



Hygroscopic polymer microcavity fiber Fizeau interferometer incorporating a fiber Bragg grating for simultaneously sensing humidity and temperature

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ABSTRACT

This work proposes a hygroscopic polymer microcavity fiber Fizeau interferometer (PMFFI) incorporating a fiber Bragg grating (FBG) for the simultaneous measurement of relative humidity (RH) and temperature (T). The PMFFI was fabricated by attaching the hygroscopic polymer to a single-mode fiber endface to form a low-finesse Fabry–Perot resonant microcavity. This work is the first to investigate polymer of the Norland Optical Adhesive (NOA) series with particular porous structures that responds well to the moisture and can thus be used in the fiber-optic sensing of relative humidity. Additionally, the NOA materials have a high thermal expansion coefficient and so can be used in the highly sensitive measurement of temperature. The adsorption/desorption of water molecules and variations in temperature both change the optical path of the microcavity, shifting the fringes in the interference spectra. Incorporating a general FBG that is nonreactive to RH but sensitive to T judges the variation in T . The combined sensor supports the simultaneous measurement of both parameters RH and T by gauging of the individual spectral responses of PMFFI and FBG, respectively. Experimental results demonstrate that the RH and T can be simultaneously measured with high sensitivity and accuracy using the proposed sensing configuration.

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1. Introduction

Relative humidity (RH) is the amount of water vapor in air relative to the amount of water vapor in saturation at a static temperature (T). RH depends mainly on the T of the environment. The simultaneous measurement of both RH and T has important applications, such as in semiconductors, food processing, and biomedical and industrial technologies. These two physical properties of the environment can affect the quality and yield of manufactured products. Therefore, the simultaneous measurement of these two parameters is becoming increasingly important. Although the RH/T measurement instruments that are based on the electronic devices are the commonly used, however, they will soon be replaced by sensors that are based on photonic structures. The reason is that the electronic humidity sensors do not perform well in harsh environments, such as in the presence of corrosive substances or high temperature. The fiber optic sensors have always been regarded as sensitive and potential candidates owing to their many advantages, including non-electrical operation, tiny size, high sensitivity,

corrosion resistance, effectiveness in remote measurement and rapid response [1–33]. However, few all-silica-based fiber optic humidity sensors have rarely been developed because their main constituent material, silica, is not a favorable hygroscopic substance. Hygroscopic materials, such as agarose [1,13,20,22,24,27], polyvinyl alcohol (PVA) [14,16,18,19,21,23,29,30], polymeric substances [2,3,5,6,9,15,26] or others [7,10,12,17,28] have been coated onto the main elements of the fiber sensors. Optical signals are modulated by the physical and chemical reactions of these materials to the RH of the environment. In relevant studies, special fibers, such as those with hollow cores (HCF) [12], multimode fibers (MMF) [9,17,23,29], photonic crystal fibers (PCF) [8,13,16,18,19,22,24,27] and plastic optical fibers (POF) [3], have been used for measuring humidity. Regardless of the hygroscopic materials that are used in the fibers, the sensing mechanism is usually based on very slight variations of the refractive indices (RI) and thicknesses of the hygroscopic materials upon the absorption of H_2O molecules [1–32]. Thus, the types of interferometric fiber sensors are especially suitable for the extremely insignificant changes of the RI and thicknesses of the hygroscopic materials due to their miniature size, high sensitivity and very high resolution. RH depends strongly on T . Thus, the variations in RH can be well evaluated only if T can be measured at the same time. Accordingly, the simultaneous

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measurement of the RH and T parameters of a system is of scientific and technological importance. Some fiber humidity sensors that are incorporated into fiber gratings have been developed with hybrid structures for simultaneously sensing other physical parameters. These works have especially focused on the simultaneous sensing of RH and T parameters [2,11,19,24,30].

This work develops a very simple, easy, and flexible prototype polymer micro-cavity fiber Fizeau interferometer in which is incorporated a general FBG for the simultaneous measurement of RH and T . The simultaneous measurement is based on the different responses of the PMFFI and the FBG to the RH and T . The PMFFI is coated with a layer of Norland Optical Adhesive (NOA) polymer by a convenient and efficient UV-cured method, as presented in Fig. 1. In this work, for the first time, materials from the NOA series are utilized in the fibers with favorable hygroscopic properties [31,32] and strong responses to T [33]. The NOA that is used herein is an optical gel whose porosity causes physical adsorption and desorption of water molecules from and to the surroundings [34]. Therefore, the optical path of the Fizeau cavity varies owing to H_2O adsorption and desorption as the humidity changes. Hence, the proposed device can be expected to be a good humidity sensor. The NOA 61 also has a high sensitivity to T owing to its high thermal expansion coefficient (TEC) of $2.2 \times 10^{-4} \text{ }^\circ\text{C}^{-1}$ [35] and has much higher RI than that of fiber, so it is more suitable for use in our device. Besides, it is designed to give an excellent bond to glass surfaces and may be polished after UV-curing [36]. Thus, the polymer surface can be treated as smooth mirror so the surface roughness is ignored. By incorporating a simple bare FBG that is almost unaffected by humidity and so exhibits a spectral shift only with a variation in T , allows the simultaneous measurement of both RH and T and the individual responses of the sensor to both parameters to be evaluated.

