ORIGINAL RESEARCH PAPER

The impact of polarization-maintaining and multimode fibre lengths on strain and temperature sensitivities of single-mode–multimode–polarization-maintaining–multimode–single-mode-based fibre optic sensors

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Abstract
A fibre loop mirror sensor is proposed and demonstrated for strain and temperature measurements in experiment. In these schemes, fibre loop mirrors are constructed with single-mode-multimode-polarization-maintaining-multimode-single-mode optical fibre (SMPMS) structures. The strain and temperature characteristics of the sensor, depending on the lengths of multimode fibre (MMF) and polarization-maintaining fibre (PMF), are studied in the experiment. The results indicate that PMF and MMF lengths have less impact on strain sensitivity but a remarkable impact on temperature sensitivity, which is consistent with the theoretical analysis. The best strain and temperature sensitivities of an SMPMS structure sensor can reach up to 39.0 pm/με and 2.366 nm/°C, respectively. The sensors have the merits of easy fabrication, cost-efficiency and high temperature sensitivity and are quite suitable for fields requiring high-precision measurement.

1 | INTRODUCTION

Fibre-optic sensors based on single-mode-multimode-single-mode optical fibre (SMS) have been used widely in parameter monitoring due to their potential applications and distinct advantages over traditional electronic sensors, such as easy manufacture, high sensitivity, cost-effectiveness, reduction of electromagnetic interference, and resistance to chemical corrosion [1,2]. The SMS structure can be simply fabricated by splicing two sections of single-mode fibre (SMF) to the ends of multimode fibre (MMF). The principle of SMS structure-based fibre sensors is that multimode interference excited in the MMF section can be influenced by external perturbation. So external parameters such as temperature and strain can be demodulated based on the variation of resonant fringe wavelength [3]. Because of the superiority of multimode interference, the SMS fibre structure has been comprehensively applied in strain and temperature sensing [4], displacement measurement [5], refractive index (RI) monitoring [6], and even in use as a fibre filter [7]. Based on the SMS fibre structure, sensors based on a multimode–single-mode–multimode [8,9] or single-mode-tapered coreless multimode-single-mode structure [10] are also demonstrated and developed.

Sensitivity is the important performance parameter of a sensor. To improve sensing sensitivity, many meaningful works have been performed. Shi et al. structured a temperature sensor using a fibre ring laser. Assisted by a reflecting Sagnac loop, the obtained temperature sensitivity of the sensor reaches 1.739 nm/°C [11]. Li et al. reported a special SMS fibre structure-based temperature sensor. In their scheme, a high thermal optical coefficient of polymer is used to coat the MMF, and the sensitivity of the sensor can reach 3.195 nm/°C [12]. Zhang et al.
demonstrated a temperature sensor using a bent-SMS structure, and the acquired temperature sensitivity reaches up to 6.5 nm/°C [13]. In their proposal, the cladding of the MMF was etched and replaced with a liquid material with a higher RI than the core of the MMF. Qian et al. presented an alcohol-filled HiBi-PCF (photonic crystal fibre) Sagnac sensor with a sensitivity of 6.6 nm/°C [14]. Shao et al. demonstrated an optical fibre temperature sensor by applied Lyot–Sagnac interferometer, and a super-high temperature sensitivity of 17.99 nm/°C was obtained; the sensor can also be used to measure rotation [15]. These schemes can effectively enhance the sensitivity of sensors. However, using a high-cost special optical fibre such as PCF or complex fabrication (coating with polymer or etched the cladding of fibre) and experimental setup (fibre ring laser structure) for these schemes more or less increases the cost and complexity of fabrication and operation. Recently, a cost-efficient and easy-to-manufacture temperature sensor was presented in our laboratory [16]. In this sensor, a circled single-mode-multimode-polarization-maintaining-multimode-single-mode optical fibre (SMPMS) structure was used, and a temperature sensitivity of 1.476 nm/°C was obtained. However, it should be noted that the SMPMS structure must be bent into a circle, and the radius of the circle has a significant influence on temperature sensitivity, which may increase the uncertainty of this approach for practical application. In addition, the impacts of the lengths of the MMF or polarization-maintaining fibre (PMF) on sensitivity, as well as the strain characteristic of the sensor, have not been investigated.

