Dual-Polarization Distributed Feedback Fiber Laser Sensor Based on Femtosecond Laser-Inscribed In-Fiber Stressors for Simultaneous Strain and Temperature Measurements

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ABSTRACT We propose and experimentally demonstrate a novel dual-polarization distributed feedback fiber laser (DFB-FL) sensor based on femtosecond laser-inscribed in-fiber stressors. The resonant cavity of the DFB-FL sensor consists of a phase-shifted fiber Bragg grating (PS-FBG) in the fiber core of a section of heavily erbium-doped fiber (EDF), together with two stressors in the fiber cladding around the PS-FBG. The PS-FBG was fabricated by means of a scanning UV laser beam and shielded phase mask technique. The two in-fiber stressors, i.e. a sawtooth stressor and a straight stressor, were directly inscribed at two orthogonal planes in the EDF cladding using a near-infrared femtosecond laser. The two stressors could precisely adjust the fiber birefringence in the laser cavity, and hence the DFB-FL sensor can operate in two polarization modes. Moreover, simultaneous measurement of axial strain and temperature was demonstrated by detecting the polarization beat frequency $\nu_B$ and lasing wavelength $\lambda$ of the dual-polarization DFB-FL sensor. Experimental results exhibit strain sensitivities of 34.5 kHz/$\mu$e, 1.25 pm/$\mu$e and temperature sensitivities of 684.6 kHz/$^\circ$C, 11.5 pm/$^\circ$C, respectively. As such, the proposed dual-polarization DFB-FL sensor could be used for simultaneous strain and temperature measurements, and hence is promising for application in many areas, such as smart structures and intelligent robotics.

INDEX TERMS Fiber gratings, fiber lasers, optical fiber sensors.

I. INTRODUCTION

Recently, there has been considerable interest in developing new methods that enable optical fibers to simultaneously measure strain and temperature. This is not only because eliminating the cross sensitivity is critical for the practical applications of fiber-optic sensors, but also because multi-parameter sensors can reduce the complexity of sensing systems in situations requiring multi-parameter and/or multi-point measurement [1]. The principle of simultaneous strain and temperature sensing is usually based on the detection of two physical parameters, which have different sensitivities to strain and temperature [2]. Fiber Bragg grating (FBG) sensors have attracted much attention for their intrinsic advantages such as resistance to electromagnetic interference, compact size, and wavelength multiplexing capability [3], [4]. Various FBG-based techniques, for example, using two superimposed FBGs [5], using two
distinct FBGs written in different fiber types [6]–[8], or using highly-birefringent FBGs [9], have been reported to simultaneously measure the strain and temperature. Broadband sources or wavelength-tunable lasers are commonly used to interrogate the FBG sensors. However, the passive FBGs typically have a broad bandwidth of around several hundreds of picometers in the reflection spectra. The relatively large bandwidth could lead to low resolution in FBG sensors [10]. Moreover, the optical signals reflected from FBG sensors are always weak, especially when the FBGs are located at a long distance away from the interrogator. The large bandwidth and the limited signal-to-noise ratio (SNR) could reduce the accuracy in measuring strain and temperature [11], [12].

The FBG-based fiber lasers sensors, for example, distributed feedback fiber laser (DFB-FL) sensors or distributed Bragg reflector fiber laser (DBR-FL) sensors, typically have much narrower bandwidth (i.e., linewidth for fiber lasers) and higher SNR than conventional passive FBG sensors. In particular, the polarimetric DFB-FLs exhibit nearly ideal characteristics for applications in fiber-optic sensing due to their advantages of compact structure, high SNR, narrow linewidth, and the capability of operating without longitudinal mode hoping [13]–[15]. These DFB-FLs could produce a stable low beat frequency between the two orthogonal polarization modes due to the fiber birefringence [16]–[18]. Hence, the strain and temperature cross sensitivity could be neglected by monitoring the two parameters, i.e., beat frequency and lasing wavelength of the DFB-FL. Unfortunately, the beat frequency of the DFB-FL is typically strain insensitive due to the compensation between the strain-induced birefringence change and material index change [19]. In previous work, we fabricated a sawtooth stressor in the fiber cladding and increased the strain sensitivities of the fiber birefringence [9]. However, this sawtooth stressor-assisted highly birefringent FBG exhibits a relatively large bandwidth of ~0.5 nm, which leads to a low strain resolution for such passive FBG sensors.

