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Temperature Compensated Solution Concentration Measurement Based on a Cascaded SMS/LPFG Fiber Structure

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Abstract

In this paper, a hybrid optical fiber structure for solution concentration measurement with the temperature compensation is proposed. The structure consists of long period fiber grating (LPFG) and single mode-multimode-single mode (SMS) fiber structures. The sensing mechanism of the device is studied and verified by experiments. LPFG is sensitive to solution concentration and is affected by temperature crosstalk. SMS structure is not affected by solution concentration, but sensitive to ambient temperature. It can be used as a temperature compensation system. The sensitivity coefficients of LPFG and SMS on temperature and concentration were measured experimentally, and a dual-wavelength matrix was established to realize simultaneous measurement of solution temperature and concentration.

Keywords

Long Period Fiber Grating, Multimode Mode Fiber, Solution Concentration, Temperature, Dual-Wavelength Matrix

1. Introduction

Corrosion is the destruction or deterioration of materials or their properties in the environment. Salt spray corrosion is one of the most common and destructive forms of corrosion. Salt fog here refers to chloride, its main component is chloride salt-sodium chloride (NaCl) [1] [2] [3]. Therefore, it is very important to measure the concentration of NaCl to monitor the corrosion intensity, so as to avoid the impact of corrosion in engineering. In practical engineering, it is inconvenient and lack of real-time to collect samples manually to measure the concentration of NaCl in salt spray or solution. LPFG has the advantages of being sensitive to the surrounding refractive-index, low insertion loss and working in high corrosive and dangerous environment. In addition, LPFG can be easily connected with computer and optical fiber transmission system for real-time measurement [4] [5]. Monitoring the liquid concentration by LPFG can not only save the labor of manual sampling, but also detect the concentration accurately in real time. Accurate measurement and on-site monitoring of liquid concentration are very important in chemical and biological fields. However, in the process of measurement, liquid concentration measurements are unreliable because temperature changes will interfere with the sensor. The influence of temperature change on the accuracy of concentration measurement is eliminated. In this paper, we propose a simple and feasible hybrid fiber structure, LPFG and SMS fiber cascade. LPFG will be affected by change of temperature and solution concentration, while SMS structure is only affected by temperature and is insensitive to the solution concentration. It can be used as a temperature compensator to eliminate the influence of temperature changes when measuring concentration.

2. Experimental Principle

The LPFG couples the core mode (LP_{01}) to the cladding modes of the same azimuthally symmetry (LP_{0m}). Here, the resonance wavelength λ_D^m satisfying the phase-matching condition is given by,

$$\lambda_D^m = (n_{eff}^{co} - n_{eff}^{cl,m}) \cdot \Lambda \tag{1}$$

where λ_D^m is the resonance wavelength, Λ is the periodicity of the grating, n_{eff}^{co} and $n_{eff}^{cl,m}$ are the effective refractive indices in the core and cladding respectively. n_{eff}^{co} is determined by core radius a_1, core refractive index n_1 and cladding refractive index n_2, $n_{eff}^{cl,m}$ is determined by core and cladding radius a_1, a_2 and refractive index of core, cladding and external environment n_1, n_2, n_3. The parameters a_1, a_2, n_1, n_2, n_3 remain unchanged, and λ is determined only by the refractive index of the external environment. When the refractive index of the solution to be measured changes and n_3 becomes n_3', the expression of the relationship between the central wavelength shift of LPFG and the refractive index of the external environment is obtained as follows Formula (2). There is a linear relationship between the concentration and the refractive index of solution [6] [7] [8].

$$\Delta\lambda = \lambda' - \lambda_0 = \frac{U_\infty^2}{n_2 a_2^3 K^3}\left(\frac{1}{\sqrt{n_2^2 - n_3^2}} - \frac{1}{\sqrt{n_2^2 - n_3'^2}}\right) \tag{2}$$

Since the effective refractive index of the fundamental mode and cladding modes, and grating period are all functions of temperature, the two sides of the Formula (1) are divided into temperature (T) differential and λ_D^m is replaced by λ_{res}^m. The temperature sensitivity of LPFG is [9] [10],

$$\frac{d\lambda_{res}^m}{dT} = \left(\frac{dn_{eff}^{co}}{dT} - \frac{dn_{eff}^{cl,m}}{dT}\right)\Lambda + \left(n_{eff}^{co} - n_{eff}^{cl,m}\right)\frac{d\Lambda}{dT} \tag{3}$$

