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Research Article

Improving the Sensitivity of Humidity Sensor Based on Mach-Zehnder Interferometer Coated with a Methylcellulose

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A novel humidity sensor based on Mach-Zehnder interferometer (MZI) with the single-mode fiber (SMF) coated with methylcellulose (MC) is proposed and experimentally demonstrated. The MZI consists of two waist enlarged structures. Such an all-fiber MZI incorporates an intermodal interference between the core mode and cladding modes. The MC is coated on the surface of the SMF. External humidity changes the refractive index of MC, causing the intensity changes of the interference pattern. The proposed sensor is linearly responsive to refractive humidity (RH) within the range from 45% to 85% RH, with sensitivity of 0.094 dB/%RH. Moreover the insensitivity of the fiber to the temperature makes this structure more suitable for practical measurement.

1. Introduction

The optical fiber humidity sensor has the advantages of high measuring accuracy, high relative speed, simple fabrication, and compact size. Different types of humidity sensors based on fiber optical sensing have been proposed, such as polymer-coated Bragg grating fiber [1], long period fiber gratings (LPFG) [2], agarose-infiltrated photonic crystal fiber (PCF) interferometers [3], nonadiabatic tapered fiber coated with PDDA/Poly-R-478 film [4], U-shaped fiber coated by phenol red-doped PMMA [5], and interference structures [6]. Above all, the interference structures, particularly MZI, are more practical because of their compact structure, low cost, and easy fabrication and are widely used for temperature, strain, and refractive index measurement [7]. The humidity sensor based on MZI with waist enlarged structure is constructed by two waist enlarged fusion bitapers sandwiched between the SMFs. The core mode and the cladding mode have been coupled and recombined, the latter sensitive to outside environment refractive index (RI) with some humidity sensitive material coated on the SMF-MZI [8].

In the research of optical fiber humidity sensor, although optical fiber humidity sensor type and structure design are very important, humidity sensitive material also plays a key role in improving measurement performance of optical fiber humidity sensor [9]. In order to improve humidity sensor sensitivity, researchers tried to adopt various materials as humidity sensitive material, such as polyvinyl alcohol [10], metal oxide films [11], and chitosan [8]. However, all of these sensors have their own disadvantages. MC, as a special kind of high polymer chemical products, has good dispersion, thickening, film forming, and so on and is becoming a feasible material for biological sensing studies [12]. Recently, the layer-by-layer self-assembly technique has attracted significant attention because of its precise control of thickness at the nanometer level and construction on nonflat surfaces [8, 13]. Owing to its unique properties, it has been widely used for the construction of ultrathin multilayer films.

In this article, a methylcellulose coated humidity sensor based on MZI with waist enlarged structure is demonstrated. It can be monitored by intensity, which makes this sensor production of low cost and easy to make.

2. Design and Principle

A schematic diagram of a proposed humidity sensor structure is shown in Figure 1. It consists of two waist enlarged structures. The light which comes from the optical power source

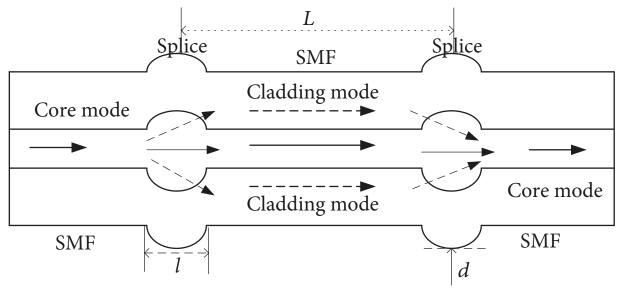


Figure 1: The schematic of a proposed humidity sensor structure; the inset shows the image of the MC material.

passes through the SMF to the first waist enlarged region; the cladding mode is excited and propagates inside the SMF cladding region [8]. When the two lights reach the second waist enlarged structure region, since two lights of optical path are different, interference will occur in the second waist enlarged structure region. The first waist enlarged structure is equivalent to the beam splitter, and the second waist enlarged structure plays the role of coupler.