In this paper, a fibre Sagnac loop mirror constructed by non-circled SMPMS fibre structures is proposed, and its temperature and strain characteristics depending on PMF and MMF lengths are experimentally studied in detail. The results indicate that PMF and MMF lengths have less impact on strain sensitivities but show a noticeable influence on temperature sensitivity. The best strain and temperature sensitivities of the SMPMS structure sensor reach 39.0 pm/με and 2.366 nm/°C, respectively.

2 | EXPERIMENTAL SETUP AND PRINCIPLES

The schematic diagram of the proposed sensor is depicted in Figure 1. The optical fibre Sagnac loop mirror consists of a conventional 3-dB coupler and an SMPMS structure within the fibre loop. The light source used in the experiment is a broadband light source (BBS). The light wave from the BBS is split into two equal beams of light by a 3-dB coupler; one beam of light travels clockwise and the other counterclockwise. Interference happens when they recombine at the 3-dB coupler because of the relative phase difference. The transmission spectra are monitored by an optical spectrum analyser (OSA). To reduce the influence of polarization state, an optical fibre polarization controller (PC) is inserted in the fibre Sagnac loop mirror. When performing experiments, the PC is fixed at some polarization state.

To fabricate the SMPMS fibre structure, commercial MMF and Panda PMF (PM1550-HP) are employed. The core diameter of the MMF is 50 μm, and its cladding diameter is 125 μm. The core and cladding diameters of the PMF are 8.5 and 125 μm, respectively. The core of the PMF is doped with germanium, and the beat length is 3 mm (@1550 nm); there are two stress zones located on both sides of the core. The SMPMS fibre structure is simply fabricated by a commercial splicer in auto automatic core-alignment mode. That is, the two ends of the PMF are spliced with two sections of MMF. Then, two pieces of common SMF with core and cladding diameters of 9 and 125 μm, respectively, are spliced to the two ends of the MMF–PMF–MMF structure to use for input and output pigtails. Finally, the MMF–PMF–MMF fibre structure is formed as a Sagnac loop mirror with a 3-dB coupler.

The working process of the sensor is described as follows (see Figure 1b). The light propagating along the input SMF injects into the MMF and then excites a number of guided modes in the MMF because of the core diameter mismatch between the SMF and MMF. Moreover, an extra phase difference is introduced because the guided modes travel along different paths in the Panda PMF. After passing through the PMF, the guided modes excite other guided modes when propagating in MMF. Finally, guided modes couple back into the core when the light propagates from the MMF into the SMF. The interference of the proposed sensor dominantly involves the core mode and high-order modes.

Based on the light beam travelling process and ignoring loss, the interference spectrum of the fibre loop mirror can be expressed as [17]

\[ T = \frac{1 - \cos \phi}{2} \]  

where \( \phi \) is the total phase difference caused by the sensing structure and can be written as [18]

\[ \phi = \phi_p + \phi_M = \frac{2\pi}{\lambda} (L_M \Delta n_M + L_p B_p) \]  

where \( \phi_p \) is the phase difference between two polarization modes caused by PMF, \( B_p \) is the birefringence of the PMF, \( L_p \) is the length of the PMF, \( \lambda \) is the wavelength, \( \phi_M \) is the phase difference between the core mode and cladding modes caused by the two sections of MMF, \( \Delta n_M \) is the effective RI difference of guided-modes propagating along the MMFs, and \( L_M \) is the total length of the two MMFs.