In the SMS structure, the fundamental mode transmitted in single mode fibers is coupled to multimode fibers, which excites the fundamental modes and higher modes in multimode fibers. Different modes interfere in the multimode core which results in the energy redistribution. The final interference optical spectrum is determined by multiple mode interferences [11]. When the temperature changes, the multimode optical fibers are affected by thermal optic effect and thermal expansion effect. The relationship between the coupling wavelength of SMS structure and temperature is expressed as follows [12],

$$\frac{\Delta\lambda_{T,SMS}}{\lambda_0} = \frac{\partial n_{co}}{n_{co}}\frac{\Delta T}{\partial T} + 2\frac{\partial a}{a\partial T}\Delta T - \frac{\partial L}{L\partial T} = \left(a_{MMF} + \xi\right)\cdot\Delta T \tag{4}$$

where λ_0 is the central wavelength, n_{co} is the effective refractive index of multimode fiber, a is the core radius of multimode fiber, L is the length of multimode fiber, α and ξ are the thermal expansion coefficient and thermal-optical coefficient of multimode fiber, respectively.

Temperature and concentration coefficients of SMS and LPFG were measured respectively and substituted into Formula (5) to form a dual-wavelength matrix. The unique variation of temperature and concentration in solution environment was determined according to the simultaneous variation of two wavelengths.

$$\begin{bmatrix}\Delta\lambda_{LPFG}\\ \Delta\lambda_{SMS}\end{bmatrix} = \begin{bmatrix}K_{T_{LPFG}} & K_{RI_{LPFG}}\\ K_{T_{SMS}} & K_{RI_{SMS}}\end{bmatrix}\begin{bmatrix}\Delta T\\ \Delta RI\end{bmatrix} \tag{5}$$

3. Experimental Process and Measurement Results

In the measurement of LPFG Temperature and Solution Concentration, as shown in **Figure 1**, SLED broadband source (BBS) is used as the input. The waveform is smooth with the spectral width of 600 - 1700 nm, which meets the need of grating for light source modulation. Optical spectrum analyzer (OSA, AQ6317B) is used to receive the signal. The spectrum receiving range is 800 - 1700 nm, and the highest resolution is 0.01 nm. It can fully display the spectral characteristics of grating modulation. The temperature change of grating is realized by temperature control box.

In the experiment of solution concentration measurement, LPFG is fixed at both ends, connected with BBS and OSA respectively, and the grating is suspended in full contact with NaCl solution. The grating is placed in 1 L of clear

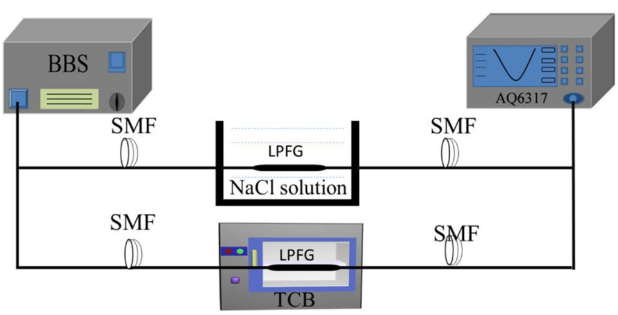

Figure 1. Measurement structure of LPFG temperature and concentration.

water, and NaCl is gradually added to change the concentration of solution. As shown in **Figure 2**, in the range of 0% - 17% concentration, with the increase of NaCl solution concentration, the central wavelength of the grating drifts to the short wavelength direction. For each change of solution concentration of 1%, the central wavelength drifts to the short wave direction averagely by 0.14 nm, which has a good linear relationship.

In the LPFG temperature measurement experiment, the temperature change of grating is realized by temperature control box. The temperature measurement range is 40˚C - 90˚C. As shown in **Figure 3**, with the increase of temperature, the coupling wavelength drifts to the long wavelength direction. The wavelength shift is 0.074 nm for each degree of temperature rise, and the linear fitting degree is 0.99.

