

Research Article

Distributed Fiberoptic Sensor for Simultaneous Temperature and Strain Monitoring Based on Brillouin Scattering Effect in Polyimide-Coated Fibers

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A unique multiparameter sensor for distributed measurement of temperature and strain based on spontaneous Brillouin scattering in polyimide-coated optical fiber is proposed, which is an excellent candidate for the cross-sensitivity problem in conventional Brillouin sensing network. In the experimental section, the discrimination of strain and temperature is successfully demonstrated by analysing the unequal sensing coefficients of the Brillouin frequency shifts generated by different acoustic modes. The Brillouin frequency shifts of the main two peaks are successfully measured to discriminate the strain and temperature with an accuracy $19.68 \mu\epsilon$ and 1.02°C in 2.5 km sensing range. The proposed distributed Brillouin optical fiber sensor allows simultaneous measurement of temperature and strain, thus opening a door for practical application such as oil explorations.

1. Introduction

Brillouin scattering is one of the most prominent optical effects. It has been broadly studied for several decades and gained rapid progress in pulse shaping (time domain and frequency domain) [1–5], the amplification of weak signals [6–8], and in distributed strain/temperature sensors in recent years [9, 10]. For the case of distributed fiberoptic sensing systems, Brillouin-based distributed sensors have been intensively investigated due to their extended distances up to hundreds of kilometres, high spatial resolution, and high accuracy. This makes Brillouin-based distributed fiberoptic sensors especially attractive for the structural health monitoring (SHM) of civil infrastructures, energy, or geophysical research such as bridges, nuclear facilities, tunnels, power cables, oil explorations, slopes, and others. To date, distributed sensing measurement systems based on Brillouin scattering effects have been previously realized using several techniques [11–14]: Brillouin optical correlation domain analysis (BOCDA), Brillouin optical frequency

domain analysis (BOFDA), Brillouin optical time domain analysis (BOTDA), Brillouin optical correlation domain reflectometry (BOCDR), Brillouin optical frequency domain reflectometry (BOFDR), and Brillouin optical time domain reflectometry (BOTDR). Among them, BOTDR is considered as one of the most promising techniques that can obtain distributed sensing information (e.g., temperature, strain, or vibrations) by single-end injection and random accessibility. Temperature and strain are the most common measurement parameters for Brillouin-based fiberoptic sensors, as these are the quantities to which the optical sensing fibers are inherently sensitive. However, the temperature and strain cross-sensitivity problem is easily deteriorating the sensing performance of the single-mode fiber- (SMF-) based Brillouin sensors. In order to address this cross-sensitivity problem effectively, many scholars have done a lot of research studies to accomplish the simultaneous measurement of temperature and strain. Some groups combine stimulated Brillouin scattering (SBS) with stimulated Raman scattering (SRS) to remove the joint crosstalk effects of multiple

external disturbances by comparing the difference [15]. Other groups combine SBS effect with the multicore optical fiber (MCF) to separate the temperature and strain information by analysing the Brillouin gain spectra (BGSs) in different fiber cores [16]. Obviously, as are mentioned above all, these techniques require rather complicated sensing structure.

On the other hand, Weng et al. [17] present a novel method based on multiple optical modes in the few-mode fiber (FMF) to realize the single-end simultaneous strain and temperature sensing. The FMF can contribute two BFSs at least. Xu et al. [18] propose a unique multiparameter fiberoptic sensor based on the stimulated scattering of higher order acoustic modes of orbital angular momentum- (OAM-) guiding fiber. The multippeak feature in the BGS of OAM guiding fiber is attributed to the couplings among the guided modes and acoustic modes. By selecting any two Brillouin peaks in BGS, the proposed method can be used to discriminate simultaneously temperature and strain along the fiber under test (FUT). As the laser sources usually work in the fundamental mode, it might add extra difficulties to convert the fundamental mode into the desired spatial mode. Sheng et al. [19] propose a novel technique based on the BOTDR scheme, which employs a large effective area nonzero dispersion-shifted fiber (LEAF) with four Brillouin peaks as the sensing fiber to solve the cross-sensitivity problem. Remarkably, most of the distributed fiberoptic sensor using Brillouin scattering is based on standard SMF with acrylate coating, which can sustain a maximum temperature of +85°C. This limited range is insufficient for many structural sensing applications. Meanwhile, the simultaneous distributed measurement of temperature and strain based on spontaneous Brillouin scattering (SpBS) effect in polyimide-coated optical fiber seems less reported.

