Long-Period Grating Relative Humidity Sensor With Hydrogel Coating

Yang Liu, Liwei Wang, Min Zhang, Dongsheng Tu, Xianhui Mao, and Yanbiao Liao

***Abstract*—The long-period grating (LPG) coated with the hydrogel was investigated for monitoring the relative humidity (RH) levels—the ratio of the amount of water vapor in the air at a specific temperature to the maximum amount that the air could hold at that temperature. The experimental results showed that the resonant wavelength of the hydrogel-coated LPG was shifted when the RH varied from 38.9% to 100%, with a linearity of 99.5% and an accuracy of ±2.3% RH.**

***Index Terms*—Hydrogel, long-period grating (LPG), optical fiber sensors, relative humidity (RH).**

I. Introduction

Relative humidity (RH) has a significant impact on many fields such as corrosion monitoring in industry and foodstuff preservation in agriculture. The optical RH sensors can overcome many limitations of the electrical RH sensors, such as electromagnetic interference and the inability to measure humidity near 100%. The long-period grating (LPG) has periodic refractive index modulation in the core of a single-mode optical fiber. It couples light from the propagating core mode into the copropagating cladding modes at the discrete wavelengths, causing several attenuation bands in the fiber transmission. The resonant wavelength and amplitude of the LPG are very sensitive to the perturbation of the environment. So the LPG sensors have been used to measure strain, temperature [1], refractive index [2], or chemical concentration [3].

An RH sensor with fiber Bragg grating was presented with the sensitivity of $(2.21 \pm 0.10) * 10^{-3}$ nm/% RH and a high RH sensor using gelatin-coated LPG was reported in [5] with the measurement range from 90% to 100%. In this letter, a hydrogel-coated LPG RH sensor was demonstrated to measure the RH with the range from 38.9% to 100%. Instead of the traditional three-layered step index waveguide model, a four-layered model was used to analyze the influence of the index of the thin hydrogel film of various component proportions. The results of the experimental investigation showed that the hydrogel-coated LPG RH sensor can be used in a wide range from 38.9% to 100%, with an accuracy of ±2.3% RH.

II. Theoretical Analysis

Usually, we use the resonance wavelength as the sensing parameter when we are using the LPG sensors. The resonance wavelength given by the phase-matching condition can be accurate enough. The phase-matching condition is given as a function of mode effective indexes of the core, $n_{\mathrm{core}}(\lambda_v)$, and of the cladding, $n_{\mathrm{clad}}^{(v)}(\lambda_v)$ [1]

$$\lambda_v = \left[n_{\mathrm{core}}(\lambda_v) - n_{\mathrm{clad}}^{(v)}(\lambda_v) \right] \Lambda \tag{1}$$

where Λ is the grating period, v is the mode number, and λ_v is the vth-order resonance wavelength. $n_{\mathrm{core}}(\lambda_v)$ and $n_{\mathrm{clad}}^{(v)}(\lambda_v)$ are determined by the propagation constant of the core mode and the cladding mode: $\beta_{\mathrm{core}}(\lambda_v)$ and $\beta_{\mathrm{clad}}^{(v)}(\lambda_v)$. The traditional three-layer step index model cannot be used when the layer's refractive index is higher than the cladding's. So we use the four-layer step index waveguide model (as shown in Fig. 1) to calculate the mode effective indexes.

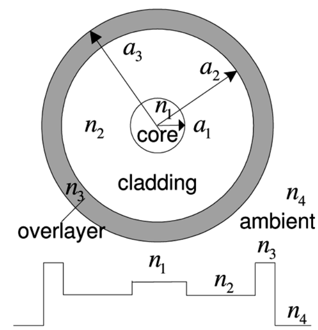

Fig. 1. Four-layered step index waveguide model.

The mode eigen value equation can be calculated using a step-index approximation. Here we use the mode eigen value equation given by Tsao [7]

$$R(r) = \begin{cases} A_1 Z_{v,1}(u_1 r), & r \le a_1 \\ A_2 Z_{v,2}(u_2 r) + B_2 T_{v,2}(u_2 r), & a_1 \le r \le a_2 \\ A_3 Z_{v,3}(u_3 r) + B_3 T_{v,3}(u_3 r), & a_2 \le r \le a_3 \\ B_4 K_v(w_4 r), & r \le a_3 \end{cases} \tag{2}$$

