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Temperature-Compensated Magnetic Field Sensing with a Dual-Ring Structure Consisting of Microfiber Coupler-Sagnac Loop and Fiber Bragg Grating - Assisted Resonant Cavity

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Temperature-compensated magnetic field sensing with a dual-ring structure consisting of microfiber coupler-Sagnac loop and fiber Bragg grating-assisted resonant cavity

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A novel temperature-compensated magnetic field sensor based on a ring erbium-doped fiber laser combined with a fiber Bragg grating (FBG) and a Sagnac loop containing a microfiber coupler (MFC) and magnetic fluid is proposed and investigated. Thanks to the dual-ring structure of the MFC-Sagnac loop and the FBG-assisted resonant cavity, the output of the structure has two distinct laser peaks. In addition to the magnetic field sensing capability, the proposed structure can simultaneously provide temperature information. The maximum experimentally demonstrated sensitivity to a magnetic field determined from the spectral shift of one laser peak is 102 pm/mT in the magnetic field range from 0 to 60 mT. The spectral position of the other laser peak is independent of the magnetic field but shifts toward longer wavelengths with temperature with a sensitivity of 18 pm/°C. The proposed magnetic field sensor is advantageous for applications requiring measurement accuracy over a wide magnetic field range with a compensating of temperature information. © 2019 Optical Society of America

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1. INTRODUCTION

Magnetic field strength measurements play an important role in many areas, such as information storage, environmental monitoring, hazard forecasts, and aeronautics [1–4]. Fiber-optic sensors for magnetic fields have many advantages compared to their electronic counterparts, such as high sensitivity, fast response, and low power consumption.

A variety of fiber-optic structures have been proposed for magnetic field sensing. Optical microfiber couplers (MFCs) have become a topic of special interest in optical fiber sensing due to their excellent sensing properties [5,6]. Microfiber-based magnetic field sensors show higher sensitivity to surrounding refractive index (RI) than traditional optical structures utilizing interference, because their much smaller diameter means that a larger proportion of the evanescent field surrounding the microfiber can interact with the local environment. Examples of such structures include an optical microfiber mode interferometer coated with a magnetic fluid (MF) [7,8], an MFC combined with a Sagnac loop [9], and an MFC surrounded with

MF [10]. Several researchers reported experimental and theoretical studies of fiber sensors where an asymmetric taper for sensing of RI or magnetic field showed that a very high sensitivity is achievable with such structures [11]. However, the fabrication of such an asymmetric taper structure requires accurate manual adjustment of the fibers' positions within the fusion splicer during the application of multiple discharges, leading to poor reproducibility.

Other structures have also been proposed for simultaneous measurement of magnetic field strength and temperature. For example, Yan *et al.* [12] proposed a dual-parameter scheme based on an etched thin core fiber modal interferometer cascaded with a fiber Bragg grating (FBG), reaching a magnetic field and temperature sensitivity of -0.017 dB/Oe and 0.133 dB/°C, respectively, while the Bragg wavelength of the FBG was insensitive to magnetic field and had a temperature sensitivity of 13.23 pm/°C. However, the process of etching a thin core fiber is difficult to precisely control. Chen *et al.* [13] proposed a magnetic field and temperature sensor based on a

combination of a macrobending fiber structure and an FBG. However, this sensor was difficult to fabricate with precision. Previously we proposed a similar dual-ring structure consisting of an MFC-Sagnac loop and an FBG-assisted resonant cavity [5]. However, the sensitivity was only 15 pm/mT in the magnetic field range from 0 to 100 mT and 13 pm/°C in the temperature range from 25°C to 44°C. Besides, that sensor could not offer simultaneous measurements of magnetic field and temperature at the same region in space because the MFC temperature had to be kept constant at 25°C, which is a limitation in applications that demand not only simultaneous measurement of magnetic field strength and temperature but also measurement at the same point in space.

Finally, it is well known that optical fiber sensors take many forms to suit a wide variety of measurands, but those based on fiber lasers have the additional advantages of high signal-to-noise ratio, narrow linewidth, and ease of interrogation, allowing for measurements with high resolution [14].

