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Experimental research on FLM temperature sensor with an ethanol-filled photonic crystal fiber

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ABSTRACT

A compact optical fiber temperature sensor based on the principle of fiber loop mirror (FLM) was proposed. Different from the conventional ones, an ethanol-filled high birefringence photonic crystal fiber (HB-PCF) is inserted into the FLM as a temperature sensing element. Two structures based on the FLM were designed, one is to insert a short length of ethanol-filled HB-PCF in the FLM, and the other is to make a reflective probe with the ethanol-filled HB-PCF, since the independent probe is more suitable for practical application. The refractive index of the ethanol filled in the cladding air holes of HB-PCF would change versus the applied temperature, and the birefringence of the HB-PCF would change as well, which would affect the output wavelength shifts of the FLM. Experiments were carried out to verify the sensor principle. Preliminary experimental results indicated that the temperature sensitivity of the two structures were 0.8833 nm/°C and 0.7896 nm/°C, respectively, for a 10-cm-long HB-PCF.

1. Introduction

Fiber loop mirrors have attracted much attention in recent years since they have been widely applied in optical sensing and communications fields [1]. The conventional FLM consists of a 3 dB coupler and a high birefringence fiber (HBF). Various kinds of sensors based on FLMs have been demonstrated for applications, such as temperature sensors, strain sensors and curvature sensors [2–4]. However, the birefringence of conventional HBF is on the order of 10^{-4}, while the HB-PCF is on the order of 10^{-3} [5]. Therefore, HB-PCF seems to be the best choice to make sensors based on FLMs. Taking the temperature measurement as an example, HB-PCF cannot be used to measure temperature due to the low thermo-optic and thermo-expansion coefficient [6]. The flexibility of the air holes in HB-PCF has provided a more convenient platform for the infusion of sensitive materials. As a result of higher thermo-optic coefficient of ethanol, sensors based on FLM with ultrahigh temperature sensitivity of 6.6 nm/°C has been demonstrated by Qian et al. [7].

The temperature sensitivity of the temperature sensor is closely related to the thermo-optic coefficient of the sensitive materials filled in the air holes. So some researchers focused on the filling technology, for example, Han demonstrated a Sagnac interferometer based on a selective-filling photonic crystal fiber with an ultrahigh sensitivity of 26.0 nm/°C [8] and Zhao demonstrated an alcohol not full-filled HB-PBF temperature sensor based on FLM. With the sensitivity of 1.17 nm/°C [9].

In this paper, we report on a compact temperature sensor based on FLM with a short length of ethanol-filled HB-PCF inserted as a temperature element. Experiments are done to prove the simulation results by detecting the wavelength shifts of the resonance peak under different temperatures in OSA. Moreover, a different structure, in which the ethanol-filled HB-PCF was taken as an independent probe, proposed in the previous work [10] was also verified.

2. Principle of the temperature sensor based on FLM

2.1. Sensor structure and principle

The proposed temperature sensor based on an ethanol-filled HB-PCF FLM, as shown in Fig. 1, consists of a 3 dB couple and a short ethanol-filled HB-PCF inserted in the FLM. The 3 dB coupler splits the input light (1550 nm) equally into two counterpropagating waves. After propagating around the loop, interference will happen since the two waves transmit through the HB-PCF. Therefore we can see an interference spectrum from the optical spectrum analyzer (OSA).

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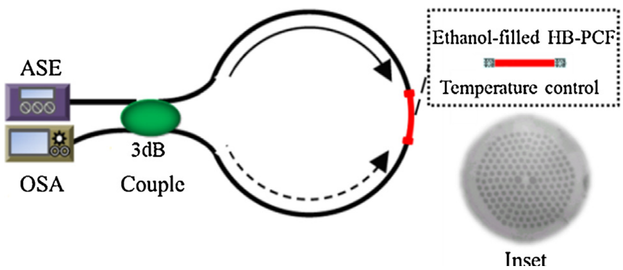

Fig. 1. Schematic diagram of temperature sensor based on an ethanol-filled HB-PCF FLM. Inset: Optical microscopic picture of cross section of the used HB-PCF.

In this experiment we inject ethanol into the air holes of the HB-PCF with a syringe. The force that drives the ethanol into the air holes is provided by an external pressure on the syringe pump. As shown in Fig. 2(a) and (b), the ethanol filled in the air holes of HB-PCF presents a different refractive index from the air under the optical microscope. Then we splice the 10-cm-long ethanol-filled HB-PCF between two SMFs with the help of a fusion splicer (Fitel S178). Fig. 2(c) shows a perfect fusion splicing with a small fiber end face angle. However, the total loss of the two splicing points detected by PD is 3.67 dB, which is relatively high due to the mismatched mode field area and numerical apertures between the HB-PCF and SMF. It is noted that the high loss will not affect the accuracy of the experimental results since we use the wavelength demodulation. The wavelength shift was measured by OSA (Yokogawa, AQ6370) with a wavelength resolution of 0.02 nm.