In this work, we propose and experimentally report a novel BOTDR scheme, for what we believe to be the first time, which employs a polyimide-coated optical fiber with different temperature and strain coefficients in core as the sensing fiber to monitor the distributed temperature and strain simultaneously in harsh environments (maximum temperature of +300°C). This presented method needs only the measurement of Brillouin frequency shifts of the BGSs and can simultaneously achieve the high spatial resolution and accuracy of temperature and strain measurement without modifying the sensing FUT. In experiment, the sensitivities of the fundamental acoustic mode are 1.16 MHz/°C and 0.0646 MHz/ $\mu\epsilon$, respectively. Moreover, by analysing the temperature and strain coefficients of different acoustic modes, discrimination of temperature and strain are successfully demonstrated with a temperature measurement accuracy of 1.02°C and a strain measurement accuracy of 19.68 $\mu\epsilon$ in 2.5 km sensing range, which is about three times enhancement compared with the LEAF fiber-based method [19].

2. Theory

According to the previous experimental results [20], the multippeak structure in BGS of a sensing FUT originates from the different acoustic velocities V_a and optical refractive

indexes n , which are due to different compositions or doping concentrations in the core. It should be noted that V_a and n vary with temperature or strain. As a result, the BFSs of the main two peaks (peak 1 and peak 2) relating to strain change $\Delta\epsilon$ and temperature change ΔT are described as follows:

$$\Delta V_B^1 = C_\epsilon^1 \Delta\epsilon + C_T^1 \Delta T, \quad (1)$$

$$\Delta V_B^2 = C_\epsilon^2 \Delta\epsilon + C_T^2 \Delta T, \quad (2)$$

where ΔV_B^1 and ΔV_B^2 are the change of BFS contributed by the 1- and 2-order acoustic mode, respectively. C_ϵ^1 , C_ϵ^2 , C_T^1 , and C_T^2 represent the strain and temperature coefficients of the 1- and 2-order acoustic mode in the polyimide-coated optical fiber, respectively. Therefore, the changes in strain and temperature can be given by the following equations:

$$\Delta T = \frac{C_\epsilon^2 \Delta V_B^1 - C_\epsilon^1 \Delta V_B^2}{C_T^1 C_\epsilon^2 - C_T^2 C_\epsilon^1}, \quad (3)$$

$$\Delta\epsilon = \frac{C_T^1 \Delta V_B^2 - C_T^2 \Delta V_B^1}{C_T^1 C_\epsilon^2 - C_T^2 C_\epsilon^1}.$$

It is apparent that the proposed approach can be used to address the crosstalk problem along the length of the FUT link through the frequency analysis of the measured BGSs. Furthermore, error analysis for the measurement of temperature and strain is expressed as [21]

$$\delta T = \frac{|C_\epsilon^2| \delta V_B^1 + |C_\epsilon^1| \delta V_B^2}{|C_T^1 C_\epsilon^2 - C_T^2 C_\epsilon^1|}, \quad (4)$$

$$\delta\epsilon = \frac{|C_T^1| \delta V_B^2 + |C_T^2| \delta V_B^1}{|C_T^1 C_\epsilon^2 - C_T^2 C_\epsilon^1|}. \quad (5)$$

3. Experimental Setup

In order to demonstrate the capabilities of the proposed method, the experimental setup depicted in Figure 1 is assembled. The light source is a standard distributed feedback (DFB) laser. Nominal power is about 15 dBm with a vacuum emission wavelength of 1550 nm and linewidth close to 10 kHz. The output of a continuous wave laser is split into two branches by a 3 dB coupler (OC1). In the upper branch, the continuous light is shaped to a 30 ns Gaussian pulse by an electrooptic modulator (EOM1) with a 45 dB high extinction ratio (ER), which is driven by a waveform generator (AWG). The probe pulse width is 30 ns meaning that the spatial resolution is 3 m. Two polarization controllers (PC1 and PC2) are required just before the EOM1 and EOM2 to obtain the modulated output signal with good performance, respectively. After amplified by an erbium-doped fiber amplifier (EDFA), the Gaussian pulse is injected into the other end of the sensing FUT (YOFC, HT1510-B) through a circulator (CIR). The peak power of the Gaussian pulse can be conveniently controlled by means of a variable optical attenuator (VOA) to match the sensing range. The

