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Nafion film temperature/humidity sensing based on optical fiber Fabry-Perot interference

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ABSTRACT

A simple method based on Capillary action is proposed to fabricate an optical fiber Fabry-Perot sensing probe for temperature and humidity measurement. Nafion film serves as the thermal and humidity sensing material in this optical fiber sensor. The sensor is constructed by manually depositing a drop of Nafion solution in the capillary and inserting a single mode optical fiber into the capillary. For humidity sensing, we use a fiber Bragg grating (FBG) as temperature compensator. The sensitivity, repeatability, and stability of the sensor were evaluated by analyzing the reflection spectra of the interference fringes. The results indicate that Nafion can be used as the sensing phase of an optical fiber temperature and humidity sensor based on the optical fiber Fabry-Perot interference, presenting a sensitivity of 2.71 nm/°C and 3.78 nm/%RH.

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1. Introduction

Fiber-optic temperature sensors are commonly applied across a variety of industries as they are immune to electromagnetic interference, compact in size, and yield highly stable measurements. A number of temperature sensing methods currently exist, including fiber Bragg gratings (FBG) [1,2], single mode-multimode-single mode (SMS) fiber [3], and Mach-Zehnder interference (MZI) [4]. Recent researchers have focused on microstructure fiber (MSF) because it prevents diffusion at high temperatures and exhibits flexibility in regards to sensor design [5]; for example, photonics crystal fiber (PCF) can be combined with single mode fiber (SMF) [6] or SMF with hollow core fiber (HCF) [7]. Microstructure optic fiber can readily and compatibly accomplish temperature measurement [8,9] but certain aspects merit further improvement with the above-mentioned sensors, such as its high cost and complex fabrication process.

Fiber-optic Fabry-Perot interferometers (FPIs) have been successfully utilized for many sensing applications, such as humidity sensing [10,11], refractive index (RI) sensing [12], and high temperature sensing [13]. Fiber-optic FPI sensors have been demonstrated as a suitable option for temperature and humidity sensing due to their high sensitivity, temperature resistance, rapid response, and high resolution [14,15]. The low-cost fiber-optic extrinsic Fabry-Perot interferometer (EFPI) sensor, for example, exhibits a linear response and temperature sensitivity as high as 5.2 nm/°C [16]. A micro F-P sensor has been proven capable of accurately measuring temperature up to 1100 °C [17]. The fiber-optic sensor based on a silicon F-P cavity has a temperature resolution of 6×10^{-4} °C and response time as short as 0.51 ms [18].

There are two forms of F-P cavities: Intrinsic (which can be produced by splicing a section of multimode fiber using fusion splicer between two single-mode fibers [19]) and extrinsic (e.g., The compensation for the thermal expansion of F-P cavity is realized by assembling a glass capillary and optical fibers through a CO_2 laser welding [20]) F-P cavity. The interference signals induced by two reflections at the two end surfaces of the F-P cavity are sensitive to variations in the cavity [21]. Typically, an EFPI is fabricated by inserting SMFs into a quartz capillary [14] or splicing a section of hollow-core fiber between two SMFs [22]. Recent studies have reported the fabrication of EFPIs by fusion-splicing a tiny segment of main-HCF and another section of feeding-HCF [23,24].

Nafion, which exhibits high hydrophilicity, chemical stability, small expansion thermal coefficient [25], high conductivity, and mechanical toughness [26] is a suitable material for many applications in the electrochemical [27] and chemical gas sensing [28,29] fields. Nafion film has recently been tested for humidity sensing based on optical fiber FPI and showed a sensitivity of 3.5 nm/%RH [10] due to its water absorption capability [30]. But, the practica-

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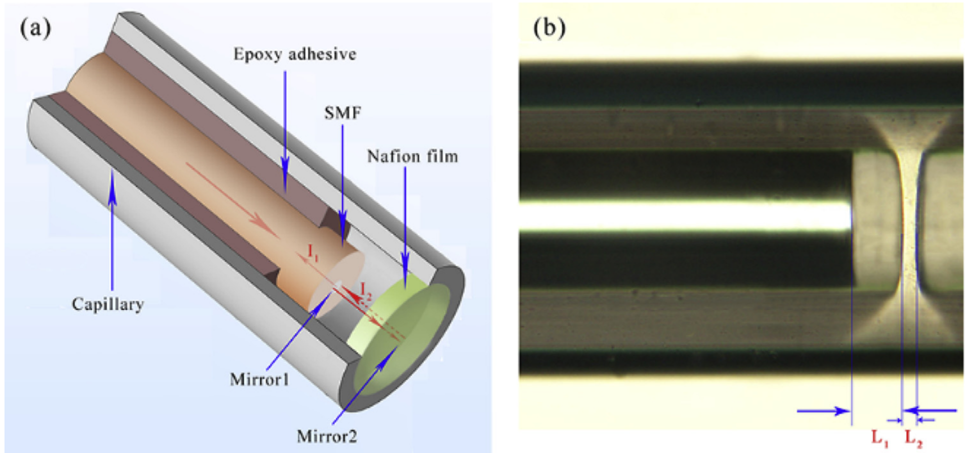

Fig. 1. (a) Schematic of proposed sensor structure. (b) Micrograph of the sensor probe (L_1 is air cavity length, L_2 is Nafion film thickness).

bility has been restricted by the temperature cross-sensitivity. For temperature sensing, Nafion film is used to indicate changes in color resulting from the equilibrium shift between different forms of marker dyes [31]. It is rarely used for thermal sensing and humidity-temperature cross sensing in optical applications, however.

