

Quasi-Distributed Hybrid Interferometric and Fiber Bragg Grating Sensing System Enabled by an Ultra-Broadband Bi/Er Co-Doped Fiber Source

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Abstract: Quasi-distributed smart sensing systems using fiber Bragg grating arrays have found many practical applications in structure health, electricity grid, aerospace, etc. However, the broadband light sources used for the sensing system are generally constrained to the telecom C-band, limiting the available number of sensors, hence hindering deployment of massive sensing heads for the next generation of Internet of Things (IoT) and integrated sensing and communication. Here, we demonstrate a hybrid sensing system enabled by an ultra-broadband Bi/Er co-doped fiber (BEDF) light source pumped at 830 nm. Leveraging the global excitation capability of the $\lambda=830$ nm pump, the source provides an unprecedented operating bandwidth spanning from O- to L-bands. Quasi-distributed sensing of the temperature and strain for 21 spatially separated nodes is demonstrated using the single BEDF-based Mach-Zehnder interferometer and 20 fiber Bragg gratings. Our proof of the principle system exhibits the maximum temperature sensitivity of 56 pm/°C and maximum strain sensitivity of 0.9 pm/ $\mu\epsilon$. To address the issue of the colored noise measured across the spectrum arising from the source itself due to different contributions of varying environmentally sensitive defects responsible for Bi emission, not present in the Er component, we propose the use of data-driven statistical learning methods to quantitatively characterize and mitigate the measurement uncertainties that limit their applicability in precision sensing. Specifically, an adaptive residual bootstrap strategy for uncertainty quantification is used here for the first time,

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providing a more accurate evaluation of system uncertainty than the conventional normal distribution analysis. The system achieves measurement uncertainties of less than 4.1% for the temperature and 6.4% for the strain. Overall, the proposed sensing system has the huge potential for practical applications in large-scale structural health monitoring, the IoT, etc.

Keywords: Quasi-distributed sensing; Bi/Er co-doped fiber; fiber Bragg grating; dual-parameter measurement

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1. Introduction

The temperature and strain are critical physical parameters that require precise monitoring in fields such as precision manufacturing, smart healthcare, and aerospace [1]. Variations of these parameters directly impact the material and structural stability, device performance, and system reliability. For example, in the industrial infrastructure and biomedical systems, even minor temperature variations or strain accumulation may indicate potential failure, underscoring the importance of accurate multi-parameter monitoring [2]. In practical engineering applications, such sensing often needs to cover multiple spatial locations and provide real-time responses. Driven by these demands, quasi-distributed fiber sensing systems supporting Internet of Things (IoT) applications have become indispensable [3].

Characterized by their unique spectral precision features, fiber Bragg gratings (FBGs) have become the most commonly used sensing elements where a broadband light source is normally utilized for signal excitation [4]. Broadband sources are preferred over wavelength swept sources for the broader spectral coverage, cost, and reliability. Moreover, integration of other types of fiber interferometers within FBG arrays can further enhance sensing performance for multi-parameter monitoring [5]. Over the recent years, considerable efforts have been devoted to improving conventional C+L-band FBG sensing array systems to increase the sensing capacity and reduce the crosstalk,

including optimizing the source bandwidth, grating linewidth, and multiplexing schemes [6–8]. These approaches have enabled arrays containing up to tens of FBGs with the improved signal-to-noise ratio (SNR), but their number remains limited in most cases by the commonly used telecoms window. Beyond this window, O-band FBG arrays have also been reported for high-temperature sensing [9]. However, issues such as bandwidth mismatch and modal interference presently limit their practicality. Meanwhile, although continuous efforts have been made to enhance array performance and multiplexing techniques in the C+L-band, the available physical bandwidth remains inherently limited. Therefore, even with advanced algorithms and optimized device parameters, it is still difficult to accommodate future high-density sensing networks comprising hundreds or even thousands of nodes. This challenge becomes more pronounced as applications demand the higher scale, accuracy, and real-time performance utilizing the broader spectrum, making a single C+L-band solution inadequate. To address this limitation, it is essential to develop broadband gain fibers and corresponding light sources extending to all low-loss fiber transmission bands including O-, E-, S-, and U-bands.

