

RESEARCH ARTICLE

Machine-Learning-Enhanced Dual-Diameter Sapphire Fiber Bragg Gratings for Simultaneous High-Temperature and Strain Sensing

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ABSTRACT

Fiber-optic multiparameter sensors are versatile tools for in situ health monitoring of critical components in hypersonic vehicles, including thermal protection systems and turbine engine blades. Sapphire fiber Bragg gratings (SFBGs), owing to excellent high-temperature performance, offer a competitive solution for such applications. However, these devices suffer from cross-sensitivity, complicating the discrimination between temperature and strain responses. Here, we propose a concise and robust sensing scheme based on dual-diameter SFBGs (DD-SFBGs), with machine learning (ML)-assisted demodulation. Two line-by-line SFBGs are inscribed by a femtosecond laser into an etched dual-diameter sapphire fiber. By tailoring the fiber geometry, this design overcomes the cross-sensitivity limitation within a single sapphire fiber. The DD-SFBGs exhibit markedly different strain sensitivities of 4.16 and 0.92 pm/ $\mu\epsilon$ at 1450°C, which can be further tailored by etching fibers with different geometries, far exceeding the capability of silica-based sensors. Furthermore, we employ the XGBoost gradient boosting algorithm to demodulate the multimode, wide-bandwidth reflection spectra. This ML-enhanced approach achieves high sensing performance, with root mean square errors (RMSE) of 0.41°C for temperature and 5.76 $\mu\epsilon$ for strain. This compact, reliable, and high-precision approach thus represents a significant advance in simultaneous temperature-strain sensing, with promising applications in aerospace structural health monitoring.

1 | Introduction

Strain and temperature are two critical parameters in structural health monitoring (SHM) of advanced equipment such as aerospace vehicles, gas turbines, and power plants [1–6]. Such equipment typically operates under extreme conditions, necessitating sensors capable of measuring both parameters at ultra-high temperatures. For example, hypersonic vehicles are prone to structural deformations caused by aerodynamic

heating and mechanical loading, which can compromise thermal protection systems (TPS) and potentially lead to catastrophic disintegration during high-angle maneuvers [1]. Turbine engines, as the core of aerospace propulsion systems, require comprehensive strain monitoring of key components such as alloy blades and transmission shafts under extreme conditions (e.g., 1500°C) [1]. Existing sensors for temperature and strain measurements include infrared thermography, thermocouples, strain gauges, and digital image correlation (DIC) systems. However, these

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methods suffer from inherent limitations such as low accuracy, limited operating temperature, and susceptibility to electromagnetic interference. Fiber-optic sensors, particularly fiber Bragg gratings (FBGs) [7–13], offer unique advantages for high temperature and strain sensing. For example, Type II FBGs inscribed by a femtosecond laser exhibit sustained operational stability above 1000°C [9–11]. However, conventional silica FBGs are fundamentally constrained by the glass transition temperature, rendering them unsuitable for strain measurements above 800°C.

Single-crystal sapphire fibers, with a high melting point (2045°C), exceptional chemical stability, and superior mechanical strength, have emerged as promising candidates for high-temperature sensing [14]. Various sensing mechanisms have been demonstrated for high-temperature measurements, including blackbody radiation [15], Fabry–Perot (F–P) interferometers [16], Bragg gratings [17–19], Raman scattering [20], and ultrasonic signal detection [21]. Among these, sapphire fiber Bragg gratings (SFBGs) offer remarkable advantages, including high stability, enhanced signal-to-noise ratios (SNR), and inherent multiplexing capabilities. SFBGs can operate at 1900°C [22] and run continuously for 1000 h at 1500°C [23], with the potential for high-speed dynamic measurements. Stable strain measurement of SFBGs has also been demonstrated at high temperatures [24, 25]. For SHM in harsh environments, significant progress has been made in sapphire fiber growth [26], cladding fabrication [27], and embedding [28] into ceramic matrix composites. However, strain measurement accuracy at high temperatures is compromised by cross-sensitivity between temperature and strain, an issue exacerbated by the low intrinsic strain sensitivity of SFBGs (~ 1.4 pm/ $\mu\epsilon$). Because the strain sensitivity of an FBG scales inversely with the fiber cross-sectional area, tailoring the fiber geometry offers a potential route to enhance it. Addressing this challenge is critical for SFBG-based strain sensing and its practical application in extreme environments.

To overcome this problem, researchers have proposed a dual-parameter detection scheme that integrates blackbody radiation signals with Bragg grating spectra [29]. However, this method can only be used at temperatures above 650°C, resulting from the weak blackbody radiation signal at lower temperatures. In addition, a cascaded structure on sapphire-derived fiber has been developed, consisting of an F–P cavity for strain sensing and an FBG for temperature compensation. This configuration achieves high-temperature strain sensing up to ± 1000 $\mu\epsilon$ at 1150°C [30]. However, this method does not support multi-point measurements. Decoupling of temperature and strain can also be achieved using dual-wavelength FBGs with different temperature or strain sensitivities [31, 32]. For example, fourth-order and fifth-order SFBGs have been investigated, exhibiting temperature sensitivities of 28.7 and 23.0 pm/°C, and strain sensitivities of 1.27 and 1.02 pm/ $\mu\epsilon$, albeit at the cost of reduced strain sensitivity [33]. However, the small difference between these sensitivities reduces decoupling accuracy. Recently, two SFBGs [34], i.e., one parallel to the fiber axis and the other tilted at 2.29° relative to it, were proposed and exhibited distinct strain sensitivities of 1.8 and 0.4 pm/ $\mu\epsilon$. However, this method reduces the strain sensitivity of SFBGs. Other approaches for decoupling temperature and strain in silica fibers involve creating FBGs with different strain sensitivities, for instance by splicing dissimilar silica FBGs [35] or etching silica FBGs [36]. However, fabricating analogous

structures in sapphire fiber is challenging because single-crystal sapphire is brittle, hard, and corrosion-resistant [14]. Hence, decoupling temperature and strain in an SFBG sensor remains an open challenge.

Moreover, the multimode reflection spectrum of SFBGs, characterized by broad bandwidth, complicates accurate spectral demodulation and poses a challenge for simultaneous temperature and strain retrieval. Machine learning (ML) [37–39] has emerged as a powerful tool for enhancing spectrum demodulation performance compared with traditional methods, such as long-wave length-edge detection [40] and cross-correlation [23]. For instance, a deep neural network (DNN) was used to demodulate temperature from coarsely sampled SFBG spectra with an accuracy of 0.23°C at a 5 kHz acquisition rate [41]. A PCA-KNN algorithm achieved robust high-temperature demodulation up to 1700°C with an accuracy of 2.43°C, effectively suppressing vibration-induced crosstalk [42]. However, extending the output from a single parameter (temperature) to multiple parameters (temperature and strain) further increases the complexity of the learning task, especially when high-dimensional spectral inputs are used with experimentally limited datasets [43, 44]. The well-defined optical and material responses of SFBGs provide physical priors for constructing compact, sensing-related spectral features, thus avoiding the need to directly process all sampled spectral points with high-capacity models. After feature extraction, the demodulation problem can be formulated as a nonlinear regression task. XGBoost is particularly suitable for such structured numerical features, as it effectively captures nonlinear feature interactions with good generalization on limited experimental datasets [45]. Therefore, we employ XGBoost to investigate simultaneous temperature–strain demodulation based on the compact wavelength-domain features of the DD-SFBG spectra.

In this work, we propose and demonstrate a dual-parameter sensor based on dual-diameter SFBGs (DD-SFBGs) directly inscribed into an etched sapphire fiber by a femtosecond laser. By developing an etching technique for sapphire fiber, we successfully fabricate a fiber with two distinct diameters. Subsequently, two Bragg gratings are inscribed in the etched section (E-SFBG) and the unetched section (U-SFBG) of the dual-diameter sapphire fiber, yielding a high-SNR reflection spectrum. By optimizing the DD-SFBGs structure, we improve the strain sensitivities to 4.16 and 0.92 pm/ $\mu\epsilon$, which facilitates decoupling of high temperature and strain. Furthermore, we employ the XGBoost gradient boosting algorithm to demodulate high temperature and strain from the DD-SFBGs spectra. This tree-based model captures nonlinear relationships and interaction effects among features. As a result, we achieve low root mean square errors (RMSE) of 0.41°C for temperature and 5.76 $\mu\epsilon$ for strain over the entire tested ranges.

