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Highly sensitive temperature sensor based on an isopropanol-filled photonic crystal fiber long period grating

Chao Du [a], Qi Wang [a,b,*], Yong Zhao [a,b], Jin Li [a]

[a] College of Information Science and Engineering, Northeastern University, Shenyang 110819, China
[b] State Key Laboratory of Synthetical Automation for Process Industries (Northeastern University), Shenyang 110819, China

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ABSTRACT

A high sensitivity measurement method for temperature has been proposed and investigated based on an isopropanol-filled photonic crystal fiber long period grating (PCF-LPG). Due to the high thermo-optic coefficient (TOC) of isopropanol, the sensitivity of the proposed temperature sensor could be effectively improved by filling isopropanol in the air waveguides of PCF. It can be found that the resonant dip will be split in two dips after filling isopropanol and the two dips have different sensitivities to surrounding temperature. Because of PCF-LPG is sensitive to the refractive index (RI) of internal filled liquid, the isopropanol-filled PCF-LPG temperature sensor has a high sensitivities of 1.356 nm/°C in the range of 20–50 °C. The simplicity and the excellent performance of our proposed device make it potential for the applications of high-precision temperature measurement is required.

1. Introduction

As a key physical parameter, temperature is closely related to the characteristics of material. The measurement of temperature has great significance to the fields where high-precision temperature measurement is required, especially in food industries or chemical for quality control and biochemical reactions monitoring [1]. Compared to other temperature sensors, optical temperature sensors have many advantages such as compact structure, fast response, high sensitivity, high stability, resistance to electromagnetic interference [2]. In recent years, various types of optical temperature sensors have been widely studied, such as interferometer structures [3–8], fiber loop structures [9,10], fiber grating structures [11–13], etc. The measurement mechanisms of most devices mainly depend on the thermo-optic properties of silica. Due to a low thermo-optic coefficient (TOC) of pure silica, the temperature sensitivities of them are relatively low. In order to enhance the sensitivities of optical fiber temperature sensors, there have been many reports about the combinations of optical fiber sensors and materials with a high TOC [14,15]. The thermo-optic effect and thermal expansion effect of sealed liquid can turn it into an ultrasensitive temperature sensor, because of the microfiber taper is highly sensitive to the surrounding RI. Although the temperature sensitivity is as high as 3 nm/°C, it is easy to be broken due to the diameter of the taper is only about 10 μm.

With the emergence and development of PCF, temperature sensors based on PCF structures have been widely reported. 2011, Wang et al. proposed a selectively infiltrated PCF with ultrahigh temperature sensitivity, the average temperature sensitivity achieved is 54.3 nm/°C [16]. Such a device is demonstrated in their experiment by filling standard 1.46 RI liquid into one of the air holes of the commercially available PCF by use of femtosecond laser-assisted complicated technique. The disadvantage of these selectively infiltrated PCF temperature sensors is that the fabrication process is complicated and expensive. 2012, Qian et al. proposed a high-sensitivity temperature sensor based on an alcohol filled PCF loop mirror, and experimental results demonstrated that the temperature sensitivity can reach up to 6.6 nm/°C [17]. Due to complicated sensing structure, the loop structure measurement systems always show poor stability.

The material with a high TOC will produce a large RI change with surrounding temperature variation, so the measurement of temperature can be achieved by monitoring RI change. LPG written in PCF can couple the core mode to the forward propagating cladding modes, and shows relatively high RI resolution of 10^{-5}–10^{-7} RIU because of the strong interaction between cladding modes and filled medium [18,19], so it can be used for the measurement of temperature. Isopropanol is a transparent liquid with a high TOC and its RI is lower than that of the silica core region [20], which is easy to be integrated with PCF. In this letter, a highly sensitive

* Corresponding author at: Northeastern University, College of Information Science and Engineering, P. O. Box 321, Shenyang, Liaoning 110819, China.
E-mail address: wangqi@ise.neu.edu.cn (Q. Wang).

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temperature sensor based on an isopropanol-filled PCF-LPG has been reported and analyzed. The results indicated that the sensitivity of the proposed temperature sensor can reach 1.356 nm/°C with a LPG length of 2.7 cm and a grating period of 180 μm, in the range of 20 °C to 50 °C. It has a high measurement resolution of 0.015 °C and advantages of easy fabrication, compact structure, and good linearity.

2. Sensing structure and measurement mechanism

The schematic diagrams of the isopropanol-filled PCF-LPG sensing system are shown in Fig. 1. A broadband light source (ASE) and an optical spectrum analyzer (OSA) with a wavelength resolution of 20 pm were adopted to record the transmission spectra of the proposed device. In actual measurements, the sensing probe should be placed in a temperature-controlled chamber and fixed with two fiber holders to keep it straight.

As shown in Fig. 1, the adopted PCF has a hole-diameter of 4.88 μm and a hole-spacing of 7.67 μm. In general, the air waveguides of PCF can be filled with isopropanol by capillary action. The length of PCF was set to 5 cm, which ensured the LPG was completely immersed in isopropanol. Finally, the isopropanol-filled PCF-LPG temperature sensor was obtained after splicing with SMFs by using a commercial fiber splicer.

