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High sensitive LPFG magnetic field sensor based on dual-peak resonance

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ABSTRACT

A high sensitivity magnetic field sensor based on magnetic-fluid-clad LPFG structure with dual peak resonance is presented and experimentally investigated. Based on coupled mode theory, the sensing principle of this sensor is originated from the sensibility of the dual peak based LPFG to the environment refractive index. In experiment, a dual peak interval change was available to 38 nm with a magnetic field strength varying from 0 to 12 mT when the temperature was 17.3 °C, and the dual peak interval displays a cubic polynomial dependence with the magnetic field strength at the low field regime. The sensitivity of this sensor to the magnetic field can be available to 4.08 nm/mT, and it is one order and two orders of magnitude higher than that of the sensors based on MSM and SMS fiber structure, respectively. The novel sensor has many advantages of simple technology, structure stability and high sensitivity.

1. Introduction

Magnetic fluids (MF) is a kind of stable colloidal suspension system composed of surfactant-coated magnetic nanoparticles with typical sizes of 10 nm dispersed in a suitable liquid carrier [1]. MF possesses both the features of magnetic property of solid magnetic materials and fluidity of liquids, which makes it have a variety of excellent tunable optical properties, such as magnetic light [2], magneto discoloration [3,4], and heat light characteristics [5]. It is found that the refractive index (RI) of MF increase linearly with the increasing of magnetic field intensity, enabling it to be used in the magnetic field sensor. Recently, the magnetic field sensor based on fiber structure appears constantly, such as the magnetic field sensor which uses the magnetic fluid (MF) as the cladding of the singlemode-multimode-singlemode [6] optical fiber (SMS) structure or the multimode-singlemode-multimode [7] optical fiber (MSM) structure, the magnetic field sensor based on superfine fiber coated with MF [8], and the magnetic field sensor by injecting MF into the microporous of PCF [9], and so on. They also have the flaws of structure instability and complicated technology.

Long period fiber grating (LPFG) is a kind of device that can couple the core mode to the codirectional cladding modes and produce the discrete attenuation bands in the transmission spectra. Its properties of small size, immune to electromagnetic fields and sensitive to the RI of environment, make it widely used in all kinds of RI sensor [10,11]. Recently, the dual peak resonance based on higher order mode in a LPFG has been attracted attention due to its high RI sensitivity [12,13]. Gu et al. [14,15] investigated the dual peak resonance of coated LPFG, and proposed a sensor based on dual peak resonance. The numerical simulation shows that the sensor has giant sensitivity to the RI sensitive film. Therefore, if the MF is coated on the cladding of dual peak based LPFG, it would obtain a high sensitivity magnetic field sensor. The research on this aspect has not yet been reported.

This paper presents a magnetic field sensor based on MF and LPFG with dual peak resonance. Based on coupled mode theory, the response characteristics of the RI of the sensor are studied. Experimentally, the MF is encapsulated on the dual peak based LPFG by capillary to construct the magnetic field sensor, and the sensor is put into a magnetic field to test the magnetic field sensing characteristics. Finally, the relationship between the wavelength interval of the dual peak and the magnetic field strength is obtained, and the sensitivity of this sensor to magnetic field is given in experiment.

2. Sensing principle

The structure of this kind of coated LPFG sensor may be regarded as a double-cladding LPFG model. MF is the second cladding. There are two reasons to make the assumption, one is the thickness of the MF encapsulated on the LFPG is 487.5 μm, because the inner diameter of the glass tube used to encapsulate MF is

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1.1 mm in the experiment. Another one is that the MF is absorbent material, so the light will not be able to penetrate MF into the air. Fig. 1 shows the structural diagram and the RI profile of this sensor. The refractive indices of the core, cladding, MF are n_1, n_2, n_3, respectively. a_1, a_2 are the radii of the core and cladding. In the study, n_1, n_2, a_1 and a_2 are 1.4681, 1.4628, 4.15 μm and 62.5 μm, respectively.

The phase-matching condition of LPFG coupling between the fundamental core mode propagating in the fiber and the co-propagating cladding modes is

$$\beta_{11}^{co} - \beta_{1\nu}^{cl} - 2\pi/\Lambda = 0 \quad (1)$$

where Λ is the grating period. β_{11}^{co} and $\beta_{1\nu}^{cl}$ are the propagation constant of the core and cladding modes, respectively. According to the expression $\beta = k_0 n_{eff}$, the phase-matching condition is also expressed as:

$$n_{eff,co}(\lambda) - n_{eff,cl}^{\nu}(\lambda) = \frac{\lambda}{\Lambda}, \quad \nu = 1,2,3,\ldots \quad (2)$$

where $n_{eff,co}(\lambda)$ is the effective RI for the fundamental core mode which can be obtained by solving the core mode eigenvalue equation [16]; $n_{eff,cl}^{\nu}(\lambda)$ is the effective index for the νth cladding mode which can be obtained by solving the cladding mode eigenvalue equation [17]. The effective refractive indexes of the fundamental core mode and the cladding mode are a function of the wavelength. The wavelength λ which satisfies the Eq. (2) is called the resonant wavelength. When Λ is much shorter, the dual resonant wavelengths may satisfy the Eq. (2).