2 | Principle of Operation

2.1 | Principle of Simultaneous High-Temperature and Strain Sensing

As illustrated in Figure 1a, the DD-SFBGs sensor consists of two gratings inscribed in a sapphire fiber with two distinct diameters: an etched section (E-SFBG) and an unetched section

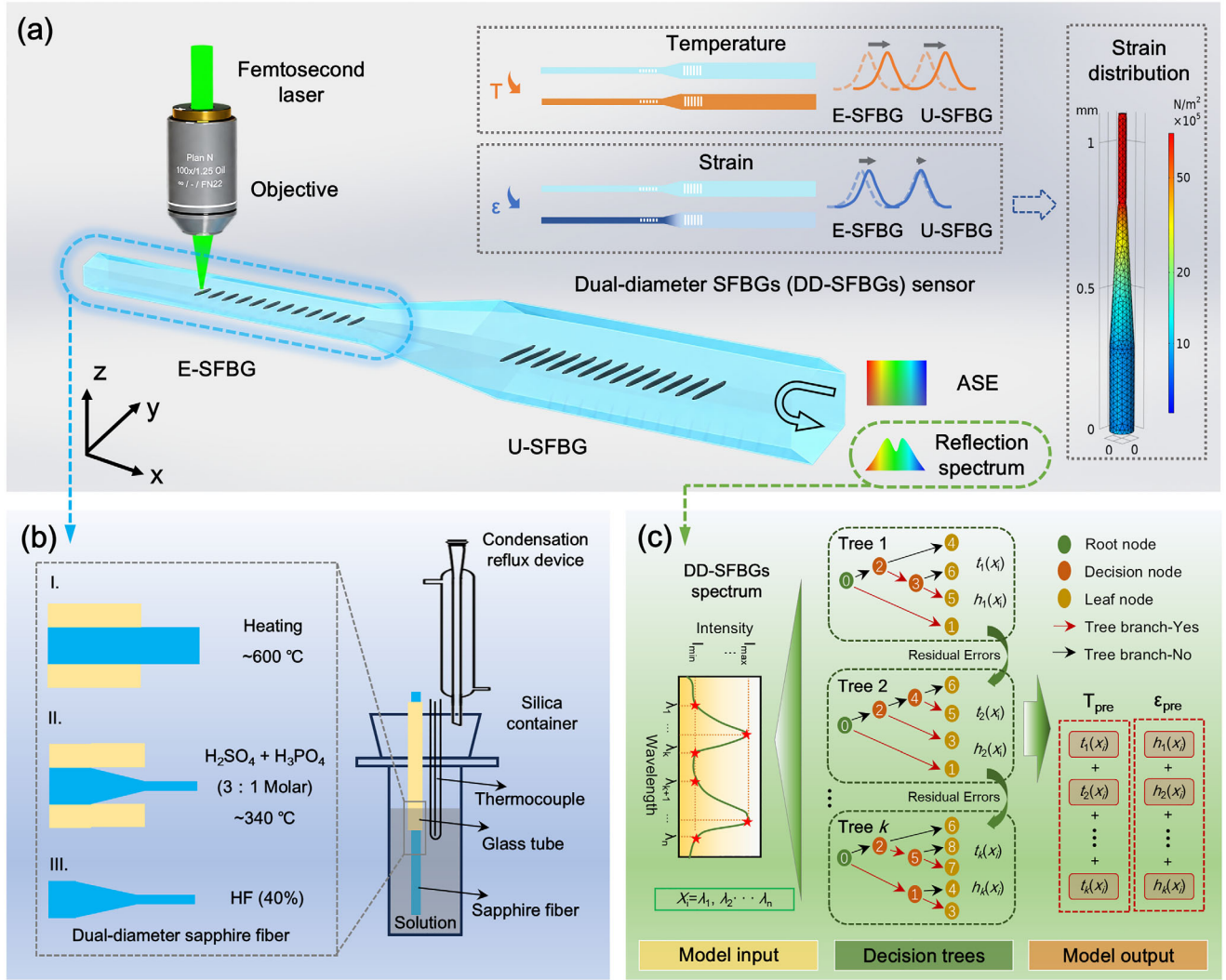


FIGURE 1 | Dual-diameter sapphire fiber Bragg gratings (DD-SFBGs) sensor for simultaneous high-temperature and strain sensing. (a) Femtosecond laser line-by-line inscription of two SFBGs in a dual-diameter sapphire fiber and the sensing mechanism. (b) Fabrication of the dual-diameter sapphire fiber by wet etching. (c) Machine-learning-enhanced demodulation scheme for the DD-SFBGs sensor.

(U-SFBG). The inset in Figure 1a shows that temperature and strain variations applied to the DD-SFBGs induce different Bragg wavelength shifts in these two gratings. Finite-element simulation shows that E-SFBG bears greater stress. The temperature and strain sensitivities of a SFBG are determined by the thermal expansion coefficient, thermo-optic coefficient, Poisson's ratio, and photoelastic coefficient (Note S1). Since etching primarily modifies the fiber geometry and the mechanical strain distribution without intentionally altering the intrinsic sapphire material, the E-SFBG and U-SFBG are expected to exhibit comparable temperature sensitivities. This theoretical expectation is further supported by the experimental results presented in Section 3.4.1. However, due to the reduction in fiber diameter in the etched section, when the fiber is subjected to axial tension ($\Delta\epsilon$), the stress distribution between the E-SFBG and U-SFBG affects the local strain. This effect is expressed as $\Delta\epsilon_E = \alpha_E \cdot \Delta\epsilon$ and $\Delta\epsilon_U = \alpha_U \cdot \Delta\epsilon$, where α_E and α_U are coefficients introduced to describe this effect. Consequently, the Bragg wavelengths λ_B of the E-SFBG and U-SFBG experience shifts

$$\Delta\lambda_E = \Delta T \cdot k_{T,E} + \Delta\epsilon \cdot \alpha_E k_{\epsilon,E} \quad (1)$$

$$\Delta\lambda_U = \Delta T \cdot k_{T,U} + \Delta\epsilon \cdot \alpha_U k_{\epsilon,U} \quad (2)$$

where $k_{T,E}$, $k_{T,U}$, $k_{\epsilon,E}$, and $k_{\epsilon,U}$ are the temperature and strain sensitivities of the E-SFBG and U-SFBG, respectively. Under axial tension, the two sections of the DD-SFBGs sustain the same axial force, i.e., $F_E = F_U = F$. The local axial strains in the E-SFBG and U-SFBG are therefore given by $\Delta\epsilon_E = F/(S_E \cdot E)$ and $\Delta\epsilon_U = F/(S_U \cdot E)$, where E is the Young's modulus of sapphire. S_E and S_U are the cross-sectional areas of the etched and unetched sapphire fiber, respectively. Accordingly, α_E and α_U are given by

$$\frac{\alpha_E}{\alpha_U} = \frac{S_U}{S_E} \quad (3)$$

Equation (3) indicates that the ratio of the strain sensitivities of the E-SFBG and U-SFBG is inversely proportional to the ratio of their cross-sectional areas. Considering the strain relationship $\Delta\epsilon = \Delta L/L$, $L = L_E + L_U$, and $\Delta L = \Delta L_E + \Delta L_U$, where L_E and L_U denote the lengths of the etched and unetched sections,

respectively, α_E and α_U can be expressed as:

$$\alpha_E = \frac{L_E + L_U}{L_E + \frac{S_E}{S_U} \cdot L_U} \quad (4)$$

$$\alpha_U = \frac{L_E + L_U}{\left(\frac{S_U}{S_E}\right) \cdot L_E + L_U} \quad (5)$$

