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Magnetic field and temperature sensor based on a no-core fiber combined with a fiber Bragg grating

Chao Li, Tigang Ning, Xiaodong Wen, Jing Li*, Chan Zhang, Chuanbiao Zhang

Key Lab of All Optical Network & Advanced Telecommunication Network of EMC, Institute of Lightwave Technology, Beijing Jiaotong University, Beijing 100044, China

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ABSTRACT

An optical fiber magnetic field sensor based on the no-core fiber (NCF) and magnetic fluid (MF) is proposed and demonstrated. By using the temperature sensing property of fiber Bragg grating (FBG), the magnetic field sensor with dynamic temperature compensation can be achieved. The transmittance of the NCF that is sealed in a capillary with MF is highly sensitive to the surrounding magnetic field. Experimental results show that the sensor has the magnetic field sensitivity of 9.2 pm/mT ranging from 0 to 9 mT and the temperature sensitivity of 11.9 pm/°C ranging from 15 to 45 °C. The prototype might be attractive due to its low fabrication cost and simple configuration, which are desirable features in magnetic field measurement.

1. Introduction

Optical fiber magnetic field sensors have been widely used in many applications due to their advantages of low power consumption, ability to withstand corrosive environment, high sensitivity and long distance between signal generation and detection [1,2]. On the other hand, MF has been investigated intensively in magnetic field measurement as a new kind of optical functional material. MF is a kind of stable colloidal suspension in which single domain magnetic nanoparticles dressed with suitable surfactant are uniformly dispersed in the carrier liquid. The MF has many diverse and remarkable optical properties. Recently, various optical fiber magnetic field sensors have been achieved by coating MF on the surface of various optical fiber devices, such as interferometers [3–5], fiber gratings [6–8] and photonic crystal fiber (PCF) [9–11], and measurement of magnetic field is realized through the effect of changeable refractive index of the MF with magnetic field. However, an unavoidable fact is that the magnetic field sensors are sensitive to both magnetic field and temperature which may lead to a difficulty in discrimination between them or their simultaneous measurement. In 2012, a magnetic field sensor based on MF and hollow-core photonic crystal fiber (HC-PCF) was proposed by Ref. [12]. Since the HC-PCF is insensitive to temperature, the temperature cross effect on the sensor can be well eliminated. In 2013, a novel fiber optic Fabry–Perot magnetic field sensor was proposed by Ref. [13]. And a FBG was used for temperature compensation in the measurement results of magnetic field. However, the sensors mentioned above are either of complicated design or high cost, which restricts their practical applications.

In this paper, we present an optical fiber magnetic field sensor based on the NCF incorporating with magnetic fluid. By using the temperature sensing property of FBG, the magnetic field sensor with dynamic temperature compensation can be achieved. The FBG is placed in the downstream of NCF. The experimental results show that the magnetic field sensitivity is 9.2 pm/mT ranging from 0 to 9 mT and the temperature sensitivity is 11.9 pm/°C ranging from 15 to 45 °C. Its low fabrication cost and simple configuration have attractive potential applications in magnetic field measurement.

2. Principle

The schematic diagram of the proposed sensor is shown in Fig. 1. A section of NCF is spliced between the leading SMF and a FBG imprinted SMF (SMFBG). The NCF is sealed in a capillary tube which is filled with MF and sealed at both ends with epoxy glue. When the light is launched into the NCF through the leading SMF, the multiple modes (LP_{nm}) of the NCF will be excited due to the mode field mismatch. Considering the circular symmetry of the fibers and assuming that the SMF and NCF are ideally aligned, only the symmetric modes (LP_{0m}) can be excited [14,15]. Denoting the field profile of (LP_{0m}) as $\Psi_m(r)$, the input light field of the NCF $E(r,0)$ can be expressed as

* Corresponding author.
E-mail address: lijing@bjtu.edu.cn (J. Li).

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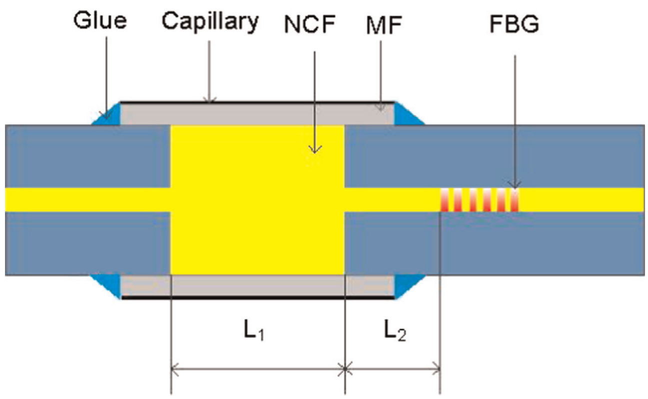

Fig. 1. Schematic diagram of the sensor structure.

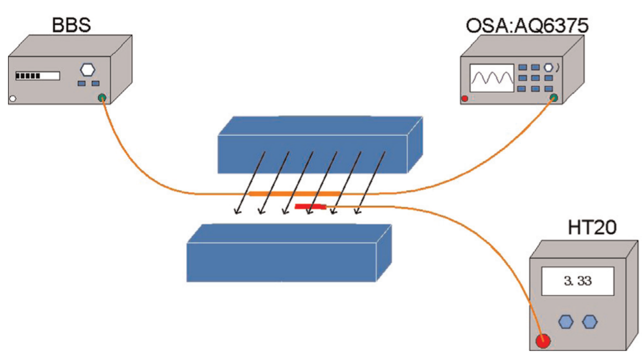

Fig. 2. Schematic diagram of the experimental setup. (BBS, broadband source; OSA, optical spectrum analyzer).