where

$$Z_{v,j}(x) = \begin{cases} J_v(x) \\ I_v(x) \end{cases}$$

$$T_{v,j}(x) = \begin{cases} Y_v(x), & n_{\mathrm{eff}} < n_i \\ K_v(x), & n_{\mathrm{eff}} > n_i \end{cases}$$

$$u_i = \frac{2\pi}{\lambda}\sqrt{|n_i^2 - n_{\mathrm{eff}}^2|}, \qquad i = 1,2,3$$

$$w_4 = \frac{2\pi}{\lambda}\sqrt{n_{\mathrm{eff}}^2 - n_4^2}$$

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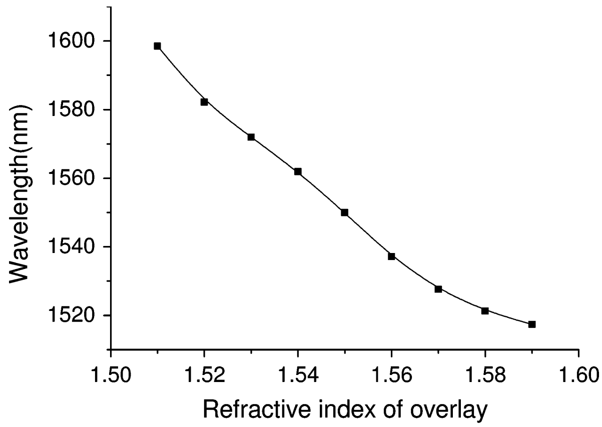

Fig. 2. Refractive index.

where J_v and I_v are the ordinary Bessel functions of first and second kind of order v. Y_v and K_v are the modified Bessel functions of first and second kind of order v, respectively. a_1 and a_2 are the core and cladding radius, $a_3 - a_2$ is the thickness of the hydrogel film. n_1, n_2, n_3 and n_4 are the core, cladding, hydrogel film, and ambient indexes, respectively. n_{eff} is the effective index which can be calculated from the eigen value equation. The calculating results were shown in Fig. 2 with the following parameters:

$$n_1 = 1.458, \quad n_2 = 1.45, \quad a_1 = 4.15\,\mu\text{m}$$
$$a_2 = 62.5\,\mu\text{m}, \quad a_3 - a_2 = 600\text{ nm}.$$

In the calculation, we use the fifth cladding mode LP_{05} because its resonance wavelength is just about 1550 nm. A 600-nm-thick layer is a compromise between stability and response sensitivity. If the layer is thicker, the stability increases and the sensitivity will be lower; otherwise, things go the other way around.

Since in this experiment, we use the LPG to measure the index change of the overlay, we can fix the ambient refractive index equal to 1, which is the refractive index of air, and change the overlay's index, shown in Fig. 2. It shows that the resonant wavelength of the LPG was shifted to short wavelength when overlay's index increased. We choose to use an overlay with its refractive index about 1.55 so that the resonance wavelength can be right at 1550 nm. When the ambient RH changes, the index of this overlay changes, so the resonance wavelength will shift accordingly.

III. Experimental Results and Discussion

The LPG used in the experiments was written by a CO_2 laser on G.652 single-mode fiber with a period of 500 μm and a period number of 60. The LPG section was then coated with a thin film of hydrogel. The component of the hydrogel included acrylic acid, vinyl pyridine, benzoyl peroxide, and $N - N'$ dimethyl bisacrylamide. The refractive index of acrylic acid and vinyl pyridine are 1.4224 and 1.5530, respectively. Through adjust the proportion between acrylic acid and vinyl pyridine, and exposure to ultraviolet light from a UV lamp, we can get the hydrogel which has the appropriate refractive index (higher than the refractive index of cladding). Fig. 3 shows the schematic diagram of the experimental setup. The hydrogel-coated LPG was fixed in V-groove and placed in a thermo-stated container where the temperature and RH were both adjustable. Temperature was maintained at $25° \pm 2$ throughout the experiments. One end of the LPG was connected to an ASE light source (C-band) while the other end was connected to an optical spectrum analyzer (86140B) of AGILENT with the spectrum resolution of 0.1 nm and the sensitivity of -45 dBm.