Therefore, the effective strain sensitivities of the DD-SFBGs depend on both the cross-sectional areas and the length distribution of the two sections. The E-SFBG and U-SFBG exhibit distinct strain responses. The short conical transition is neglected in Equations (4) and (5), as it does not affect the strain-sensitivity ratio, which is primarily determined by the cross-sectional-area ratio. Hence, temperature and strain can be simultaneously discriminated by solving the following sensitivity matrix using their Bragg wavelength shifts:

$$\begin{bmatrix} \Delta T \\ \Delta \varepsilon \end{bmatrix} = \begin{bmatrix} k_{T,E} & \alpha_E \cdot k_{\varepsilon,E} \\ k_{T,U} & \alpha_U \cdot k_{\varepsilon,U} \end{bmatrix}^{-1} \begin{bmatrix} \Delta \lambda_E \\ \Delta \lambda_U \end{bmatrix} \quad (6)$$

2.2 | Principle of Sensor Fabrication

The DD-SFBGs sensor is fabricated through controlled chemical etching, with one SFBG inscribed in the etched area (E-SFBG) and another in the unetched area (U-SFBG) using a femtosecond laser. Figure 1b shows a schematic of the dual-diameter sapphire fiber fabrication process by wet etching. The procedure begins with wet-etching a single-crystal sapphire fiber to form a two-diameter structure, as detailed in the *Experimental Section (Fabrication of Dual-Diameter Sapphire Fiber)*. In the second step, two SFBGs are inscribed in different sections of the dual-diameter sapphire fiber using a femtosecond laser line-by-line scanning technique [46], as shown in Figure 1a. The inscription parameters are detailed in the *Experimental Section (Fabrication of SFBG)*. Two interrogation systems, i.e., an optical spectral analyzer (OSA) and a high-speed FBG interrogator, are used to record the reflection spectra of the DD-SFBGs, as described in the *Experimental Section (Interrogation Systems)*.

2.3 | Principle of Machine-Learning-Enhanced Demodulation

Machine learning has become an increasingly important tool in multimode optical fiber sensing due to its ability to handle complex data, model nonlinear relationships, and adapt to various sensing scenarios. XGBoost is an ensemble learning method based on gradient-boosted decision trees, in which multiple weak learners are added sequentially to reduce the prediction errors of the existing ensemble. This structure enables the model to effectively learn the nonlinear mapping from spectral features to the target parameters. Figure 1c shows the ML-based demodulation scheme for DD-SFBG sensors, consisting of three stages: feature input, decision-tree-based regression, and model output. After balancing spectral information and model complexity, 31 feature wavelengths were extracted from each reflected Bragg envelope using fixed-percentage intensity points on both sides of the peak,

yielding a total of 62 input features (Note S4). These features were then used to predict temperature and strain through the XGBoost model. Notably, the regularization mechanism of XGBoost helps suppress overfitting and improve generalization performance. This method enables accurate temperature and strain sensing of DD-SFBG sensors, even when a commercial fast demodulator with coarse spectral resolution is employed.

3 | Device Fabrication and Characterization

3.1 | Fabrication and Characterization of DD-SFBGs

We first fabricated three dual-diameter sapphire fiber samples (S1–S3) with different diameter ratios, as the ratio of strain sensitivity between the E-SFBG and U-SFBG is inversely proportional to their cross-sectional areas. We introduce the square ratio of diameters (SRoD), defined as $(D_U:D_E)^2$, which is equivalent to the cross-sectional area ratio. Here, D_U and D_E are the diameters of the unetched and etched sections, respectively, as illustrated in Figure 2a. The SRoD values of S1, S2, and S3 are 1.8, 4, and 9, respectively. All samples have an initial diameter of 100 μm and a total length of 14 cm, with the two sections having comparable lengths. The diameter of the etched sapphire fiber was reduced at a rate of approximately 2.4 $\mu\text{m}/\text{h}$. Figure 2b1–b3 show top-view optical micrographs of S1–S3. The etched sections are smooth, while the unetched sections remain in their original state. Continuous etching creates a conical transition zone between the two regions. The cone lengths of S1–S3 are 0.56, 0.81, and 1.16 mm, with corresponding taper angles of 1.3°, 1.8°, and 1.7°. Although the conical transition in the diameter-modified structure may induce mode-dependent loss, the smooth transition profile and stable optical coupling conditions effectively minimize the associated spectral perturbations, resulting in a negligible influence on the measurements.

SFBGs were then inscribed in S1–S3 using a femtosecond laser near the cone region. The fabrication parameters for the U-SFBG were: pulse energy of 32 nJ, period of 1.78 μm , track length of 55 μm , and grating length of 2 mm. For the fabrication of E-SFBG, the parameters were: pulse energy of 11–24 nJ, period of 1.76 μm , track length of 15–35 μm , and grating length of 2 mm. Insets of Figure 2b1–b3 show top-view micrographs of the inscribed SFBGs with different etched fiber diameters. The reflection spectra of S1–S3 were recorded using the OSA-based interrogation system described in the *Experimental Section (Interrogation Systems)*. As shown by the blue curves in Figure 2c, the 3 dB bandwidth of the E-SFBG increases as the fiber diameter decreases from S1 to S3. This broadening is attributed to the differential blueshifts of the modal resonances, with higher-order modes shifting more strongly toward shorter wavelengths. When the fiber diameter decreases, more propagating mode energy enters the cladding region, reducing the effective refractive index, with higher-order modes carrying more energy outside the core. Apart from the bandwidth, the overall reflectivity shows only small variation with decreasing fiber diameter, consistent with previous reports [47]. Notably, the peaks on the reflection envelope of S3 suggest a reduction in the number of supported modes.