Among various gain fibers, Bi/Er co-doped fibers (BEDFs) have attracted considerable attention for their near-infrared emission spanning from the O- to U-bands [10]. BEDF-based sources are ideal for broadening the bandwidth and improving the scalability of both telecom and optical fiber sensing systems. This ultra-broadband spectrum arises from

multiple defect site contributions of mostly exposed d equivalent electrons coupled with Bi related defects. The exact nature of these defects remains debated and it is known they are not environmentally shielded when compared to the f-f transitions of rare earth ions such as Er^{3+} operating in the telecom C-band window centered around $\lambda=1\,520\text{ nm}$ and $\lambda=1\,550\text{ nm}$. This means that at least two parts of the emission spectra of these fibers – the Er- and Bi-related parts – differ substantially in response to environmental parameters, such as the temperature and strain, and have correspondingly large differences in noise. This generates the colored noise instead of the typical white noise associated with standard erbium-based sources alone. Such complexity is further exacerbated when the gain medium is subject to incomplete or imbalanced excitation, leading to localized fluctuations across the spectrum. Moreover, the choice of the pump wavelength fundamentally dictates the excitation efficiency across different active centers; a mismatch in absorption cross-sections can result in insufficient amplified spontaneous emission (ASE) intensity to overcome system insertion losses, thereby critically degrading the sensing SNR. The severe source noise can overwhelm the measured signal, precluding the practical use of Bi-based sources. Moreover, extending the sensing range across the BEDF spectrum amplifies the source noise, complicating uncertainty quantification [11]. Given that there is a relationship among the accessible electronic excitation, bandwidth, and noise, the challenge remains bedeviling and materially unresolved. Therefore, identifying an optimal pumping scheme to stabilize the spectral output, maximize emission intensity, and suppress intrinsic noise is critical. Achieving this is key to unlocking the practical potential of BEDF-based sources as reliable workhorses for next-generation and high-capacity multiplexed sensing systems.

Previously [12], we investigated the sensitivity enhancement of a BEDF-based Mach-Zehnder interferometer (MZI) sensor using gamma irradiation. This sensor demonstrates excellent temperature sensitivity. However, the BEDF-based ultra-broadband sensing system for wavelength-division multiplexing remains unexplored.

Specifically, an FBG array is integrated with a newly developed BEDF source [13] to realize a quasi-distributed, if noisy, sensing system. Our BEDF light source overcomes the C+L-band limitation and expands the optical operating bandwidth to the O-, E-, and S-bands. While the non-flat and complex emission profile of the BEDF poses additional practical challenges regarding varying resolution and noise across the entire spectrum, these are mitigated by optimizing the diode pumping configuration to ensure spectral uniformity. Importantly, the system accuracy and scalability can only be improved if the noise can be mitigated across sensing nodes. This is done by using statistical learning (SL) [14] to tailor noise suppression over each emission band through the novel application of an adaptive residual bootstrap strategy for uncertainty quantification (ARB-UQ). This is the first time that a non-parametric bootstrap is applied in an optical fiber sensing system to assess signal measurement uncertainty. The results show strong consistency with experimental data, confirming the robustness of the proposed sensing system and opening up a new era of amplifiers and sources that are no longer constrained by material noise properties. For sensing, this extension is estimated to enable simultaneous support for at least 166 FBGs in dual-parameter sensing configurations. Such advances can relieve the sensor network capacity bottlenecks and suppress crosstalk, thus providing a feasible path toward ultra-large-scale sensing networks.

2. Experimental results

2.1 Ultra-broadband BEDF source

Figure 1 presents the comprehensive experimental results, comparing BEDF emission characteristics and the response of an MZI under five distinct pump wavelengths: 830 nm, 1 178 nm, 1 240 nm, 1 270 nm, and 1 310 nm. All experiments are conducted in a forward-pumping setup. A spectrum analyzer (AQ6370D, Japan, with the resolution $\Delta\lambda=2$ nm) is used to record the optical spectra. This resolution is specifically selected to achieve an optimal balance between the spectral resolution and SNR across the 1 050 nm–1 650 nm range. This ensures the most effective presentation of the global ASE envelope while maintaining high scanning efficiency. These results confirm that the pump photon energy determines not only the activation efficiency of luminescent centers but also fundamentally governs the SNR and temporal stability of the sensing system. Spectral analysis initially reveals the prominent capability of the $\lambda=830$ nm pump in constructing an ultra-broadband source. Its high-energy photons simultaneously satisfy the ground-state absorption energy requirements of Al-related bismuth active centers (BAC-Al), Si-related bismuth active centers (BAC-Si), and Er^{3+} . This facilitates synergistic activation across the full λ of the 1 050 nm–1 650 nm band. In contrast, longer wavelength pumps, such as $\lambda=1$ 310 nm, exhibit a significant reduction in single-photon energy. Following the $E=hc/\lambda$ relationship, the energy drops from $E\sim 1.49$ eV at $\lambda=830$ nm to $E\sim 0.95$ eV at $\lambda=1$ 310 nm. This energy falls strictly below the bandgap excitation threshold of BAC-Al. Consequently, short-wave emission in the λ of the 1 100 nm–1 250 nm range is completely quenched. These results confirm that the excitation of specific bismuth active centers depends fundamentally on the pump photon energy matching the intrinsic