This paper proposes a fiber-optic EFPI based on a Nafion-filled glass capillary for temperature, sensing applications and temperature-compensated humidity sensing based on a FBG. The F-P cavity is formed by inserting an SMF into a partially Nafion-filled glass capillary. The length of the F-P cavity can be precisely controlled via a three-dimensional translation stage. This allows the EFPI to be fine-tuned for the desired sensitivity, which is not possible in PCFs; further, the system is altogether lower in cost. The fiber-optic humidity sensor has many distinctive advantages over other humidity sensors based on fiber-optical, such as temperature compensation, easy fabrication and simple configuration. The proposed sensor can reach sensitivity of up to 2.71 nm/°C and 3.78 nm/%RH.

2. Sensing principle

A schematic diagram of the proposed FPI temperature sensor is shown in Fig. 1(a). The sensor probe consists of a section of SMF, a section of capillary and a Nafion film. The SMF and Nafion film serve as lead-in fiber and reflection components, respectively. The SMF and capillary are fixed together with UV adhesive. The end face of the SMF and outer face of the Nafion film act as Mirror 1 and Mirror 2, respectively, forming the F-P cavity. The light reflected from the Nafion film outer face thus interferes with the light reflected from the fiber end face. The total length of the F-P cavity consists of air cavity length (L_1) and Nafion film thickness (L_2), as shown in Fig. 1(b). The internal diameter of the capillary is 200 μm, which makes it readily fixable to the fiber to form the Nafion film.

The FPI can be modeled using the following two-beam optical interference equation [11]:

$$I_0 = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\left(\frac{2\pi\delta}{\lambda} + \varphi_0\right) \quad (1)$$

where I_0 is the intensity of the interference signal, I_1 and I_2 are the reflections at the cavity mirrors, respectively, φ_0 is the initial phase of the interference, λ is the free space wavelength, and δ is the optical path difference of the two beams. The loss of light by absorption within the Nafion film is not taken into account here. The absorption of Nafion film just affects the extinction ratio and fines of reflection spectrum, which might reduce the resolution of sensitivity. The optical path difference can be derived as follows:

$$\delta = 2 \times (n_1 L_1 + n_2 L_2) \quad (2)$$

where n_1 and n_2 are the RI of air and Nafion film, and L_1 and L_2 are the air cavity length and Nafion film thickness, respectively.

According to Eq. (1) and (2), the interference reaches its minimum when the phase of the cosine term becomes an odd number of π. The two adjacent interference minimums have a phase difference of 2π. In order to express more precisely, the λ^2 was completely expression as $\lambda_1{}^*\lambda_2$. Therefore, the wavelength spacing of two adjacent minimums is known as free spectral range (FSR), which can be derived as follows:

$$FSR = \frac{\lambda_1 * \lambda_1}{2(n_1 L_1 + n_2 L_2)} \quad (3)$$

where λ_1 and λ_2 are the adjacent valleys with phase difference of 2π. According to Eq. (3), the FSR depends on the RI of the air cavity and Nafion film, as well as air cavity length and Nafion film thickness. For the humidity sensing, changes in the cavity due to RH cause a phase shift in the interference spectra that can be figured out by tracking the wavelength shift of the channeled spectrum using a spectrum analyzer. Alternatively, using a read-out interferometer and well establish demodulation techniques the wavelength shift can be converted into the phase of an electronic carrier signal that can be tracked with higher accuracy.

The wavelength of the m^{th} fringe valley (λ_m) is calculated as follows:

$$\lambda_m = \frac{4(n_1 L_1 + n_2 L_2)}{2m + 1} \quad (4)$$

where m is an integer. Variations in external temperature alter the n_2 value and thereby the λ_m value. By taking a Eq. (3) derivative with respect to temperature, the wavelength shift is expressed as $\Delta\lambda = 2\Delta\delta/(2m+1)$. In consideration of the variation range of temperature from −30 to 85 °C, the thermal expansion of the Nafion film cannot be considered negligible [25] and the air cavity is an enclosed space. The internal air pressure is approximately equal to 1 atm. With the changing of temperature, the elastic character of air chamber just partly limited the Nafion film inward expansion and the changing of air cavity length must be taken into consideration. In addition, the RI variation of the air cavity with temperature is only 10^{-5} [32,33], which can be considered negli-

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