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Optical fiber magnetic field sensors with peanut-shape structure cascaded with LPFG*

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An optical fiber magnetic field sensor for the dual-parameter simultaneous measurement is proposed and demonstrated. The sensor head is constructed by a peanut-shape structure and long period fiber grating (LPFG) coated by magnetic fluid (MF). The external magnetic field intensity can be measured by the variation of characteristic wavelength (Dip1 and Dip2) in interference spectrum since the effective refractive index of MF changes with external magnetic field intensity. When the external magnetic field intensity changes from 0 mT to 20 mT, the magnetic field sensitivities of Dip1 and Dip2 are −0.064 nm/mT and −0.041 nm/mT, respectively. Experimental results show that the temperature sensitivities of the Dip1 and Dip2 are 0.233 nm/°C and 0.186 nm/°C, respectively. Therefore, the simultaneous measurement of the magnetic field intensity and temperature is demonstrated based on the sensitive matrix. It has some potential applications in aerospace, environmental monitoring and medical sensing fields.

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Compared with the traditional magnetic sensor, which is with large size and influenced by electromagnetic interference easily, optical fiber magnetic field sensor has outstanding merits in magnetic sensing. It has been widely applied in aerospace technology, environmental monitoring and medical fields[1-3]. Since the optical fiber itself is insensitive to the magnetic field, magnetic field sensor based on ferrofluid[4,5] is widely researched by domestic and foreign scholars. In 2011, Zu et al[6] proposed an optical fiber Sagnac magnetic field sensor based on magnetic fluid (MF), where the magnetic field sensitivity is 16.7 pm/Oe when MF film parallels to the direction of the external magnetic field. In 2011, Wu et al[7] improved a magnetic field sensor based on MF and long period fiber grating (LPFG), where the magnetic field sensitivity is 31 pm/mT. In 2012, Gao et al[8] proposed a magnetic field sensor based on LPFG within a D-shaped fiber, where the magnetic field sensitivity is 176.4 pm/mT. In 2015, Luo et al[9] presented a magnetic sensor based on a hybrid LPFG and an ester-based Fe_3O_4 MF, where the temperature and magnetic intensity sensitivities are −0.044 9 nm/°C and −0.005 2 nm/Oe, respectively.

In this paper, a magnetic field sensor based on peanut-shape structure cascaded with LPFG is proposed. It can realize sensing for external magnetic field and temperature through observing the drift of interference valleys. The sensor achieves simultaneous measurement of magnetic field and temperature based on a sensitivity matrix. It has a widely application in aerospace, environmental monitoring and medical field.

Schematic diagram of the experimental setup and the sensor structure is shown in Fig.1. The length between peanut-shape structure and LPFG is L=3 cm. The peanut-shape structure is made by a commercially available fusion splicer (FITEL S176). Firstly, two spherical structures should be fabricated with two sections of single mode fiber (SMF). In this step, the fusion splicer's discharge intensity is 200 bit, and discharge time is 750 ms. Secondly, the two spherical structures are welded to form the peanut-shape structure. In this step, the fusion splicer's discharge intensity is 115 bit, and the discharge time is 1 350 ms. The length of LPFG used in our experiment is 2 cm, and the resonant wavelength is 1 548.87 nm at room temperature.

Light emitted from the broadband light source (BBS) is transferred into the peanut-shape structure and then coupled to LPFG. Some light propagates in fiber core, and the other is coupled into the cladding and propagates as cladding modes which is more sensitive to the envi-

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ronment. Finally, these modes are transmitted to optical spectrum analyzer (OSA) through the SMF. Peanut-shape structure and LPFG act as the sensing area to monitor the change of external parameter.

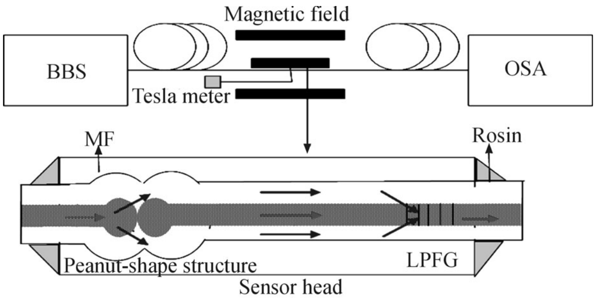


Fig.1 Schematic diagram of the experimental setup and the sensor structure

The fringe visibility of interference spectrum can be described as[10-12]

