CONFERENCE PROGRAM

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Individual or simultaneous temperature and strain monitoring by high birefringence fiber loop mirror with reduced cross sensitivity

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ABSTRACT

Individual or simultaneous monitoring of the temperature and strain variations by use of the high birefringence fiber loop mirror is newly proposed and demonstrated with reduced cross sensitivity. It is accomplished by incorporating two types of high birefringence fibers in the loop arm, which are spliced together to act as the compact sensing head. By properly choosing their birefringence, cutting their lengths and setting their relative orientation with respect to the primary axes, the temperature and strain may be individually or simultaneously measured with the effectively reduced cross sensitivity.

Keywords: Fiber sensors, high birefringence fiber, fiber loop mirror, temperature and strain monitoring

1. INTRODUCTION

The fiber loop mirror incorporating one or more sections of high birefringence fibers (HBFs) as an optical fiber filter is of considerable interest due to its unique advantages such as easy fabrication, good stability and great flexibility. Specifically, the HBF loop mirror is constructed by just fusion splicing of HBFs, the two optical beams involved in the Sagnac interference traverse the same optical path and its spectral response may be freely tailored by cascading several sections of HBFs with adjustment of their relative orientations of the primary polarization axes. On account of the merits mentioned above, it is often employed in fiber lasers [1] and sensors [2]. For the latter, the Sagnac interference shows higher responding sensitivity than the mode coupling in fiber gratings, Mach-Zehnder interference or Fabry-Perot interference. As a result, it has been widely used to measure many physical parameters including the temperature, strain, pressure, liquid level and so on.

Recently, the HBF loop mirror has been reported to individually or simultaneously detect the temperature and strain variations. For individually measuring the temperature, a Panda HBF is inserted into the loop arm [3]. Commonly, the sensing head should be fastened to a hardware device for avoiding the random mechanical perturbations. But their thermal expansion coefficients are usually different. As a result, the Panda HBF may suffer from undesired longitudinal stress during the temperature measurement, which induces the cross sensitivity between the temperature and strain. For individually monitoring the strain, the environmental temperature variation definitely generates the cross sensitivity. In order to reduce the temperature influence, the high birefringence photonic crystal fiber is used due to its low temperature sensitivity. But its strain sensitivity coefficient is also small [4]. To simultaneously measure the temperature and strain, one section of HBF and a long-period fiber grating are combined [5] or a type of small core microstructured HBF [6] is used in the loop arm. However, only two elements are of the same sign in the 2×2 sensitivity matrix, which induces high cross sensitivity arising from the two-parameter monitoring.

In this work, we present an approach to enhance the sensor performances of the HBF loop mirror for individually or simultaneously monitoring the temperature and strain variations. The operation mechanism is theoretically analyzed and experimentally realized by measuring the shift of one or two wavelength dips in the spectral response of the proposed HBF loop mirror. The problem of cross sensitivity may be effectively reduced to increase the measurement resolution. Moreover, the response sensitivities are still high for both the individual and simultaneous monitoring cases.

2. SCHEMATIC SETUP AND OPERATIONAL PRINCIPLE

Figure 1 illustrates the experimental configurations which contain an optical broadband source, fiber loop mirror and optical spectrum analyzer (OSA) with a resolution of 0.01 nm. The fiber loop mirrors are formed by a 3-dB fiber optical...
coupler (OC), an optical polarization controller (PC) and two types of HBFs (HBF1 and HBF2) jointed together by the polarization maintaining fusion splicer to act as the compact sensing head. The sensing heads are fastened to a translation stage with a resolution of 1 μm and enclosed within a temperature-controlled oven with an error of about 0.1 °C. The HBF1 is one type of commercial HBF with birefringence \( B_1 \) and HBF2 is another type of commercial HBF with birefringence \( B_2 \). In Fig. 1(a), two sections of HBFs are used for individual measurement of the temperature or strain. One is the HBF1 with length \( L_1 \) and the other is the HBF2 with length \( L_2 \). In Fig. 1(b), three sections of HBFs are employed to simultaneously monitor the temperature and strain. Among them, the first two sections with length \( L_1 \) and \( L_2 \) are the HBF1, and the third section is the HBF2 with length \( L_3 \).

