Intelligent Multiparameter Fiber-Optic Sensing for Ocean Observation

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Abstract

With the increasing needs for the protection of marine and fresh water environment, there is surging demand for effective technologies to monitor different environmental parameters. Among different new technologies, fiber-optic sensing technology has found its unique roles in the measurement of different environmental parameters with advantages such as immunity to electromagnetic interference, compact size, low cost, and the possibility of distributed measurement over a long distance. In this study, we demonstrate a novel approach to realize intelligent multiparameter fiber-optic sensing to achieve simultaneous measurement of temperature and other parameters for marine observation, including salinity, flow rate, and chemical sensing. The temperature sensitivities of the acrylate and polyimide-coated fiber sensors are 0.0102 and 0.0094 nm/°C, respectively. The salinity sensitivity of the fiber sensor on potassium chloride concentration is 0.0126 nm/M.

Keywords: fiber-optic sensing, ocean observation, environmental monitoring

Introduction

With the increasing needs for the protection of marine and fresh water environment, there is surging demand for effective technologies to monitor different environmental parameters (Smith, 2001). In addition to its powerful roles in modern telecommunications, fiber-optics, in particularly, fiber-optic sensing technologies, have found their unique roles in the measurement of different environmental parameters with advantages such as immunity to electromagnetic interference, compact size, low cost, and the possibility of distributed measurement over a long distance (Kuzyk, 2006 and Graham-Rowe, 2007).

For environmental conservation, food industries, and biomedical applications, *in situ* monitoring of different physical, chemical, and biological parameters in water is of great importance, in which versatile sensors are highly demanded to achieve simultaneous measurement of temperature and other parameters, for example, salinity, flow rate, and chemical composition. Monitoring of chemical composition could include concentrations of water-soluble substances such as metal ions, metal compounds, and chemical traces. Majority of commercial instruments are only capable of monitoring single parameter. However, in practical applications, multiparameter sensing achieved by single sensing system is highly preferred.

In this study, we demonstrate a novel approach to realize intelligent multiparameter fiber-optic sensing to achieve simultaneous measurement of temperature and other parameters for marine observation including salinity, flow rate, and chemical sensing. The temperature sensitivities of the acrylate and polyimide-coated fiber sensors are 0.0102 and 0.0094 nm/°C, respectively. The sensitivity of the fiber sensor on potassium chloride concentration is 0.0126 nm/M.

Experimental Details

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. FBGs have been used as sensors for measurement of many environmental parameters including temperature, strain, vacuum, and flow [Chen, 2005 and 2006]. For environmental conservation, food industries, and biomedical applications, *in situ* monitoring of physical, chemical, and biological parameters in water is of great importance, in which versatile sensors are highly demanded to achieve simultaneous measurement of temperature and different chemical parameters, for example, concentrations of water-soluble substances including sugar, metal ions, metal compounds, and chemical traces. In practical applications, it is necessary for the sensor system to be capable of measuring more than one of these parameters.

This paper reports a new scheme constructed with two different polymer-coated FBGs to achieve simultaneous measurement of temperature and salinity of solutions with different concentrations of water-soluble substances such as potassium chloride (KCl). Previous research on the use of FBG sensors to measure the concentrations of soluble substances adopted etched fibers to measure the refractive indices of the materials. Bennion *et al.* (Zhou, 2004 and Chen, 2004) proposed a dual-parameter optical sensor based on a hybrid long-period grating – FBG structure in a D fiber to deduce the concentration of an aqueous sugar solution from the measurement of its refractive index. Iadicicco *et al.* (2005 and 2006) reported the use of non-uniform thinned FBGs for self- temperature compensated refractive index measurement. Lu *et al*. (2009) recently reported the simultaneous measurement of the refractive index and temperature by using a tapered fiber Mach-Zehnder interferometer. However, in these techniques, part of the cladding layer was removed by wet chemical etching in a buffered hydrofluoric acid (HF) solution or the fiber is tapered, which made the sensors to be more fragile and susceptible to damage by external force. In the approach reported here (Fig. 1), two polymer materials, i.e., polyimide and acrylate, are used as the fiber coating materials. Polyimide and acrylate have excellent strength and can resist breakage, which are innocuity and harmless to human-beings and the environment. In order to measure the concentrations of water-soluble substances in addition to the simultaneous measurement of temperature, two FBGs have been adopted in this sensor system, in which an acrylate-coated FBG is not sensitive to KCl concentration and functions as a temperature sensor, while a polyimide-coated FBG is sensitive to KCl concentration and acts as a substance sensor. The experimental results indicate that other water-soluble substances can also be detected by this sensor system.