The transmission of the interferometer can be expressed in the equation stated below [14]:

$$I = I_{\text{core}} + I_{\text{cladding}} + 2\sqrt{I_{\text{core}} I_{\text{cladding}}} \cos\left(\Phi + \Phi_0\right), \quad (1)$$

where I_{core} and I_{cladding} are the intensities of the core and cladding modes, Φ_0 is the initial phase, and Φ is the phase difference between the core mode and the cladding mode, defined as

$$\Phi = \frac{2\pi \Delta n_{\text{eff}} L}{\lambda}, \quad (2)$$

where λ is the wavelength and Δn_{eff} is the effective refractive index difference between the core and the cladding and L is the length of interference.

The change in the RI of the external environment affects the effective RI of the cladding mode and results in a variety in Δn_{eff}. Δn_{eff} leads to changes in Φ, which eventually results in variety in I.

The MC is coated on the surface of single-mode fiber, and it acts as the external environment converter of RI. The external environment will change the humidity sensitive film RI; humidity sensitive film material will affect the effective index of the cladding mode and make the different refractive index between the core and the cladding.

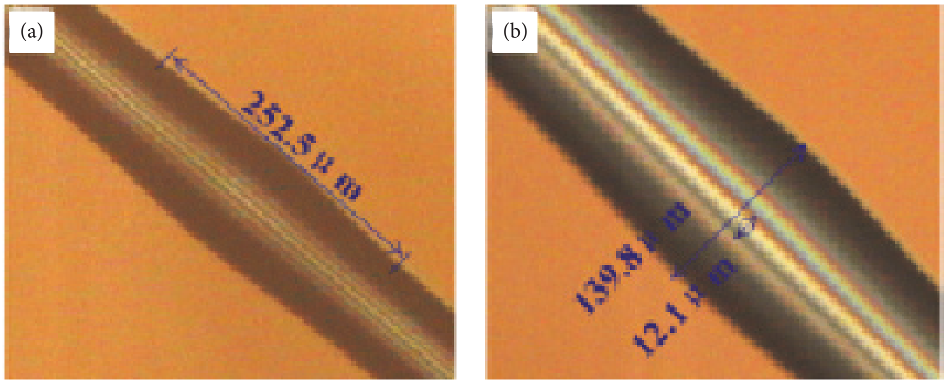
3. Experimental Results and Discussions

Fiber optic sensor based on waist enlarged structure is an ordinary single-mode fiber (SMF G.652). The production process was as follows: using stripping pliers to take off two single-mode fiber coating layers; cutting the end together with a cutter (EFC-6S); placing two segments of optical fiber on the FSM-60; changing the procedure of the welding machine; and setting overlap at 120 μm. The program was used to fuse two single-mode optical fibers. In the stripped-off processing before the process of splicing, the fiber ends of the SMF must be cut by a high-precision cleaver and spliced to the SMF, by a conventional fiber splicer, in a manual operation program (Fujikura FSM-40S). With precise manual adjustments, two prepared SMF stubs were butt-coupled and aligned along axis. To form a waist enlarged fiber bitaper, the splicing parameters in the manual mode must be default, but a large overlapping distance in which the two fibers are pushed further together was 80 μm for fusion splicing correspondingly [14].

By the above method, a waist enlarged structure can be obtained. Figure 2 shows microscope photograph of the sensor structure with 8x magnification. The waist enlarged structure diameter is 12.1 μm and length is 139.8 μm. The distance L between the two waists enlarged structures is 252.5 μm, which is the length of the interference.