If the phase condition \( \phi = 2\pi \cdot m \) (m is a random integer) is satisfied, the wavelength of the resonant dip can be expressed as [19,20]

\[ \lambda = \frac{(L_M \Delta n_M + L_p B_p)}{m} \]  

Then, the wavelength of the resonant dip will shift with the change of the surrounding temperature and strain, which can be written as [2]
\[ \Delta \lambda = \lambda \left( \frac{1}{B_p} \frac{\partial B_p}{\partial T} + \frac{1}{L_p} \frac{\partial L_p}{\partial T} + \frac{1}{\Delta n_M} \frac{\partial \Delta n_M}{\partial T} \right) + \frac{1}{L_M} \frac{\partial L_M}{\partial T} \Delta T \]

\[ \Delta \lambda = \lambda \left( \frac{1}{B_p} \frac{\partial B_p}{\partial \varepsilon} + \frac{1}{L_p} \frac{\partial L_p}{\partial \varepsilon} + \frac{1}{\Delta n_M} \frac{\partial \Delta n_M}{\partial \varepsilon} \right) + \frac{1}{L_M} \frac{\partial L_M}{\partial \varepsilon} \Delta \varepsilon \]

\[ = \lambda \left( \frac{1}{B_p} \frac{\partial B_p}{\partial \varepsilon} + \frac{1}{L_p} \frac{\partial L_p}{\partial \varepsilon} + \frac{1}{\Delta n_M} \frac{\partial \Delta n_M}{\partial \varepsilon} + 2 \right) \Delta \varepsilon \]

where \( \Delta \varepsilon = \Delta L / L = \Delta \varepsilon \) indicates strain variation. According to Equations (4) and (5), the resonant dip wavelength shifts when temperature and strain change. Temperature sensitivity is relevant to PMF and MMF lengths, while strain sensitivity is nearly independent of PMF and MMF lengths.

3 | RESULTS AND DISCUSSION

In the experiments, a BBS (1310–1650 nm) is used. To reveal the sensitivities of the sensors depending on PMF and MMF length, the strain and temperature characteristics of the SMPMS fibre structure sensor are separately investigated. In the temperature test, an incubator (TC, WD2005) with an operating temperature ranging from \(-20^\circ\)C to \(120^\circ\)C was used, and the temperature resolution was 0.1°C. The SMPMS structure-based fibre loop was fixed in the TC, as shown in Figure 1. In strain measurements, strain was applied to the section of SMPMS fibre structure using a micro-displacement platform. One end of the SMF was fixed firmly, and the other end was stretched by the micro-displacement platform. The other part of fibre in the loop was fastened with tape to avoid external disturbance. Transmission spectra were monitored by the OSA (AQ6370 C), and the resolution of the OSA was set to 0.02 nm in the following experiments. The insertion loss of the entire SMPMS structure was about 2 dB.

The functions of PMF are similar to those in our previous work [18] and are used to enhance the extinction ratio (ER) of the resonant dip. To confirm the function of the PMF in the sensor structure, the transmission spectra of SMS and SMPMS structures are measured; these are shown in Figure 2. The ERs of the SMS and SMPMS can be seen to be 0.64 and 17.4 dB, respectively. It is clear that using PMF can significantly enhance the ER of the resonant dip.

3.1 | Influences on strain sensitivity

We first studied the PMF length influence on strain characteristics. In the experiments, the MMF length is constant at 15 cm, and PMFs with lengths of 15, 12, 10, 8, and 6 cm are successively used. The total lengths of the SMPMS fibre structures are kept at 58 cm in all of the following experiments.