$$K=\frac{2\sqrt{I_{\mathrm{core}}/I_{\mathrm{clad}}}}{1+I_{\mathrm{core}}/I_{\mathrm{clad}}},\tag{1}$$

where I_{core} and I_{clad} are the light intensity in fiber core and cladding, respectively. Theoretically, while $I_{\mathrm{core}}\approx I_{\mathrm{clad}}$, K will be the maximum, and the interference fringe pattern will be the best. Therefore, it's important to control the diameter of the peanut-shape structure. The phase matching condition between the fundamental core mode and the ith cladding mode of fiber can be expressed as[13]

$$\varphi_i=\frac{2\pi(n_{\mathrm{eff}}^{\mathrm{core}}-n_{\mathrm{eff}}^{\mathrm{clad},i})\mathrm{L}}{\lambda}=\frac{2\pi L\Delta n_{\mathrm{eff}}^{i}}{\lambda},\tag{2}$$

where $n_{\mathrm{eff}}^{\mathrm{core}}$ and $n_{\mathrm{eff}}^{\mathrm{clad},i}$ are effective refractive indices of the core and the ith order cladding mode, respectively, L is the distance between the peanut-shape structure and LPFG, and $\Delta n_{\mathrm{eff}}^{i}$ is the effective index difference between the fundamental core mode and ith order cladding mode of fiber. The interference fringe is obvious when $\varphi_i=(2n+1)\pi$ (n=0,1,2,…).

The sensing structure coated by MF is naturally encapsulated in capillary with rosin to avoid the influence of strain and curve. The magnetic fields perpendicular to the fiber axis with various intensities are applied. Tesla meter is used to measure the intensity of the magnetic field. The experimental results are measured and recorded by a step of 2 mT when the magnetic field intensity is changed from 0 mT at room temperature. The experimental results are shown as Fig.2.

Fig.2(a) shows that Dip1 and Dip2 both blue shift with the increase of magnetic field intensity. Dip1 changes from 1 537.32 nm to 1 536.06 nm, and Dip2 changes from 1 537.32 nm to 1 536.06 nm. Fig.2(b) shows that the magnetic field sensitivities of Dip1 and Dip2 are −0.064 nm/mT and −0.041 nm/mT, respectively. The drift of interference valley is significantly reduced when magnetic field intensity increases over 20 mT. When the external magnetic field intensity increases to nearly magnetic saturation, the variation of MF's effective refractive index reduces, so the shift of interference valley significantly reduces.

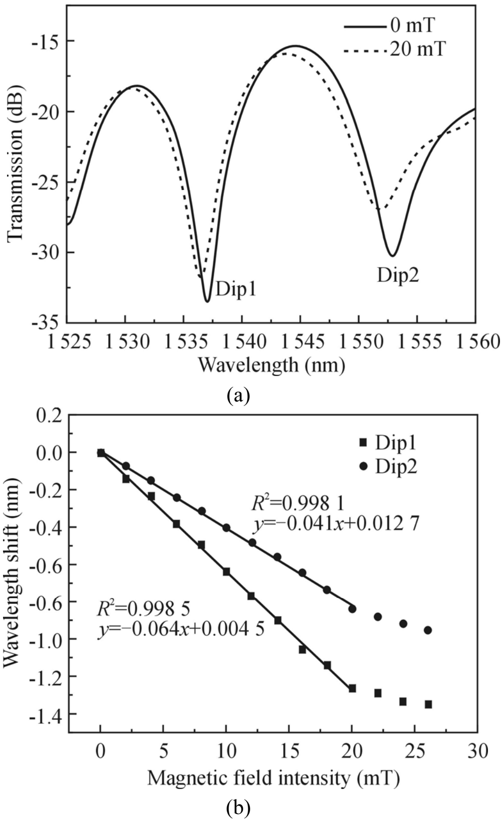


Fig.2 (a) Output spectrum with different magnetic field intensities of 0 mT and 20 mT; (b) Magnetic field intensity response characteristic curve

The sensor is fixed straightly along the surface of a thermostatic heater plate and connected to the measurement system. In the experiment, the temperature changes from 25 °C to 43 °C with a step of 2 °C.