MC has certain moisture absorption and film forming ability and can be quickly dispersed in hot water and expanded to form a definite or cloudy colloidal solution. The real image of MC is shown in Figure 3. In the experiment, 2 g MC material was dissolved in 100 ml deionized water and dissolved in a magnetic mixer for 1 hour at room temperature. After the preparation of MC solution, the deposition was achieved by dipping the sensor into the MC solution for 15 min. To create a reproducible and reliable approach for the coating process, repeating trials had to be conducted to achieve smooth and uniform coating on the SMF. Then the SMF-MZI was drawn from the solution at the rate of 30 mm/min by a stepper motor. This drawing process should be repeated for at least three times, upon the completion of which the coated SMF-MZI is placed in for 1 hour to get dried.

The experimental system of this proposed humidity sensor is shown in Figure 4. The humidity chamber is fixed, in which the MC coated SMF-MZI fiber sensing probe has been held by two clamps and referential humidity meter (TRACEABLE VWR L207080). The fixed chamber could avoid sensor movement and fiber refixing in measurements, which is very important in decreasing the influence of bending and twisting. The corresponding transmission spectra of the sensor at different humidity levels are measured by a combination of a broadband light source (BBS, Asef15296410) and an optical spectrum analyzer (OSA, Yokogawa AQ6370) with a resolution of 0.02 nm. In the humidity measurement experiment, the sensing head is put into a closed humidity control box; the temperature of the humidity control box is kept at a room temperature of about 25°C. In order to measure



(a) (b)

Figure 2: Microscope photograph of the sensor structure with 8x magnification.

Figure 3: Real image of MC.

the response of the sensor head to humidity, the humidity in the humidity control box is controlled by pumping dry or moist gas into it, and the humidity gauge in the humidity control box is used to monitor the change of humidity in the humidity control box. The change of interference spectrum with the change of humidity in the humidity control box can be observed by the OSA.

In the humidity test, both ends of the sensor are fixed. The wavelength shift of interference spectrum is monitored between the range from 35% to 85% RH and the measured data is recorded when the humidity is kept stable in the humidity control box. Figure 5 shows that the interference intensity increases with the increasing of the humidity. The result shows the intensity dip shift from −11.36 to −7.32 dB with a total shift of 4.04 dB. As showed in Figure 6, the wavelength shift of the dip has a linear relationship with the refractive index changing, for which the sensitivity of the sensor is 0.094 dB/%RH.

Because of the change in the refractive index of MC coating, the change rate of the wavelength is higher than that of the intensity, which is completely consistent with Lorenz theoretical analysis [15]. The MC refractive index will rise with the increase of humidity at the temperature below 50°C. When MC is expanded in the water, its refractive index will reach the cladding one, which leads to the fact that most higher-order modes in the cladding will not be guided by the reducing intensity of transmitted light. The shift of the spectra is caused by the change of MC in water swelling, which will affect the effective refractive indices of the fast and slow axis of the SMF-MZI; interference is modulated by the RH and brought in the shifting of the spectra.

The experimental result showed that when the ambient humidity is increased, MC will absorb water and the RI will decrease. When the moisture sensitive film absorbs more water molecules, the RI of the humidity sensitive film itself will be reduced and the intensity of the interference spectrum will be increased, which is completely consistent with [8] analysis. According to [8], the change of RH will alter the effective RI of both bare cladding and MC coating. With the increase of RH, more water molecules will diffuse into MC coating, which leads to the MC swelling and increase in the thickness of coating. Same as other swelling polymers, the increase of polymer in water will decrease the RI of MC coating. Meanwhile, the thickness of the coating also will improve the effective RI of the cladding modes. When RH is above 70% RH, the changes of the MC thickness will increase effective RI and result in the increase in extinction ratio of the spectrum. When the MC coating RI is equal to the RI of the fiber cladding, the sensitivity increases greatly [16].