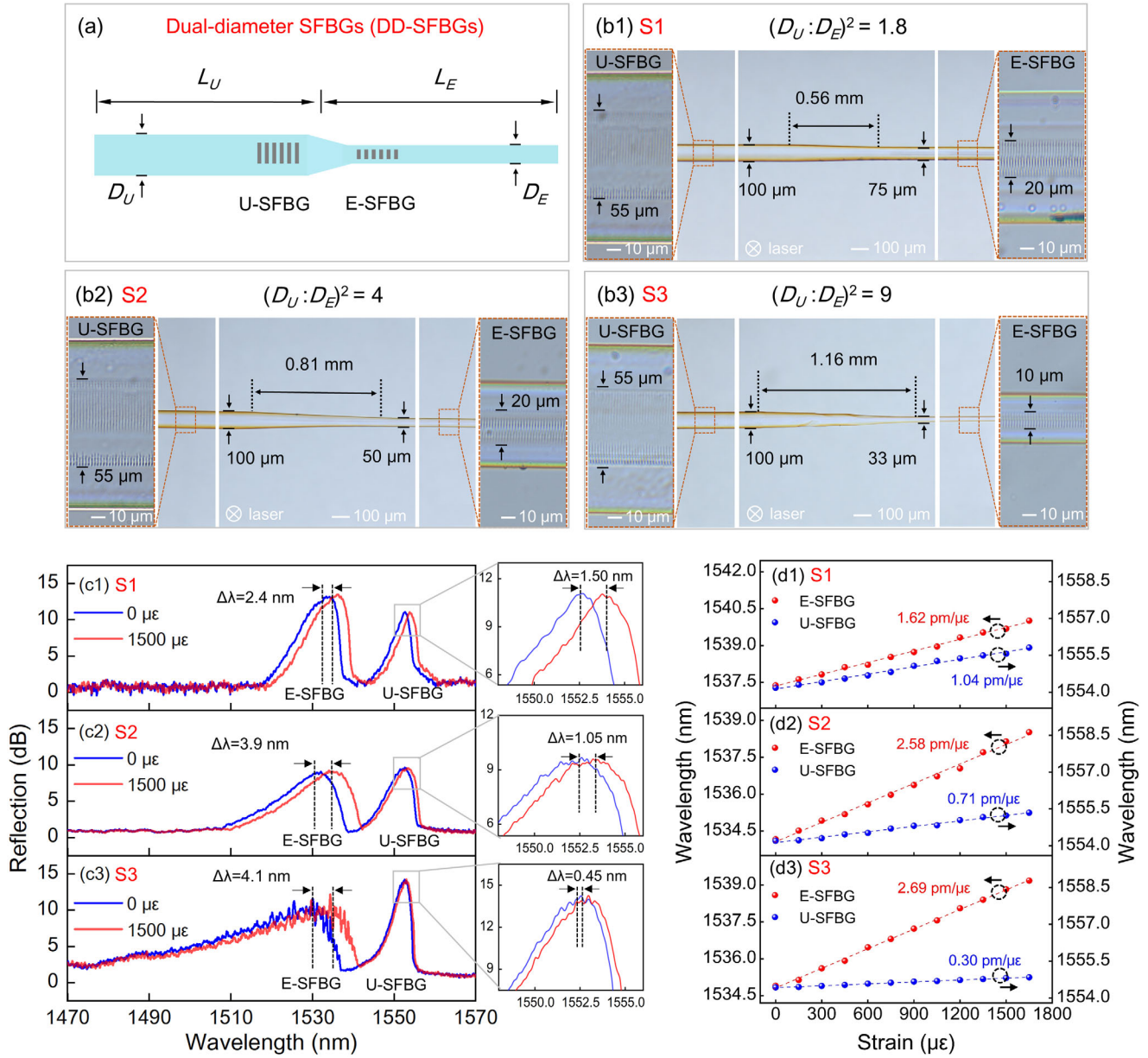


FIGURE 2 | Structural configuration, optical microscopy images, reflection spectra, and strain response of three DD-SFBG samples, denoted as S1–S3, with SRoD values of 1.8, 4, and 9, respectively. (a) Schematic of the DD-SFBGs structure. (b) Optical micrographs of the dual-diameter sapphire fiber, and the inscribed E-SFBG and U-SFBG in S1–S3. (c) Reflection spectra of S1–S3 under an applied strain of $1500 \mu\epsilon$. (d) Bragg wavelength as a function of strain for S1–S3.

The strain response of the DD-SFBGs was investigated at room temperature, and the corresponding reflection spectra are shown by the red curves in Figure 2c1–c3. Upon applying a strain of $1500 \mu\epsilon$ to S1–S3, the E-SFBG exhibits a redshift of 2.4, 3.9, and 4.1 nm, while the U-SFBG shows a redshift of 1.50, 1.05, and 0.45 nm (see inset). With increasing SRoD of the DD-SFBGs, the difference in redshift between the two resonant peaks becomes larger. The wavelength-shift ratios of the E-SFBG to the U-SFBG under strain are 1.6, 3.7, and 9.1 for S1–S3, corresponding to SRoD values of 1.8, 4, and 9, respectively. Figure 2d shows the Bragg wavelength response of S1–S3 to strain at room temperature. For S1–S3, the strain sensitivities of the E-SFBG are 1.62, 2.58, and 2.69 pm/ $\mu\epsilon$, while those of the U-SFBG are 1.04, 0.71, and 0.30 pm/ $\mu\epsilon$. These values differ from

the commonly reported value for a conventional SFBG (~ 1.4 pm/ $\mu\epsilon$) [24]. They are consistent with the values calculated using Equations (4) and (5). Minor deviations may arise from sample preparation, strain experiments, and peak-searching algorithms. Therefore, by controlling the SRoD of the DD-SFBGs, the strain sensitivities can be flexibly adjusted to achieve a significant difference.

3.2 | Device Optimization for Sensitivity and Measurement Range

To achieve either higher strain sensitivity or a larger strain measurement range, we optimized the DD-SFBGs structure by

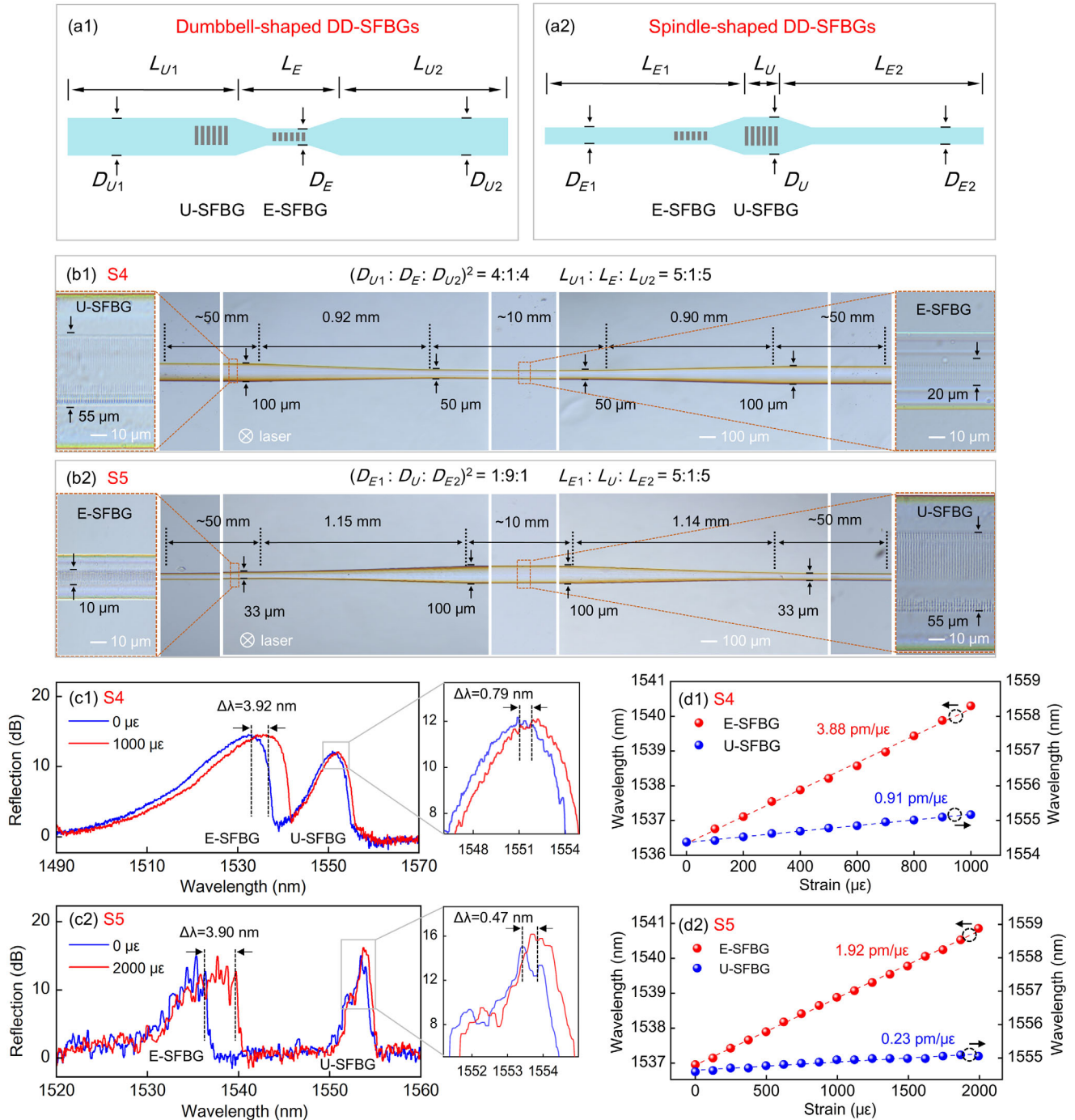


FIGURE 3 | Structural configurations, optical microscopy images, reflection spectra, and strain responses of two DD-SFBG samples with dumbbell-shaped and spindle-shaped geometries (S4 and S5), featuring high sensitivity and a large measurement range, respectively. (a) Schematics of the dumbbell-shaped and spindle-shaped geometries of the DD-SFBGs. (b) Optical micrographs of the dumbbell-shaped and spindle-shaped DD-SFBG samples S4 and S5. (c) Reflection spectra of S4 and S5 under applied strains of 1000 $\mu\epsilon$ and 2000 $\mu\epsilon$, respectively. (d) Bragg wavelength as a function of strain for S4 and S5.