A standard telecommunication single-mode optical fiber (Corning SMF-28) was soaked in high-pressure hydrogen atmosphere (1900 psi) at room temperature for 2 weeks and then stored in a freezer at -70 ℃ before use. Two FBGs with a grating length of 1 cm for each were inscribed on the hydrogen-loaded fiber using a KrF excimer laser and a phase mask. After the grating fabrication, the FBG sample was baked at 150 ℃ for overnight to eliminate the residual hydrogen and the unstable UV-induced index changes. One section of the grating area was then recoated with polyimide polymer while the other grating area recoated with acrylate polymer. The recoating process resulted in a fiber diameter of 173 μm at the grating section. From an optical microscopy, the thickness of the polyimide coating was observed to be 24.1 ± 1.0 μm. The transmission spectrum of the FBG sensor system, as measured by an optical spectrum analyzer (Ando 6315E), is shown in Fig. 2, indicating two Bragg wavelengths at 1549.020 and 1550.244 nm with reflection signals of 9.24 and 13.47 dB. The two Bragg wavelengths correspond to the acrylate- and polyimide-coated FBGs, respectively. In the study of the temperature response of the FBG sensor, a microcomputer-controlled water bath was used to control the variations of the environmental temperature, in which the water is the corresponding ambient medium. When the two sections of the polymer-coated FBGs had been completely immersed in the water bath, certain amount of KCl was added into the water to adjust the concentration of the solution and then the relationship between the salinity (concentration of KCl) and the Bragg wavelengths of the FBG sensor will be measured.

Figure 1. Illustration of fiber Bragg gratings coated with different polymers for sensing.

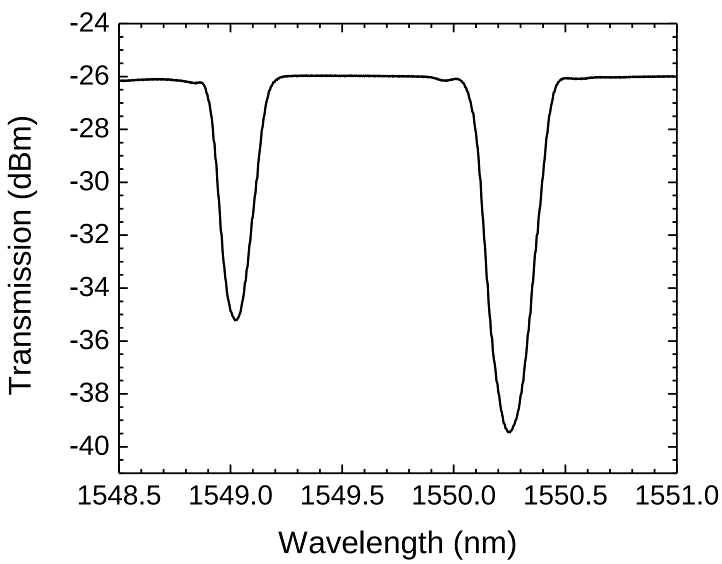

Figure 2. Transmission spectrum of the FBG sensor used in this study. The Bragg resonance wavelengths for the acrylate- and polyimide-coated gratings are 1549.020 and 1550.244 nm, respectively.

Results and Discussion

Measurement of Temperature Sensing Performance

In order to eliminate the strain or bending cross effects, the section of the polyimide-coated grating was fixed and tightened during the temperature sensing measurement. When the polyimide-coated FBG was transferred from an environmental chamber with the ambient medium of air to the water bath at a constant temperature of 20^{o}C, it was found that the Bragg wavelength red-shifted from 1550.218 to 1550.408 nm and stabilized after half an hour. The increase in the Bragg wavelength was due to the expanding grating period, which was caused by the stretched fiber. After the transmission spectrum of the polyimide-coated FBG in the water bath stabilized, the Bragg wavelength red-shifted from 1550.430 nm to 1551.088 nm when the temperature was increased from 20^{o}C to 90^{o}C (Fig. 3). The temperature coefficient of the polyimide-coated FBG in water, k_{Twater}, can thus be calculated as 0.0094 nm/℃. Following the same procedure mentioned above, the temperature response of the acrylate-coated FBG in water was also studied. During the process of transferring the acrylate-coated FBG from the environmental chamber to the water bath, no apparent shift in the Bragg wavelength was found while the temperature coefficient in water, k_{Twater}, was measured to be 0.0102 nm/^{o}C, as shown in Fig. 3.