electronic transition thresholds. It is worth noting that the ASE spectrum for the $\lambda=830$ nm pump shown in Fig. 1(a) is obtained under restricted experimental conditions: only 100 mW of pump power and a 1 m fiber length. This stands in contrast to the other wavelengths, which utilize the high power of 700 mW and a 10 m fiber length. Furthermore, the intensity dip observed at $\lambda\sim 1$ 380 nm is attributed primarily to the strong absorption by residual hydroxyl groups ($-\text{OH}$) in the silica matrix, rather than an intrinsic lack of emission. Regardless of these constraints, the source pumped at 830 nm demonstrates its robustness as a high-quality interference source through its continuous full-spectrum coverage. Notably, despite its ultra-broadband nature, the generated light maintains high spatial coherence, as the entire spectrum remains single-mode within the BEDF.

Before integrating the source into the sensing system, we introduced the difference between residual pump power and ASE peak power as a tracking metric. This allows precise evaluation of the intrinsic stability of the gain medium, independent of pump source power fluctuations. The calculations indicate an average signal (gain) fluctuation of less than ~ 0.12 dB over a 300 minute period [Fig. 1(c)]. This low-level fluctuation confirms that the pump absorption rate and energy transfer efficiency within the fiber remain nearly constant, even under sustained excitation.

Building on this superior stability and its spatial fundamental mode characteristic, we evaluate the MZI performance [Fig. 1(d)]. The $\lambda=830$ nm pump demonstrates a clear advantage, yielding the highest average extinction ratio (ER) of 1.37 dB and the lowest root mean square (RMS) noise of 10.6. In contrast, the RMS noise levels for the $\lambda=1$ 240 nm, $\lambda=1$ 270 nm, and $\lambda=1$ 310 nm pumps are significantly higher, at 68.2, 59.4, and 60.6, respectively. This discrepancy is primarily due to the

spectral spikes appearing in regions of low ASE intensity, where a degraded SNR introduces random power fluctuations that inflate the RMS noise. Furthermore, no effective interference is observed under $\lambda=1\,178\text{ nm}$ pumping, as the wavelength falls within the BEDF's absorption valley, resulting in an excitation efficiency too low to overcome the MZI's insertion loss. The superior low-noise performance under $\lambda=830\text{ nm}$ pumping is fundamentally rooted in the photon statistical properties of the broadband ASE source [15]. According to ASE noise theory, a dominant noise source is the spontaneous-spontaneous beat noise [16]. The power spectral density of this noise is inversely proportional to the effective optical bandwidth. A broader bandwidth therefore directly leads to a lower relative intensity noise (RIN). The $\lambda=830\text{ nm}$ pump excites an ultrabroad spectrum covering O- to L-bands. This implies the existence of a massive number of independent optical frequency components. The effective optical bandwidth is determined by this number, which provides the

physical basis for averaging a large number of independent noise contributions. The random beating between these components results in a net suppression of the total relative intensity fluctuation [17]. This noise suppression, together with the high output power of the ASE, enables an enhancement in the system SNR while maintaining a high extinction ratio. Conversely, the narrow-band emission and spectral fragmentation associated with long-wavelength pumping limit the effective bandwidth available for this noise averaging mechanism. Furthermore, incomplete population inversion under long-wavelength pumping results in spectral narrowing and elevated relative intensity noise of the ASE. These effects manifest as intensified intensity fluctuations of incoherent photons, ultimately leading to a significant deterioration of system noise performance. In summary, the $\lambda=830\text{ nm}$ pumping scheme is confirmed as the optimal light source choice based on the BEDF for high-capacity, high-SNR quasi-distributed fiber sensing systems.