As shown in Figure 7, whether the humidity increases or decreases, the relative difference between the intensities is less than 0.2 dB, which proved that the proposed sensor has a good stability. In order to further verify the stability of the proposed humidity sensor, the experiment coated with MC film formed by 10 mg/ml MC solution was done under 55% and 75% fixed RH level, respectively. The experiment results in Figure 8 showed that only small fluctuations (maximum 0.3% at 55% RH and 0.7% at 75% RH) were recorded in the two cases over a period of 60 min. As we know, MC is one kind of the high polymer and the space structure is long chain, which has curve revolving ability and many active groups in MC [17]. By adsorbing colloidal particles with active groups, the polymer has different configurations, thus forming a network structure. Just this main unique property in MC makes MC coated humidity sensor have better stability and offer perfect film forming capability.

The temperature is a vital parameter in the measurement of fiber humidity. Figure 9 shows that when the temperature was increased from 20°C to 90°C, the intensity only had

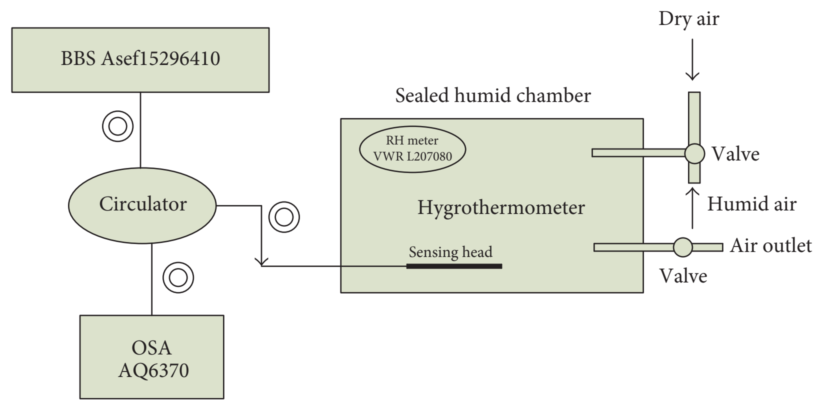


FIGURE 4: Experimental setup for the proposed humidity sensor.

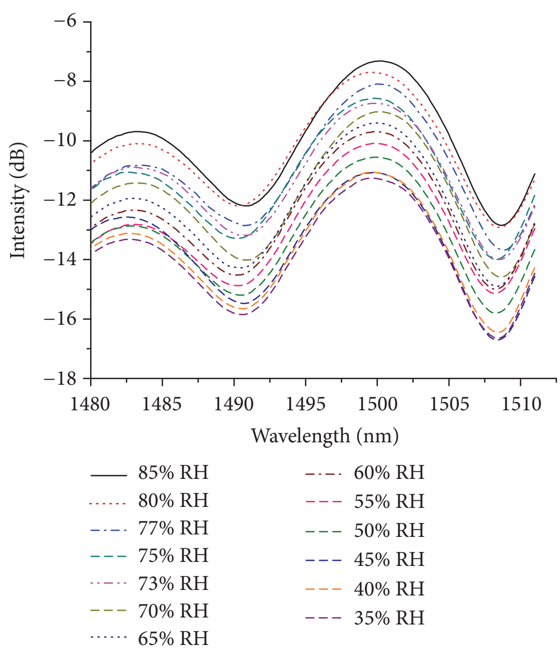


FIGURE 5: The interference spectrum with the change of humidity in the external environment sensor.

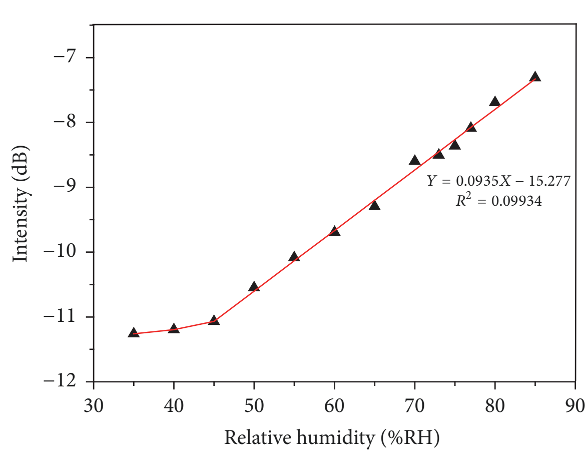


FIGURE 6: The relationship between the intensity change and humidity.