In this paper, we propose and investigate a novel magnetic field sensor structure consisting of a ring erbium-doped fiber (EDF) laser combined with an FBG and an MFC-based Sagnac loop. In addition to sensing of the magnetic field, the proposed structure is capable of simultaneously providing temperature information and can provide measurement of both measurands at the same region in space. The cross sensitivity of the MFC-Sagnac loop to temperature is also considered and analyzed. The output spectrum of the proposed sensor contains two laser peaks: one peak is associated with the FBG, and its central wavelength position provides the temperature information, while the second peak is associated with the output of the MFC-Sagnac loop, and its spectral posit calibration has taken place.

2. FABRICATION OF THE SENSOR

A schematic diagram of the proposed fiber laser sensor is shown in Fig. 1(a). The structure comprises a typical ring laser cavity with a 980 nm laser diode (LD) pump, coupled into the ring cavity through a wavelength selective coupler. A section of EDF with a length of 15 m absorbs the pump light at a 980 nm wavelength and emits light at 1550 nm. The optical isolator (ISO) is used to ensure that the light circulation within the ring occurs in the clockwise direction only. Another branch of the loop (Part A in the figure) is formed by the circulator and the FBG (with a Bragg wavelength of 1548.5 nm and 3 dB bandwidth of 0.38 nm) coupled with the ring cavity by means of the 3 dB optical coupler A (OCA). Part A of the structure functions as the wavelength selective element for the laser, since only the light reflected by the FBG will re-enter the ring cavity through a second 3 dB optical coupler B (OCB). Simultaneously, as the light at the resonant wavelength circulates within the cavity, it is also split into two beams by the OCA. One beam enters the FBG loop and is eventually fed back into the ring cavity, while another beam is launched into the MFC-Sagnac loop (Part B), whose output interference spectrum strongly depends on the RI surrounding the MFC waist. The resulting output of the proposed structure [monitored by the optical spectrum analyzer (OSA)] contains two lasing peaks. The spectral position of the first peak is determined by the FBG, while the central

Fig. 1. (a) Schematic diagram of the proposed sensor with MFC-Sagnac; (b) transmission spectrum of only MFC with waist diameter of 2.6 μm (FSR 20.6 nm); (c) transmission spectrum of only MFC-Sagnac structure immersed in MF solution.

wavelength of the second peak is associated with Part B of the structure (MFC-Sagnac loop). In our experiment, the magnetic field and temperature changes were only applied to the sensor head area (the red dashed box).

The MFC-Sagnac loop, operating as the sensor's head, is shown schematically in Fig. 1(a). One of the critical parameters of the MFC is its waist diameter, since it determines both the coupling ratio of the MFC and its RI sensitivity [15]. In our experiment, the MFC is fabricated by simultaneously fusing and tapering of two standard single-mode fibers (SMFs) using a method known as the microheater brushing technique [16]. The waist diameter of the fabricated MFC was $\sim 2.6 \mu\text{m}$. The transmission spectrum of only the MFC is shown in Fig. 1(b). It is possible to achieve a higher RI sensitivity by using an MFC with a smaller waist diameter, but in practice there is a trade-off between the sensitivity and mechanical stability of the MFC, since thinner waists are more fragile.

In order to improve the mechanical stability of the MFC in our experiment, polydimethylsiloxane (PDMS) material is used to package the MFC by encapsulating it in the center of a

prefabricated slot with the opposite MFC ends immobilized by a UV curable glue [Fig. 1(a)]. The PDMS package has another function, as it serves as a container for the MF. The PDMS container is prefabricated in a shape of a cuboid with dimensions of 70 mm × 40 mm × 10 mm. A narrow slot with a cross section of 4 mm × 4 mm is cut at the center of the cuboid along the 70 mm side to accommodate the MFC and MF. The MFC is positioned and fixed within the slot, and then the surface of the slot is covered by a thin layer of PDMS and sealed with epoxy resin. Small holes are cut in the top PDMS layer near the ends of the slot to facilitate injection of the MF and exhaust for the air displaced by the MF. As a result, the MFC waist is fully immersed into the MF. The FBG is pasted next to the MFC package to make sure the two sensing elements are at the same region in space.