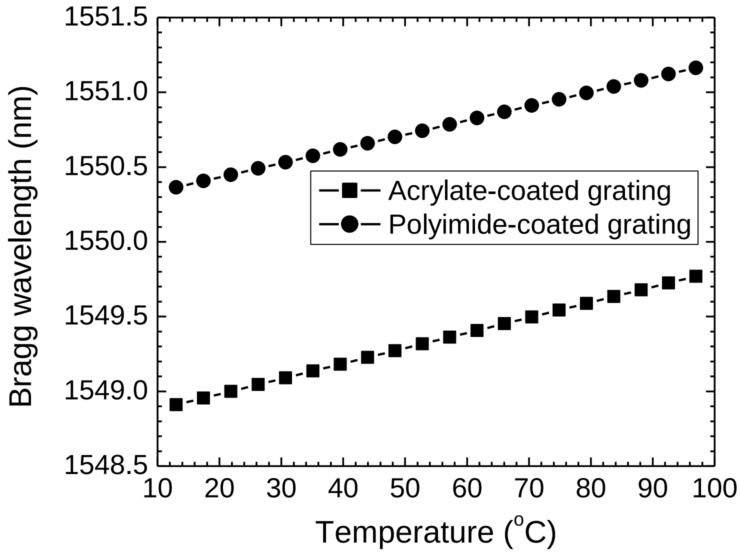

Figure 3. Bragg wavelengths of the acrylate- and polyimide-coated FBGs as a function of temperature in the water bath.

Measurement of Salinity in Water

After both of the polyimide- and acrylate-coated FBGs had been completely immersed in the water bath with a constant temperature of 20^{o}C for half an hour, a certain amount of KCl powder was added into the water to adjust the salinity of the water solution. When the KCl powder was added into the water bath, the water concentration surrounding the grating decreased, which resulted in the decrease of the corresponding water concentration in the polyimide coating. In the experiments, for each time the KCl powder was added, sufficient waiting time was allowed to make the FBG spectrum immovability. Figure 4 shows the Bragg wavelengths of the two FBGs as functions of the salinity of the solution. The sensitivity decreases when the polyimide-coated FBG is exposed to solutions of higher KCl concentrations as the solubility approaches saturation. It shows that the average sensitivity of the polyimide-coated KCl on sugar concentration is 0.0126 nm/M.

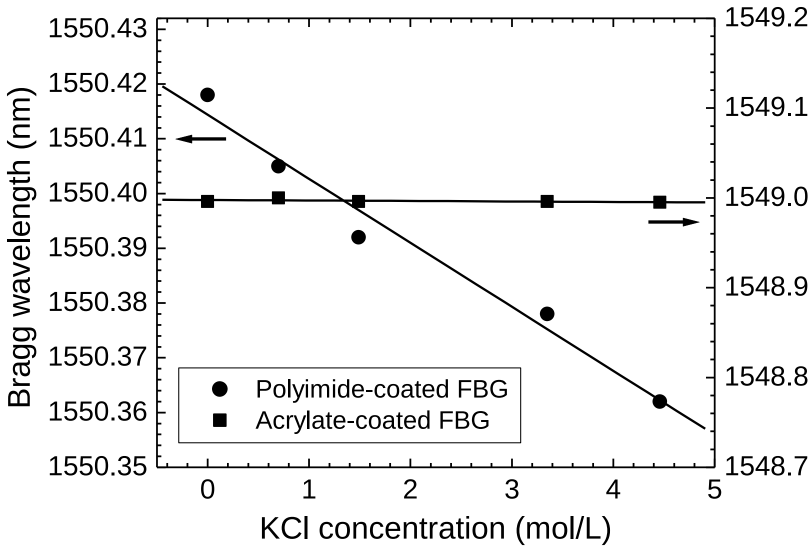

Figure 4. Bragg wavelengths of polyimide- and acrylate-coated FBGs as functions of KCl concentration.

