Intelligent multiparameter sensing with fiber Bragg gratings

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An approach to achieve intelligent sensing of multiple environmental parameters with a single-fiber sensor system is demonstrated through the use of multiplexed fiber Bragg gratings (FBGs) with coatings of different polymers and specifications. Using three FBGs of either acrylate or polyimide coating and polyimide coatings of different thicknesses, *in situ* discrimination of saccharinity, salinity, and temperature from the changes in the optical responses of the Bragg wavelengths of the gratings has been realized with sensitivities of 1.10×10^{-3} nm/%, 3.80×10^{-3} nm/% (blueshift), and 1.10×10^{-2} nm/°C (redshift), respectively. © *2008 American Institute of Physics*.
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Fiber Bragg gratings (FBGs) have been used as sensors for the measurement of many environmental parameters[1] including temperature,[2] strain,[3] vacuum,[4] and flow[5] as well as chemical sensors for detecting chemical species.[6] In these applications, the measurand or the material to be measured needs to be known in advance as the cross sensitivity effects exist in the gratings as well as different responses of the gratings to different measurands. In many cases, the material system to be investigated is not monocomponent, in which parameters unique to specific components need to be distinguished as well as different extents in the responses of different components to the same parameters. FBG sensors reported so far are predominantly designed for the measurement of one or two parameters, especially for the measurement of strain and temperature.[7,8] Only a few papers have reported the measurement of three parameters.[9–14] Techniques to perform simultaneous measurements of strain, temperature, and vibration for structural health monitoring were reported by the use of a wavelength-multiplexed in-fiber-Bragg-grating/fiber-Fabry–Pérot sensor system[9] or a FBG/extrinsic Fabry–Pérot interferometer hybrid sensor system with a wavelength-swept fiber laser or laser diode combined through a wavelength division multiplexer (WDM),[10] or a fiber core with a plurality of Bragg grating elements wherein the grating elements comprise a periodic or a quasiperiodic modulated microcrystalline and rigid silicon dioxide tetrahedral structure.[11] Multiple parameter vector bending and temperature sensors based on asymmetric multimode or polarization maintaining single-mode FBGs inscribed by an infrared femtosecond laser were reported.[12,13] A technique has been recently developed to separate longitudinal loading, transverse loading, and temperature change by using a dual Bragg grating fiber sensor.[14] These techniques utilized either complicated configurations (interferometry and WDM) or special materials and structures in the fiber cores (microcrystallines), or special grating fabrication techniques (femtosecond lasers) in order to distinguish specific measurands, which resulted in bulky sensor systems restricted for special applications. Realization of simultaneous multiparameter sensing by FBGs with technically easy accessible approaches persists to be a challenge with significant merits of high integration, versatility, and low cost.

In this paper, an approach to achieve intelligent sensing of multiple environmental parameters with FBGs of different polymer coatings and specifications is proposed. As a demonstration of this approach, simultaneous measurements of saccharinity, salinity, and temperature have been achieved with a single-fiber sensor system, in which two FBGs are coated with polyimide layers of different thicknesses and the other one is coated with an acrylate layer. Since the standard FBG fabrication technique needs to strip the protective plastic coating off the fiber before grating inscription and recoat a polymeric layer afterward 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 the reported literatures, this approach realizes one-fiber solution for versatile applications of the FBGs rather than single specialized use.