A section of polarization-maintaining fiber (PMF) with a length of ~70 cm connects two output ports of the MFC to form a Sagnac loop. A polarization controller (PC) is inserted into the loop to control the light polarization. The output laser spectrum is recorded using an OSA with a resolution of 10 pm. The MF (IO-A10-1, from Cytodiagnostics Inc.) is a stabilized water-based ferrofluid containing Fe₃O₄ magnetic nanoparticles with an average diameter of 10 nm at a concentration of 1 mg/ml. The RI of the MF in the absence of a magnetic field is 1.340. Magnetic fields in the range from 0 to 100 mT were applied to the sensor using an electromagnet, as shown in Fig. 1(a). The transmission spectrum of the MFC-Sagnac structure immersed in MF solution is shown in Fig. 1(c).

3. OPERATING PRINCIPLE AND THEORETICAL ANALYSIS

The operating principle of a Sagnac loop is based on the interference between the clockwise and counterclockwise beams in the fiber loop. The MFC itself typically has a transmission spectrum containing interference fringes, for which the visibility and free spectral range (FSR) along with the coupling ratio are strongly affected by the coupler's waist diameter [17]. By optimizing the length of the PMF loop, it is possible to achieve a good match between the FSR of the MFC and the FSR of the Sagnac loop, so that the combined MFC-Sagnac laser output is maximized. When magnetic field acts upon the MFC waist section covered by the MF, the overall interference spectrum changes due to the variation in the MF's RI. As a result, by monitoring the wavelength shift of the interference spectrum, the strength of the applied magnetic field can be measured, assuming a suitable calibration has taken place. The transmission of the MFC-Sagnac loop is determined by the combined interference effects within the loop and the MFC. The transmission equation for the proposed structure can be written as [17]

$$T_{\text{MFC-Sagnac}}(\lambda) = [(1 - 2\rho)^2 + 4\rho(1 - \rho) \cdot \sin^2(\theta_1 + \theta_2)] \times \cos^2\left[\frac{-2\pi l(n_o - n_e)}{\lambda}\right] \cdot \cos^2(r_{\text{MFC}} \cdot L), \quad (1)$$

where l is the length of the PMF section, L is the effective length of the MFC, $(n_o - n_e)$ is the birefringence of the PMF, λ is the operating wavelength, θ_1 and θ_2 are the angles between light polarizations at both ends of the PMF, and ρ is the coupling coefficient of the MFC coupler. Light whose

polarization is perpendicular to the optical axis is governed by the RI n_o . Light whose polarization is in the direction of the optic axis sees a RI n_e . Given the fixed length of the PMF, the birefringence $(n_o - n_e)$ of the loop is constant. In our proposed configuration, the coupling coefficient of the coupler is not constant as in a conventional fiber coupler but depends on both input light wavelength and surrounding RI as [18]

$$r_{\text{MFC}} = \frac{\pi\sqrt{n_1^2 - n_2^2}}{2an_1} e^{-2.3026(A+B(\frac{d}{a})+C(\frac{d}{a})^2)}, \quad (2)$$

where $A = a_1 + a_2V + a_3V^2$, $B = b_1 + b_2V + b_3V^2$, $C = c_1 + c_2V + c_3V^2$,

$$\begin{aligned} a_1 &= 2.2926, & a_2 &= -1.5910, & a_3 &= 0.1668, \\ b_1 &= -0.3347, & b_2 &= 0.5321, & b_3 &= -0.0066, \\ c_1 &= -0.0076, & c_2 &= -0.0028, & c_3 &= 0.0004, \end{aligned}$$

n_1 and n_2 are the RIs of the silica fiber and surrounding medium, a is the radius of the microfiber waist, d is the center-to-center spacing between fibers forming the MFC, and V is the normalized frequency defined as $V = \frac{2\pi a}{\lambda} \sqrt{(n_1^2 - n_2^2)}$.