Considering that the free spectral range (FSR) of the sensor is different for sensors with different MMF and PMF lengths, we set the maximum strain at 688 μe to ensure that the loaded strain would not overlap the resonant dips, and the selected dip can be distinguished over the whole range of measurements. The strains from 0 to 688 μe with an interval of 172 μe were applied to the SMPMS fibre structure. The experimental results are shown in Figure 3. The typical interference spectra changes with loading strain are depicted in Figure 3a, and the dip
wavelength shifts in response to loaded strain for different PMF lengths are enlarged in Figure 3b. The spectra of the sensor has significant red-shifts with increasing strain. Figure 3c illustrates the strain characteristics of the sensor with different PMF lengths, and the transmission spectra shifts towards longer wavelengths with increased strain. According to Figure 3c, the obtained strain sensitivities are 37.9, 39.0, 34.8, 32.8 and 36.9 pm/με when the PMF lengths are 15, 12, 10, 8 and 6 cm, respectively. For the sake of clarity, the strain sensitivity depending on PMF length is plotted in Figure 3d. It is obvious that there is not an evident relationship between the measured sensitivities and PMF lengths, and the obtained strain sensitivities fluctuate from 32.8 to 39.0 pm/με for the five PMF lengths. The experimental results agree with the theoretical analysis in Equation (5). The sensitivity fluctuation is derived from the different alignment directions when PMFs of different lengths are spliced to MMFs, and the lights show different polarization states when travelling in the Sagnac loop, which affects sensitivity [21].
**Figure 4** (a) Spectra shift with the increasing strain (b) Dip shifts versus applied strain (c) Strain responses of sensor (d) Strain sensitivity changes with increased multimode fibre length.

**Figure 5** (a) Temperature response of spectra for different lengths of polarization-maintaining fibre (b) Temperature sensitivity distribution by polarization-maintaining fibre length.
Next, the influence of MMF length on sensitivity is analysed. For the following experiments, the PMF length is set to 10 cm, and MMF lengths of 15, 12, 10, 8, 6 cm are successively used. The total length of the SMPMS fibre structure is kept at 58 cm. A strain ranging from 0 to 688 με was respectively applied to the SMPMS fibre structures, and the experimental results are shown in Figure 4. The typical interference spectra shift with increases in the applied strain, as displayed in Figure 4a and Figure 4b, and the strain response of and sensitivity distribution for different lengths of MMF are plotted in Figure 4c and Figure 4d. According to the results shown in Figure 4, the transmission spectra of the sensor shift towards longer wavelengths as the strain increases. The obtained sensitivities are 35.9, 32.8, 32.8, 36.9 and 37.0 pm/με, respectively. The obtained strain sensitivities fluctuate from 32.8 to 37.0 pm/με for the five given MMF lengths. But there is no evident relationship between sensitivity and MMF length, which agrees with the theoretical analysis in Equation (5).

3.2 Influences on temperature sensitivity

Firstly, the impact of PMF length on temperature characteristics is studied. In the experiments, MMF length was set at 15 cm, and PMF lengths of 15, 12, 10 and 8 cm were used in succession. The SMPMS structures were placed in an incubator (WD2005), and the resolution of the incubator is 0.1°C. A temperature ranging from 25°C to 45°C with an interval of 5°C was employed, and the interference spectra at each temperature point were recorded by the OSA after 10 min to fully reach thermal equilibrium. The temperature response of and the sensitivity distribution for different PMF lengths are shown in Figure 5. According to the results presented in Figure 5, the interference spectra are blue-shifted as temperature increases. The obtained temperature sensitivities of the sensor are 1.67 nm/°C, 1.88 nm/°C, 1.92 nm/°C and 2.00 nm/°C when the PMF lengths are 15, 12, 10 and 8 cm, respectively. Sensitivity decreases with increasing MMF length as expected in the theoretical analysis of Equation (4). The temperature sensitivity reaches a maximum of 2.00 nm/°C when an 8-cm-long PMF is used. It should be noted that the temperature measurement range is relatively small because the sensor has a high sensitivity and a small FSR, and the larger temperature range leads to aliasing of the resonant trough and is difficult to identify. In fact, the sensor can work in other temperature zones as well.

Second, the impact of MMF length on temperature characteristics is studied. In the following experiments, a constant 10-cm-long PMF was used, and the MMF length was set at 15, 12, 10, 8 and 6 cm in turn. The temperature response and sensitivity distribution for different MMF lengths are shown in Figure 6. The obtained temperature sensitivities are 2.366 nm/°C, 1.946 nm/°C, 1.688 nm/°C, 1.670 nm/°C and 1.565 nm/°C when the MMF lengths were 6, 8, 10, 12 and 15 cm, respectively. The sensitivity of temperature is inversely proportional to MMF length, which is consistent with the theoretical analysis of Equation (4). The best temperature sensitivity of 2.366 nm/°C was achieved when the MMF length was 6 cm. The obtained sensitivity was close to the result (2.38 nm/°C) of our previous work in which the MCF–PM structure fibre loop mirror was used [22]. But the sensing structure of this work is cheaper.