varying the length ratio between the etched and unetched sections. Increasing the diameter ratio enlarges the strain-sensitivity difference between the E-SFBG and U-SFBG, whereas the length ratio further adjusts their absolute strain sensitivities by redistributing the total elongation between the different-diameter sections. Two additional samples, S4 and S5, were designed and fabricated. As shown in Figure 3a1, S4 features a dumbbell-shaped structure (thick at both ends and thin in the middle)

designed for higher strain sensitivity. An approximately 10-mm-long middle section of a 14-cm-long sapphire fiber was etched. The SRoD, defined as $(D_{U1}:D_E:D_{U2})^2$, is 4:1:4, and the length ratio $L_{U1}:L_E:L_{U2}$ in the strain experiment after adhesive curing is 5:1:5. As shown in Figure 3a2, S5 features a spindle-shaped structure (thick in the middle and thin at both ends) designed for a larger strain measurement range. In this case, the entire fiber except for a central ~10-mm-long section was etched. The

SRoD, $(D_{E1}:D_U:D_{E2})^2$, is 1:9:1, and the length ratio $L_{E1}:L_U:L_{E2}$ in the strain experiment is 5:1:5. Notably, the SRoD of S4 was selected by balancing sensitivity and strain measurement range. A larger SRoD could be adopted for dynamic strain sensing applications, where only a limited strain measurement range is required. The inscription parameters for the SFBGs in S4 and S5 are similar to those used for S2 and S3, respectively. Top-view micrographs of S4 and S5 are shown in Figure 3b1,b2.

As shown by the blue curves in Figure 3c1,c2, the spectrum of S4 resembles that of S2, while the spectrum of S5 exhibits the more pronounced multi-peaks in its reflection envelope, suggesting a reduced number of supported modes. This behavior is likely related to the mode-coupling condition between the etched sapphire fiber and the multimode fiber (SI 105/125), since S5 has a much smaller diameter (33 μm) than S1–S4 (100 μm). Upon applying a strain of 1000 $\mu\epsilon$ to S4, the resonant peaks of the E-SFBG and U-SFBG exhibit redshifts of 3.92 and 0.79 nm, corresponding to strain sensitivities of 3.88 and 0.91 $\text{pm}/\mu\epsilon$, respectively, as shown in Figure 3c1,d1. For S5, when a strain of 2000 $\mu\epsilon$ was applied, the resonant peaks of the E-SFBG and U-SFBG redshifted by 3.90 and 0.47 nm, corresponding to strain sensitivities of 1.92 and 0.32 $\text{pm}/\mu\epsilon$, respectively, as shown in Figure 3c2,d2. The more evident multi-peak behavior of the S5 reflection spectrum originates from the reduced number of guided modes supported by the 33 μm sapphire fiber. Despite this spectral feature, no significant spectral instability was observed during the strain test. These results demonstrate that the strain characteristics of DD-SFBGs can be effectively tailored by the length ratio of the different-diameter sections. The experimental results confirm that these fiber sensors can be designed to provide either higher strain sensitivity or a larger measurable strain range. For subsequent high-temperature strain sensing and temperature-strain decoupling, the optimized dumbbell-shaped sample S4, owing to its high strain sensitivity, was selected for further investigation.

3.3 | Strain Stability at High Temperatures

3.3.1 | Plastic Deformation of SFBG

The long-term operational capability of optical temperature and strain sensors in extreme environments is critical for structural health monitoring. Plastic deformation, which depends strongly on the operating temperature, can lead to failure of SFBG-based high-temperature strain monitoring [25, 48]. We first investigated the stability of the strain characteristics of a pristine SFBG at high temperatures. The grating inscription parameters were consistent with those of the U-SFBG described above. The testing system is detailed in the *Experimental Section (High-Temperature Tensile System)*. A constant strain of 750 $\mu\epsilon$ was applied to the SFBG at 1050, 1160, 1280, 1450, 1530, and 1600°C for ~ 100 min, with reflection spectra recorded every 2 min. At 1530°C, as shown in Figure 4a1,b1, no evident change in the spectral shape is observed. The Bragg wavelength remains stable, with a maximum fluctuation of 0.29 nm, and the tensile stress does not decrease significantly. Similar results are obtained at 1050–1450°C, as shown in Figure S1 (Note S2). However, at 1600°C, the reflection peak exhibits a redshift of 2.63 nm (from 1586.02 to 1588.65 nm), and the bandwidth gradually broadens

from 4.60 to 5.43 nm within 90 min under the applied strain (Figure 4a2,b2). The tensile stress shows a significant decrease of 0.57 N. These results indicate the onset of creep-induced permanent deformation of the SFBG when subjected to 750 $\mu\epsilon$ at 1600°C. Therefore, under the present test conditions, stable strain sensing was achieved up to at least 1530°C for the pristine SFBG.

3.3.2 | Plastic Deformation of DD-SFBGs

We subsequently investigated the strain stability of the dumbbell-shaped DD-SFBGs sensor (S4) at high temperatures. A constant strain of 300 $\mu\epsilon$ was applied to the DD-SFBGs at 1050, 1160, 1280, 1450, and 1530°C for ~ 100 min, with reflection spectra recorded every 2 min. At 1450°C, as shown in Figure 4c1,d1, no evident change in the spectral shape is observed. The Bragg wavelengths of the E-SFBG and U-SFBG remain stable, with a maximum fluctuation of 0.19 nm, and the tensile stress does not decrease significantly. Similar results are obtained at 1050–1280°C, as shown in Figure S2 (Note S3). The stable operation of the S4 sample at 1450°C demonstrates that the dumbbell-shaped structure effectively enhances strain sensitivity while maintaining sufficient mechanical stability under high-temperature loading. However, at 1530°C, as shown in Figure 4c2,d2, the reflection peak of the E-SFBG exhibits a redshift of 1.37 nm (from 1584.31 to 1585.68 nm), and the 1 dB bandwidth gradually broadens from 7.16 to 10.49 nm within 90 min under the constant applied strain. In contrast, the spectral shape and Bragg wavelength of the U-SFBG remain stable. This difference is attributed to the fact that the E-SFBG experiences a much higher stress of 397 MPa, compared to only 99 MPa for the U-SFBG. Moreover, plastic deformation of single-crystal sapphire fiber depends on both temperature and stress. The DD-SFBGs sensor can operate stably at 1450°C under the applied strain, but become unstable during long-term operation at 1530°C when the stress in the E-SFBG reached 397 MPa.