![Schematic setup of the proposed fiber sensor for (a) individual and (b) simultaneous monitoring of the temperature and strain. X: the spliced point.](image)

For Fig. 1(a), the slow axis of HBF1 is oriented \( \pi/2 \) with respect to that of HBF2 at their spliced point. Omitting all device loss, the transmissivity of Fig. 1(a) may be derived by use of the Jones matrix and written as (\( \lambda \) is the wavelength and \( \theta \) the rotation angle of the PC)

\[
T = \cos^2 \left[ \frac{\pi (B_1 L_1 - B_2 L_2)}{\lambda} \right] \sin^2 \theta \tag{1}
\]

It can be seen from (1) that the transmission dip appears at the wavelength satisfying \( B_1 L_1 - B_2 L_2 = (p+1/2) \lambda \) (\( p \) are integers). Its response sensitivity may be expressed as

\[
\frac{d\lambda}{d\xi} = \frac{B_1 L_1 \kappa_{11} - B_2 L_2 \kappa_{12}}{B_1 L_1 - B_2 L_2} \tag{2}
\]

Here \( \xi \) represents the variation of temperature \( \Delta T \) or strain \( \Delta \varepsilon \). \( \kappa_{11} \) and \( \kappa_{12} \) are the corresponding sensitivity coefficients of the HBF1 and HBF2 if individually implemented in the fiber loop mirror. Normally, the temperature sensitivity is negative because the birefringence decreases with temperature. Differently, the birefringence increases with strain and thus has positive strain sensitivity. Besides these, the degree of sensitivity hardly depends on the HBF length when it is well fabricated. Therefore, it can be obtained from (2) that the value of \( d\lambda/d\Delta T \) or \( d\lambda/d\Delta \varepsilon \) may be zero by properly selecting the types and cutting the lengths of HBF1 and HBF2 to satisfy the relation

\[
(B_1 L_1 \kappa_{11} - B_2 L_2 \kappa_{12}) = 0 \quad \text{or} \quad (B_1 L_2 \kappa_{11} - B_2 L_1 \kappa_{12}) = 0 \tag{3}
\]

Meanwhile, the corresponding value of \( d\lambda/d\Delta T \) or \( d\lambda/d\Delta \varepsilon \) is nonzero due to the fact that the HBF1 and HBF2 have different sensitivity ratio of the temperature to strain. Therefore, the temperature or strain may be individually monitored with immunity to the longitudinal stress or environmental temperature of the sensing head, respectively.

In order to simultaneous measurement of the temperature and strain with reduced cross sensitivity, three sections of HBFs are inserted into the loop arm as shown in Fig. 1(b). The slow axis of HBF1 with length \( L_2 \) is oriented \( \pi/2 \) with respect to that of HBF2 with length \( L_3 \). In addition, the primary polarization axes are angled \( \gamma \) between the two sections of HBF1 with length \( L_1 \) and \( L_2 \). When the PC rotation angle is adjusted to be \( \gamma \), the transmissivity of Fig. 1(b) may be derived and written as (\( \lambda \) is the wavelength)

\[
T' = \cos^2 \left[ \frac{\pi (B_1 L_1 - B_2 L_2)}{\lambda} \right] \cos^2 \left[ \frac{\pi (B_1 L_2 - B_2 L_3)}{\lambda} \right] \sin^2 \gamma \tag{4}
\]

It can be seen from (4) that zero transmissivity appears at the wavelength satisfying \( B_1 L_1 = (p+1/2) \lambda_a \) or \( (p+1/2) \lambda_b \) (\( p \) and \( q \) are integers) when the angle \( \gamma \) is nonzero. Therefore, the temperature and strain variations may be decoupled by simultaneously monitoring the shifts of the \( \lambda_a \) and \( \lambda_b \). Their response sensitivities may be expressed as

\[
\frac{d\lambda_a}{d\xi} = \frac{\lambda_a}{B_1 L_1} \frac{d(B_1 L_1)}{d\xi} = \kappa_{11} \tag{5}
\]

\[
\frac{d\lambda_b}{d\xi} = \frac{B_2 L_3 \kappa_{11} - B_1 L_2 \kappa_{12}}{B_1 L_2 - B_2 L_3} \tag{6}
\]
From (6), it may be derived that the \( \frac{d\lambda_b}{d(\Delta \varepsilon)} \) and \( \frac{d\lambda_b}{d(\Delta T)} \) are of the same sign if properly selecting the types and lengths of the HBF\(_1\) and HBF\(_2\) to satisfy the relation

\[
(B_2L_2\kappa_{\varepsilon 1} - B_1L_1\kappa_{\varepsilon 2})(B_1L_1\kappa_{T 1} - B_2L_2\kappa_{T 2}) > 0
\]

Based on the above analysis, it follows that three elements in the 2×2 sensitivity matrix may be of the same sign and then the problem of cross sensitivity is solved effectively.