In this paper, for the first time to our knowledge, we demonstrate a novel method for simultaneously measuring strain and temperature using a stressor-assisted dual polarization DFB-FL sensor, which consists of a π phase-shifted FBG (PS-FBG) in the fiber core together with two stressors (i.e., a strong modulated sawtooth-stressor and a straight-stressor) in the fiber cladding. The PS-FBG was directly inscribed in the core of the heavily erbium-doped fiber using a scanning UV laser beam with a shielded phase mask. These stressors were fabricated at two orthogonal planes near the PS-FBG using near-infrared femtosecond (fs) laser irradiation. The strain and temperature responses could be obtained by monitoring the two parameters (i.e., beat frequency and lasing wavelength) of the proposed DFB-FL. The experimental results exhibit strain sensitivities of ~34.5 kHz/µε, 1.25 pm/µε, and temperature sensitivities of 684.6 kHz/°C, 11.5 pm/°C, respectively. The proposed dual-polarization DFB-FL sensor can be used for simultaneous strain and temperature measurements.

II. PRINCIPLE OF OPERATION

Figure 1 shows the experimental setup of the proposed DFB-FL sensor. The sensor consists of a π PS-FBG together with a strong modulated sawtooth stressor at XZ plane and a straight stressor at YZ plane, as shown in the inset of Fig. 1. The output from a 980 nm pump laser (PL) was launched into the fiber laser cavity (i.e., PS-FBG) through a wavelength division multiplexer (WDM). A single-mode fiber (Corning SMF-28) with a core/cladding diameter of 8.2/125 µm was spliced with the heavily erbium-doped fiber (EDF). In this experiment, the backward output laser was launched into a 3 dB coupler through an isolator (ISO, Golight ISO-1550-S), which was used to isolate the unwanted emitting laser that reflected from the fiber end face. The output laser was divided into two branches. One branch was launched into an optical spectrum analyzer (OSA, YOKOGAWA AQ6370C) for real-time monitoring the lasing output. The other branch was projected into a high speed photodetector (PD, Newfocus 1592). The beat signal from the DFB-FL was generated by the two polarization modes and monitored using an electrical spectrum analyzer (ESA, Rohde & Schwarz FSV4). The DFB-FL sensor was placed into a temperature controller (TC) with one end fixed on a stationary stage (SS) and the other end fixed on a translation stage (TS), which could be moved manually with a stepping resolution of 0.01 mm. The TC was used for heating the DFB-FL sensor to a preset temperature with an accuracy of 0.1°C, and it also has the function of heat insulation and vibration isolation, which could ensure the sensor head avoid interference from external environment.

The DFB-FLs can operate in single longitudinal mode with two orthogonal polarization states. The polarization beat signal could be detected with a high speed photodetector and electrical spectrum analyzer when the two orthogonal polarization modes are optically mixed. The beat frequency νB is given by [18]

$$\nu_B = \nu_x - \nu_y = \frac{c}{\lambda_x} - \frac{c}{\lambda_y} = \frac{cB}{n_0\lambda_0},$$

(1)

where λx and λy are lasing wavelength of the two orthogonal polarization modes, c is the light speed in vacuum, λ0 is the laser wavelength, n0 and B are the average index and
birefringence of the optical fiber, respectively. According to Ref. [19], the birefringence in DFB-FL is insensitive or low sensitive to strain because the axial strain applied on active optical fiber generates the same refractive index change in the fast and slow axes. In order to increase the sensitivities of the beat frequency of the DFB-FL to axial strain and temperature, a strong modulated sawtooth-stressor at XZ plane was induced in fiber cladding near the PS-FBG, as shown in the inset of Fig. 1. The birefringence will be changed due to a larger internal stress variation on the fiber core when the proposed DFB-FL is subjected to the strain or temperature perturbation [9]. The response of the beat frequency of the proposed DFB-FL to strain and temperature can be expressed as [20]:

\[
\frac{\delta v_B}{v_B} = \left[ \frac{1}{B} \frac{\delta B}{\delta \varepsilon} - (1 + 2p_c) \right] \delta \varepsilon |_{T=\text{const}} + \left[ \frac{1}{B} \frac{\delta B}{\delta T} - (\alpha + 2\beta) \right] \delta T |_{\varepsilon=\text{const}},
\]

