Optical Fiber Technology 41 (2018) 1–6

Contents lists available at ScienceDirect

Optical Fiber Technology

journal homepage: www.elsevier.com/locate/yofte

# Multi-modes interferometer for magnetic field and temperature measurement using Photonic crystal fiber filled with magnetic fluid

Xue-gang Li*, Xue Zhou, Yong Zhao, Ri-Qing Lv

*College of Information Science and Engineering, Northeastern University, Shenyang 110819, China*

## ARTICLE INFO

*Keywords:*
Fiber-optic sensor
Magnetic field
Temperature
Photonic crystal fiber
Magnetic fluid

## ABSTRACT

An in-line modal Mach–Zehnder interferometer (MZI) based on a magnetic fluid-filled photonic crystal fiber (PCF) was proposed in this paper. The Mach–Zehnder interference was induced by the single mode fiber (SMF)-photonic crystal fiber (PCF)-single mode fiber (SMF) structure. And the photonic crystal fiber was filled with magnetic fluid to measure the magnetic field and temperature. There are multiple cladding modes are involved into the interference. Hence simultaneous measurement of temperature and refractive index can be achieved by simultaneously monitoring the two different modes interference spectra. The sensitivities of magnetic field and temperature can reach up to 0.072 nm/Gs and −0.080 nm/°C, respectively.

## 1. Introduction

Magnetic field is an important parameter in the field of safety engineering. In recent years, magnetic field sensors have been extensively researched. The traditional electrics magnetic field sensors suffered the disadvantages that they are easily damaged along with their subsequent circuits owing to unpredictable high intensity of magnetic field. In addition, they need active devices which make them unsuitable for remote detection. However, fiber-optic sensors have a series of outstanding advantages over traditional electrics magnetic field sensor, such as small size, compatibility with harsh environments, electromagnetic interference immunity and remote detection, etc. [1–10].

So far, many fiber-optic magnetic field sensors were built using magnetic fluid (MF) [1–10], whose refractive index (RI) could be varied with the change of the magnetic field. Most of those magnetic field sensors were based on Fabry-Pérot (FP) cavity [8,9], but they did not take the thermal effect of the MF into consideration. The refractive index of the MF also changes with temperature, which is an important security parameter in the magnetic field environment. So, it is necessary to design a sensor to achieve the simultaneous measurement of magnetic field and temperature. In 2014, Zhao et al. proposed a magnetic field sensor based on a magnetic fluid-filled FP-FBG structure to achieve the simultaneous measurement of magnetic field and temperature [9]. The FP cavity filled with MF was used to measure magnetic field and the FBG structure was used to measure temperature. In 2016, Xia et al. also achieved the simultaneous measurement of magnetic field and temperature by using a similar structure [10], but these sensors suffered complicated device fabrication processes and low temperature sensitivity, which is lower than 20 pm/°C. In addition, in 2016, we also proposed a composite interferometer used to simultaneously measure the magnetic field and temperature [11]. It has the advantages of easier demodulation and high temperature sensitivity, but it still suffered complicated device fabrication processes, which needed to splice three different type fibers. In recent years, some double-parameters sensors based on the in-line modal interferometers have been extensively researched, due to their simple structure, high sensitivity and multi-parameters sensing [12–15], such as a tapered bend-resistant fiber modal interferometer for simultaneously measuring of refractive index and temperature [12], a multimodal interferometer based on a suspended core photonic crystal fiber for simultaneously measuring strain and temperature [13], a spherical structure modal interferometer for simultaneously measuring refractive index and temperature [14], a thin-core fiber modal interferometer for simultaneously measuring displacement and temperature measurements [15], and so on. But those fiber-optic modal interferometers cannot combined with MF to measure the magnetic field, because the fibers cannot be filled with MF. However, the unique air hole structure of the photonic crystal fiber (PCF) provide a chance to fill liquid.

In our work, we designed and implemented a novel high-sensitivity dual-parameters sensor based on an in-line modal Mach–Zehnder interferometer by combining the filling feature of PCF and tunable refractive index feature of MF. The interference was induced by SMF – PCF – SMF structure. There are multiple cladding modes are involved into the interference. Previous research showed different modes have different sensing sensitivities, because different modes involved in the interference pattern have varies evanescent field [16]. Hence

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* Corresponding author.
*E-mail address:* lixuegang@stumail.neu.edu.cn (X.-g. Li).

https://doi.org/10.1016/j.yofte.2017.12.002
Received 20 September 2017; Received in revised form 28 November 2017; Accepted 4 December 2017

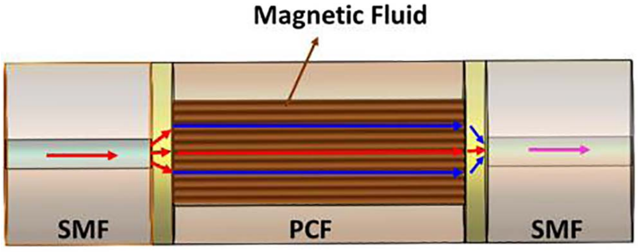


**Fig. 1.** Schematic diaphragm of the designed sensor.

simultaneous measurement of temperature and magnetic field can be achieved by simultaneously monitoring two different modes interference spectra.