2. Sensing principle

The Fizeau interferometer is a Fabry–Perot interferometer (FPI) whose cavity has a low reflectivity. Thus, sensing principle using the proposed PMFFI exploits the characteristics of the low-finesse fiber FPI. The polymer coating of the NOA series on the SMF swells or shrinks in response to ambient RH/T changes, affecting the optical length of the Fabry–Perot cavity as well as the phase difference between the consecutively reflected light beams. Monitoring the variation of interference fringes that are reflected from the two interfaces yields obtain the information about the changes of RH/T from the ambient space. Most importantly, this work is the first in which hygroscopic characteristics of the porous structures of the NOA series of materials are exploited to sense changes in RH and T [31–33].

In the configuration of the sensor that is shown in Fig. 1, when the Fresnel reflectivity of the interfaces is low, the behavior of the cavity can be approximated using a two-beam interferometric model, given by the equation,

$$r = r_1 + r_2 \pm 2\sqrt{r_1 r_2} \cos(\phi) \quad (1)$$

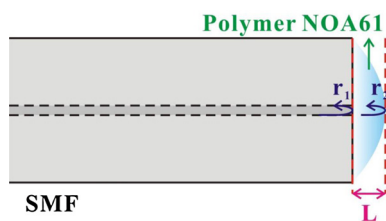


Fig. 1. Configuration and operating principle of PMFFI.

where r is the reflected intensity of the interference signal; r_1 and r_2 denotes the intensities that are reflected at the interfaces, and ϕ denotes the optical phase of the interferometer, given by Eq. (2).

$$\phi = \frac{4\pi nL}{\lambda} \quad (2)$$

where n is the refractive index of the medium NOA 61 that is formed as the Fizeau cavity and λ is wavelength of the light source. The phase difference between both interference beams depends upon the optical path nL , where L is the thickness and n refractive index of the cavity. The periodicity of the spectral fringes of the spectra can be expressed using the free spectral range (FSR),

$$\text{FSR} = \frac{\lambda_m \lambda_{m+1}}{2nL} \quad (3)$$

$\text{FSR} \cong \lambda_{m+1} - \lambda_m$, where m is an integer and λ_m and λ_{m+1} are the central wavelengths of the two peaks/dips adjacent to the m th dip in the spectrum. Changes in the cavity that are caused by RH/T variations cause phase shifts in the interference signal that can be retrieved by tracking the wavelength shift of the interference spectrum using an optical spectrum analyzer (OSA). Thus, the m th wavelength (λ_m) of the spectral minimum with the condition $\phi = 2m\pi$ is given by the expression of Eq. (4).

When the PMFFI sensor is exposed to the different RH/T levels, the NOA 61 cavity expands/shrinks, changing the optical length (nL) of the cavity, shifting the λ_m , which satisfies,

$$\lambda_m = \frac{2nL}{m} \quad (4)$$

The incorporated FBG whose grating written in the core of SMF is insensitive to humidity but sensitive to T . Owing to the high sensitivity of the PMFFI to T , T and RH can be simultaneously measured using the combination of the PMFFI and the FBG. If the T and RH change, the wavelength shifts that are caused by both the FBG and the PMFFI can be respectively estimated by using the following equations.

$$\frac{\Delta\lambda_{\text{FBG}}}{\lambda_{\text{FBG}}} = \frac{1}{\Lambda} \frac{\partial \Lambda}{\partial T} \Delta T + B \Delta RH = A \Delta T + B \Delta RH \quad (5a)$$

$$\frac{\Delta\lambda_{\text{PMFFI}}}{\lambda_{\text{PMFFI}}} = \frac{1}{d} \frac{\partial d}{\partial T} \Delta T + D \Delta RH = C \Delta T + D \Delta RH \quad (5b)$$

where A , C and B , D are the temperature and humidity sensitivity coefficients of the PMFFI and the FBG, respectively; d and Λ denote the cavity of the PMFFI and grating period of the FBG, respectively. The coefficients A , B , C and D can be determined by measuring the responses of spectral sensitivities of the PMFFI and the FBG in the combined device to variations in T and RH , respectively. Then, the matrix inversion method is used to obtain the variations of temperature (ΔT) and relative humidity (ΔRH) simultaneously from the wavelength shifts of the PMFFI ($\Delta\lambda_{\text{PMFFI}}$) and the FBG ($\Delta\lambda_{\text{FBG}}$), respectively. The relationship between the above parameters is as follows.

$$\begin{pmatrix} \Delta T \\ \Delta RH \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix}^{-1} \begin{pmatrix} \frac{\Delta\lambda_{\text{FBG}}}{\lambda_{\text{FBG}}} \\ \frac{\Delta\lambda_{\text{PMFFI}}}{\lambda_{\text{PMFFI}}} \end{pmatrix} \quad (6)$$

Eq. (6) can be simplified as,

$$\begin{pmatrix} \Delta T \\ \Delta RH \end{pmatrix} = \begin{pmatrix} A' & B' \\ C' & D' \end{pmatrix}^{-1} \begin{pmatrix} \Delta\lambda_{\text{FBG}} \\ \Delta\lambda_{\text{PMFFI}} \end{pmatrix} \quad (7)$$

where A' , C' , B' and D' are the normalized coefficients of the sensitivities of the FBG to T and RH and of the PMFFI to T and RH , respectively. As a result, the obtained variations of the center wavelength of the FBG ($\Delta\lambda_{\text{FBG}}$) and the shifts of peaks/dips of the PMFFI

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