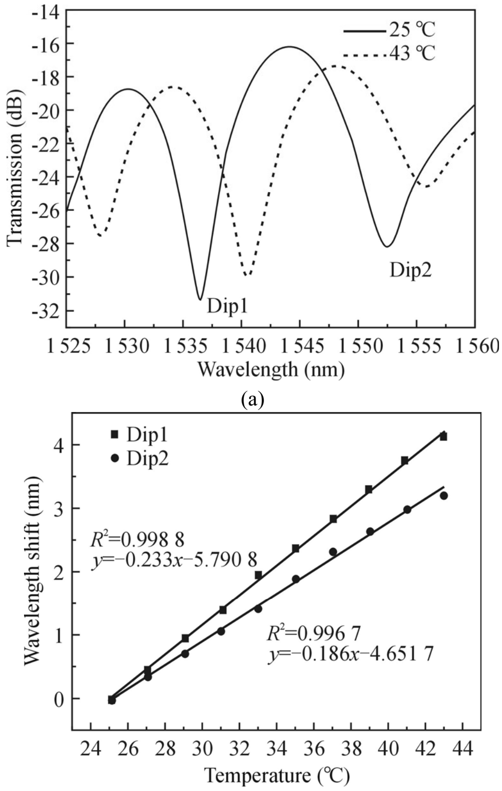
The thermo-optical effect and thermal expansion effect both have important influence on temperature sensitivity[14,15]. It can be seen from Fig.3(a) that the interference valleys shift to longer wavelength with the increase of temperature. The experimental results shown in Fig.3(b) show that temperature sensitivities of Dip1 and Dip2 are 0.233 nm/°C and 0.186 nm/°C, respectively.

According to the above experimental results, the magnetic field and temperature sensitivity coefficients of Dip1 and Dip2 are obtained, respectively. The relationship between the shifts of Dip1 and Dip2 and the external magnetic field, temperature can be expressed in matrix form as

$$\begin{bmatrix}\Delta\lambda_1\\ \Delta\lambda_2\end{bmatrix}=\begin{bmatrix}K_{T1} & K_{H1}\\ K_{T2} & K_{H2}\end{bmatrix}\begin{bmatrix}\Delta T\\ \Delta H\end{bmatrix},\tag{3}$$

where $\begin{bmatrix}K_{T1} & K_{H1}\\ K_{T2} & K_{H2}\end{bmatrix}$ is sensitivity matrix, and $\Delta\lambda_1$ and $\Delta\lambda_2$

are the shifts of the Dip1 and Dip2, respectively. K_{T1} and K_{H1} are the temperature sensitivity and magnetic field sensitivity of Dip1, respectively. K_{T2} and K_{H2} are the temperature sensitivity and magnetic field sensitivity of Dip2, respectively. ΔT and ΔH are the change of temperature and magnetic field, respectively.



(a)

(b)

Fig.3 (a) Output spectrum with different temperatures of 25 °C and 43 °C; (b) Temperature response characteristic curve

It can be obtained from Eq.(3) that

$$\begin{bmatrix}\Delta T\\ \Delta H\end{bmatrix}=\frac{1}{D}\begin{bmatrix}K_{H2} & -K_{H1}\\ -K_{T2} & K_{T1}\end{bmatrix}\begin{bmatrix}\Delta\lambda_1\\ \Delta\lambda_2\end{bmatrix}, \tag{4}$$

where $D=K_{T1}K_{H2}-K_{T2}K_{H1}$.

Substituting the sensitivity coefficients into the sensitivity matrix, it can be obtained that

$$\begin{bmatrix}\Delta T\\ \Delta H\end{bmatrix}=-\frac{1}{2.27\times10^{-3}}\begin{bmatrix}-0.041 & 0.064\\ -0.186 & 0.233\end{bmatrix}\begin{bmatrix}\Delta\lambda_1\\ \Delta\lambda_2\end{bmatrix}, \tag{5}$$

As a result, when magnetic field intensity and temperature change simultaneously, the change of temperature and magnetic field ΔT and ΔH can easily be got according to Eq.(5).

An optical fiber magnetic sensor is proposed based on peanut-shape structure cascaded with LPFG. The sensing structure and MF are encapsulated in capillary. Experimental results show that magnetic field sensitivity and temperature sensitivity of Dip1 are −0.064 nm/mT and 0.233 nm/°C, respectively. And the magnetic field sensitivity and temperature sensitivity of Dip2 are −0.041 nm/mT and 0.186 nm/°C, respectively. The sensor can be used to measure magnetic field and temperature simultaneously. It can be widely applied in aerospace technology, environmental monitoring and medical fields.

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