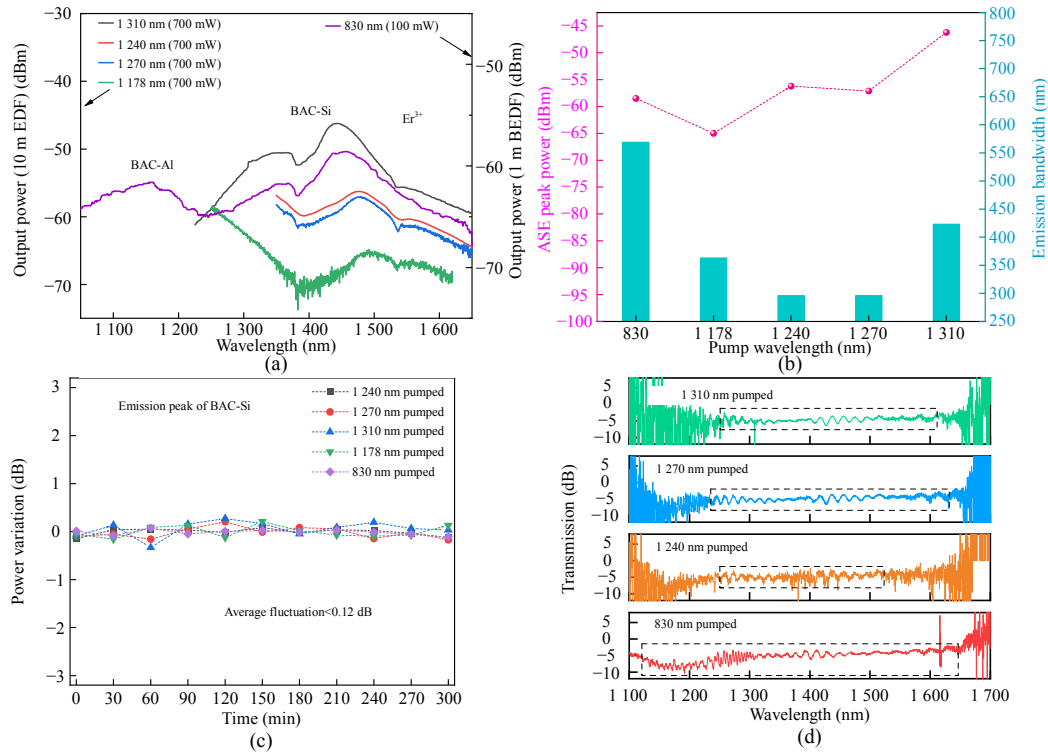


Fig. 1 Characterization of the BEDF-based ASE source: (a) ASE spectra under different pump wavelengths, (b) comparison of the ASE peak power and bandwidth, (c) temporal power stability, and (d) BEDF MZI spectra.

2.2 System configuration

The proposed quasi-distributed sensing system is shown in Fig. 2. A $\lambda=830$ nm laser is used to pump the long BEDF (ultra-broadband source), providing broadband emission for the sensor array. The sensor array consists of one BEDF MZI and two FBGs. The MZI is an in-line modal interferometer [single-mode fiber (SMF)-BEDF-SMF] that utilizes the phase difference between core and cladding modes. It is highly sensitive to the temperature due to the significant thermo-optic effect of the BEDF, while remaining insensitive to the strain because the physical elongation and photo-elastic effect effectively compensate for each other in this thin-diameter fiber structure. Detailed characterization of the BEDF source, as well as the MZI's operating principles and sensitivity enhancement via gamma irradiation, can be found in [12]. Specifically, FBG1 has a central wavelength of $\lambda \sim 1530$ nm with a full width at half maximum (FWHM) of 0.21 nm, and FBG2 has a central wavelength of $\lambda \sim 1465$ nm with an FWHM of 0.22 nm. Both FBGs exhibit a reflectivity of $R \geq 90\%$ and a length of 10 mm. The system spectrum is recorded using an optical spectrum analyzer (OSA, Agilent 86141B, USA) with a resolution bandwidth of 1.0 nm. The MZI, FBG1, and FBG2 are placed at different positions on the hot plate, forming a quasi-distributed sensing structure. The hot plate has dimensions of $x \times y = 200 \text{ mm} \times 180 \text{ mm}$. The MZI and FBG1 are placed close to each other on the hot plate to minimize errors caused by the temperature non-uniformity. Given the inherent non-uniformity of the hot plate's temperature field and the wide spacing between the sensors, this configuration effectively simulates a realistic quasi-distributed sensing environment. The strain in the sensor array is controlled by regulating the displacement of the 3-dimensional (3D) positioner. Importantly, FBG2 serves as a reference sensor, which is unaffected by the strain.