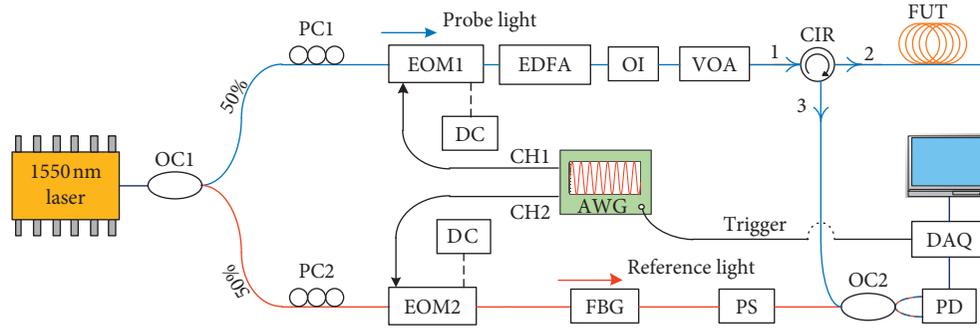


FIGURE 1: Experimental setup of polyimide-coated optical fiber-based BOTDR system. EOM, electro-optic modulator; EDFA, erbium-doped fiber amplifier; FUT, fiber under test; PC, polarization controller; AWG, arbitrary waveform generator; OI, optical isolator; PD, photodetector; FBG, fiber Bragg grating; VOA, variable optical attenuator; OC, optical coupler; DAQ, data acquisition card; CIR, circulator; and PS, polarization scrambler.

backscattered sensing signal is collected in the same access. The lower branch is used as the reference light. The reference light is modulated by EOM2 using the second channel (CH2) of AWG through a wide-band amplifier around zero-transmission bias point of the EOM2. As a result of this biasing, the carrier is suppressed at the optical output of the EOM2 and converted into two sidebands. The output of EOM2 is filtered by a fiber Bragg grating (FBG) with a 3 dB bandwidth of 0.4 nm to retain the lower sideband (Stokes component). Then, the reference light passes through a polarization scrambler (PS) and launches into one end of the polyimide-coated optical fiber. The polarization fading noise is avoided by the PS, which leads to higher signal-to-noise ratio (SNR), higher sampling rate, and simplified system configuration. Finally, the sensing signal of the back-scattered SpBS and the reference light are mixed by means of a 2×2 coupler (OC2), and then the beat light is collected by a balanced photodetector (PD) and a high-speed data acquisition (DAQ) card.

4. Experimental Results and Discussion

In the experiment, the loss coefficient of the used polyimide-coated optical fiber is measured. Figure 2 illustrates the relationship between the polyimide-coated optical fiber attenuation and the sensing range. It can be seen that the FUT consists of three segments with a total length of 2.5 km. Meanwhile, it has the feature with a loss coefficient of 0.76 dB/km, which is about 4.2 times attenuation compared with the SMF fiber (~ 0.18 dB/km). Therefore, it is worth mentioning that a 2.5 km sensing FUT is only used to demonstrate the sensing capability, and moreover, it is able to improve the sensing range up to dozens of kilometres with an elaborate light power.

To fully demonstrate the performance of the proposed BOTDR sensing system, temperature and strain measurements are performed by placing a part of the polyimide-coated optical fiber into a thermally insulated oven (DF/8700BS) to exert experimental temperature and fixing another segment of the sensing fiber to a pair of microstages (Zolix MC600) to change the environmental strains. Figure 3 highlights the measured multippeak BGS

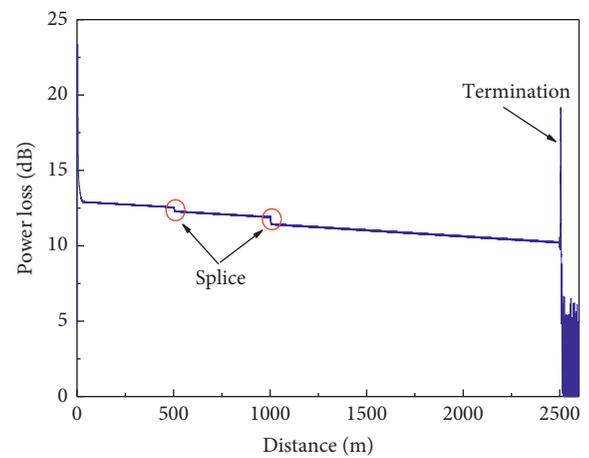


FIGURE 2: Measurement of polyimide-coated optical fiber attenuation as a function of distance.