Suppose the center of the grating is the origin of the z-axis, the boundary conditions for a long-period grating L in length are $A^{co}(z = -L/2) = 1$ and $A_{\nu}^{cl}(z = -L/2) = 0$. The transmissivity through the grating is defined as

$$T = A^{co}(L/2)/A^{co}(-L/2). \quad (3)$$

Fig. 2 shows the transmission spectra of the 19th cladding mode of the double-cladding LPFG when the grating period Λ is 181 μm. We can see that the dual resonant wavelengths shift in opposite directions with the variation of the second cladding RI, and the amplitude of the resonance peak also changes with the second cladding RI. And the wavelength intervals between the dual resonance peaks increase with the increasing of the second cladding RI. It is indicated that the dual resonance peaks are sensitive to RI of the second cladding, which is said, if the second cladding is MF, the dual peak sensor would be sensitive to the RI of MF which is varied by the magnetic field. So the dual peak LPFG can be applied to construct the magnetic field sensors.

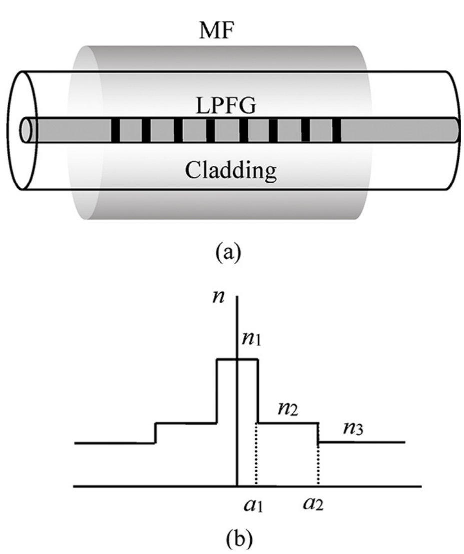

Fig. 1. (a) Structural diagram of the sensor; (b) the RI profile of the sensor.

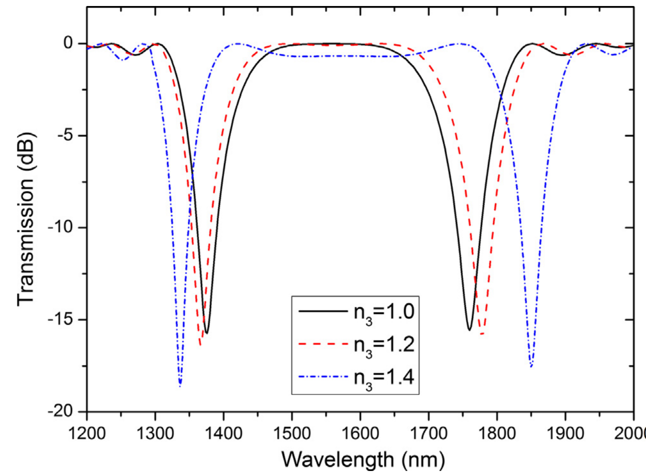

Fig. 2. Transmission spectra of the 19th cladding mode of the double-cladding LPFG.

3. Fabrication

In experiment, the used fiber was Corning SMF-28 which was hydrogen loaded in advance for two weeks to enhance its photo sensitivity. The gratings were fabricated by illuminating the fiber core with 248 nm KrF excimer laser. The pulse energy, frequency and exposure time were 24 mJ, 200 Hz and 15 s, respectively. The fabrication of a dual peak based LPFG was performed writing the grating with period 184.7 μm, and the length of this LPFG was about 25 mm. All of these procedures were automatically performed by the control of computer programs. To improve thermal stability, the fabricated dual peak based LPFG was annealed at 120 °C for 12 h.

Fig. 3 shows the real-time measured transmission spectra of dual peak based LPFG in the process of the cladding corrosion. It can be seen that the right peak of the LPFG was invisible due to the wavelength limit of the used OSA (see black solid line). It is known that the cladding reducing could decrease the effective index of cladding modes, further make the resonant wavelength

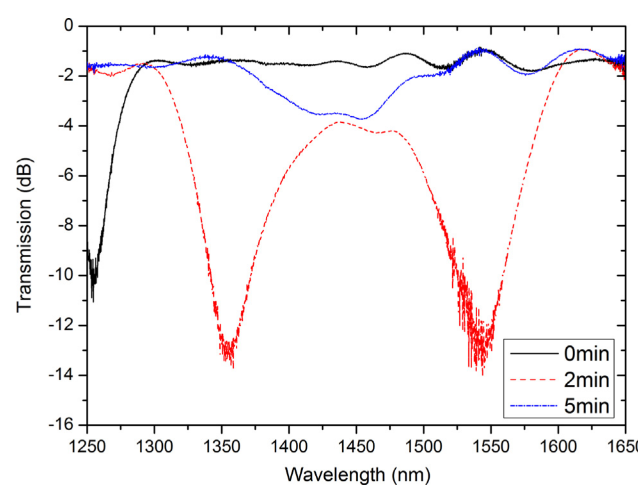

Fig. 3. Measured transmission spectra of dual peak based LPFG in the process of the cladding corrosion.