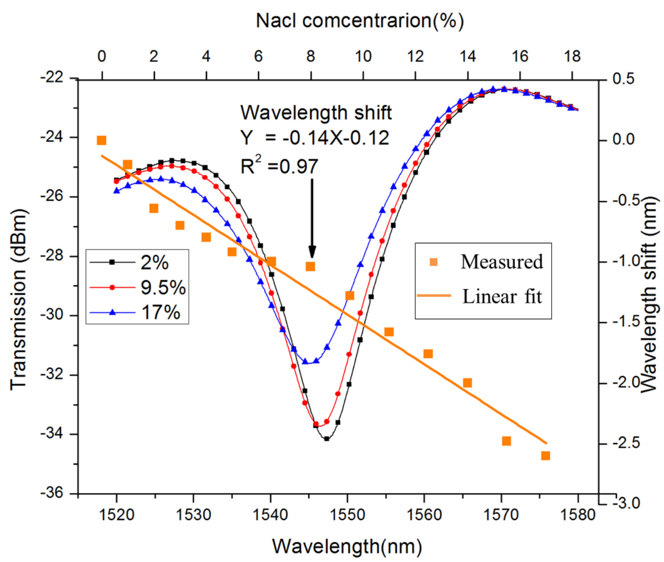

Figure 2. Measurement results of LPFG concentration.

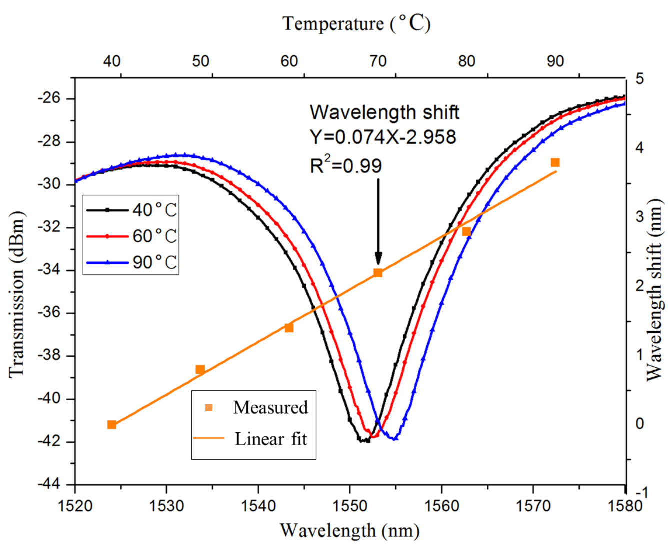

Figure 3. Measurement results of LPFG temperature.

As shown in **Figure 4**, single mode and multimode fibers are selected as the intermediate connecting fibers in this experiment. By manually adjusting the fusing machine, the single mode fibers are fused into the core of multimode fibers. More fundamental mode energy in single mode fibers can stimulate the high-order modes in multimode fibers, and the redistributed energy can be fully coupled output.

The temperature measurement step is the same as that of LPFG. The measured results are shown in **Figure 5**. With the increase of temperature, the coupling wavelength drifts to the short wavelength direction. The wavelength shift is 0.077 nm for each degree of temperature rise, and the linear fitting degree is 0.96.

The sensitivity parameters of LPFG and SMS structures are cascaded as shown in **Figure 6**.

The concentration coefficient $K_{RI_{LPFG}}$ of LPFG is 0.14 nm/%, the concentration coefficient $K_{RI_{SMS}}$ of SMS is 0, the temperature coefficient $K_{T_{LPFG}}$ of LPFG is 0.074 nm/˚C, and the temperature coefficient $K_{T_{SMS}}$ of SMS is −0.077 nm/˚C. Formula 6 can be obtained by substituting each sensitivity into the matrix.

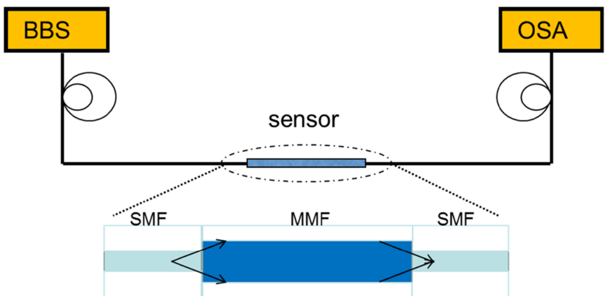

Figure 4. SMS structure.