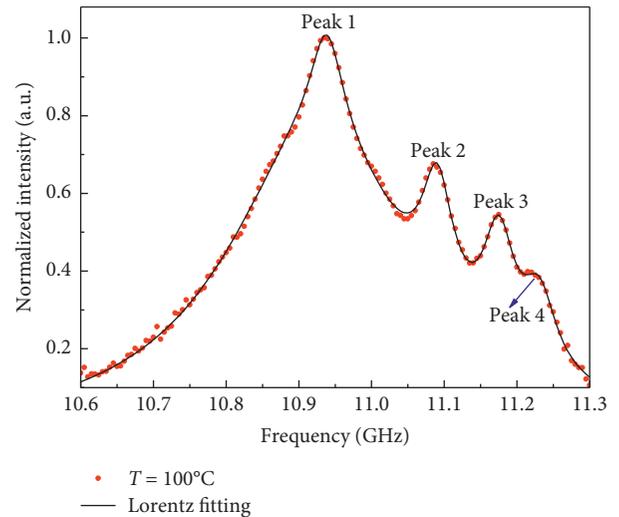


FIGURE 3: The measured Brillouin spectrum of polyimide-coated sensing fiber after Lorentz fitting under heated temperature of 100°C and strain of $0\ \mu\epsilon$.

at one position of the heated section when the environmental temperature is 100°C and exerted strain is

about $0\mu\epsilon$. As displayed in Figure 3, the measured Brillouin central frequencies of four peaks are 10.935 GHz, 11.085 GHz, 11.175 GHz, and 11.225 GHz for peak 1~peak 4, respectively. Therefore, the BFS of different Brillouin peaks in the polyimide-coated optical fiber can be obtained by measuring the BGS at different environmental strains and temperatures. As mentioned in Section 2, utilizing the polyimide-coated optical fiber with multiple peaks as sensing fiber, a distributed simultaneous temperature and strain measurement system can be realized, which is based on multiple acoustic modes in SpBS effect. Remarkably, we think it is possible to demodulate the strain and temperature with any two peaks, as introduced by equations (1) and (2). Here, peak 1 and peak 2 are chosen for high intensity, which is able to provide a high SNR. Therefore, the measurement error of discrimination can be reduced, so that the performance of the proposed fiberoptic sensor can be improved.

In order to effectively weaken the influence of the cross-sensitivity problem, namely, strain and temperature, the sensing location is free of strain and keep unchanged when monitoring the temperature coefficients, and vice versa. The length of the heated segment is about 4 m which is longer than the spatial resolution (3 m). This part of the FUT is put into the thermally insulated oven, and the temperature is increased from 100°C to 300°C with 20°C per step. Then, the relation between temperature and BFS in the polyimide-coated sensing fiber is plotted in Figure 4, where linear regression is performed to obtain temperature sensitivities, respectively. From the data, the temperature sensitivities of the BFS C_T^1 and C_T^2 are determined to be $1.16\text{ MHz}/^{\circ}\text{C}$ and $1.21\text{ MHz}/^{\circ}\text{C}$, respectively. Furthermore, it can be observed from Figure 4 that the BFS is changed when temperature changes and moves to the higher frequency as the temperature increases.

Subsequently, an experiment is carried out to measure the strain coefficients. The detailed measurement process of BGSs is the same as mentioned above. The axial strain is applied to the polyimide-coated optical fiber by gradually moving the linear stage with $200\mu\epsilon$ per step, and the stressed segment of the FUT is about 5 m. The measured experimental results of the FUT ($\sim 2.5\text{ km}$) through home-made BOTDR system at room temperature are shown in Figure 5. As expected, the BFSs show a strong dependence on the strain. The strain coefficients of the FUT are therefore measured to be $0.0646\text{ MHz}/\mu\epsilon$ and $0.0510\text{ MHz}/\mu\epsilon$, respectively. As the strain and temperature coefficients of the two main peaks contributed by different acoustic modes are different from each other, the influence of strain and temperature on the FUT can be simultaneously discriminated. At the same time, the measurement accuracy of temperature and strain discrimination is calculated by solving equations (4) and (5). The respective errors of strain and temperature using experimental results in Figures 4 and 5 are calculated to be 1.02°C and $19.68\mu\epsilon$.

