

Tuning the sensing responses of polymer-coated fiber Bragg gratings

Ping Lu, Liqiu Men, and Qiying Chen^{a)}

Department of Physics and Physical Oceanography, Memorial University of Newfoundland, St. John's, Newfoundland A1B 3X7, Canada

(Received 21 September 2008; accepted 2 November 2008; published online 15 December 2008)

We demonstrate the application of polyimide-coated fiber Bragg grating (FBG) as a substance sensor and reveal the dependences of the sensitivity and time response on the coating thickness as well as factors influencing these properties. As an example of polyimide-coated sensor for detecting soluble substances, the use of the grating for salinity measurement shows that a judicious selection of coating thickness is needed in order to achieve suitable sensitivity and time response for specific application. The experimental results indicated that the salinity sensitivities of the polyimide-coated FBGs with coating thicknesses of 11, 17, 20, and 24 μm were 1.45, 2.45, 2.95, and 3.70 pm/% (blueshifted), respectively. In addition, the response time is another signature for discriminating different parameters. © 2008 American Institute of Physics. [DOI: 10.1063/1.3042227]

Fiber Bragg gratings (FBGs) are important components in modern telecommunication and optical sensor networks with unique advantages such as immunity to electromagnetic interference, compact size, low cost, and the possibility of distributed measurement over a long distance.¹ FBGs have been used as sensors for measurement of many environmental parameters including temperature,² strain,³ vacuum,⁴ and flow.⁵ However, the sensitivities and time responses of these sensors have not been well understood. Bare FBGs have been widely applied in on-line high-speed sensors for their high sensitivities in the shifts of the Bragg wavelengths on environmental axial strain and temperature. When the grating section is recoated with different polymeric materials, the sensitivity and response time of the sensor will be modified.^{6–8} The response times of FBG sensors range from 1 ns to several hours in different application fields.⁹ Yeo *et al.*⁶ discussed the use of polyimide-coated FBG to measure humidity through the swelling of the polymer coating. Buric *et al.*⁷ reported that infrared power laser light can be used to induce heating in the palladium coating of a FBG, which dramatically decreases hydrogen sensor response time and increases the sensor's sensitivity at low temperatures. We recently reported that FBGs can be used for simultaneous measurement of salinity and temperature, in which the polyimide-coated grating responses to the variations in both temperature and salinity while an acrylate-coated grating is sensitive to the environmental temperature only.⁸ The difference in the sensing responses of the acrylate- and polyimide-coated FBGs lies in the differences in the thermo-optic and elasto-optic properties of their polymeric coatings.

In this paper, we will demonstrate the application of polyimide-coated FBG as a substance sensor and reveal the dependences of the sensitivity and time response on the coating thickness as well as factors influencing these properties. Since the standard FBG fabrication technique needs to strip the protective plastic coating off the fiber before FBG inscription and recoat a polymeric layer afterward to protect the grating, revelation of the coating-dependent properties is

extremely important, which provides additional possibility to discriminate different measurands by adopting different polymers and specifications without extra cost or complexity in the FBG fabrication. On the other hand, identification of the sensitivity and time response of the polymer-coated FBG is another crucial aspect for sensing applications. Our experiments indicated that the sensitivity and time response vary significantly with different coating materials. Even for the same coating material, different coating thicknesses can impact on the sensitivity and the response time of the measurement as well. Judging on either the sensitivity or time response or both of these two parameters of a polyimide-coated FBG, it is possible to detect environmental measurands and discriminate different substances.

The Bragg resonance wavelength λ_B of a FBG depends on the effective refractive index n_{eff} of the fiber core and the grating periodicity Λ through the equation $\lambda_B = 2n_{\text{eff}}\Lambda$, in which n_{eff} and Λ are sensitive to changes in strain and temperature. The shift in the Bragg wavelength due to changes in temperature ΔT and axial strain $\Delta\epsilon$, which is the relative change in the length defined as $\Delta l/l$, can be described by¹⁰

$$\Delta\lambda = \Delta\lambda_{B,T} + \Delta\lambda_{B,S} = \lambda_B(\alpha + \zeta)\Delta T + \lambda_B(1 - \hat{P}_e)\Delta\epsilon, \quad (1)$$

where α is the thermal expansion coefficient of the fiber, the parameter ζ represents the thermo-optic coefficient, and \hat{P}_e is an effective photoelastic constant.