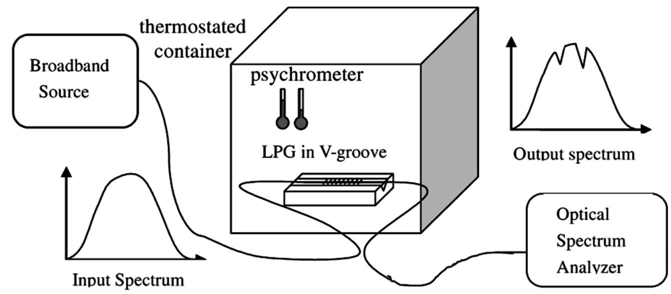

Fig. 3. Schematic diagram of the experimental setup.

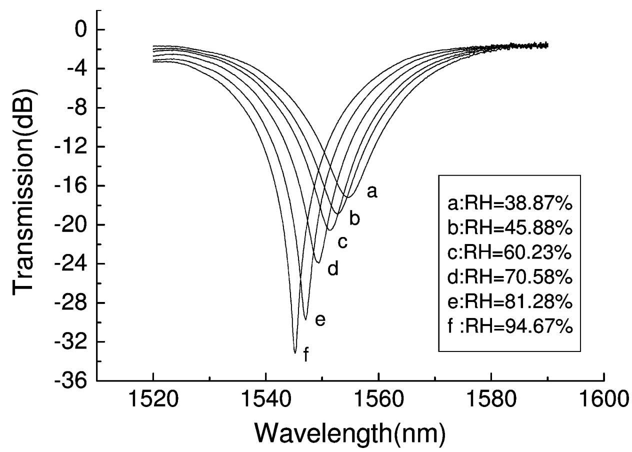

Fig. 4. Hydrogel-coated LPG spectrum response with different RH.

LPG coated with high refractive index hydrogel were investigated. Figs. 4 and 5 showed the LPG spectrum response and peak wavelength to different RH. As RH increases, the response wavelength shifts toward the shorter-wavelength direction, and the resonance dip increases; this means there is an increase of coupling strength.

The resonant wavelength was 1554.9 nm at the RH 38.9% (curve a in Fig. 3), and then shifted to 1543.6 nm at the RH 100% (curve f in Fig. 3). The resonant wavelength shift between this RH range was 11.3 nm. The lower RH level was limited by the condition of experiments. In theory, the hydrogel-coated LPG RH sensor is also sensitive to RH from 0% to 38.9%. Those results are in accordance with the simulation shown in Fig. 2. The experimental points of the resonant wavelength shift were linear fitted. The linear expression was shown in (3), with a linearity of 99.5%

$$y = 0.374 - 0.0575x \tag{3}$$

where x is the resonant wavelength shift, and y is the RH. It was calculated that the hydrogel-LPG sensor had a sensitivity of 0.2 nm/%RH with an accuracy of $\pm 2.3\%$ RH, respectively.

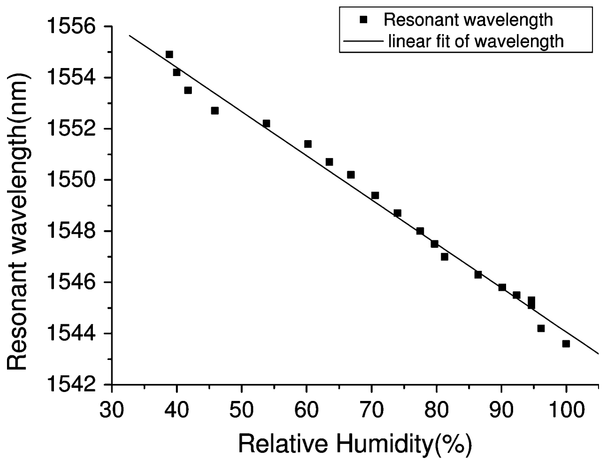

Fig. 5. Resonant wavelength shift of LPGs coated with hydrogel.

As shown in other papers, temperature response is also an inevitable variance. The temperature response of the LPG we use in our experiment is about 0.38 nm/degree. As we show in Section II, coated LPG will have a much higher response to the change of RH, and it has almost the same response to temperature shifts, so we can use another uncoated LPG to adjust the temperature effects (which we will not show in this letter).

IV. Conclusion

The LPG coated with hydrogel can be used to measure the RH variation efficiently in a wide range from 38.9% to 100% RH with a sensitivity of 0.2 nm/%RH, and an accuracy of $\pm$2.3% RH (standard deviation of the error). The LPG sensors coated with two types of hydrogel were experimentally investigated. The results show that the response wavelength and resonant dip were correlative with the refractive indexes of both hydrogel and ambient, which is in accordance with the theoretical analysis by the use of the four-layered step index waveguide model.

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