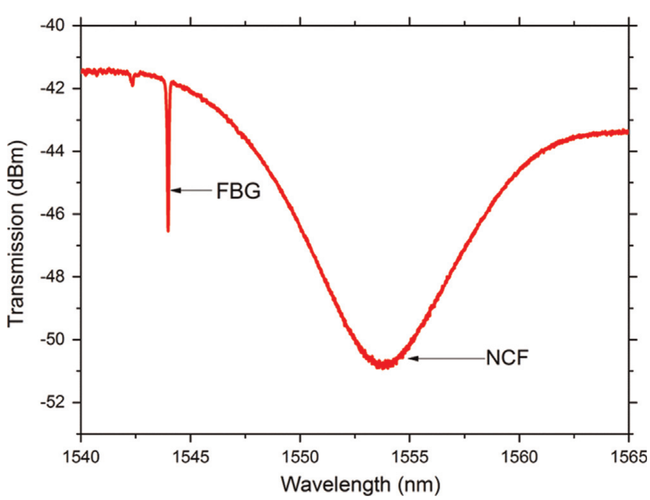

Fig. 3. Measured transmission spectrum of the sensor at room temperature under the magnetic field strength of 0 mT.

$$E(r,0)=\sum_{m=1}^{M} c_m \Psi_m(r) \tag{1}$$

where r is the radial coordinate in the cross section of the fiber, M is the number of modes excited in the NCF core, and c_m is the excitation coefficient of the each mode and it can be expressed as [16]

$$c_m=\frac{\int_0^\infty E(r,0)\Psi_m(r)r\ \mathrm{d}r}{\int_0^\infty \Psi_m(r)\Psi_m(r)r\ \mathrm{d}r} \tag{2}$$

The evanescent field in the vicinity of the interface between the NCF and MF will induce a non-negligible attenuation to the light field as it passes through the NCF. The distribution of the total light field at a propagation distance z can thus be calculated as follows [17]:

$$E(r,z)=\sum_{m=1}^{M} c_m \Psi_m(r)\exp(-\gamma_m z)\exp\left(i\beta_m z\right) \tag{3}$$

where γ_m is the evanescent absorption coefficient and β_m is the propagating constant of each mode. Based on the evanescent field absorption theory in a multimode fiber, γ_m can be given by [18]

$$\gamma_m=\frac{\alpha_\lambda \lambda n_f\ \cos\ \theta_m\ \cot\ \theta_m}{4\pi a n_c^2 \cos^2\theta_c\sqrt{\sin^2\theta_m-\sin^2\theta_c}} \tag{4}$$

where λ is the wavelength in vacuum, α_λ is an attenuation coefficient of the MF at λ, n_f and n_c are the refractive indices of MF and NCF, respectively, a is the radius of the NCF, θ_c is the critical angle, and θ_m is the incident angle of the m-th order mode to the NCF–MF interface. Supposing that the two sections of SMF are identical, the transmittance of the SMS structure can be calculated as [19]

$$T=10\log_{10}\left[\frac{\left|\int_0^\infty E(r,L)E(r,0)r\ \mathrm{d}r\right|^2}{\int_0^\infty |E(r,L)|^2 r\mathrm{d}r\int_0^\infty |E(r,0)|^2 r\ \mathrm{d}r}\right] \tag{5}$$

where L is the length of the NCF. Both the refractive index n_f and attenuation coefficient α_λ of the MF will change with the external magnetic field and temperature [20]. On the contrary, β_m and γ_m will also change which is ultimately expressed as wavelength shift and power attenuation of the transmission spectrum.

The FBG is characterized by the periodicity Λ of the refractive index modulation and the effective refractive index of the waveguide mode n_{eff}. Therefore, this structure shows resonance behavior with a Bragg wavelength given by

$$\lambda_{FBG}=2n_{eff}\Lambda \tag{6}$$

The Bragg wavelength shift caused by temperature can be expressed as

$$\Delta\lambda_{FBG}=\lambda_{FBG}\left[\alpha_{th}+\xi\right]\Delta T \tag{7}$$

where α is the coefficient of thermal expansion of the glass fiber, ξ is the fiber thermo-optic coefficient, and ΔT denotes the change of temperature [21].

When magnetic field and temperature are simultaneously applied to the sensor, the wavelength shifts of the NCF and FBG can be expressed using a matrix as [22]

$$\begin{bmatrix}\Delta\lambda_{NCF}\\ \Delta\lambda_{FBG}\end{bmatrix}=\begin{bmatrix}K_{H,NCF} & K_{T,NCF}\\ K_{H,FBG} & K_{T,FBG}\end{bmatrix}\begin{bmatrix}\Delta H\\ \Delta T\end{bmatrix} \tag{8}$$

where $\Delta\lambda_{NCF}$ and $\Delta\lambda_{FBG}$ represent the wavelength shifts of the NCF and FBG, respectively. K_H and K_T are the sensitivity coefficients corresponding to the magnetic field and temperature change respectively. Postscripts NCF and FBG identify the contribution made by the two structures individually. The magnetic field and temperature sensitivities can be obtained as

$$\begin{bmatrix}\Delta H\\ \Delta T\end{bmatrix}=\frac{1}{K_{H,NCF}K_{T,FBG}-K_{T,NCF}K_{H,FBG}}\begin{bmatrix}K_{T,FBG} & -K_{T,NCF}\\ -K_{H,FBG} & K_{H,NCF}\end{bmatrix}\begin{bmatrix}\Delta\lambda_{NCF}\\ \Delta\lambda_{FBG}\end{bmatrix} \tag{9}$$