In our experiments, four FBGs of 1 cm each in the grating length were inscribed on standard telecommunication single-mode optical fibers (Corning SMF-28) using a KrF excimer laser and a phase mask. The polyimide from HD MicroSystems¹¹ was then coated on the bare grating sections to obtain different coating thicknesses by multiple dip coating processes at an appropriate withdraw rate of the fiber. The fiber was treated in an oven at 150 °C for 5 min after each dip coating cycle and was finally cured in an oven at 200 °C for 1 h to imidize and harden the coating. The thicknesses of the polymeric coating layers of the four different FBGs were 11 μm (FBG-A), 17 μm (FBG-B), 20 μm (FBG-C), and 24 μm (FBG-D). The inset of Fig. 1 illustrates the polyimide-coated FBG-D used in this study. Figure

^{a)}Author to whom correspondence should be addressed. Electronic mail: qiyingc@mun.ca.

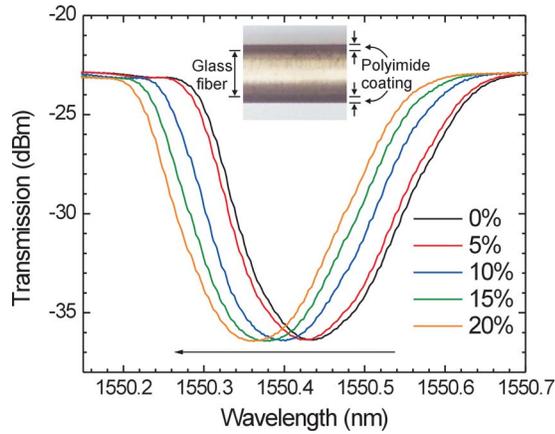


FIG. 1. (Color online) Transmission spectra of the polyimide-coated FBG-D with a coating thickness of $24 \mu\text{m}$ at different degrees of salinity at 20°C . The inset is an image of the fiber with dip-coated polyimide coating.

1 shows the transmission spectra of the FBG-D at different degrees of salinity with an initial Bragg resonance wavelength of 1550.436 nm and a reflection signal of 13.53 dB in water at a temperature of 20°C . When the salinity was changed from 0% to 20% at the same temperature, the Bragg wavelength exhibited a blueshift and the shift in the Bragg wavelength of the polyimide-coated FBG as a function of salinity indicated a sensitivity of $3.70 \text{ pm}/\%$. Swelling of the polyimide coating was mainly due to its water sorption property and was further attributed to the water molecules bound to the polymer chains and not the free water molecules.¹² When the polyimide-coated FBG was first immersed in the water bath, the bound water to the polymer chains and the free water in the space between the polymer chains were in a saturated equilibrium state. As the salinity of the solution was increased, water egressed out of the polyimide material and the volume of the coating layer shrunk. No apparent change in the fiber coating thickness was found during the water diffusion process, and thus the blueshifted Bragg wavelength induced by an axial shortening Δl of the fiber coating could be described by Eq. (1). As shown in Fig. 2, similar measurements on the dependences of the shifts in the Bragg wavelengths of the other three FBGs on the salinity were performed at 20°C with the salinity sensitivities of $1.45 \text{ pm}/\%$ (FBG-A), $2.45 \text{ pm}/\%$ (FBG-B), and $2.95 \text{ pm}/\%$ (FBG-C), respectively. The inset of Fig. 2 shows a linear dependence of the salinity sensitivity on the coating thickness with a coefficient of $1.72 \times 10^{-1} \text{ pm}/\% \mu\text{m}$. Since the degrees of polymer chain orientations slightly increase as the film thickness decreases,¹³ the FBG with a thicker polyimide coating possesses lower modulus and lower strength properties and thus a higher salinity sensitivity. Figure 2 clearly indicates that the salinity sensitivity of the polyimide-coated FBG is strongly dependent on the coating thickness with a higher sensitivity for a thicker coating.