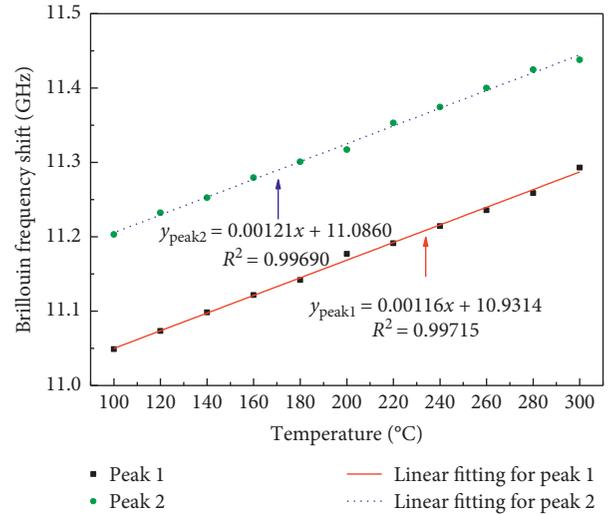


FIGURE 4: Measurement of Brillouin frequency shift as a function of temperature for peak 1 and peak 2.

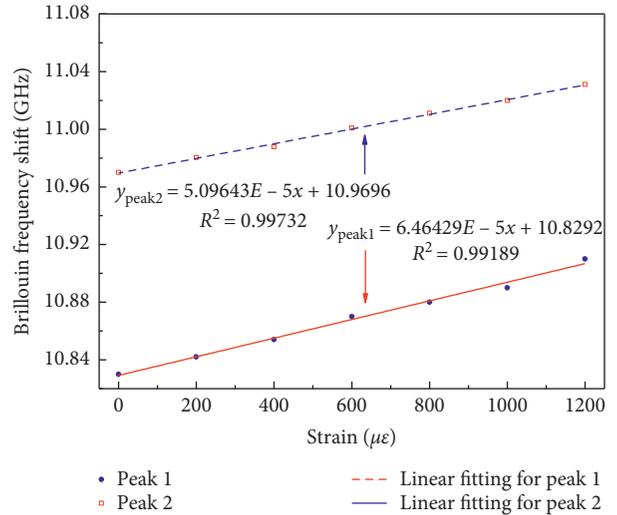


FIGURE 5: Measurement of Brillouin frequency shift as a function of strain for peak 1 and peak 2.

5. Conclusions

In conclusion, a method to accomplish simultaneously the distributed measurement of temperature and strain is proposed, which is based on a polyimide-coated optical fiber having multiple acoustic modes with different temperature and strain coefficients in SpBS effect. As a result, the simultaneous discrimination of temperature and strain is successfully demonstrated by analysing the coefficients of the BFSs introduced by different acoustic modes with a temperature accuracy of 1.02°C and a strain accuracy of $19.68\mu\epsilon$ in 2.5 km sensing range. With the help of this presented technique and experimental setup, some promising work can be also made in nuclear facilities and oil explorations in the future. In addition, through rational choice of more than two peaks in the BGS, the proposed

approach would be potentially applicable in situations where more than two parameters are needed to be distinguished.

Data Availability

The data used to support the findings of this study have not been made available because our group is a confidential unit, and the experimental data are mainly used for the development of related instruments.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