The LPG can couple the core mode to the forward propagating cladding modes. The coupling between the core mode and the mth cladding mode matches the phase-matching conditions:

$$\beta_{co} - \beta_{cl,m} = 2\pi/\Lambda \tag{1}$$

where β_{co} and $\beta_{cl,m}$ are the propagation constants of the core mode and the mth order cladding mode, respectively. Λ is the grating period. Therefore, resonant wavelength λ_{res} is determined by:

$$\lambda_{res} = (n_{eff}^{co} - n_{eff}^{cl,m})\Lambda = \Delta_{eff}\Lambda \tag{2}$$

where n_{eff}^{co} and $n_{eff}^{cl,m}$ are the effective refractive indices of core mode and the mth cladding mode, respectively.

The proposed air-filled PCF-LPG with a grating period of 180 μm and a length of 2.7 cm, and then recorded its transmission spectrum at room temperature, which is shown in Fig. 2. The resonant dip was induced by the coupling of core mode LP_{01} and cladding mode LP_{03}, and the coupled resonant wavelength is about 1500 nm.

The sensitivity of LPG temperature sensor is mainly determined by the thermal expansion and thermo-optic effects of silica.

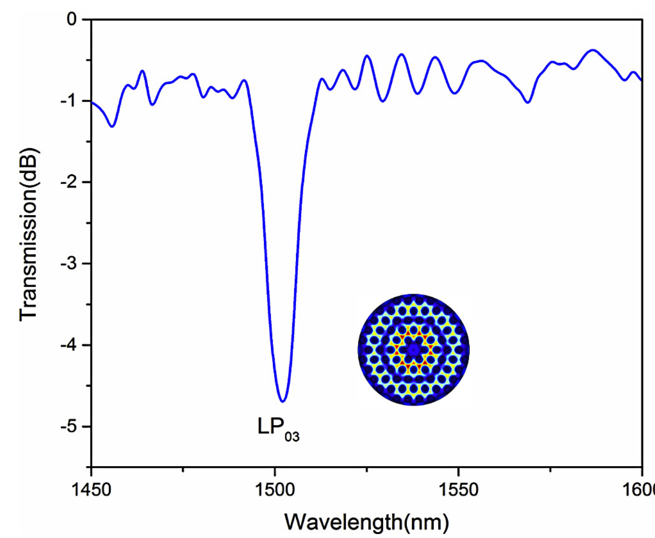

Fig. 2. Transmission spectrum of air-filled PCF-LPG at room temperature.

Considering the influence of temperature, the phase-matching conditions is given by:

$$\beta_{co}(\lambda, T) - \beta_{cl,m}(\lambda, T) = 2\pi/\Lambda \tag{3}$$

where $\beta_{co}(\lambda, T)$ and $\beta_{cl,m}(\lambda, T)$ are the propagation constants of core mode and the mth order cladding mode when temperature is T and resonant wavelength is λ. Λ is the grating period when temperature is T, as shown in Eq. (4).

$$\Lambda = (1 + \alpha\Delta T)\Lambda_0 \tag{4}$$

where α represents thermal expansion coefficient (TEC). The temperature sensitivity K_T is given by [12]:

$$K_T = \frac{d\lambda_{res}}{dT} = \left(\frac{\partial n_{eff}^{co}}{\partial T} - \frac{\partial n_{eff}^{cl,m}}{\partial T}\right)\Lambda + (n_{eff}^{co} - n_{eff}^{cl,m})\frac{\partial \Lambda}{\partial T} \tag{5}$$

As shown in Eq. (5), the thermal expansion effect changes the grating period and the thermo-optic effect changes the effective refractive indices of core mode and cladding modes. The thermo-optic effect is the dominant factor of temperature sensitivity because of the TOC (8.6×10^{-6}/°C) is an order of magnitude higher than TEC (5.5×10^{-7}/°C).

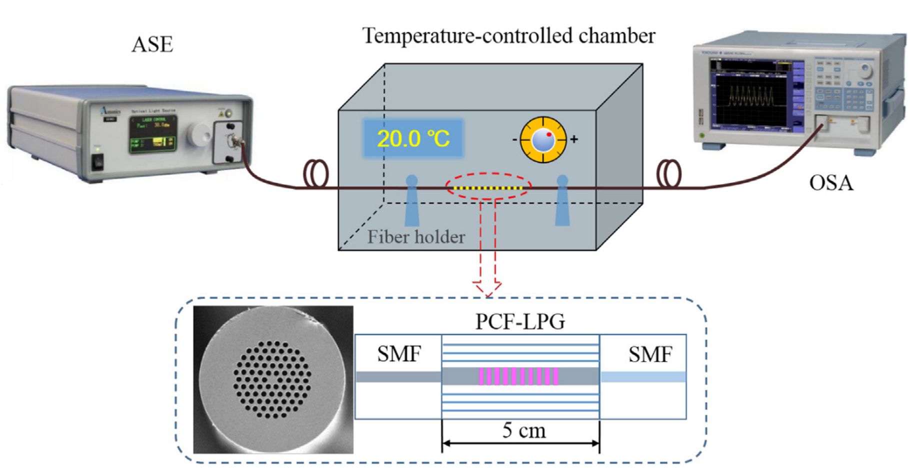

Fig. 1. Schematic diagrams of the isopropanol-filled PCF-LPG sensing system. The inset is the enlarged structure of temperature sensor.