be discovered to reveal individual parameter, in which the cross sensitivity between temperature and strain is one of the most fundamental issues. Zhao *et al.* reviewed different discrimination measurement methods on the cross-sensitivity effects of temperature and strain,[6] which includes reference FBG method, dual-wavelength superimposed FBG method, combined FBG and long-period grating method, different cladding-diameter FBG method, FBG Fabry–Perot method, and superstructure FBG method. Other methods recently reported include high birefringence fiber gratings,[3,7,8] dual-wavelength fiber laser,[9] embedded FBG,[10] fiber Raman laser with an etched FBG,[11] combined Sb–Er–Ge–codoped fiber-fluorescence and grating-based technique,[12,13] FBGs in germanosilicate and boron-codoped germanosilicate fibers,[14] and fiber-optic Fizeau interferometric strain sensor.[15] Some papers also discussed special techniques to be sensitive only to either temperature or strain.[16,17] In these reported techniques, it is necessary to use special fibers (specialty fibers with different doping elements, microstructured fibers, and photonic crystal fibers), complicated configurations (external lasers), or special spectroscopic techniques (fluorescence and interferometry) in order to distinguish temperature and strain, which result in bulky sensor systems targeting for the sole purpose of simultaneous measurement of temperature and strain only.

In this paper, an approach to resolve the cross sensitivity of FBGs is proposed and demonstrated. In our approach, acrylate and polyimide polymers, which possess excellent strength and resistance to breakage, are used as the coating materials for different FBGs. As an application of this approach, simultaneous measurement of axial strain and temperature with two FBGs of acrylate and polyimide coatings is reported. Since the standard FBG fabrication technique needs to strip the protective plastic coating off the fiber before FBG inscription and recoat a polymeric layer afterwards to protect the grating, the coating of FBGs with different polymeric materials proposed here does not complicate the procedures or add extra cost in the FBG fabrication, which can be easily achieved by fiber recoaters or dip coating technique. Furthermore, without additional optical devices or spectroscopic techniques as used in reported literatures, this approach provides one-fiber solution for multiple applications of FBGs in addition to resolve the cross sensitivity of axial strain and temperature.

The Bragg resonance wavelength of a FBG, λ_B, which is the center wavelength of light back reflected from the grating, depends on the effective index of refraction of the core (n_{eff}) and the periodic spacing of the grating (Λ) through the relation $\lambda_B = 2n_{eff}\Lambda$. Parameters such as n_{eff} and Λ are affected by changes in strain and temperature. The shift in the Bragg resonance wavelength $\Delta\lambda_B$ due to the changes in the temperature and strain can be described by[18]

$$\Delta\lambda_B = 2\left(\Lambda\frac{\partial n}{\partial T} + n\frac{\partial\Lambda}{\partial T}\right)\Delta T + 2\left(\Lambda\frac{\partial n}{\partial l} + n\frac{\partial\Lambda}{\partial l}\right)\Delta l. \quad (1)$$

The first term in Eq. (1) represents the temperature effect on the FBG and the second term describes the strain effect. The fractional wavelength shift corresponding to a temperature change ΔT as[6,19]

$$\Delta\lambda_{B,T} = \lambda_B(\alpha + \zeta)\Delta T, \quad (2)$$

where α is the thermal expansion coefficient of the fiber ($\sim 0.55\times 10^{-6}\ {}^\circ C^{-1}$ for silica cladding). The quantity ζ represents the thermo-optic coefficient, which is $8.6\times 10^{-6}\ {}^\circ C^{-1}$ for a germanium doped silica core.

The term related to the strain effect can be expressed as[6,19]

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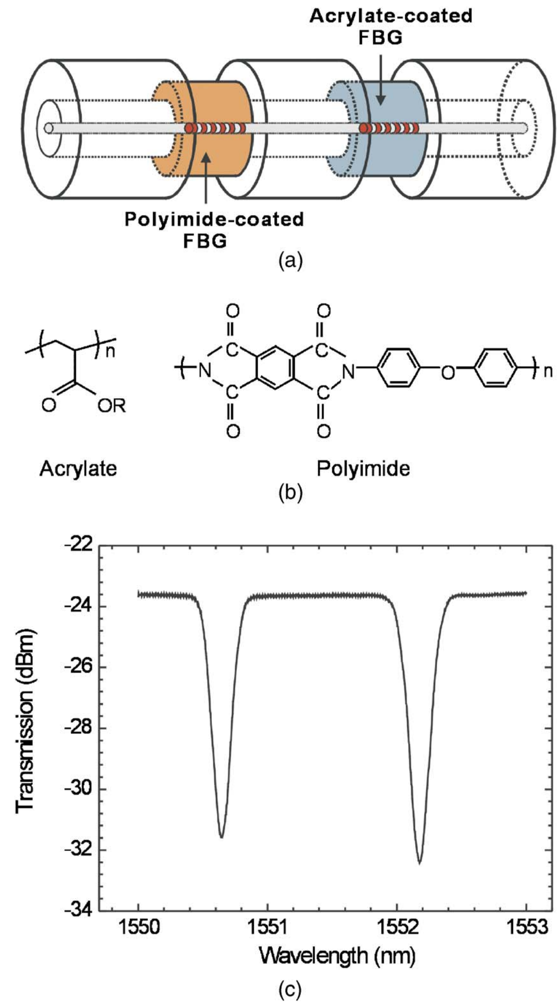

