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Agarose gel filled temperature-insensitive photonic crystal fibers humidity sensor based on the tunable coupling ratio

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ABSTRACT

An Agarose gel filled photonic crystal fiber in-line interferometric sensor for the measurement of relative humidity is proposed and experimentally demonstrated. The sensor is constructed by filling the Agarose gel between the aligned single mode fiber (SMF) and the photonic crystal fiber (PCF). A fiber in-line interferometer is fabricated by splicing the other end of the PCF and another SMF. Due to the tunable refractive index property of the Agarose gel, the mode field diameter of the propagation light is changed with the external relative humidity, which induces the change of coupling ratio between the PCF and the SMF. The relative humidity is measured by interrogating the fringe visibility of the white-light interferogram. The experimental results show that the sensitivity of up to 2.2 dB/RH is achieved. The proposed method possesses high resolution and low temperature cross-sensitivity.

1. Introduction

Measurement of relative humidity is increasingly essential in many areas, such as chemical and food processing industry, environmental monitoring and meteorological services [1]. In recent years, fiber optic humidity sensors have been extensively investigated due to their advantages, such as low weight, small size, and long distance signal transmission for remote operation [2].

Many forms of humidity sensors based on optical fibers have been developed, such as long period gratings [3], fiber Bragg gratings [4], side polished fibers [5], plastic optical fibers [6], surface plasmon resonance [7], and tapered optical fibers [8]. Most optical fiber based humidity sensors are constructed by using the hygroscopic material. Based on the properties of these hygroscopic material, fiber optic sensors for the measurement of the relative humidity can be approximately classified into two types: the size method and the refractive index (RI) method. In the size method, the hygroscopic material will expand in size with the increase of the humidity, which would change the optical path difference (OPD) of the interferometer, and the humidity can be measured by tracking the wavelength valley in the interference fringe. A fiber optic humidity sensor based on the size method can be constructed by coating a chitosan film or producing a Fabry–Perot cavity [9,10]. However, such sensors always suffer from serious temperature cross-sensitivity. On the other hand, the RI technique can be realized in many ways, such as a fiber Bragg grating deposited with the N-ethyl-4-vinylpyridinium chloride layer [11], a long period grating coated with the polyvinyl alcohol [12], or a hetero-core structure optical fiber filmed with porous sol–gel silica (PSGS) [13]. The relative humidity is measured by utilizing the tunable RI property of the hygroscopic material. The RI method possesses many attractive characteristics, such as high sensitivity, linear response, and low temperature cross-sensitivity.

In this paper, we propose a compact relative humidity sensor based on the PCF and the Agarose gel. The humidity sensor is constructed by aligning a SMF and a PCF, and the Agarose gel is filled into the gap between the SMF and the PCF. A fiber in-line interferometer is fabricated by splicing the other end of the PCF to another SMF. Due to the tunable RI property of the Agarose gel, the mode field diameter of the propagation light is changed with the increase of the relative humidity, and the relative humidity is measured by interrogating the fringe visibility of the white-light interferogram. The proposed method possesses high sensitivity and low temperature cross-sensitivity.

2. Operation principle

2.1. The RI response of the Agarose gel for the water molecules

In general, the optic fiber humidity sensors are based on the humidity – sensitive materials, such as polyvinyl alcohol (PVA), chitosan and cyclic olefin copolymer. Although these materials

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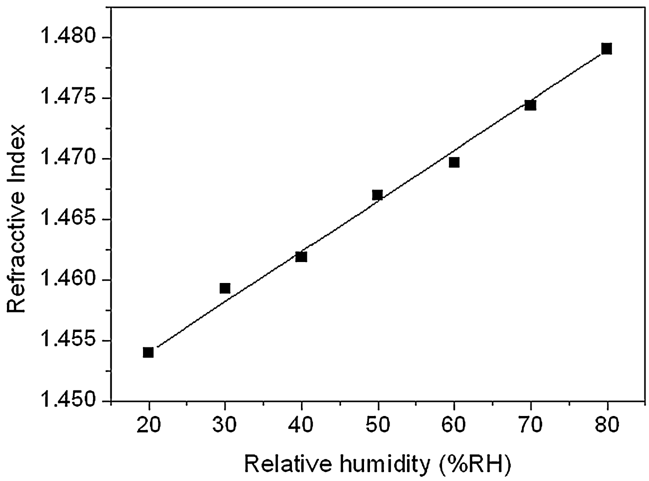

Fig. 1. The RI of the Agarose gel response to the ambient humidity.

have many attractive characteristics, such as high sensitivity, small size, and low temperature cross-sensitivity, some of materials are not suitable for sensing a wide humidity range; some of other materials provide a non-linear response because these materials are soluble in water very easily [14].