3.4 | Simultaneous High-Temperature and Strain Sensing

3.4.1 | High-Temperature and Strain Response of the DD-SFBGs

We further investigated the temperature-strain decoupling performance of the DD-SFBGs sensor (S4) at high temperatures. The furnace temperature was increased from 700°C to 1450°C and maintained for 30 min at each measurement point, during which the spectra of the DD-SFBGs were recorded. As shown in Figure 5a1, a gradual redshift is observed in the reflection spectra as the temperature increases. The reflection peaks of the SFBGs remain stable at high temperatures, with a slight decrease in SNR due to blackbody radiation. As shown in Figure 5a2, the Bragg wavelengths of the E-SFBG and U-SFBG exhibit a good linear fit ($R^2 > 0.99$) to temperature. The E-SFBG exhibits a temperature sensitivity of 32.7 $\text{pm}/^\circ\text{C}$, while the U-SFBG shows a comparable value of 32.4 $\text{pm}/^\circ\text{C}$. Subsequently, the furnace was held at 1450°C, and a strain of 500 $\mu\epsilon$ was applied to the DD-SFBGs sensor in steps of 33 $\mu\epsilon$. Figure 5b1 shows that the Bragg wavelengths undergo a redshift as the strain increases. In contrast to detecting

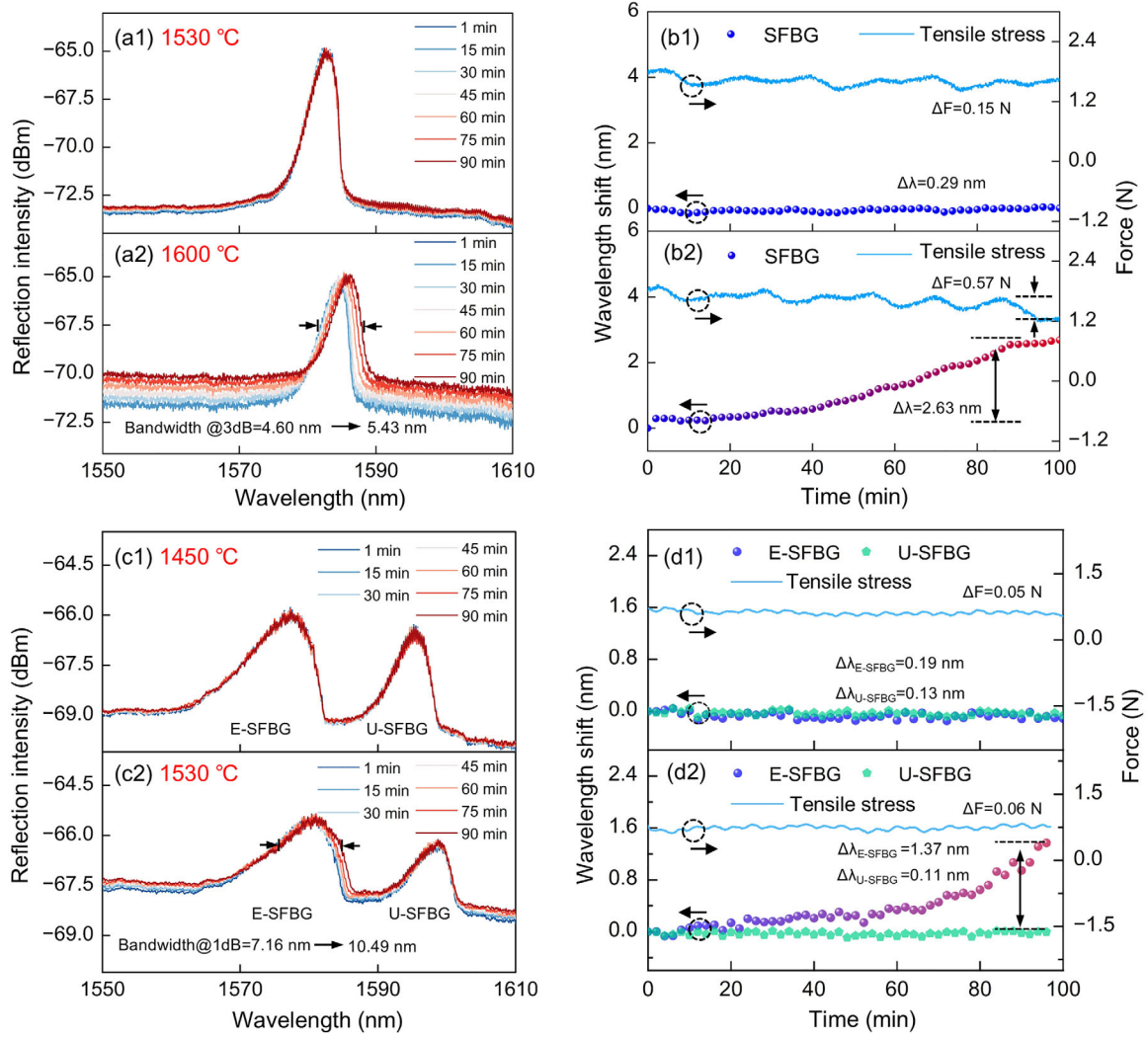


FIGURE 4 | Long-term stability of the SFBG and DD-SFBG sensors under constant strain at elevated temperatures. (a) Spectral evolution, and (b) wavelength shift and tensile stress fluctuation of a pristine SFBG under an applied strain of $750 \mu\epsilon$ at 1530°C and 1600°C . (c) Spectral evolution, and (d) wavelength shift and tensile stress fluctuation of the DD-SFBGs sensor under an applied strain of $300 \mu\epsilon$ at 1450°C and 1530°C .

the peak wavelength, we tracked a more stable wavelength located at the low-order modal resonances of the SFBG reflection envelope (see inset of Figure 5b1 for spectra with Savitzky–Golay filtering) [40]. Moreover, as shown in Figure 5b2, both gratings exhibited excellent linear fits ($R^2 > 0.99$). The strain sensitivities of the E-SFBG and U-SFBG at 1450°C are 4.16 and $0.92 \text{ pm}/\mu\epsilon$, respectively, demonstrating the high-temperature strain sensing capability of the DD-SFBGs sensor. Hence, the temperature and strain sensitivities of the E-SFBG are $32.7 \text{ pm}/^\circ\text{C}$ and $4.16 \text{ pm}/\mu\epsilon$, respectively, while those of the U-SFBG are $32.4 \text{ pm}/^\circ\text{C}$ and $0.92 \text{ pm}/\mu\epsilon$, respectively. The determinant of the transfer matrix in Equation (6) is approximately 104.7 , which is sufficiently far from zero, confirming that the sensitivity difference introduced by the diameter modulation provides an effective solution for temperature–strain decoupling.

According to the error propagation analysis [49], the theoretical uncertainties in temperature and strain demodulation of the DD-SFBG sensor were evaluated. Note that the errors in the measured coefficients were assumed to arise solely from measurement errors of λ_1 and λ_2 . The maximum errors in temperature (T) and

strain (ϵ) can be expressed as:

$$|\delta T| \leq \frac{|k_{\epsilon,U} \cdot \alpha_U| |\delta \lambda_E| + |k_{\epsilon,E} \alpha_E| |\delta \lambda_U|}{|\Delta|} \quad (7)$$

$$|\delta \epsilon| \leq \frac{|k_{T,U}| |\delta \lambda_E| + |k_{T,E}| |\delta \lambda_U|}{|\Delta|} \quad (8)$$

For a consistent comparison, the wavelength resolution error was fixed at 1 pm , corresponding to the resolution of a high-spectral-resolution spectrometer. Based on Equations (7) and (8), the theoretical errors in δT and $\delta \epsilon$ were estimated to be 0.05°C and $0.62 \mu\epsilon$, respectively, indicating high demodulation accuracy under the given interrogation conditions. As summarized in Table 1, the proposed sensor compares favorably with previously reported devices, delivering a notably high strain sensitivity of $4.2 \text{ pm}/\mu\epsilon$ together with a low cross-sensitivity of $7.8 \mu\epsilon/^\circ\text{C}$, which demonstrates its strong potential for temperature–strain decoupling.