The shrinkage of the polyimide coating in KCl solutions results in the blue-shift of the Bragg wavelength of the polyimide-coated FBG, as shown in Fig. 4. In contrast, the acrylate-coated FBG is not sensitive to the change of salinity. The dependence of the Bragg wavelengths of the FBGs on the temperature and KCl concentration, ΔC_{KCl} , can be described with a matrix equation:

$$\begin{bmatrix} \Delta\lambda_{\text{acrylate}} \\ \Delta\lambda_{\text{polyimide}} \end{bmatrix} = \begin{bmatrix} 0.0102 & 0 \\ 0.0094 & -0.0126 \end{bmatrix} \begin{bmatrix} \Delta T \\ \Delta C_{\text{KCl}} \end{bmatrix} \tag{1}$$

where $\Delta\lambda_{\text{acrylate}}$ and $\Delta\lambda_{\text{polyimide}}$ are the shifts in the Bragg wavelengths of the acrylate- and polyimide-coated FBGs, respectively. ΔT and ΔC_{KCl} stand for the changes in temperature and KCl concentrations, respectively. The positive and negative signs of the matrix elements correspond to the red- and blue-shifts of the Bragg wavelengths of the gratings, respectively.

Since the sensing mechanism of the FBG sensor discussed here is based on the hygroscopic properties of the polyimide coating, water-soluble substances other than the concentration of KCl could have the similar swelling effects on the polyimide coating. However, different substances will result in different extents of responses manifested in the changes of the Bragg wavelengths. Therefore, it is possible to detect other soluble substances with the same sensor system. In order to validate the feasibility, an experiment on the determination of the saccharinity of a solution has been performed, which also shows the blue-shift of the Bragg wavelength indicating the shrinkage of the polyimide coating in sugar solutions. However, the Bragg wavelength of the acrylate-coated FBG is not sensitive to the change in saccharinity. This study demonstrates that not only salinity but also saccharinity can be identified by the FBG sensor. Furthermore, it can distinguish different soluble materials from the difference in the corresponding concentration sensitivities. For a general case described by Eqn. (2), a character matrix M_{TA} related to the sensitivities of measurands is defined to represent the sensing performance of the sensor system, for example, temperature and specific material, and different character matrix M_{TA} can be used to determine different species and the concentration of the material.

$$\begin{bmatrix} \Delta\lambda_{\mathrm{acrylate}} \\ \Delta\lambda_{\mathrm{polyimide}} \end{bmatrix} = M_{\mathrm{TA}} \begin{bmatrix} \Delta T \\ \Delta C \end{bmatrix} \tag{2}$$

This scheme offers a number of advantages over other techniques to discriminate different substances. With the FBG sensor system proposed here, it is possible to measure different water-soluble materials by utilizing the polyimide-coated FBG while simultaneously measure the temperature with the acrylate-coated FBG. For other parameters, such as Na^+, Li^+, and Ca^{2+} ions, that can swell the polyimide coating in solutions, the same FBG sensor system discussed here can differentiate and quantify these substances from the different responses of the grating (sensitivity, rate, etc.) once a calibration curve for different substances is developed. Since the FBG fabrication process and recoating technique required for the sample preparation are quite simple, the approach proposed here is promising to realize low-cost substance sensors in ocean environment. In addition, it is possible to introduce more wavelength channels other than two in this study to realize quasi-distributed measurement, thus enables a possibility to realize three-dimensional mapping of the ocean parameters. Our study also demonstrated that such a fiber-optic sensing technique is also capable to achieve simultaneous measurement of flow rate and direction in water [Lu, 2008].

Conclusions

In our study, we demonstrate a novel approach to realize intelligent multiparameter fiber-optic sensing to achieve simultaneous measurement of temperature and other parameters for marine observation, which can also be used for chemical sensing and flow measurement. The temperature sensitivities of the acrylate and polyimide-coated fiber sensors are 0.0102 and 0.0094 nm/°C, respectively. The salinity sensitivity of the fiber sensor on potassium chloride concentration is 0.0126 nm/M. The technique reported here is a one-fiber solution to achieve multiparameter sensing without prior knowledge once a calibration curve is developed. The technique is also promising to be used as a real-time sensing system to monitor oil spill in ocean.

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