The wavelength shift caused by the variations of the surrounding temperature and RI can be described as [17,19]

$$\begin{aligned} \Delta\lambda &= \lambda_{\text{FBG}} \left(\delta + \frac{\epsilon_{co}n_{co} - \epsilon_{cl}n_{cl}}{n_{co} - n_{cl}} \right) \Delta T \\ &+ \lambda_{\text{MFC}} \left(\frac{\epsilon_{cl}n_{cl} - \epsilon_{MF}n_2}{n_{cl} - n_2} \right) \Delta T \\ &+ \frac{\partial(T_{\text{MFC-Sagnac}}(\lambda))}{\partial(r_{\text{MFC}})} \frac{d(r_{\text{MFC}})}{d(n_2)} \Delta n_2, \end{aligned} \quad (3)$$

where n_{co} is the effective RI of the core of the silica SMF, n_{cl} is the effective RI of its cladding, and n_2 is the effective RI of the MF. Furthermore, λ is the operating wavelength. δ is the thermal expansion coefficient, and ϵ_o , ϵ_{cl} , and ϵ_{MF} are the thermo-optical coefficients for the SMF core, cladding, and MF, respectively. It can be seen that the wavelength shift is a function of the RI and temperature. After the tapering process, since the core and cladding of the MFC are fused together, the RI difference between the silica fiber core and cladding is much smaller than that between the cladding and the MF liquid surrounding the MFC, say $(n_{co} - n_{cl}) \ll (n_{cl} - n_2)$. For the MFC-Sagnac loop, the wavelength shift in the MFC transmission spectrum is mainly caused by the interaction of evanescent wave with the change of RI, while for the FBG any spectral shift of the central wavelength is due to the temperature dependence of the grating's effective RI.

A characteristic matrix can be used to derive in a useful manner how the changes in magnetic field and temperature result in the spectral shifts experienced by both laser peaks, associated with the MFC-Sagnac and FBG loops. The characteristic matrix can be written thus [19]:

$$\begin{bmatrix} \Delta\lambda_{\text{MFC}} \\ \Delta\lambda_{\text{FBG}} \end{bmatrix} = \begin{bmatrix} K_{\text{MFC}}^{\text{RI}} & K_{\text{MFC}}^T \\ 0 & K_{\text{FBG}}^T \end{bmatrix} \begin{bmatrix} \Delta\text{MFS} \\ \Delta T \end{bmatrix}, \quad (4)$$

where ΔMFS is the change in the magnetic field strength, and ΔT is the temperature change affecting the FBG and MFC.

$\Delta\lambda_{\text{MFC}}$ is the wavelength shift produced by the Sagnac interferometer under the influence of the magnetic field applied to the MFC. $\Delta\lambda_{\text{FBG}}$ is the wavelength shifts produced by the Sagnac interferometer and FBG due to temperature changes. $K_{\text{MFC}}^{\text{RI}}$ is the RI sensitivity coefficient of the MFC. K_{MFC}^T and K_{FBG}^T are the temperature sensitivity coefficients associated with the MFC and the FBG, respectively. The coefficients of the characteristic matrix can be determined experimentally. Using the characteristic matrix, simultaneous measurement of the applied magnetic field strength and surrounding temperature can be realized with the proposed sensor.

4. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 2 illustrates combined output spectra of the laser outputs from both the MFC-Sagnac loop and the loop containing FBG at different values of the magnetic field strength. The laser peak at 1549 nm is associated with the FBG, and the peak at 1559.5 nm is due to the output from the MFC-Sagnac loop (at zero magnetic field). The extinction ratio of the MFC-Sagnac peak is estimated as 37 dB, with a 3 dB bandwidth of 0.24 nm. On applying a magnetic field with a strength up to 60 mT, the spectral position of the MFC-Sagnac laser peak experiences a blueshift. At magnetic field strengths higher than 60 mT, the peak remains stable at 1557.46 nm, which indicates saturation of the sensor's response. As expected, and what is clearly visible from Fig. 2, the peak associated with the FBG does not change its position as a function of the magnetic field strength.