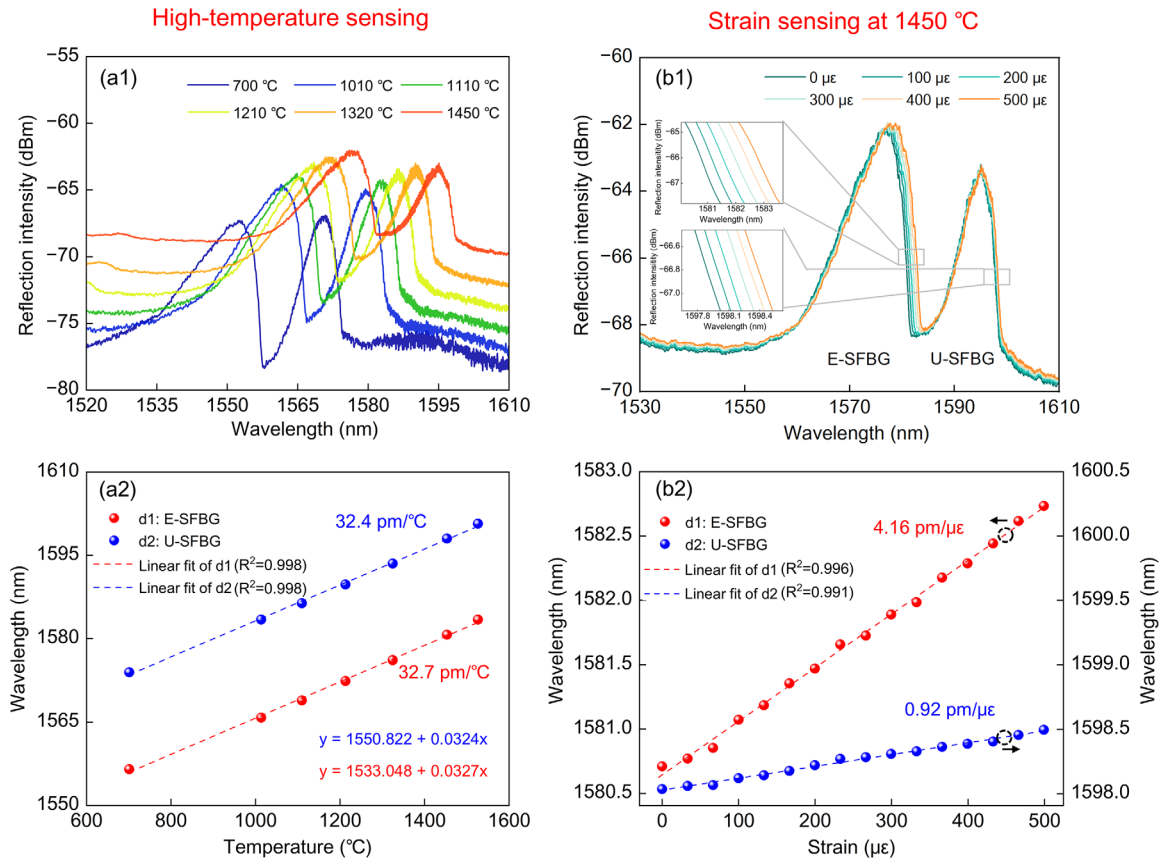


FIGURE 5 | High-temperature and strain response of the DD-SFBGs sensor. (a) Spectral evolution and wavelength shift as the temperature increases from 700 °C to 1450 °C. (b) Spectral evolution and wavelength shift as the strain increases from 0 μ ε to 500 μ ε.

TABLE 1 | Performance comparison of dual-FBGs sensors for simultaneous temperature and strain sensing.

Fiber material	Device structure	Sensing range	Strain sensitivity (pm/μ ε)	Temperature sensitivity (pm/° C)	Cross-sensitivity (μ ε/° C)	References
Silica (amorphous glass)	Heterogeneous-waveguide FBGs	0–2000 μ ε @ < 700 °C	1.0, 1.0	11.4, 9.4	9.4	[32]
	Spliced DD-FBGs		0.7, 0.3	11.8, 12.1	16.9	[35]
Sapphire (single crystal)	High-order SFBG	0–150 μ ε @ 1690 °C	1.3, 1.0	28.7, 23.0	22.1	[33]
	Angled SFBGs	0–1000 μ ε @ 1600 °C	1.8, 0.4	27.4, 26.2	15.2	[34]
	Etched DD-SFBGs	0–500 μ ε @ 1450 °C	4.2, 0.9	32.7, 32.4	7.8	This work

3.4.2 | Simultaneous Temperature-Strain Sensing at High Temperatures Using Machine Learning

While the matrix-based decoupling method provides a physically interpretable solution, its accuracy may be affected by spectral distortions and nonlinear variations in practical measurements. Recently, machine learning approaches have been increasingly explored for extracting sensing information from complex optical responses [50]. Therefore, a

machine learning (ML)-assisted strategy is further introduced to exploit the full spectral information of DD-SFBGs and enhance the robustness of simultaneous temperature-strain sensing. Details of dataset construction and model training are provided in the *Experimental Section (Dataset and Model Training)*. Temperature-strain calibration experiments were performed using a high-speed FBG interrogator, and the acquired spectral data were used to construct the dataset for model training and validation.

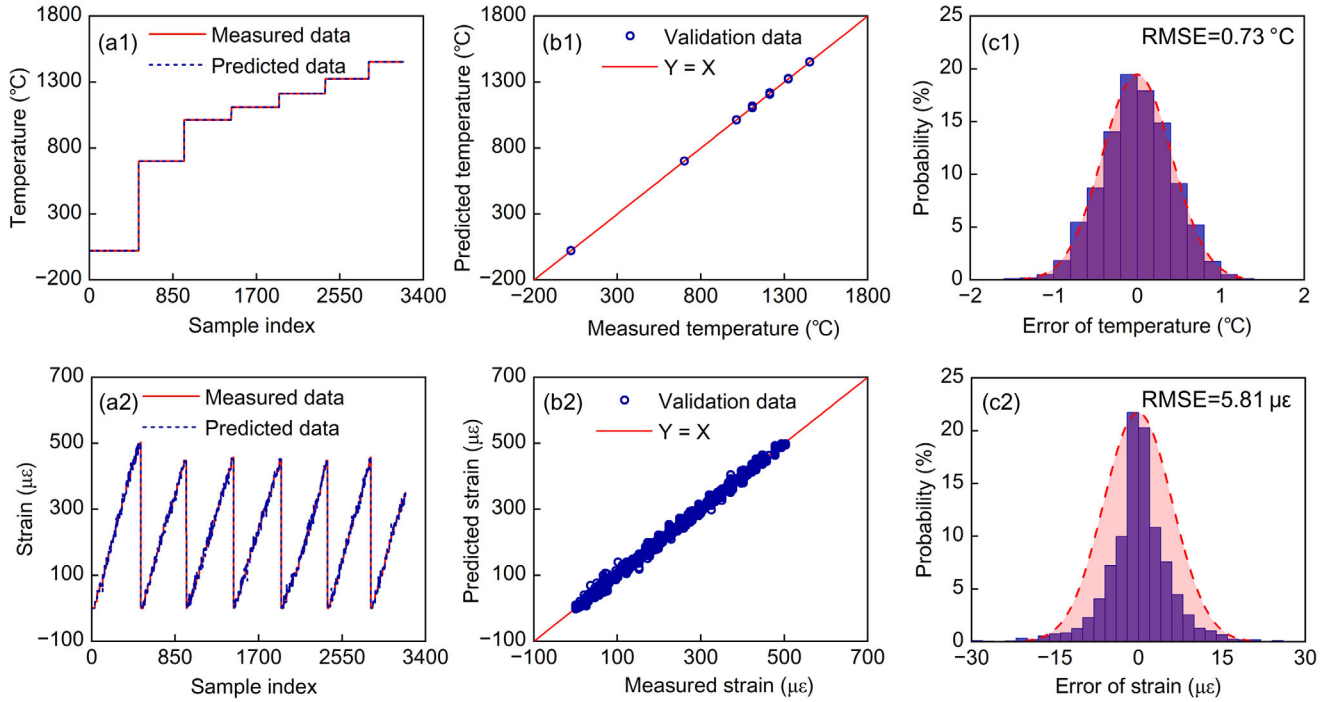


FIGURE 6 | Machine-learning-enhanced simultaneous temperature-strain sensing of the DD-SFBG sensor using the XGBoost model. (a) Comparison between the XGBoost model predictions (blue curves) and measured data (red curves) acquired using a thermocouple for temperature and a displacement sensor for strain. (b) Correlation between measured and predicted temperature and strain values. (c) Histogram of prediction errors.