- [1] Z. Bai, H. Yuan, Z. Liu et al., "Stimulated Brillouin scattering materials, experimental design and applications: a review," *Optical Materials*, vol. 75, pp. 626–645, 2018.
- [2] Z. X. Bai, Y. L. Wang, Z. H. Liu et al., "Demonstration of an ultraviolet stimulated Brillouin scattering pulse compressed hundred picosecond laser in LiB_3O_5 crystals," *Journal of Optics*, vol. 19, no. 8, Article ID 085502, 2017.
- [3] E. Garmire, "Stimulated Brillouin review: invented 50 years ago and applied today," *International Journal of Optics*, vol. 2018, Article ID 2459501, 2018.
- [4] Z. Bai, Y. Wang, Z. Lu et al., "High compact, high quality single longitudinal mode hundred picosecond laser based on stimulated Brillouin scattering pulse compression," *Applied Sciences*, vol. 6, no. 1, p. 29, 2016.
- [5] Z. X. Bai, R. J. Williams, O. Kitzler et al., "Diamond Brillouin laser in the visible," *APL Photonics*, vol. 5, no. 3, Article ID 031301, 2020.
- [6] L. Sheng, D. Ba, and Z. Lu, "Low-noise and high-gain of stimulated Brillouin amplification via orbital angular momentum mode division filtering," *Applied Optics*, vol. 58, no. 1, pp. 147–151, 2019.
- [7] L. W. Sheng, D. X. Ba, and Z. W. Lu, "Weak laser pulse signal amplification based on a fiber Brillouin amplifier," *Chinese Optics Letters*, vol. 16, no. 11, Article ID 111901, 2018.
- [8] L. Sheng, D. Ba, and Z. Lu, "Imaging enhancement based on stimulated Brillouin amplification in optical fiber," *Optics Express*, vol. 27, no. 8, pp. 10974–10980, 2019.
- [9] X. Bao and L. Chen, "Recent progress in Brillouin scattering based fiber sensors," *Sensors*, vol. 11, no. 4, pp. 4152–4187, 2011.
- [10] X. Bao and L. Chen, "Recent progress in distributed fiber optic sensors," *Sensors*, vol. 12, no. 7, pp. 8601–8639, 2012.
- [11] D. Ba, Y. Li, J. Yan, X. Zhang, and Y. Dong, "Phase-coded Brillouin optical correlation domain analysis with 2-mm resolution based on phase-shift keying," *Optics Express*, vol. 27, no. 25, pp. 36197–36205, 2019.
- [12] D. W. Zhou, Y. K. Dong, B. Z. Wang et al., "Single-shot BOTDA based on an optical chirp chain probe wave for distributed ultrafast measurement," *Light: Science & Applications*, vol. 7, no. 1, p. 32, 2018.
- [13] Y. Mizuno, W. Zou, Z. He, and K. Hotate, "Proposal of Brillouin optical correlation-domain reflectometry (BOCDR)," *Optics Express*, vol. 16, no. 16, pp. 12148–12153, 2008.
- [14] Y. Koyamada, Y. Sakairi, N. Takeuchi, and S. Adachi, "Novel technique to improve spatial resolution in Brillouin optical time-domain reflectometry," *IEEE Photonics Technology Letters*, vol. 19, no. 23, pp. 1910–1912, 2007.
- [15] Z. Zhao, Y. Dang, M. Tang et al., "Spatial-division multiplexed hybrid Raman and Brillouin optical time-domain reflectometry based on multi-core fiber," *Optics Express*, vol. 24, no. 22, pp. 25111–25118, 2016.
- [16] Y. Mizuno, N. Hayashi, H. Tanaka, Y. Wada, and K. Nakamura, "Brillouin scattering in multi-core optical fibers for sensing applications," *Scientific Reports*, vol. 5, no. 1, Article ID 11388, 2015.
- [17] Y. Weng, E. Ip, Z. Pan, and T. Wang, "Single-end simultaneous temperature and strain sensing techniques based on Brillouin optical time domain reflectometry in few-mode fibers," *Optics Express*, vol. 23, no. 7, pp. 9024–9039, 2015.
- [18] Y. P. Xu, M. Q. Ren, Y. Lu, P. Lu, X. Y. Bao, and S. Laroche, "Multi-parameter sensing based on the stimulated Brillouin scattering of higher-order acoustic modes in OAM fiber," in *Proceedings of the 24th International Conference on Optical Fibre Sensors*, Curitiba, Brazil, September 2015.
- [19] L. Sheng, L. Li, L. Liu, L. Hu, M. Yuan, and J. Yan, "Study on the simultaneous distributed measurement of temperature and strain based on Brillouin scattering in dispersion-shifted fiber," *OSA Continuum*, vol. 3, no. 8, pp. 2078–2085, 2020.
- [20] T. R. Parker, M. Farhadiroushan, V. A. Handerek, and A. J. Roger, "A fully distributed simultaneous strain and temperature sensor using spontaneous Brillouin backscatter," *IEEE Photonics Technology Letters*, vol. 9, no. 7, pp. 979–981, 1997.
- [21] W. Jin, W. C. Michie, G. Thursby, M. Konstantaki, and B. Culshaw, "Simultaneous measurement of strain and temperature: error analysis," *Optical Engineering*, vol. 36, no. 2, pp. 598–609, 1997.