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A carboxy-methyl cellulose coated humidity sensor based on Mach-Zehnder interferometer with waist-enlarged bi-tapers

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ABSTRACT

A fiber-optic Mach-Zehnder interferometer (MZI) humidity sensor is proposed, comprising a pair of waist-enlarged bi-tapers and carboxy-methyl cellulose (CMC) coating. The MZI utilizes intermodal interference between the core mode and cladding modes for the measurement of the effective refractive index (RI) of the CMC film that varies with surrounding humidity, through change in the sensor's interference pattern. The proposed sensor is linearly responsive to relative humidity (RH) within the humidity range from 70% RH to 85% RH, with maximum sensitivity of −0.8578 dB/% RH. The advantages of this sensor are its compact size and a facile fabrication process. More importantly, humidity sensitivity can be improved by changing the thickness of the CMC film, which makes this structure a highly promising for real-time, practical RH monitoring application.

1. Introduction

Relative humidity (RH) is an important factor in agricultural, industrial and chemical fields. Fiber-optic humidity sensors are superior to those conventional electrical ones in some aspects as the former offers many specific advantages such as compact size and insensitivity to electromagnetic interference. Several fiber-optic sensors have been proposed for humidity monitoring, such as long-period grating (LPG) [1–3], bent fiber [4,5], photonic crystal fiber (PCF) [6–11] and Michelson structures [12,13]. Various humidity-sensitive hydroscopic materials, including gels [1,2,16], metal oxides [17] and polymeric matrices [13–15],have been coated on fiber optic sensors to render them sensitive to RH. Still, there are limitations of these sensors, such as complex fabrication process of the Michelson structures, fragileness of bent fiber sensors as well as highly cost of PCF. Moreover, films require complicated chemical handling, which has finally brought up manufacturing difficulties.

For this fiber optic humidity sensor, its sensitivity could be improved through selection of a suitable hydroscopic material coating. Carboxy-methyl cellulose (CMC), one of the most abundant cellulose ethers, nontoxic and easily dissoluble in aqueous solutions, is widely used in industrial production, and has been regarded as an excellent choice for humidity sensing with its high hydroscopicity and thermal stability.

In this paper, a fiber-optic humidity sensor, based on CMC coated MZI, is being thoroughly studied. The humidity sensitivity is markedly improved compared with other waist-enlarged taper humidity sensors without any humidity-sensitive films [18]. It is also found out that the thickness of humidity-sensitive films, controlled by the coating time, has a great effect on RH sensitivity. Our work provides a basic method for selecting an optimized operation to produce such a humidity sensor that is easy to fabricate and offers intensity-modulation sensitivity within high humidity range.

2. Design and principle

The schematic diagram of the proposed MZI is shown in Fig. 1. The sensor consists of two waist-enlarged bi-tapers formed by cleaving and arc fusion splicing. The cladding modes are excited from the fundamental mode at the first waist-enlarged bi-taper and then propagate across the sensing region coated with the CMC film. They are then recoupled with the fundamental mode at the second waist-enlarged bi-taper. The transmission intensity of this MZI can be expressed as follows [19]:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\varphi + \varphi_0) \quad (1)$$

where I_1 and I_2 are intensity of the core mode and cladding modes respectively; φ_0 is the initial phase; φ is the phase difference between the core mode and cladding modes given by:

$$\varphi = 2\pi \Delta n_{eff} L/\lambda \quad (2)$$

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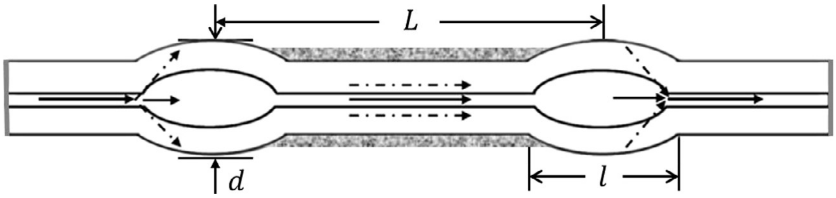

Fig. 1. Schematic diagram of the proposed MZI humidity sensor based on waist-enlarged bi-tapers.

where $\Delta n_{eff} = n_{core} - n_{cladding}$ is the effective index difference of core-cladding modes; L is the interference length, and λ is the operating wavelength. At the interference dip, φ is an integral multiple of 2π. Light traveling in the cladding is influenced by the ambient RI environment, Hence, as the RI of the CMC film varies with surrounding humidity, the Δn_{eff} and φ changes correspondingly, leading to changes in transmission intensity according to Eq. (1).

3. Experimental results and discussions

The MZI was fabricated by using a commercial fusion splicer (FSM-60s). Two pieces of this proposed commercial single mode fiber (SMF G.652) were stripped off its acrylate coating, and the fiber ends were cleaved with a fiber cleaver (EFC-6S). The prepared SMFs were fixed on the splicer and aligned. In order to obtain this kind of bi-tapers, the fusion splicer is set to the SM-SM waist-enlarged bi-taper fusion program with primary splicing parameters as follows: the overlap is 120 μm, the discharge intensity is 1 bit above the standard power, and the duration time of the discharge is set to be 1200 ms. After the arc discharge, the bi-tapers are developed. The interferometer length is 28 mm. A photograph of this taper is shown in Fig. 2, with the cladding diameter, d, of 152.3 μm, as well as the length, l, of 376.2 μm; Thus, the MZI was formed by splicing these two waist-enlarged fiber bi-tapers together.