### 3. EXPERIMENTAL RESULTS AND DISCUSSIONS

In these experiments, the HBF\(_1\) is selected to be a Panda fiber (PM-1550-HP) and HBF\(_2\) a 3M fiber (FS-PM 7621). Their birefringence, and temperature and strain sensitivity coefficients are listed in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_1 )</td>
<td>( 3.3 \times 10^{-4} )</td>
</tr>
<tr>
<td>( \kappa_{\varepsilon 1} )</td>
<td>( 4.12 \times 10^{-3} ) nm/( \mu \varepsilon )</td>
</tr>
<tr>
<td>( \kappa_{\varepsilon 2} )</td>
<td>( -1.90 ) nm/( \mu \varepsilon )</td>
</tr>
<tr>
<td>( B_2 )</td>
<td>( 4.0 \times 10^{-4} )</td>
</tr>
<tr>
<td>( \kappa_{\varepsilon 2} )</td>
<td>( 2.98 \times 10^{-3} ) nm/( \mu \varepsilon )</td>
</tr>
<tr>
<td>( \kappa_{T 2} )</td>
<td>( -0.55 ) nm/( ^{\circ} \mathrm{C} )</td>
</tr>
</tbody>
</table>

For individually monitoring the temperature variation, the \( L_1 \) and \( L_2 \) in Fig. 1(a) are carefully cut to be 18.2 mm and 20.8 mm, respectively. As expected, the sinusoidal spectral response at room temperature of 25 °C is shown as the solid line in Fig. 2(a). The temperature and strain sensitivities of the wavelength dip are illustrated as the upper triangular in Fig. 2(b) and 2(c). It is obvious that the temperature sensitivity is 2.75 nm/\( ^{\circ} \mathrm{C} \) but the strain sensitivity is almost zero. For individually measuring the strain change, the \( L_1 \) and \( L_2 \) in Fig. 1(a) are, respectively, set to be 8.7 mm and 24.8 mm. The dashed line in Fig. 2(a) is the corresponding sine transmission pattern. The temperature and strain sensitivities of the wavelength dip are shown as the down triangular in Fig. 2(b) and 2(c). Obviously, the strain sensitivity is \( 2.46 \times 10^{-2} \) nm/\( \mu \varepsilon \) and temperature sensitivity is almost zero.

![Fig. 2](image1)

**Fig. 2:** (a) the transmission spectra of the proposed HBF loop mirror as Fig. 1(a), and its temperature sensitivity (b) and strain sensitivity (c).

![Fig. 3](image2)

**Fig. 3:** (a) the transmission spectra of the proposed HBF loop mirror as Fig. 1(b), and its temperature sensitivity (b) and strain sensitivity (c).

Based on the above results, it follows that the temperature and strain changes may be individually measured with eliminating their cross sensitivity by using two types of HBFs. In order to simultaneously monitor the temperature and strain, three sections of HBFs are inserted in the loop arm as shown in Fig. 1(b). The \( L_1 \) is 21.8 mm. According to the parameter values in Table 1, the \( L_2 \) and \( L_3 \) are, respectively, cut to be 12.1 mm and 20.0 mm for meeting the relation (7). Resultantly, two wavelength dips \( D_1 \) (at \( \lambda_a \)) and \( D_2 \) (at \( \lambda_b \)) appear in the observed spectral response as shown in Fig. 3(a). Fig. 3(b) illustrates their temperature sensitivities ranging from 25 °C to 60 °C without axial stress, while their strain sensitivities are measured at room temperature as plotted in Fig. 3(c). It is clear that the temperature sensitivity of the dip
$D_1$ is negative while the other three sensitivities are positive. Therefore, the cross sensitivity is effectively reduced. With these results, the temperature and strain changes may be determined by a sensitivity matrix as below

$$\begin{bmatrix} \Delta T \\ \Delta \varepsilon \end{bmatrix} = \begin{bmatrix} -0.27 & 0.61 \\ 11.76 & 28.43 \end{bmatrix} \begin{bmatrix} \Delta \lambda_a \\ \Delta \lambda_b \end{bmatrix} \tag{8}$$

Here $\Delta T$ (in degrees Celsius) and $\Delta \varepsilon$ (in microstrain unit) are the temperature and strain variations, respectively. $\Delta \lambda_a$ and $\Delta \lambda_b$ are the wavelength shifts (in nanometer unit) of the two dips $D_1$ and $D_2$. This matrix is well conditioned based on the fact that the temperature and strain sensitivities of the dip $D_2$ are of the same sign. By multiplying the matrix in (8) to the vector with the measured $\Delta \lambda_a$ and $\Delta \lambda_b$, simultaneous monitoring of the temperature and strain can be achieved. The root-mean-square errors relative to the applied temperature and strain are estimated to be $\pm0.2 \, ^\circ$C and $\pm2 \, \mu\varepsilon$, respectively [7]. They are limited by the resolution of the OSA and measurement accuracies of devices such as the oven and translation stage.

4. CONCLUSIONS

A fiber loop mirror containing two types of HBFs is investigated for individual or simultaneous measurement of the temperature and strain changes. By properly configuring joints of these HBFs, the cross sensitivity may be effectively reduced. This technique is carefully analyzed and successfully demonstrated. By optimizing properties of the used HBFs such as birefringence, temperature and strain sensitivities, the sensing performances may be further improved.

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