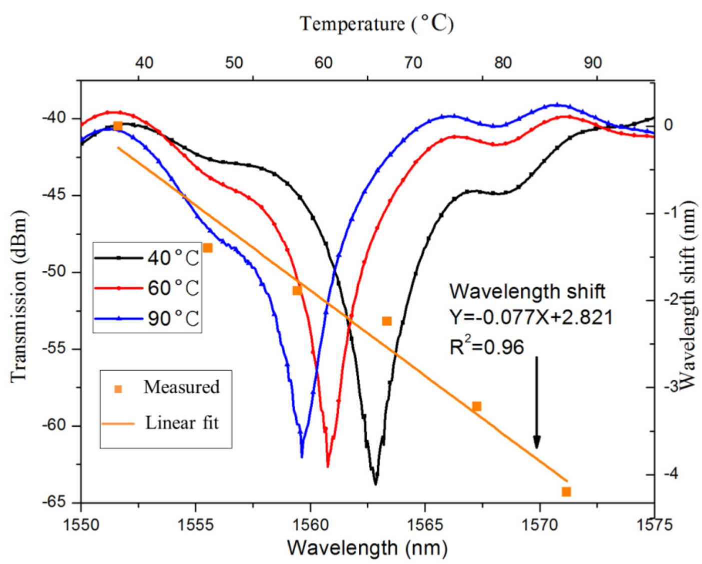

Figure 5. Measurement results of SMS temperature.

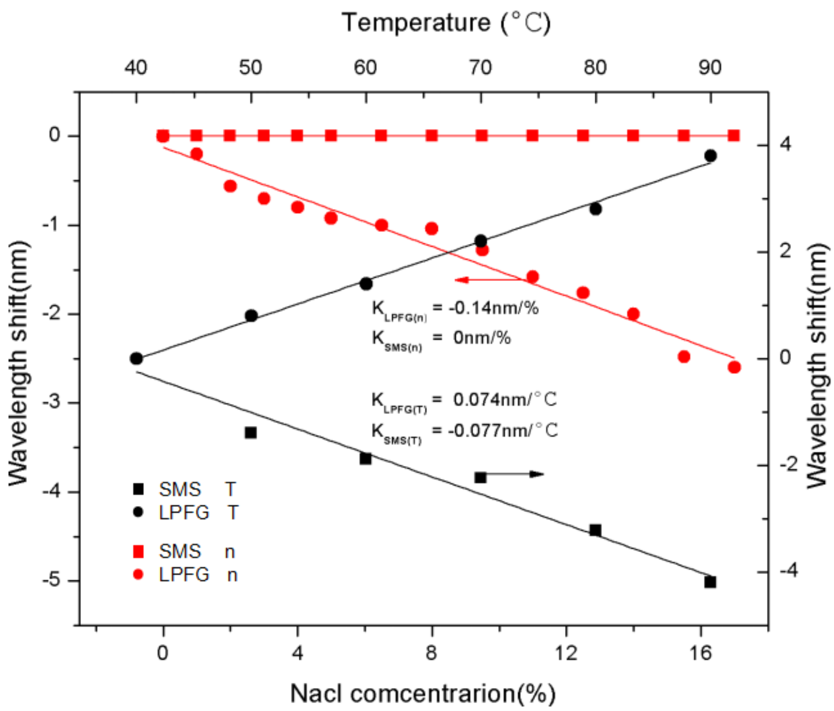

Figure 6. Cascade of sensitivity parameters for LPFG and SMS.

$$\begin{bmatrix} \Delta\lambda_{LPFG} \\ \Delta\lambda_{SMS} \end{bmatrix} = \begin{bmatrix} 0.074 & 0.14 \\ -0.077 & 0 \end{bmatrix} \begin{bmatrix} \Delta T \\ \Delta RI \end{bmatrix} \tag{6}$$

According to the change of coupling wavelength between LPFG and SMS, the change of solution concentration and temperature can be determined simultaneously when measuring solution concentration, thus eliminating the interference of temperature when measuring solution concentration.

4. Conclusion

In addition, a hybrid fiber structure composed of SMS structure and LPFG is proposed in this paper. The temperature-compensated solution concentration measurement is realized. The device solves the problem of temperature crosstalk when measuring solution concentration properly, and it has potential application prospects in biological and chemical domains. The center wavelength of LPFG will drift 0.14 nm in short wave direction with the concentration of NaCl solution changing by 1%. The coupling wavelength of SMS structure does not change with the change of NaCl concentration. The temperature coefficients of LPFG and SMS structures are 0.074 nm/˚C and −0.077 nm/˚C, respectively. A dual-wavelength matrix of sensitivity is constructed to realize simultaneous measurement of solution temperature and concentration.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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