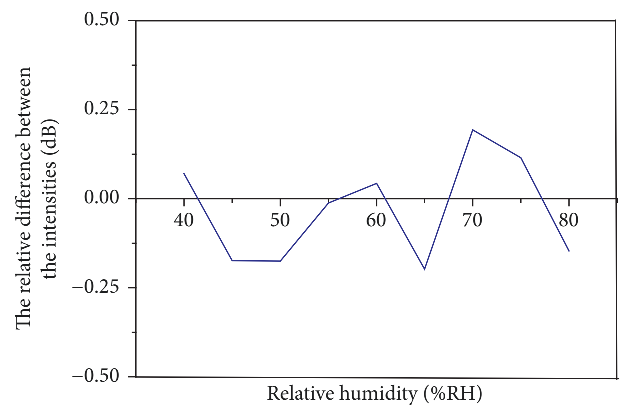


FIGURE 7: Relation of average relative difference of intensity and humidity.

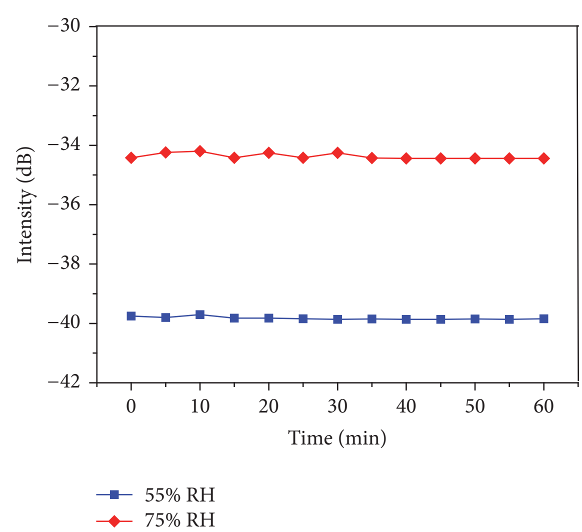


FIGURE 8: Stability testing results.

a 0.03 dB change; the maximum intensity change was only 0.16 dB, which testified that the sensor is insensitive to the temperature.

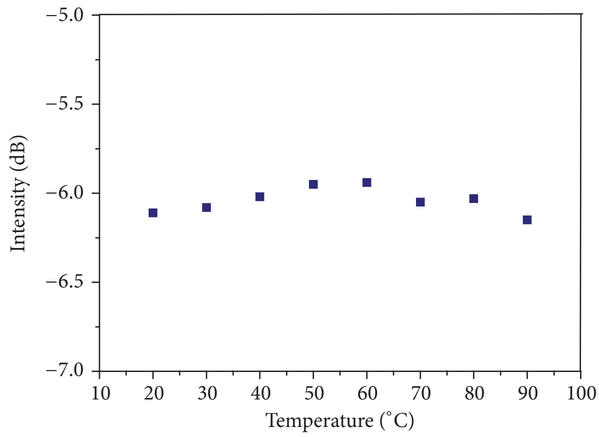


Figure 9: The variation of temperature and wavelength in the external environment.

4. Conclusion

A MC coated humidity sensor based on Mach-Zehnder interferometer with waist enlarged structure has been proposed and experimentally demonstrated. The waist enlarged structure could effectively couple guided light from the fiber core mode to the high-order cladding modes. When humidity is increased or decreased, the average relative difference between the intensities is 0.03 dB. There is a good linear relationship between humidity and intensity; the linear fit is as high as 0.9934 and has a good stability. The maximum sensitivity is up to 0.094 dB/%RH, over a range of 45% to 85% RH. In the meantime, low cost, compact size, easy fabrication, and the insensitivity to temperature make it suitable for the practical applications.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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