FIG. 1. (Color online) FBGs with different polymeric coatings: (a) illustration of the FBGs used in this study, (b) molecular structures of acrylate and polyimide, and (c) transmission spectrum of the FBG sample with acrylate and polyimide coatings.

$$\Delta\lambda_{B,S} = \lambda_B(1 - \hat{P}_e)\Delta\varepsilon, \qquad (3)$$

where $\hat{P}_e$ is an effective photoelastic constant with a value of 0.22 for fused silica.

As shown in Fig. 1(a), two FBGs of 1 cm each in the grating length were inscribed on a standard telecommunication single-mode optical fiber (Corning SMF-28) followed by coating of acrylate and polyimide on the grating sections by the use of Vytran fiber recoaters PTR-200 and PTR-200-PRL, respectively. The details on the sample preparation have been described elsewhere.[20] The acrylate material used for coating was DSM950-200 (Fiber Optic Center™, Inc.),[21] whose composition mainly includes glycol ether acrylate, multifunctional acrylates, and monomers with the molecular structure of the monomer illustrated in Fig. 1(b). The curing of the recoated acrylate layer was carried out with UV light at 365 nm for 17 sec at room temperature. The molecular structure of the polyimide polymer is shown in Fig. 1(b), which was PI2525 from HD MicroSystems L.L.C.[22] Once the polyimide recoat process is initiated, two passes were adopted, in which each pass applies a coating of resin, followed by a low-temperature (100 °C) bake to remove volatile, and then a high-temperature (200 °C) bake to imidize and harden the coating. The recoating process resulted in a fiber diameter of 147 μm at the grating areas. The basic physical properties of these polymers can be found from their product datasheets.[21,22] The transmission spectrum of the FBG sample measured by an optical spectrum analyzer (Ando 6315E) is shown in Fig. 1(c), which exhibits two Bragg resonances of the acrylate- and polyimide-coated FBGs at 1550.644 and 1552.176 nm with reflection signals of 7.96 and 8.81 dB, respectively. Differences in the thermo-optic and elasto-optic parameters of the acrylate and polyimide coatings result in different responses of the FBGs. The thermo-optic and elasto-optic parameters of the polymer-coated fiber can be found in our recent paper and elsewhere.[20–22]

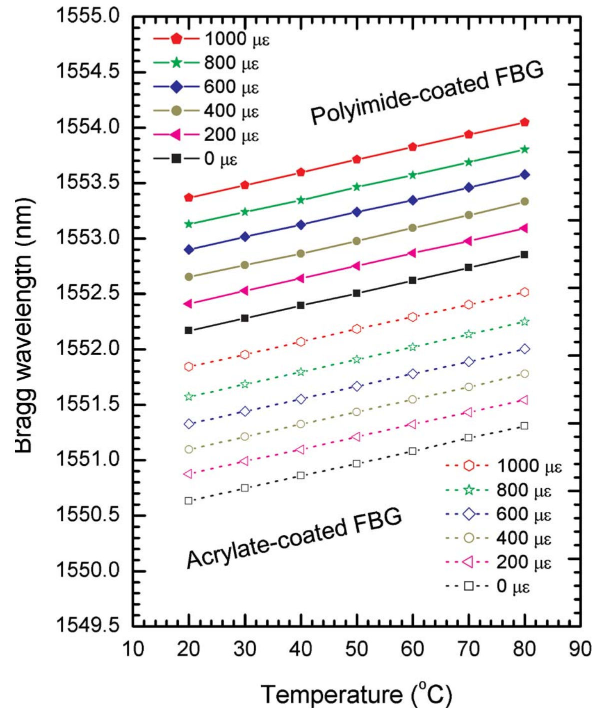

FIG. 2. (Color online) Bragg wavelengths of the acrylate- and polyimide-coated FBGs as functions of temperature under different axial strain values.