The sensitivity of temperature shows the characteristic that it is approximately inversely proportional to both PMF and MMF length, which is consistent with the theoretical analysis based on Equation (4). However, the shorter fibre length is not better. That is because the number of dips decreases when the PMF or MMF length becomes shorter, which may cause the resonance dip to move out of the spectral range of the light source and thus make it impossible to measure. Therefore, the fibre length needs to be optimised according to actual needs so as to simultaneously achieve convenient measurement and high sensitivity.

![Figure 6](image_url) (a) Temperature response of spectra for different lengths of multimode fibre (MMF) (b) Temperature sensitivity distribution by MMF length
Experimental results show that PMF and MMF lengths have obvious influences on temperature sensitivity but little influence on strain sensitivity. It is completely suitable for applications where high precision measurement is required.

| Sensor structure | Sensitivity | Strain | Refs |
|------------------|-------------|--------|------|
| Reflecting Sagnac | 1.739 nm/°C | - | [11] |
| SMS of polymer-coated | -3.195 nm/°C | - | [12] |
| Bent-SMS | 6.5 nm/°C | - | [13] |
| Alcohol-filled HiBi-PCF Sagnac | 6.6 nm/°C | - | [14] |
| Lyot-Sagnac | -17.99 nm/°C | - | [15] |
| SPMPS | -40 pm/°C | -1.27 pm/με | [23] |
| SMF-PMF-SMF | -1.73 nm/°C | - | [19] |
| SMF-NCF-SMF | 0.101 nm/°C | - | [24] |
| SMF-FM-DCCF-SMF | 52.79 pm/°C | 0.23 pm/με | [25] |
| Circled SMPMS | -1.476 nm/°C | - | [16] |
| Non-circled SMPMS | 2.366 nm/°C | 39.0 pm/με | This work |

Abbreviations: DCCF, dual-concentric core fibre; FM, few-mode fibre; NCF, no-core fibre; PCF, photonic crystal fibre; PMF, polarization-maintaining fibre; SMF, single-mode fibre; SMPMS, single-mode–multimode–polarization-maintaining–multimode–single-mode optical fibre; SMS, single-mode-multimode–single-mode optical fibre.

To compare the results with those in the existing literature, Table 1 presents some experimental results for reported sensors. Compared with Refs. [11–15,19,22–24], the proposed SMPMS temperature sensor shows a high sensitivity of 2.366 nm/°C. At the same time, compared with the sensing structure of the reference, this structure has the advantages of higher sensitivity, simple manufacture and low cost.

4 | CONCLUSION

A fibre Sagnac loop mirror constructed by a non-circled SMPMS fibre structure has been demonstrated, and its strain and temperature characteristics depending on MMF and PMF lengths are experimentally studied in detail. Theoretical analysis and experimental results show that PMF and MMF lengths have obvious influences on temperature sensitivity but little influence on strain sensitivity. Temperature sensitivity is inversely proportional to PMF and MMF length. The best strain sensitivity reaches 39.0 pm/με when PMF and MMF lengths are 12 and 15 cm, respectively, and the high temperature sensitivity of 2.366 nm/°C is obtained when the PMF and MMF lengths are 10 and 6 cm, respectively. Considering the OSA’s minimum resolution of 0.02 nm, the resolutions of strain and temperature can reach 0.5 με and 0.008°C, respectively. The proposed sensor has the merits of easy fabrication, low cost and high temperature sensitivity. It is completely suitable for applications where high precision measurement is required.

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CONFLICT OF INTEREST

The authors declare that they have no competing interests.

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