## 2. Operating principle

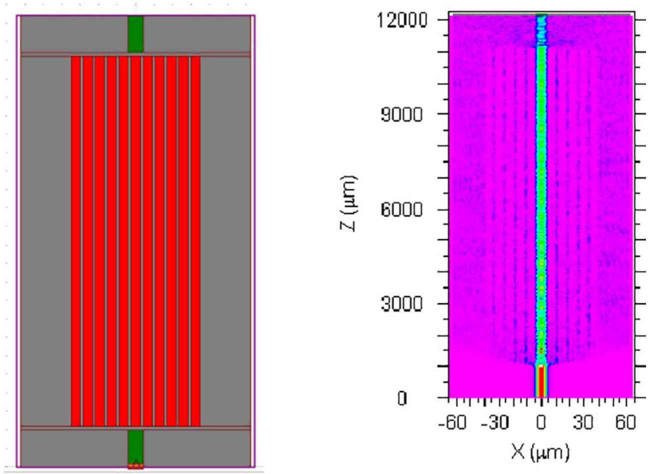
Fig. 1 shows the schematic diagram of the proposed in-line modal MZI. The sensing structure is fabricated by splicing a section of PCF between two SMFs. Before splicing, the PCF is filled with MF. The length between the PCF was the length of the sensing arm of MZI. The first splicing point excites the cladding modes, which will recouple back and interfered with other modes at the second splicing point after spreading a short distance in PCF. The splicing method also have been used in our previous work [17].

The electric field distribution of the proposed structure is simulated with Rsoft, as shown in Fig. 2. Fig. 2 shows that there is an obvious optical field distribution in the cladding of PCF, which proves the cladding modes have been excited. Different order modes have different effective refractive indices, thus the MZ interference occurs between them.

Assuming high order modes are excited in the SMF/ECF point and one of the MZ interference occurs between $i$-order mode and $j$-order mode, the transmission intensity can be expressed as:

$$I_{out} = I_i + I_j + 2\sqrt{I_i I_j}\cos\delta_m, \tag{1}$$

where $I_i$ and $I_j$ were light intensities of the $i$-order mode and $j$-order mode, and $\delta_m$ were the phase difference between them. In our case, the final spectrum is a result of superposition of several modes interference spectra, which is also the foundation of achieving the simultaneously measurement.



(a) (b)

**Fig. 2.** (a) Simulation model diagram (XZ view) of the proposed structure, (b) simulation results.

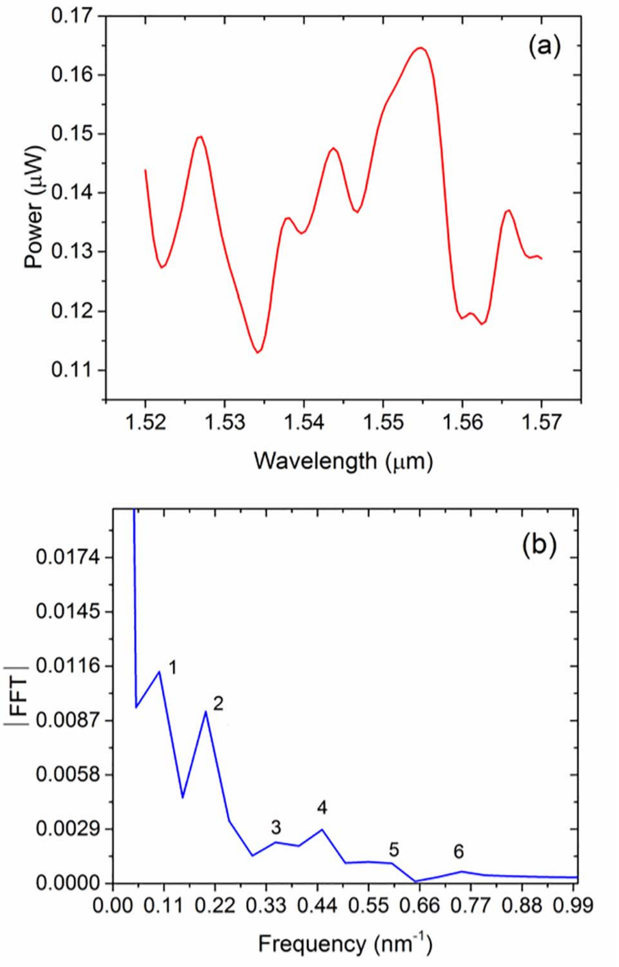


**Fig. 3.** (a) Simulated transmission spectrum of MZI (b) Spatial frequency spectrum of the MZI.

The phase difference $\delta_m$ between $i$-order mode and $j$-order mode could be expressed as

$$\delta_m = \frac{2\pi L}{\lambda} \times (n_i - n_j), \tag{2}$$

where $n_i$ and $n_j$ are effective refractive indices of the $i$-order mode and $j$-order mode, λ is the centre wavelength of the light.

Fig. 3(a) is the simulation spectrum with a 1 cm PCF. As expected, the spectrum is not uniform and more complex than that of a simple sinusoidal waveform, typical of standard two arms (modes) interference, due to the superposition of several mode interferences. Fast Fourier Transform (FFT) is used to obtain the corresponding spatial frequency spectrum, as shown in Fig. 3(b). FFT analysis of the transmission spectrum in Fig. 3(b) shows a spatial frequency spectrum with six main peaks, which imply that there are six modal interferences have been occurred in Fig. 3(a). Therefore, the complex spectrum in Fig. 3(a) can be considered as the superposition of six individual interference spectra formed by a specific pair of modes (such as, pair of 1st–2nd modes, 1st–3rd modes, 2nd–3rd modes, and so on) [16]. The effective RIs of different modes have different sensitivities to magnetic field and temperature, thanks to the different modes involved in the interference pattern have very evanescent fields. The high order modes are more sensitive to magnetic field and temperature than lower order modes and core mode, which is the foundation for the subsequent measurements.

The RI of the MF changes with different magnetic field and temperature, which have been proved by previous studies [10,11,18]. For MF filling PCF, the effective RIs of different modes will change with different magnetic field and temperature. The high order modes are