Agarose gel is a high humidity–sensitivity material which offers a wide operating humidity range with a simple producing procedure. When the Agarose gel is exposed to the humidity with high level, water molecules enter pores of the Agarose gel due to the hydrophilic nature and capillary forces. The air in the pores of the Agarose gel is replaced by water. Therefore, Agarose gel shows a linear change in its RI with respect to ambient humidity. The thermal expansion coefficient and thermo optical coefficient of the Agarose gel is $\sim 4 \times 10^{-3}/°C$ and $\sim -5 \times 10^{-4}/°C$ [15,16]. Due to the transparent property of the Agarose gel, we measured the RI of the Agarose gel response to the ambient humidity by using Abbe Refractometer (DR-M2/1550(A), ATAGO) at the wavelength of 1550 nm, as shown in Fig. 1. The RI of the Agarose gel is in linear proportion to the external humidity. On the other hand, since the Agarose is soluble in hot water [17], the producing procedure of the Agarose gel is easy. According to these factors, Agarose gel is a suitable material for fabricating the optic fiber humidity sensor.

2.2. Sensor principle

The schematic diagram of the PCF based humidity sensor is presented in Fig. 2(a), which is formed by two SMFs, a PCF and the

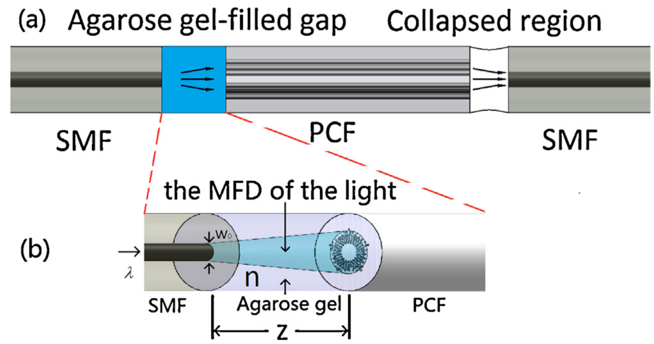

Fig. 2. (a) Schematic diagram of the PCF based humidity sensor and (b) the MFD of the light in the Agarose gel.

Agarose gel. A SMF and a PCF with cleaved ends are aligned to each other. The gap between the PCF and the SMF is filled with the Agarose gel. The other end of the PCF is spliced to a SMF by using the technique reported in [18], and the splicing loss is ~1.2 dB. At the fiber splice, a collapsed region is formed between the PCF and the SMF due to strong electric arc discharges [19].

The operation principle of the sensor is shown in Fig. 2(b). When the propagation light travels from the SMF to the Agarose gel, the mode field of the propagation light begins to expand according to the Gaussian beam approximation. Then both the fundamental core mode and cladding modes are excited when the transmission light propagates from the Agarose gel to the PCF. Two excited modes propagate along the PCF, and re-couple back into the core of the SMF at the collapsed region, which forms an in-line Mach–Zender interferometer (MZI). The PCF is essential in the proposed sensor because the collapse region is naturally formed in the splicing between the SMF and the PCF. However, the collapse region is hard to be fabricated by splicing two SMFs, which is difficult to couple cladding modes back into the core of the SMF. Although some techniques for fabricating the combiner in the SMF have been presented, such as the misaligned spliced joint [20], the peanut-shape structure [21], the tapered region [22], and the laser irradiation [23], these methods involve many complicated procedures and are very fragile in harsh environment.

The mode field diameter (MFD) of the light depends on the spot size at the end face of the SMF ω_0, the wavelength of the light λ, the length of the Agarose gel gap z, and the RI of the Agarose gel n, which is [24]

$$\mathrm{MFD} = 2\omega_0\sqrt{1+\left(\frac{z\lambda}{n\pi\omega_0^2}\right)^2}. \quad (1)$$

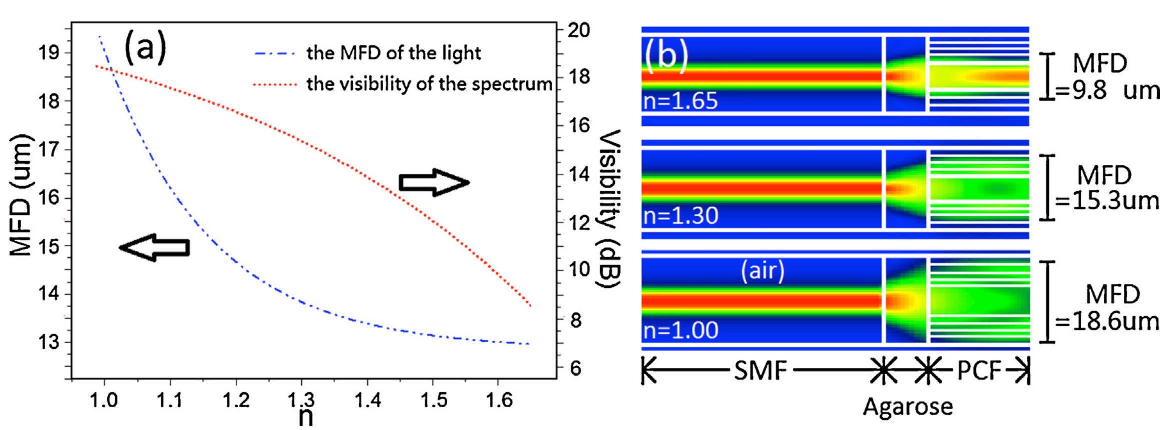

Fig. 3. Simulations for (a) the MFD of the light and the fringe visibility of the spectrum with different RI of Agarose gel and (b) intensity distributions of the propagation mode field in the Agarose gel with different RIs.