(2)

where \( p_c \), \( \alpha \), and \( \beta \) are the strain-optic coefficient, thermal expansion coefficient, and thermal-optic coefficient of the optical fiber. Generally, the lasing wavelength change of the DFB-FL with axial strain and temperature is expressed as [20]:

\[
\frac{d\lambda}{\lambda} = (1-p_c) \delta \varepsilon |_{T=\text{const}} + (\alpha + \beta) \delta T |_{\varepsilon=\text{const}},
\]

(3)

From Eq. (2) and Eq. (3), beat frequency and lasing wavelength responses of the DFB-FL to strain and temperature can be written in matrix form as:

\[
\begin{pmatrix}
\delta v_B \\
\delta \lambda
\end{pmatrix} = \begin{pmatrix}
k_{11} & k_{12} \\
k_{21} & k_{22}
\end{pmatrix} \begin{pmatrix}
\delta \varepsilon \\
\delta T
\end{pmatrix} = K \begin{pmatrix}
\delta \varepsilon \\
\delta T
\end{pmatrix},
\]

(4)

The coefficient matrix \( K \) can be defined by simultaneously measuring beat frequency \( v_B \) and lasing wavelength \( \lambda \) responses of the DFB-FL to the axial strain and temperature. For a well-conditioned matrix \( K \), i.e., \( \det K \neq 0 \), Eq. (4) can be inverted. Then the strain and temperature could be determined simultaneously by measuring two parameters \( \delta \lambda \) and \( \delta v_B \).

III. EXPERIMENT AND RESULT

A. FABRICATION OF THE DFB FIBER LASER

The fabrication process of the stressor-assisted PS-FBG includes two steps. In step 1, a uniform \( \pi \) PS-FBG with a total length of 48 mm and a shielded phase-shifted section length of \( \sim 2 \) mm was inscribed on a 65 mm long heavily EDF (Nufern SM-ESF-7/125, peak absorption: 55 dB/m @ 1530 nm) using a scanning UV laser beam with a shielded phase mask. The EDF was loaded with hydrogen (80 °C and 13 MPa for 7 days) to increase the fiber photosensitivity. The experimental setup used for fabricating PS-FBGs was similar to that presented in our previous works [21], [22]. The phase mask and fiber were installed on a high-precision translation platform. The translation process for the phase mask and fiber combination was controlled automatically using LabVIEW software. The refractive index and the length of the PS-FBG could be fine controlled. Hence, the PS-FBGs with the same refractive index, the same length and the same reflection could be obtained, and these PS-FBGs exhibited good consistency. The PS-FBG had a permanent \( \pi \) phase shift at the FBG center, a constant refractive index modulation profile and a constant grating period at both sides of the phase-shifted section.

The optical spectra of the uniform PS-FBG with a central wavelength of 1550.9 nm and transmission loss of 33.5 dB were measured using an optical spectrum analyzer, as shown in Fig. 2(a). It should be noted the phase-shift transmission slit cannot be distinguished due to the resolution limit of the OSA (i.e., 0.01 nm) [23]. Figure 2(b) illustrates the output power of the DFB-FL as a function of incident pump power using a 980 nm pump laser diode. The DFB-FL exhibits a threshold power of 11.4 mW and a slope efficiency of 0.52%. As shown in the inset of Fig. 2(b), the DFB-FL exhibits a lasing wavelength of 1550.9 nm and a signal-to-noise ratio (SNR) of 60.5 dB at a pump power of 20 mW.

![Figure 2](image-url)
of 800 nm, a pulse duration of 120 fs, and a repetition rate of 1 kHz was used. A sawtooth stressor was inscribed in the EDF cladding near the DFB-FL cavity (i.e., π PS-FBG). This fabrication method is similar to that in our previous study [9]. An oil-immersion microscopic objective (MO) of 100× magnification (NA = 1.25) was selected to eliminate the aberration introduced by the cylindrical shape of the EDF. The PS-FBG was placed under the MO and mounted on a computer-controlled three-axis (XYZ) translation stages with a resolution of ~10 nm. The PS-FBG was translated at a speed of v = 0.05 mm/s along a sawtooth trajectory on the XZ plane. During the fabrication process, a CCD camera was employed to real-time capture the microscope images of the sawtooth stressor. Moreover, both the lasing optical spectrum and beat frequency of the DFB-FL were monitored by use of an OSA with a resolution of 0.01 nm and an ESA with a resolution bandwidth (RBW) of 10 kHz. It is noted that the density and refractive index of the fused silica could be increased after exposure to focused fs laser pulses [24]. It also means the pulse energy used for the stress tracks has a significant impact on the amount of fiber birefringence [25], [26]. Hence, a weak modulated sawtooth stressor could be created with lower fs laser pulse energy, whereas a strong modulated sawtooth stressor could be created with higher fs laser pulse energy.