According to the relation $\lambda_B=2n_{\mathrm{eff}}\Lambda$, 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. Both n_{eff} and Λ are sensitive to changes in strain and temperature. The fractional Bragg wavelength shift $\Delta\lambda_{B,T}$ corresponding to a temperature change ΔT can be written as $\Delta\lambda_{B,T}=\lambda_B(\alpha+\zeta)\Delta T$, where α is the thermal expansion coefficient of the fiber and the quantity ζ represents the thermo-optic coefficient.[15] The fractional Bragg wavelength shift $\Delta\lambda_{B,S}$ related to the strain effect $\Delta\varepsilon$ can be expressed as $\Delta\lambda_{B,S}=\lambda_B(1-\hat{P}_e)\Delta\varepsilon$, where $\hat{P}_e$ is an effective photoelastic constant.[15] We recently reported that a polyimide-coated grating responds to the variations in both temperature and salinity while an acrylate-coated grating is sensitive to the environmental temperature only.[16] The different responses of these acrylate- and polyimide-coated FBGs lie in the differences in the thermo-optic and elasto-optic performances of their coatings. The technique of using a polyimide-coated FBG to detect salinity can be generalized to detect other analytes (for example, saccharinity) in solution. However, in case several substances coexist in the solution, it becomes indiscernible if only the change in the Bragg wavelength is

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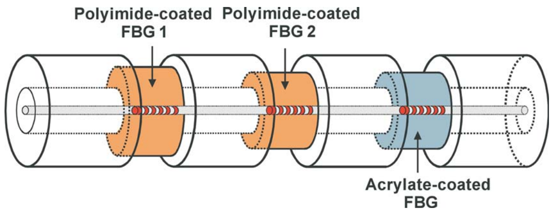

FIG. 1. (Color online) Illustration of multiplexed FBGs coated with different polymers.

monitored. In order to distinguish these different substances, FBGs with different polyimide coating thicknesses are employed in this study.

As shown in Fig. 1, three 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 dip coating, respectively. The acrylate and polyimide materials used for coating were DSM950–200 (Fiber Optic Center™, Inc.) (Ref. 17) and PI2525 from HD MicroSystems L.L.C.,[18] respectively. The details on the preparation of the acrylate-coated FBG sample have been described elsewhere.[16] The polyimide coatings were prepared by dip coating with a translation stage (ATS100) through a motion controller (U511, Aerotech, Inc.). Polyimide layers of different thicknesses can be obtained 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 in this study were 25 and 20 μm for the two polyimide-coated gratings and 20 μm for the acrylate-coated one. Figure 2(a) shows the transmission spectrum of the polyimide-coated FBG1 with a coating thickness of 25 μm at different saccharinities with an initial Bragg resonance of 1551.488 nm and a reflection signal of 8.18 dB in water. If the saccharinity of the solution is changed without the presence of salinity at 20 °C, the Bragg wavelength will blueshift and the Bragg wavelength of the polyimide-coated FBG as a function of saccharinity is shown in the inset of Fig. 2(a), which indicates a saccharinity sensitivity ΔS_{ac} of -1.10×10^{-3} nm/%. Figure 2(b) shows the dependence of the shift in the Bragg wavelength on the saccharinity and salinity in which both of the two parameters are varied independently. The salinity sensitivity ΔS_{al} of the polyimide-coated FBG1 is calculated to be -3.80×10^{-3} nm/%. The figure clearly indicates that any change in either saccharinity or salinity, or the combination of them will result in the blueshift of the Bragg wavelength; however, it is impossible to distinguish the contribution from each factor using the single polyimide-coated FBG. A similar measurement of the dependence of the shift in the Bragg wavelength on the saccharinity and salinity was performed on a polyimide-coated FBG2 with a polyimide thickness of 20 μm at 20 °C as shown in Fig. 3. The saccharinity and salinity sensitivities of this FBG are -0.73×10^{-3} and -2.95×10^{-3} nm/%, respectively. Figure 4 shows the Bragg wavelength shifts of the three FBGs (redshifted) as a function of temperature and the inset gives the transmission spectra of the acrylate-coated FBG at different temperatures. The temperature sensitivities ΔT of the acrylate-coated FBG and the polyimide-coated