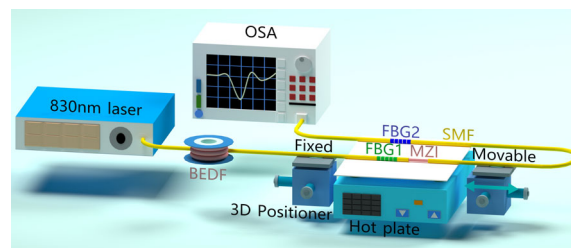


Fig. 2 Experimental setup: an 830 nm pump laser is coupled to a section of the BEDF. The sensor array, consisting of an MZI and two FBGs connected via the SMF, is mounted on a hot plate and a 3D micro-positioning stage for the thermal and strain characterization. The output signal is monitored by an OSA.

Firstly, we conduct response tests of the sensors to a single environmental variable. The sensitivity is determined based on the spectral peak shifts of the FBGs [18] and MZI [19]. The temperature is scanned from 135 °C to the room temperature (25 °C). To ensure data reliability, a sufficient dwell time is maintained at each measurement point for the thermal and mechanical equilibrium, with conditions verified by an external thermometer and force gauge to avoid potential inaccuracies in the built-in readouts. According to the spectra in Fig. 3(a), all three sensors experience independent and stable blue shifts in their spectral dips. However, we observe superimposed high-frequency ripples on the main spectral profile. This phenomenon is not due to the source instability, but rather originates from the core mode mismatch (diameter difference is $\sim 3.7 \mu\text{m}$) between the FBG (Hi 1060, China) and the single-mode fiber (Corning SMF28, USA), which leads to the excitation of weak parasitic interferences. To address this geometric artifact and extract the fundamental spectral features, a fast Fourier transform (FFT) low-pass filter [20] with a cut-off frequency of 0.35 Hz is applied. Building upon this, we analyze the sensor's response sensitivity based on the spectral variations. As shown in Fig. 3(b), the measured sensitivity is 13 pm/°C and 11 pm/°C for FBG1 and FBG2, respectively, and 56 pm/°C for the MZI sensor. The strain sensing spectra with dip markers for each sensor are shown in Fig. 3(c). The applied strain is adjusted from 80.1 $\mu\epsilon$ to 1466.3 $\mu\epsilon$. As no strain is applied to FBG2, its dip remains unchanged. Both

the MZI sensor and FBG1 are subjected to the same strain. However, the MZI sensor almost shows no spectral shift due to its insensitivity to the strain. In contrast, FBG1 shows clear wavelength shifts toward longer wavelengths as the strain increases.

Its strain sensitivity is measured to be $0.9 \text{ pm}/\mu\epsilon$, with the corresponding R^2 value shown in Fig. 3(d). These findings demonstrate the feasibility of a quasi-distributed multi-sensor multiplexing system.