The spectral positions of both laser peaks as a function of the magnetic field strength are shown in Fig. 3. As can be seen from the graph, the maximum spectral shift of the MFC-Sagnac loop

Fig. 2. Laser output spectra at different magnetic field values at constant temperature of 20°C.

Fig. 3. Laser peak wavelengths versus magnetic field measured at 20°C.

laser peak in response to the change of magnetic field strength from 0 to 100 mT was circa 4 nm. Furthermore, the laser peak associated with the FBG remained stable during the same magnetic field strength change. All the measurements were performed at 20°C.

The magnetic field and the temperature sensitivity of the sensor depends on the value of the spectral shift of the laser peak [17]:

$$\begin{cases} \text{Sensitivity}|_{\text{MFS}} = \frac{\Delta\lambda}{\Delta\text{MFS}}, \\ \text{Sensitivity}|_T = \frac{\Delta\lambda}{\Delta T}, \end{cases} \quad (5)$$

where $\Delta\lambda$, ΔT , and ΔMFS are the wavelength shift and the change in the temperature and in magnetic field strength that caused it, respectively.

It should be noted, however, that the spectral shift of the MFC-Sagnac loop laser peak in the wider magnetic field range from 0 to 100 mT is not linear. A near-linear response is observed in the range from 0 to ~20 mT (see Fig. 3), where the sensitivity was estimated as -102 pm/mT . The negative sign indicates the wavelength shifted towards the blueshift, followed by a much slower shift from 1557.46 to 1555.9 nm in the range of fields from 20 to 60 mT. This is due to a saturation of the MF magnetization at higher magnetic field strengths, when most of the nanoparticles agglomerate as magnetic chains. Above complete saturation (when all the nanoparticles are realigned, after 60 mT), the RI of the MF is no longer dependent on changes in magnetic field. Fitting of the results presented in Fig. 3 with the equation for λ_{MFC} ,

$$\lambda = 1552.49 + 3.72378 e^{\frac{-\text{MFS}}{73.1553}} + 3.72378 e^{\frac{-\text{MFS}}{73.15556}}, \quad (6)$$

from which the magnetic sensitivity coefficient in the range of magnetic fields from 0 to 60 mT can be calculated as

$$K_{\text{MFC}}^{\text{RI}} = \lambda'|_{\text{MFS}} = -0.102(e^{\frac{-\text{MFS}}{73.16}}). \quad (7)$$

When the magnetic field strength is greater than 60 mT, the lasing wavelengths remain in the same positions.

A study of the influence of temperature on the performance of the proposed sensor was also carried out. The temperature was gradually increased in small steps in the range from 20°C to 45°C. Figure 4 shows the temperature responses of the MFC-Sagnac and FBG loops simultaneously. From the linear fit of

Fig. 4. Temperature response of the FBG laser wavelength and the MFC-Sagnac laser wavelength versus temperature separately when MFS = 0.

the experimental data, the temperature sensitivities are estimated as 6 pm/°C and 18 pm/°C for the MFC-Sagnac and FBG sensors, respectively.

The temperature dependence of the MFC-Sagnac peak was weaker within the same temperature range, possibly due to the combined effect of temperature-induced changes in the PMF RI, MFC RI, and MF RI. However, as the temperature is measured independently, it should be possible to calibrate out the temperature dependence of the MF RI. Fitting of the results presented in Fig. 4 with the equation for λ_{MFC} and λ_{FBG} are

$$\begin{cases} \lambda_{MFC} = 1548.4 + 0.01869 * T \\ \lambda_{FBG} = 1559.8 + 0.00566 * T \end{cases} \quad (8)$$

in the temperature range from 20°C to 45°C.