According to the classic FLM principle [11], the transmission ratio of the HB-PCF FLM as a periodic function of the wavelength can be written as

$$T = \frac{\left(1-\cos\theta\right)}{2} \tag{1}$$

where $\theta = 2\pi BL/\lambda$ is the phase difference. The birefringence of the HB-PCF, $B = n_s - n_f$, is the difference between the effective refractive indices at slow and fast axes, L is the length of the ethanol-filled HB-PCF and λ is the wavelength of the ASE light source. The output of the interference spectrum has some peaks and dips, which satisfy $2\pi BL/\lambda = 2k\pi$, where k is an integer. So the peak wavelength λ_{peak} can be expressed as following

$$\lambda_{peak} = \frac{BL}{k} \tag{2}$$

The interference spectrum changes with the variation of temperature because of two effects: the thermo-optic effect and the thermo-expansion effect. According to Eq. (2), the transmission peak wavelength of the proposed temperature sensor can be written as

$$\Delta\lambda_{peak} = \frac{\lambda}{BL}\left(\Delta BL + B\Delta L\right) \tag{3}$$

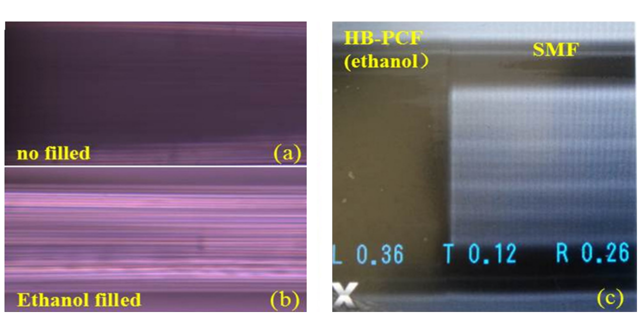

Fig. 2. (a) Optical microscopic picture of HB-PCF with nothing filled; (b) optical microscopic picture of HB-PCF with ethanol filled; (c) ethanol-filled HB-PCF spliced with SMF.

Due to the thermo-optic effect, the refractive index of the ethanol filled in HB-PCF air holes changes as a function of temperature, and so as the HB-PCF. Then the birefringence B changes either.

The length change ΔL is caused by the HB-PCF's thermo-expansion effect, and the thermo expansion coefficient $\left(\Delta L/L\Delta T\right)$ of silica is $5.5 \times 10^{-7}/^{\circ}C$ [6].

ΔT is divided on both sides of Eq. (3), the temperature wavelength sensitivity can be expressed as

$$\frac{\Delta\lambda_{peak}}{\Delta T} = \frac{\lambda}{BL}\left(\frac{\Delta B}{\Delta T}L + B\frac{\Delta L}{\Delta T}\right) \tag{4}$$

Eq. (4) can be can be simplified into

$$\frac{\Delta\lambda_{peak}}{\Delta T} = \lambda(a+b) \tag{5}$$

where we define $a = 1 \times \Delta B/B \times \Delta T$, $b = 1 \times \Delta L/L \times \Delta T$, obviously, $b = 5.5 \times 10^{-7}/^{\circ}C$. The HB-PCF we used has a birefringence of $B = 7.78 \times 10^{-3}$. In order to calculate the value of a, an experiment was designed to measure the relationship between the ethanol refractive index and temperature, and a simulation was performed to analyze the birefringence characteristics of HB-PCF by using a full-vector finite element method. The details are described as follows.

2.2. Ethanol refractive index measurement

Considering the volatility of ethanol, Abbe refractometer is not suitable to measure the relationship between the ethanol refractive index and temperature. Then a novel method of ethanol refractive index measurement using the differential circuit with sealed ethanol probe is presented.

The experimental setup of measuring the relationship between ethanol refractive index and temperature is shown in Fig. 3(a). Light from a laser source (at a wavelength of 1550 nm) was launched into a 3 dB coupler, which divided the light intensity into two beams equally. Then two beams of light passed through two circulators, respectively. Light in Beam 1 was reflected by ethanol and detected by PD1, while light in beam 2 was reflected by water and detected by PD2. The fiber–ethanol probe and the fiber–water probe were placed in the temperature controlled container to keep the same temperature. Furthermore, in terms of signal acquisition, we use the differential circuit [12], which eliminates the volatility and some of the light path intrinsic loss. More remarkable, we design a sealed sensing probe which makes the results more accurate with details illustrated in Fig. 3(b). First, a SMF with a cladding diameter of 125 μm and a glass capillary tube with inner diameter of (125 + 5) μm should be prepared. Then fix them to the six-dimensional adjustment, separately. Second, the capillary was filled with ethanol and then sealed by UV glue. Third, with the help of a microscope can the SMF be inserted into the capillary hole until the ethanol leaks out from the other end of the capillary After cleaning up the leakage, sealed this end by UV glue either.

According to Fresnel theory, when a beam of light is incident to the interface of fiber and ethanol (or water), a portion of light will be reflected back because of the differences in refractive indices. The reflectivity of light intensity I can be written as following [12]

$$I = I_0 \times \left|\frac{\tilde{n}_1 - \tilde{n}_2}{\tilde{n}_1 + \tilde{n}_2}\right|^2 \tag{6}$$

where I_0 is the output intensity of the LD. $\tilde{n}_1$ represents the refractive index of medium 1, in the experiment is the fiber core with $\tilde{n}_1 = n_{fc} = 1.467$. For the medium 2 is ethanol, there will be $\tilde{n}_2 = n_{eth} - ik_{eth}$, k_{eth} is the extinction coefficient ($k = \alpha/(4\pi\tilde{\nu})$), where α, $\tilde{\nu}$ are absorption coefficient, wave number). Absorption coefficient of ethanol α was calculated by the Beer–Lambert law from