At first, we used a relatively lower average on-target laser power of ~150 µW to fabricate a sawtooth stressor in the EDF cladding. According to Ref. [9], the sawtooth stressor with a small tilted angle could lead to a larger stress variation on the fiber core and increase the birefringence sensitivity to the temperature and strain. Hence, a sawtooth stressor with a tilted angle of θ = 30° was induced around the uniform PS-FBG in fiber cladding. Fig. 4(a) demonstrates the microscope image of a sawtooth stressor inscribed near the DFB-FL cavity (i.e., PS-FBG) at XZ plane. The sawtooth stressor has a track length of S = 10.0 µm, a tilted angle of θ = 30°, and a spacing of d = 4.0 µm between the sawtooth stressor and the fiber core. Moreover, the width W, pitch P, and total length L can be calculated by W = S·cosθ = 8.7 µm, P = 2S·sinθ = 10.0 µm, and L = N·P = 26.0 mm, where N (i.e., 2600) is the number of pitches.

The pump power was fixed to 30 mW in this experiment. It is obvious in Fig. 4(b) that the beat frequency shifts rapidly from 121.1 to 3393.4 MHz when the scanning cycles K is increased from 0 to 8. The shift in beat frequency corresponds to a birefringence change from $9.08 \times 10^{-7}$ to $2.54 \times 10^{-5}$. In the case of $K = 8$ (i.e., the sawtooth stressor was inscribed by repeating eight scanning process), as shown in the inset of Fig. 4(c), the lasing spectrum of the DFB-FL exhibited two distinct peaks due to the increased birefringence.

A strong modulated sawtooth stressor inscribed with higher fs laser intensity is in demand to increase the strain and temperature sensitivity of the birefringence [9]. However, this will also generate a high birefringence in the DFB-FL, leading to a large beat frequency shift out of the measurable range of the ESA. Consequently, we developed a two-stressors approach to solve this problem. The original DFB-FL (without a stressor in the EDF cladding), as shown in the inset P1 of Fig. 5(a1), could generate a beat frequency of 256.3 MHz at a pump power of 30 mW, as shown in Fig. 5(a1), corresponding to a birefringence of 1.92 $\times$ 10$^{-6}$. As shown in Fig. 5(b1), the DFB-FL operates in single wavelength oscillation at the lasing wavelength of 1552.04 nm. Then, as shown in the inset P2 of Fig. 5(a2), a strong modulated sawtooth was fabricated in the EDF cladding near the PS-FBG at XZ plane. An eighttimes ($K = 8$) repeated scanning process, together with an average on-target laser power of ~300 µW, was used for fabricating the strong modulated sawtooth stressor. Figure 5(a2) demonstrates the beat signal of the DFB-FL disappeared in ESA due to the limit in detection range (i.e., up to 4 GHz), whereas the laser signal remained in the optical spectrum with two peaks (i.e., 1552.02 and 1552.25 nm), as shown in Fig. 5(b2), corresponding to a high birefringence of 2.15 $\times$ 10$^{-4}$. It means the DFB-FL exhibited dual-wavelength oscillation at the pump power of 30 mW. If the strong modulated sawtooth stressor-assisted DFB-FL was used as a sensor by
monitoring the beat signal, the beat frequency should be tuned back into detection range of the ESA. As a result, we fabricated another stressor orthogonal to the previous strong modulated sawtooth stressor, i.e., a straight stressor in the EDF cladding at YZ plane, as shown in the inset P3 of Fig. 5(a3). The straight sawtooth was fabricated by an eight-times repeated scanning process ($K=8$), and the beat signal reappeared at a frequency of 1020.3 MHz, as shown in Fig. 5(a3), corresponding to a lower birefringence of $7.65 \times 10^{-6}$. Figure 5(b3) demonstrates the DFB-FL exhibited single wavelength oscillation again and a lasing wavelength of 1552.04 nm.