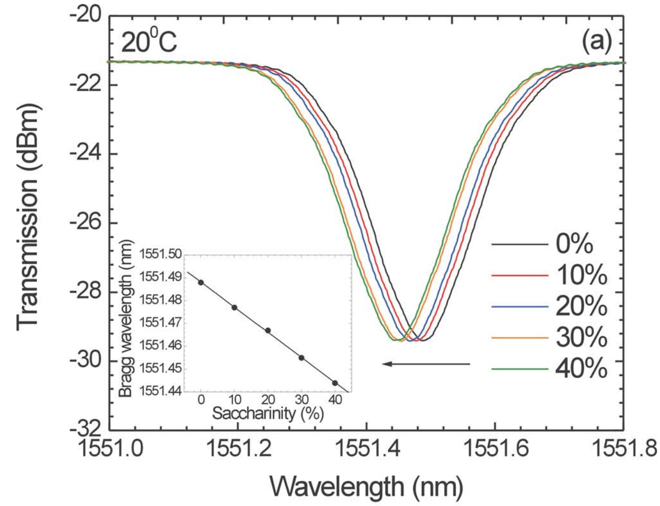

FIG. 2. (Color online) Polyimide-coated FBG for simultaneous saccharinity and salinity measurements (coating thickness 25 μm): (a) transmission spectra at different saccharinities with the inset on the Bragg wavelength as a function of saccharinity and (b) shifts in the Bragg wavelength in response to the independent changes in saccharinity and salinity.

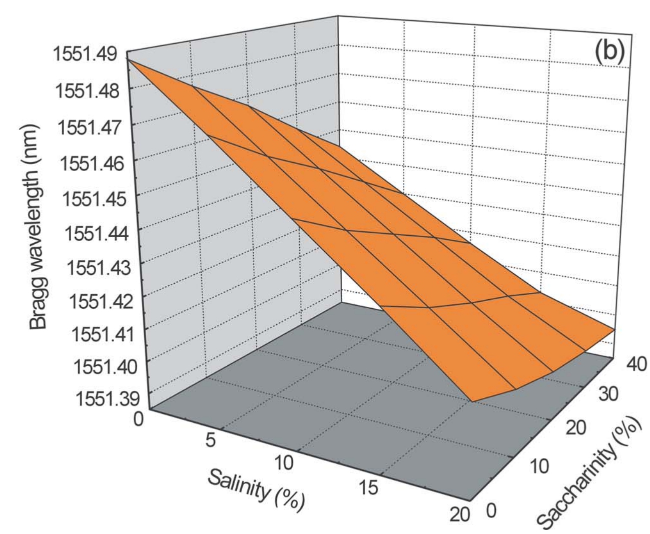

FIG. 3. (Color online) Polyimide-coated FBG for simultaneous saccharinity and salinity measurements (coating thickness 20 μm) with shifts in the Bragg wavelength in response to the independent changes in saccharinity and salinity.

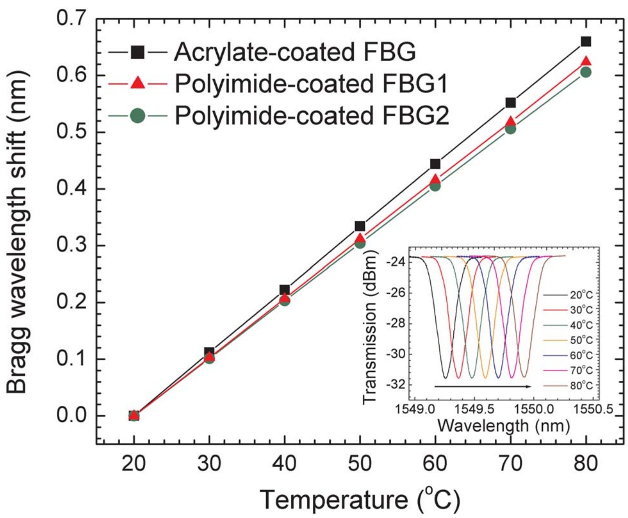

FIG. 4. (Color online) Dependences of the shifts in the Bragg wavelengths of the acrylate- and polyimide-coated FBGs on temperature. The inset shows the redshifting transmission spectra of the acrylate-coated FBG with increasing temperature.