The response of this MZI to external RI variations is studied in [20]. Different sensitivities have been achieved for the RI ranges from 1.346 RIU to 1.404 RIU and from 1.404 RIU to 1.4415 RIU, respectively. There is a higher sensitivity in the range of 1.404 RIU–1.4415 RIU. It is also observed that the RI sensitivity is higher when the external RI is close to the RI of the cladding. For RH measurements, the MZI has been coated with CMC. The CMC solution is prepared by putting CMC into deionized water to make a 2% mass ratio. Then, it is supposed to dissolve by vigorously stirring with a magnetic 85-2 homothermal magnetic stirrer, for 1 h, at room temperature. In a single time-controlled layer coating process, the prepared MZI is immersed into the CMC solution, left untouched for 15 min, removed and dried in air for 1 h. The thickness of one film layer is 2.2 μm. This coating process will be repeated several times to coat films with different thicknesses.

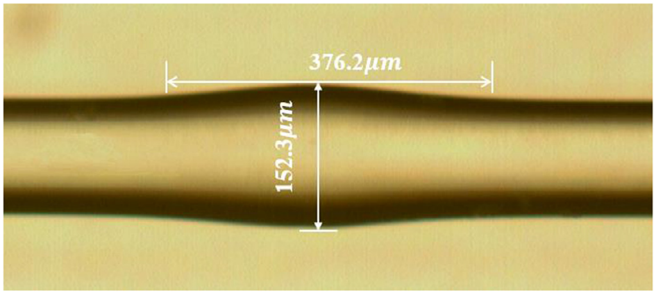

Fig. 2. Microscope photograph of one waist-enlarge d bi-taper with 10X magnification.

Fig. 3 shows the measured interference patterns of the MZI before and after the coating of CMC with several thicknesses. Before coating, the maximal extinction ratio reaches ~18 dB over the spectrum ranging from 1500 nm to 1590 nm; while after CMC coating is finished, the spectral intensity has been increased to ~22 dB. The RI of the CMC solution (nominally n_{CMC}) is 1.335. After coated on the fiber, dried polymers RI is higher than that of CMC solution and that of cladding. Hence, more power in core would be forced into cladding, inducing an increasing optical power in the cladding. Meanwhile, the ratio of this optical power within the fiber core is constant due to its isolation from the external environment. The extinction ratio of the spectrum will be maximized when the optical power transmitted inside the fiber core equals the power in the cladding. The RI of film could be increased by thickening the CMC film within the penetration depth of the cladding mode, and the thickness of the film, as controlled by coating process numbers, could be monitored by the intensity variation of the interference pattern.

For humidity testing, the sensor was placed into a custom-made enclosed chamber, as shown in Fig. 4. Air is pumped by air pumps (SB-248A) through silica gel and water to provide dry and humid air respectively into the chamber. The internal RH is regulated by controlling the relative dry and humid air flow rates using a hygro-thermometer. The test commences from 30% RH, and the humidity is slowly ramped to 85% RH, with an interval of 2% from 30% RH to 70% RH and an interval of 1% RH from 70% RH to 85% RH. All optical transmission readings were recorded by an optical spectrum analyzer (OSA YOKOGAWA AQ6370) with a broadband light source (BBS, HOYATEK) as its optical source. The intensity resolution of the OSA is 0.01 dB. The temperature inside the chamber was kept at 25 °C throughout all experiments. As is shown in Fig. 5, the extinction ratio of the interference spectrum increases relatively with RH. Apparently, there is a turning point at ~70% RH where a sharp increase in sensor's sensitivity is observed.

RH alters the effective RI of the cladding in which includes bare cladding and CMC coating in two aspects [11]. As the RH increases, more water molecules will diffuse into CMC coating, resulting in the inflation of the CMC and increase in the thickness of coating. Similar to any other swelling polymer an increase in water content will decrease the RI of CMC coating. Also, the thickness of the coating increases the effective RI of the cladding modes. These two factors may counteract below 70% RH, in which minimal changes in the transmission spectrum with RH will occur. When RH is above 70% RH, the increase in effective RI resulting from the changes in the thickness of CMC dominates, resulting in the increase in extinction ratio of the spectrum. When the CMC coating RI is equal to the RI of the fiber cladding, the sensitivity increases tremendously [12]. This may occur when the RH is 70% RH. Hence, the sensor becomes more sensitive when RH exceeds 70% RH.

Sensors coated with different thickness of films have been studied, and results of various sensors with 2.2 μm, 5 μm, 6.8 μm CMC coatings are shown in Fig. 6. A suitable thickness of coating films can be obtained through the number of coating cycles. Obviously, its sensitivity could be improved by the optimization of film thickness, with the highest being −0.5335 dB/% RH, obtained in a sensor