From Fig. 4, the temperature sensitivity coefficients K_{MFC}^T and K_{FBG}^T can be calculated as

$$K_{MFC}^T = 0.01869 \quad K_{FBG}^T = 0.00566.$$

In summary, then, from the experiments, the characteristic matrix (4) can be written as [19]

$$\begin{bmatrix} \Delta\lambda_{MFC} \\ \Delta\lambda_{FBG} \end{bmatrix} = \begin{bmatrix} -0.102(e^{\frac{-MFS}{73.16}}) & 0.01869 \\ 0 & 0.00566 \end{bmatrix} \begin{bmatrix} \Delta MFS \\ \Delta T \end{bmatrix}. \quad (9)$$

As regards the measurement of magnetic field strength and temperature within the same spatial region, in order to quantify the discrimination between magnetic field and temperature, we can find the determinant of the matrix (A) according to characteristic matrix (9) as

$$A = \begin{vmatrix} -0.102(e^{\frac{-MFS}{73.16}}) & 0.01869 \\ 0 & 0.00566 \end{vmatrix}. \quad (10)$$

The inverse of A is a so-called condition number (c), that can be used as a quantitative measure of discrimination between the magnetic field and temperature [20]. For example, $c = 7.2499$ for MFS = 100 mT. Therefore, the minimum condition number for the proposed system is 7.25. This means the system can easily discriminate between magnetic field and temperature changes.

The hysteresis behavior of the sensor was also studied by increasing the magnetic field strength from 0 to 100 mT and then decreasing it down to zero with the same step values

Fig. 5. Measured wavelength shift of the selected transmission dip (at $\lambda_0 = 1559.88$ nm) against increasing magnetic field strength from 0 to 100 mT (blue) and decreasing back to 0 mT (red).

while recording the wavelength shift for the selected transmission dip as shown in Fig. 5. The wavelength position of the selected transmission dip is offset by 0.02 nm from its initial state after the full cycle of measurements. Thus, it can be concluded that overall, the level of hysteresis is negligibly small.

Thanks to the MFC, additional losses are introduced in the cavity; this helps to suppress the mode competition and results in more stable power outputs for both laser peaks. The output power stabilities are demonstrated by monitoring the two laser peaks over a period of 1 h with 2 min scans, randomly conducted within 15 min time slots, as shown in Fig. 6. From Fig. 6, one can see that there is no obvious power fluctuation when the environmental conditions are unchanged. The power fluctuates less than 1.4% over 1 h inspection.

While the dual-ring laser structure increases the system complexity compared with the fiber structure sensors without resonant cavity and lasing action [21,22], we believe that this complexity is justified, since the system offers several significant advantages in comparison with simpler passive sensors. For example, the introduction of the MFC within the Sagnac loop along with the use of PMF can be used as a polarization control element, allowing for the adjustment of the FSR of the transmission spectrum and the sensitivity of the sensor. Sensitivity adjustment is very useful for real-world systems, as it allows the dynamic range of the sensing system to be maximized, providing maximum sensitivity when required but avoiding overload or saturation as necessary.

Fig. 6. Output laser peaks measured at random intervals within 1 h.

Fig. 7. Simulated transmission of the MFC-Sagnac structure for different lengths of PMF section.

Figure 7 shows the simulated transmission spectra for the proposed structure with three different lengths of PMF, illustrating the corresponding changes in the FSR. Thanks to the loss introduced by the MFC, the mode competition in the cavity is suppressed; the laser outputs are stabler and have a higher finesse than those without the MFC-Sagnac loop cavity. What is more, the sensing resolution is also improved because of the narrow linewidth of the laser emission.

5. CONCLUSION

In conclusion, what we believe is a novel temperature-compensated magnetic field sensor with a dual-ring structure EDF laser consisting of an FBG and an MFC-Sagnac loop and MF is proposed and experimentally demonstrated. The proposed structure can provide temperature-compensated magnetic field strength sensing by the two distinct lasing peaks. The experimentally demonstrated maximum magnetic field sensitivity of one of the laser peaks is 102 pm/mT in the magnetic field range from 0 to 60 mT. The sensitivity of the second laser peak is 18 pm/°C in the temperature range from 20°C to 45°C with a spectral position independent of the magnetic field but shifts toward long wavelengths. The RI and temperature sensitivity coefficients are calculated, and a characteristic matrix is established to determine the temperature and magnetic field strength and temperature from the sensor's response.

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