C. THE STRAIN AND TEMPERATURE RESPONSES

Subsequently, we investigated the beat frequency response of three DFB-FLs (i.e., S1, S2 and S3) to the applied strain and temperature, as shown in Figs. 6(a) and 6(b). In order to eliminate bend-induced strain, the DFB-FL was kept straight and maintained a certain tension by moving manually the translation stage before each test. S1, S2, and S3 represent the DFB-FL with a straight stressor, the DFB-FL with a weak modulated sawtooth stressor, and the DFB-FL with two stressors (i.e., a strong modulated sawtooth stressor and a straight stressor), respectively. It should be noted that S1, S2, and S3 were inscribed with the same birefringence of $7.6 \times 10^{-6}$ in the EDF. The cross-sectional view microscope images of S1, S2, and S3 are shown in Figs. 6(c)-6(e), respectively. As shown in Figs. 6(a) and 6(b), the beat frequencies of S1, S2, and S3 exhibit ‘red’ shifts with increasing strain and temperature. The strain sensitivities of S1, S2, and S3 were calculated to be 4.1, 9.7, and 34.5 kHz/µε, and the temperature sensitivities of S1, S2, and S3 were calculated to be 196.2, 365.5, and 684.6 kHz/°C. Therefore, the two-stressors approach used for fabricating a dual-polarization DFB-FL sensor, as demonstrated in sample S3, can significantly enhance the strain and temperature sensitivity. Moreover, the strain and temperature sensitivity of the current technique by beat frequency demodulation is higher than those of previously reported techniques [1], [27]–[29], as listed in Table 1.

We further studied the simultaneous measurement of the strain and temperature using the two stressor-assisted dual-polarization DFB-FL sensor (i.e., S3 with a strong modulated sawtooth stressor and a straight stressor). As shown in Figs. 7(a) and 7(b), the beat frequency $\nu_B$ of the proposed DFB-FL sensor exhibits ‘red’ shifts with a strain sensitivity of 34.5 kHz/µε and a temperature sensitivity of 684.6 kHz/°C, whereas the lasing wavelength $\lambda$ of the proposed DFB-FL sensor exhibits ‘red’ shifts with a strain sensitivity of 1.25 pm/µε and a temperature sensitivity of 11.5 pm/°C. As a result, we can obtain the second-order matrix as

$$K = \begin{pmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{pmatrix} = \begin{pmatrix} 34.5 & 684.6 \\ 1.25 & 11.5 \end{pmatrix}, \quad (5)$$
Moreover, the variations in strain and temperature can be simultaneously determined by solving the matrix equation as:

\[
\left( \frac{\Delta \varepsilon}{\Delta T} \right) = \begin{pmatrix} 1 & 11.5 \\ -465.9 & -1.25 \end{pmatrix} \begin{pmatrix} \Delta \nu \\ -684.6 \end{pmatrix} \begin{pmatrix} \Delta \lambda \end{pmatrix}. \tag{6}
\]

The proposed DFB-FL sensor was interrogated by simultaneous beat frequency demodulation and wavelength demodulation. In our experiment, the resolutions of the OSA and ESA were set to be 10 kHz and 10 pm, respectively, which denotes resolutions of 8 \( \mu \varepsilon \) and 0.87 °C for strain and temperature measurement, respectively. The beat frequency and lasing wavelength of the DFB-FL were measured every 5 minutes for 2 hours when the strain and temperature were kept unchanged. The maximum deviations of them are ±1.6 kHz and ±6 pm, respectively. According to Eq. (6), the estimated maximum errors of the simultaneously measured strain and temperature are ±4.8\( \mu \varepsilon \) and ±0.5°C, respectively.

**IV. CONCLUSION**

We demonstrate a method for simultaneously measuring strain and temperature using a stressor-assisted dual polarization DFB-FL. The sensor is formed by a \( \pi \) PS-FBG together with a strong modulated sawtooth stressor and a straight stressor at two orthogonal planes. The PS-FBG was directly inscribed in the core of the heavily erbium-doped fiber using a scanning UV laser beam with a shielded phase mask. These stressors were fabricated near the PS-FBG using near-infrared \( fs \) laser irradiation. The strain and temperature responses could be obtained by monitoring the two parameters, i.e., beat frequency \( \nu \) and lasing wavelength \( \lambda \) of the proposed DFB-FL. The experimental results exhibit strain sensitivities of 34.5 kHz/\( \mu \varepsilon \), 1.25 pm/\( \mu \varepsilon \) between 0 to 600 \( \mu \varepsilon \), and temperature sensitivities of 684.6 kHz/°C, 11.5 pm/°C between 30 to 100 °C. Hence, this proposed DFB-FL sensor is promising in many areas, such as smart structures and intelligent robotics.

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