For the measurement of the cross sensitivity between axial strain and temperature of the FBGs, the FBG sample was axially stretched at different temperatures controlled by a Sigma system with a temperature accuracy of 0.1 °C. The FBG sample was fixed to two linear translation stages (ATS100, Aerotech, Inc) using epoxy glue in which one stage was used as a fixed stage and the other one as a motion stage. The length of fiber segment containing both of the acrylate- and polyimide-coated FBGs between the two fixed points was 1190.5 mm. The axial strain was adjusted with the motion stage with an accuracy of 0.5 μm through general purpose interface bus system and LABVIEW™ programming control. Light emitted from an erbium broadband light source (EBS-7210, MPB Communications, Inc.) was monitored by the optical spectrum analyzer after passing through the FBGs. Figure 2 gives the dependences of the Bragg wavelengths of the acrylate- and polyimide-coated FBGs on temperature under different axial strain values. For the acrylate-coated FBG, the average temperature sensitivity at different axial strains is 11.256 pm/°C with a standard deviation of 0.081 pm/°C. The average axial strain sensitivity at these measurement temperatures is 1.209 pm/$\mu\varepsilon$ with a standard deviation of 0.004 pm/$\mu\varepsilon$. The average temperature and axial strain sensitivities of the polyimide-coated

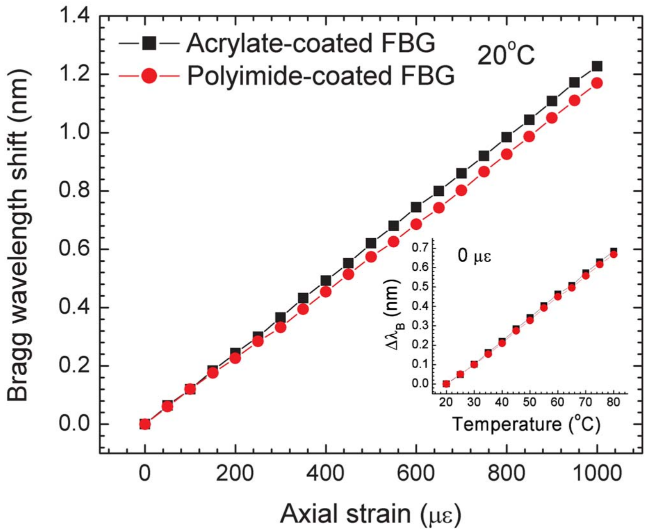

FIG. 3. (Color online) Dependences of the Bragg wavelength shifts of the acrylate- and polyimide-coated FBGs on the axial strain at 20 °C. The inset shows the temperature dependences of the Bragg wavelength shifts of these two FBGs without axial strain.

FBG are 11.322 ± 0.051 pm/°C and 1.201 ± 0.004 pm/$\mu\varepsilon$, respectively.

The FBG sample discussed here can discriminate axial strain and temperature effects due to the following two reasons: first, different sensitivities of axial strain and temperature have been observed for the two gratings of different polymeric coatings, which is due to the fact that the fiber thermo-optic coefficient α and elasto-optic coefficient $\hat{P}_e$ resulted from different polymer coating materials modify the temperature and axial strain sensitivities of the bare FBGs. Second, the temperature or axial strain sensitivity is almost identical under different axial strain values and temperatures with small standard deviations. The axial strain sensitivity and temperature sensitivity of each FBG were calibrated, respectively, to discriminate the cross sensitivity. Figure 3 shows the responses of the two gratings to the variations in the axial strain at 20 °C and the inset of Fig. 3 indicates the dependences of the Bragg wavelength shifts of the two gratings on the changing temperature without axial strain. Compared to polyimide coating, UV-cured acrylate material, which possesses relatively smaller modulus and larger thermal expansion coefficient, induces larger change of Bragg resonance wavelength under the same axial strain and temperature change. The shifts in the Bragg resonance wavelengths can be expressed as

$$\begin{bmatrix} \Delta\lambda_{\text{acrylate}} \\ \Delta\lambda_{\text{polyimide}} \end{bmatrix} = \begin{bmatrix} 1.228 & 11.433 \\ 1.170 & 11.333 \end{bmatrix} \begin{bmatrix} \Delta\varepsilon \\ \Delta T \end{bmatrix} = M_{\varepsilon T} \begin{bmatrix} \Delta\varepsilon \\ \Delta T \end{bmatrix}, \tag{4}$$

which is equivalent to the following equation through a matrix transposition:

$$\begin{bmatrix} \Delta\varepsilon \\ \Delta T \end{bmatrix} = M_{\varepsilon T}^{-1} \begin{bmatrix} \Delta\lambda_{\text{acrylate}} \\ \Delta\lambda_{\text{polyimide}} \end{bmatrix}. \tag{5}$$

In this case, a character matrix $M_{\varepsilon T}$ can be used to determine the absolute values of the axial strain and temperature from the shifts of the Bragg wavelengths of the two gratings. The character matrix, as the most important parameter of a FBG sample with different polymeric coatings, provides us with a method to simultaneously determine the axial strain and temperature applied on the fiber, thus the cross sensitivity of the axial strain and temperature is distinguished.

In conclusion, we have proposed and demonstrated an approach to resolve the cross sensitivity of FBGs by the use of gratings with different polymeric coatings, which realized discrimination of axial strain and temperature. The unlimited variety of polymers promises practical applications of this technique for simultaneously distinguishing multiple parameters, which is not bounded by some well-known polymers that can be used as fiber coatings such as acrylate, polyimide, silicone, and polyetherimide.

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