Figure 6a illustrates the strong consistency between the predictions generated by the trained XGBoost model (blue curves) and the measured data (red curves, acquired using a thermocouple for temperature and a displacement sensor for strain) across the entire experimental range. Figure 6b compares the measured temperature and strain values with their corresponding predictions. The red reference line ($y = x$) represents the ground truth, and the close alignment of the predicted points with this line confirms the effective performance of the XGBoost model. Figure 6c presents the error histogram for the 3,195 input spectra, which exhibits an approximately normal distribution. The prediction error is quantified using the root mean square error (RMSE), defined as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (y_{measured,i} - y_{predicted,i})^2}{N}} \quad (9)$$

On the validation dataset, the RMSE is 0.41 °C for temperature and 5.76 $\mu\epsilon$ for strain, respectively. Notably, despite the sparse sampling resolution of only 160 pm, the proposed ML-assisted approach achieves remarkably high sensing accuracy for both temperature and strain. Furthermore, this method reduces the need for heuristic selection of subjective parameters, such as the number of fitting points, while maintaining low detection errors.

4 | Discussion and Conclusion

By developing a wet etching process, the diameter of the sapphire fiber can be flexibly reduced, resulting in a dual-diameter structure with exceptional mechanical strength and smooth surface topography. Given the inverse proportionality

between stress and the cross-sectional area of the optical fiber, the SFBGs inscribed in dual-diameter sapphire fibers play a critical role in decoupling temperature and strain. This advancement enables in situ strain measurement within the limited space of an ultra-high-temperature environment using a single sapphire fiber, without the need for complex temperature compensation. Note that the compact millimeter-scale structure of DD-SFBGs is suitable for many practical scenarios, while strong spatial gradients may introduce additional demodulation errors. The XGBoost-assisted demodulation results demonstrate that optical sensors with well-established spectral response mechanisms can effectively leverage physics-guided feature representation. Such a strategy enables lightweight machine-learning models to achieve high demodulation accuracy while avoiding unnecessary model complexity. Moreover, controllable sapphire fiber diameter engineering combined with grating-array interrogation techniques, including wavelength division multiplexing (WDM) and optical frequency domain reflectometry (OFDR), offers a promising route toward distributed high-temperature strain monitoring.

In summary, we have successfully demonstrated a simultaneous high-temperature and strain sensing technology on a single sapphire fiber by combining flexible wet etching with femtosecond laser direct writing, supported by robust machine learning models. Experimental results show that the strain sensitivity reaches a record value of 4.16 pm/ $\mu\epsilon$, significantly reducing the cross-sensitivity between temperature and strain. Moreover, compared with conventional silica-based fiber sensors, which have an upper operating limit of approximately 700 °C, the DD-SFBGs sensor exhibits long-term, reliable strain monitoring capability up to 1450 °C. By employing machine learning for demodulation of multimode, wide-bandwidth reflection spectra,

the sensor achieves high-performance sensing with RMSE values of 0.41°C for temperature and 5.76 $\mu\epsilon$ for strain.

In the future, this technology may achieve even higher strain sensitivity through more precise etching, providing a novel approach for acoustic sensing at high temperatures. Therefore, the proposed DD-SFBGs sensor represents an important advancement in optical sensing, offering a new approach for strain and temperature measurement in extreme environments across various fields, such as safety monitoring of key structures in aerospace (e.g., turbine engines, thermal protection systems, and high-speed aircraft skins).

5 | Experimental Section

5.1 | Dual-Diameter Sapphire Fiber Fabrication

The sapphire fiber (Cryst. Elite) was wet-etched using sulfuric acid (98%, J&K Scientific) and phosphoric acid (85%, J&K Scientific) in a 3:1 molar ratio. To accelerate the reaction rate, a furnace was used to heat the solution to $\sim 340^\circ\text{C}$ [47]. A quartz container with a top opening was used to insert the fiber and a K-type thermocouple. Glass shields were used to mask the fiber sections to maintain a constant diameter and could be removed from the sapphire fiber using hydrofluoric acid (40%, J&K Scientific). Acid vapor was collected through a condensation reflux device during long-term etching. The etching times for S1–S3 were approximately 10.5, 21, and 28 h, resulting in etched diameters of approximately 75, 50, and 33 μm , respectively. Considering temperature fluctuations and manual operations, the diameter control accuracy was approximately $\pm 2 \mu\text{m}$. Geometric fabrication errors may cause deviations in the strain sensitivities of the E-SFBG and U-SFBG. These deviations are mitigated using experimentally calibrated sensitivity coefficients.

5.2 | SFBG Fabrication

The setup employed a frequency-doubled, regeneratively amplified Yb:KGW femtosecond laser (Light-Conversion, Pharos) with a wavelength of 514 nm, a pulse width of 290 fs, and a repetition rate of 200 kHz. A Leica oil-immersion objective (100 $\times$, NA = 1.25) was used as the focusing element. Due to the difference in focal depth along the dual-diameter sapphire fiber, parameters such as pulse energy and track length required careful adjustment during the fabrication of the E-SFBG and U-SFBG.

5.3 | Interrogation Systems

The first system consisted of an optical spectrum analyzer (OSA, Yokogawa, AQ6370D) with a wavelength resolution of 0.02 nm, an amplified spontaneous emission (ASE) source, a customized 1 $\times$ 2 multimode fiber coupler (50:50, SI 105/125), and a 500-m-long multimode fiber (SI 105/125) for stabilizing the mode distribution [51]. The second system (i.e., a high-speed FBG interrogator), featuring an acquisition speed of 1.6 kHz and a wavelength resolution of 160 pm, was used to rapidly record the spectra of the DD-SFBG sensors. It consisted of a 1550-nm ASE source (Golight, ASE-CL-40) with a bandwidth of 80 nm, an InGaAs-

based spectrometer (Bayspec, FBGA-F-105), a multimode silica fiber circulator (YOSC, AUL-105-3), and a 200-m-long multimode fiber (GI 62.5/125) for stabilizing the mode distribution.

5.4 | High-Temperature Tensile Testing System

A customized high-temperature tensile testing system was established, consisting of a universal testing machine (TSMT, EM1.504-S) and a compact high-temperature furnace (MHI, THM500). The system was used to apply tensile strain to the fiber at temperatures up to 1450°C. Moreover, a B-type thermocouple was placed adjacent to the sample to record the temperature, and an electromechanical dial indicator (Mitutoyo, S112X) was used as a displacement sensor to measure the fiber deformation, providing an accuracy of 0.002 mm. The strain was then derived as $\epsilon = \Delta L / L_0$, where ΔL is the measured displacement and L_0 is the total length of the deformation region.

5.5 | Dataset and Model Training

A dataset containing 15 975 spectra was constructed from more than 110 repeated measurements at each temperature–strain combination, including 20 strain values and 7 temperature points. The collected data were divided into 80% for training and 20% for validation. The training set was used for model fitting, while the validation set was used to evaluate the generalization performance. To enhance the learning performance of XGBoost, we extracted 31 wavelengths with fixed intensity thresholds from top to bottom at each reflection peak of the DD-SFBGs, which maximized the spectral information utilization. Model training was completed within 5 s using 100 boosting rounds. Further technical details are provided in Note S4.

Author Contributions

Zhuoda Li: Writing – original draft, Writing – review and editing, data curation, visualization, investigation, conceptualization, methodology, validation, software. **Zongwei Cai:** data curation, formal analysis, software, validation, writing – original draft. **Xizhen Xu:** conceptualization, methodology, investigation, project administration. **Runxiao Chen:** writing – review and editing, investigation, conceptualization, methodology. **Zhiwei Qin:** data curation, software, formal analysis, visualization. **Zhiyong Bai:** resources, methodology. **Zhiwei Lin:** funding acquisition, supervision, resources. **Yiping Wang:** resources, funding acquisition, supervision, project administration. **Jun He:** writing – review and editing, conceptualization, supervision, funding acquisition, visualization, resources, investigation, methodology, project administration.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting File: lpor71927-sup-0001-SuppMat.docx.