To satisfy a specific application, the response time or the diffusion time of the polyimide-coated FBG should be evaluated in order to identify a coating thickness with suitable sensitivity and time response. When the FBG is initially placed in the water bath where the environmental medium is a constant concentration source, the water outside the fiber

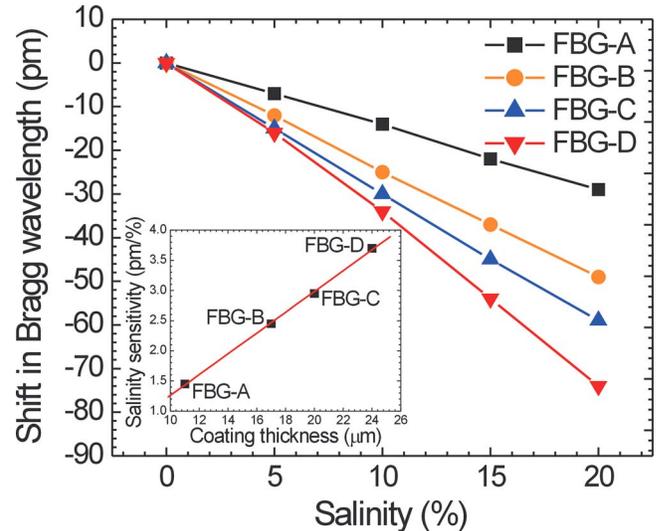


FIG. 2. (Color online) Dependences of the shifts in the Bragg wavelengths of the four polyimide-coated FBGs on salinity. The thicknesses of the polyimide coatings for FBG-A, -B, -C, and -D are 11 , 17 , 20 , and $24 \mu\text{m}$, respectively. The inset shows the dependence of the salinity sensitivity on the coating thickness.

coating with a concentration of C_{ext} , which is equal to 1, will consequently diffuse into the fiber coating until a saturated equilibrium state is reached. Given a sufficient water diffusion time ($t \rightarrow \infty$), the initial water concentration inside the fiber coating c_i will be equal to C_{ext} from the following equation:⁸

$$c_i(r,t) = C_{\text{ext}} \operatorname{erfc}\left(\frac{r}{\sqrt{4Dt}}\right), \quad (2)$$

where D is the diffusion coefficient of the water, t is the diffusion time, and r is the radial distance from the center of the fiber.

With the increase in the salinity of the environmental medium, the water concentration in the fiber coating will be higher than that in the environmental medium and the water will egress into the environmental medium from the fiber coating until an equilibrium state is reached. The final water concentration inside the fiber coating c_f can be expressed as

$$c_f(r,t) = C_{\text{ext}} \operatorname{erf}\left(\frac{r}{\sqrt{4Dt}}\right). \quad (3)$$

During the process of adding salt into the water bath, the change in the water concentration in the polyimide coating is expressed by

$$\Delta c = c_i - c_f = 1 - C_{\text{ext}} \operatorname{erf}\left(\frac{r}{\sqrt{4Dt}}\right), \quad (4)$$

and $\Delta c = 0$ when $t = 0$.

Based on the facts that the external salinity change results in a longitudinal expansion of the coated fiber only and the shift in the Bragg wavelength is proportional to the axial strain, the normalized blueshift in the Bragg wavelength is proportional to the change in the water concentration in the coating material. Therefore, we obtain the relation between the normalized shift in the Bragg wavelength and the salinity,

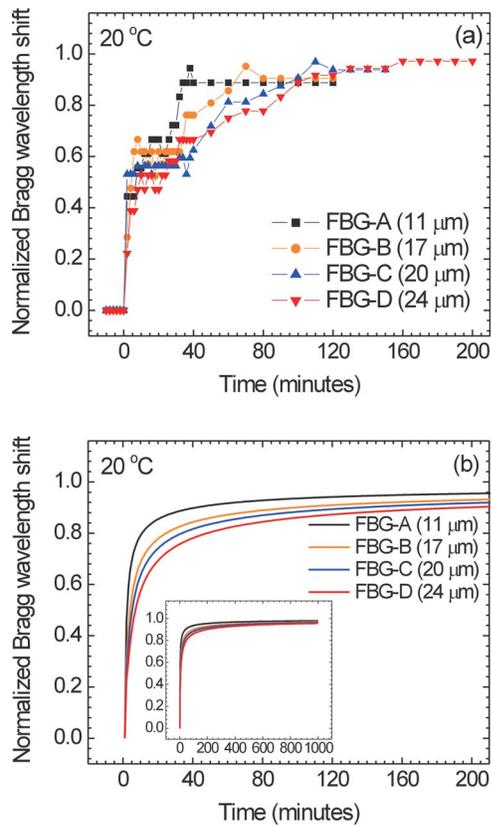


FIG. 3. (Color online) Time-dependent evolutions of the normalized shifts in the Bragg wavelengths of the four polyimide-coated FBGs after being transferred from an environmental salinity of 0% to 20% in solution: (a) experimental results and (b) simulation results with the inset showing the changes in the normalized shifts in the Bragg wavelengths on a longer time range.