FBG1 and FBG2 in water were found to be 1.10×10^{-2}, 1.04×10^{-2}, and 1.01×10^{-2} nm/°C, respectively. The sensing responses of these FBGs have been observed to be reversible and the reset of the responses can be realized by placing the gratings in de-ionized water.

The experiment of simultaneous measurements of saccharinity, salinity, and temperature indicates that not only the different polymeric coating materials will affect the FBG sensing performance, but for the same polymeric coating material, different thicknesses of the coating will modify the grating sensitivities of the environmental parameters as well. The shifts in the Bragg resonance wavelengths of the FBGs discussed here can be expressed as

$$\begin{bmatrix}\Delta\lambda_{\text{acrylate}}\\ \Delta\lambda_{\text{polyimide1}}\\ \Delta\lambda_{\text{polyimide2}}\end{bmatrix} = \begin{bmatrix}1.10\times10^{-2} & 0 & 0\\ 1.04\times10^{-2} & -1.10\times10^{-3} & -3.80\times10^{-3}\\ 1.01\times10^{-2} & -0.73\times10^{-3} & -2.95\times10^{-3}\end{bmatrix} \times\begin{bmatrix}\Delta T\\ \Delta S_{\text{ac}}\\ \Delta S_{\text{al}}\end{bmatrix} = M_{\text{TSS}}\begin{bmatrix}\Delta T\\ \Delta S_{\text{ac}}\\ \Delta S_{\text{al}}\end{bmatrix}, \tag{1}$$

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

$$\begin{bmatrix}\Delta T\\ \Delta S_{\text{ac}}\\ \Delta S_{\text{al}}\end{bmatrix} = M_{\text{TSS}}^{-1}\begin{bmatrix}\Delta\lambda_{\text{acrylate}}\\ \Delta\lambda_{\text{polyimide1}}\\ \Delta\lambda_{\text{polyimide2}}\end{bmatrix}. \tag{2}$$

In this case, a character matrix M_{TSS} can be used to determine the absolute values of the saccharinity, salinity, and temperature from the shifts of the Bragg wavelengths of the three gratings. When this approach is extended to a general case of distinguishing multiple measurands, the character matrix M for quantifying multiparameters becomes

$$\begin{bmatrix}\Delta P_1\\ \Delta P_2\\ \vdots\\ \Delta P_n\end{bmatrix} = \begin{bmatrix}M_{11} & M_{12} & \cdots & M_{1n}\\ M_{21} & M_{22} & \cdots & M_{2n}\\ \vdots & \vdots & \vdots & \vdots\\ M_{n1} & M_{n2} & \cdots & M_{\text{nn}}\end{bmatrix}\begin{bmatrix}\Delta\lambda_1\\ \Delta\lambda_2\\ \vdots\\ \Delta\lambda_n\end{bmatrix} = M^{-1}\begin{bmatrix}\Delta\lambda_1\\ \Delta\lambda_2\\ \vdots\\ \Delta\lambda_n\end{bmatrix}, \tag{3}$$

in which P_1, P_2,…, and P_n stand for multiple parameters to be measured such as strain, temperature, force, and displacement or pressure, and $\Delta\lambda_1$, $\Delta\lambda_2$,…, and $\Delta\lambda_n$ correspond to the shifts in the Bragg wavelengths of multiple FBGs with different polymeric coatings and thicknesses. Once the sensor system is calibrated, the operation of the sensor does not require prior knowledge of the measurands or materials to be measured; thus, an intelligent sensing is achieved.

In conclusion, we have proposed and demonstrated an approach to realize intelligent multiparameter sensing with FBGs of different coating materials and specifications. As an application of the approach realizing simultaneous measurements of saccharinity, salinity, and temperature, the FBG system can be employed as a substance or chemical sensor for trace analysis. The technique to vary the FBG coating material and specifications provides us with an opportunity to realize in-fiber sensors with unprecedented high degree of integration, versatility, multiplexiability, quasidistribution measurement, compatibility with the existing fabrication techniques, and low cost.

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