$$\Delta\lambda = \lambda_{\text{salt},t} - \lambda_{\text{water},0} = \gamma\Delta c = \gamma \left[1 - C_{\text{ext}} \operatorname{erf}\left(\frac{r}{\sqrt{4Dt}}\right) \right], \quad (5)$$

or

$$\lambda_{\text{salt},t} = \lambda_{\text{water},0} + \gamma \left[1 - (1 - S) \operatorname{erf}\left(\frac{r}{\sqrt{4Dt}}\right) \right], \quad (6)$$

where S is the salinity of the environmental medium and γ is a proportional coefficient. $\lambda_{i,t}$ stands for the Bragg wavelength of the fiber in either saline solution ($i=\text{salt}$) or water solution ($i=\text{water}$) at time t . Obviously, $\lambda_{\text{salt},0} = \lambda_{\text{water},0}$ when $t=0$.

The normalization of the Bragg wavelength defines $\lambda_{\text{water},0}=0$ and $\lambda_{\text{salt},t \rightarrow \infty}=1$. It is easy to find out that $\gamma=1$ when $t \rightarrow \infty$. Therefore,

$$\lambda_{\text{salt},\infty} = \lambda_{\text{water},0} + \left[1 - (1 - S) \operatorname{erf}\left(\frac{r}{\sqrt{4Dt}}\right) \right]. \quad (7)$$

Due to the limitations of the measurement apparatus (i.e., resolution of the optical spectrum analyzer) and finite measurement time in practical applications, the value of γ deviates from 1. Figure 3(a) shows the experimentally observed time-dependent evolutions of the normalized Bragg wavelengths of the polyimide-coated gratings with different coating thicknesses transferred from an environmental salin-

ity of 0% to 20% in solution. For the FBG-A, -B, -C, and -D, the diffusion times observed from the times needed for the transmission spectra of the gratings to be stabilized were 38, 70, 110, and 160 min, respectively. By using Eq. (6) and the diffusion coefficient D of $10^{-12} \text{ m}^2/\text{s}$,¹⁴ the values of γ corresponding to FBG-A, -B, -C, and -D can be calculated to be 1.06, 1.08, 1.10, and 1.11, respectively. This increasing proportional coefficient γ indicates that the same change in the environmental salinity induces a larger blueshift of the Bragg wavelength for a FBG with a thicker polyimide coating. Figure 3(b) depicts simulated time-dependent evolutions of the normalized shifts in the Bragg wavelengths of the four polyimide-coated FBGs, calculated with Eq. (5) or Eq. (6). Both the experimental results and analysis demonstrate that the grating with a thicker polyimide coating has a longer response time and a higher sensitivity. Due to the separate measurement for each data point in Fig. 3(a) over a time interval, the experimental data exhibit a reasonable fluctuation, as compared with the smooth simulated curves in Fig. 3(b).

In conclusion, we have revealed the sensitivities and time responses of polyimide-coated FBGs as well as the factors influencing these properties for applications as substance sensors. The water diffusion process through the polymeric coating and its effect on the grating properties have been modeled and analyzed, which is in good agreement with the experimental results. The sensitivity of the grating is strongly dependent on the coating thickness, while the response time is another parameter for detecting and quantifying different measurands. The technique to vary the polymer coating material and change the FBG specifications provides a general approach to tune the sensing responses of polymer-coated FBGs to satisfy different applications.

This work has been supported by the Natural Sciences and Engineering Research Council of Canada (NSERC DG312421-2008), Canada Research Chairs Program, Canada Foundation for Innovation, the Province of Newfoundland and Labrador, and the Memorial University of Newfoundland.

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