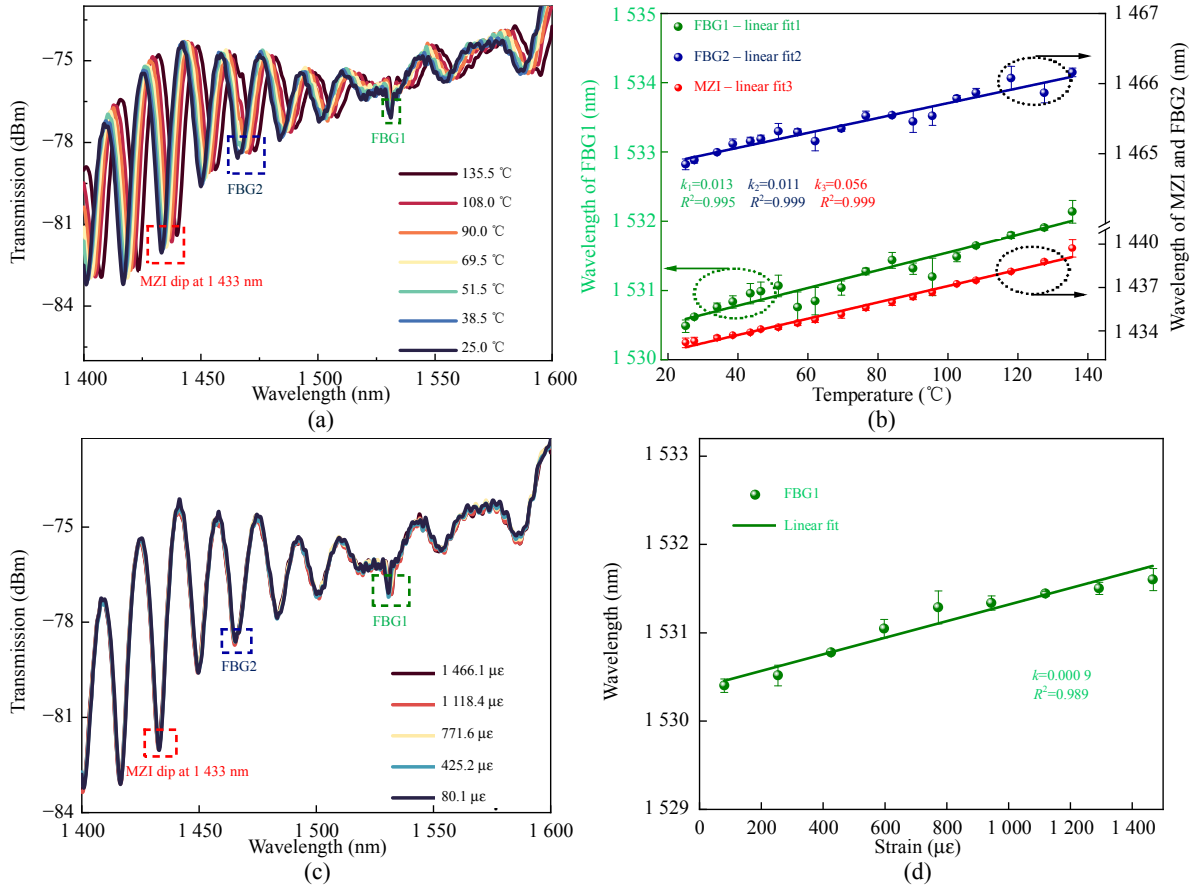


Fig. 3 Spectral responses and sensitivity characterization: (a) temperature sensing spectra, (b) temperature sensitivity, (c) strain sensing spectra, and (d) strain sensitivity.

2.3 Simultaneous dual-parameter sensing

The response sensitivity of each sensor is a critical parameter for constructing the decoupling matrix [14]. Consequently, repeatability tests are conducted under the same experimental conditions as the initial calibration. The second set of temperature sensitivity measurement yields values of $55 \text{ pm}/^\circ\text{C}$ for the MZI, $12 \text{ pm}/^\circ\text{C}$ for FBG1, and $11 \text{ pm}/^\circ\text{C}$ for FBG2. These results represent relative errors of 1.8%, 7.6%, and less than 0.1%, respectively, compared to the first calibration. Furthermore, the second strain sensitivity

measurement for FBG1 is $0.9 \text{ pm}/\mu\epsilon$, which remains highly consistent with the initial results, exhibiting a negligible relative error. Overall, each sensor exhibits a small relative error between two tests, demonstrating the good repeatability of the proposed quasi-distributed system. Therefore, either set of sensitivity results can be used to construct the decoupling matrix. To ensure consistency and standardization in data processing, the sensitivity values from the first calibration are used in all subsequent analyses. Specifically, (1) is the inverse decoupling matrix derived from the sensitivity for parameter demodulation. While the MZI is

insensitive to the strain, all coefficients in the inverse matrix are utilized to simultaneously extract temperature and strain variations from the measured spectral shifts. Equation (1) is formulated using the MZI sensor and FBG1, based on their respective sensitivity to the temperature and strain:

$$\begin{bmatrix} \Delta\epsilon \\ \Delta T \end{bmatrix} = \begin{bmatrix} -0.258 & 1.111 \\ 0.017 & 0.000 \end{bmatrix} \begin{bmatrix} \Delta\lambda_{\text{MZI}} \\ \Delta\lambda_{\text{FBG1}} \end{bmatrix} \quad (1)$$

where ΔT is the change in the temperature, $\Delta\epsilon$ is the change in the strain, $\Delta\lambda_{\text{MZI}}$ is the shift in the spectral peak of the MZI, and $\Delta\lambda_{\text{FBG1}}$ is the shift in the spectral peak of FBG1. Similarly, (2) is derived using FBG1 and FBG2:

$$\begin{bmatrix} \Delta\epsilon \\ \Delta T \end{bmatrix} = \begin{bmatrix} -1.313 & 1.111 \\ 0.090 & 0.000 \end{bmatrix} \begin{bmatrix} \Delta\lambda_{\text{FBG2}} \\ \Delta\lambda_{\text{FBG1}} \end{bmatrix}. \quad (2)$$

Using (1) and (2), the simultaneous measurement of the temperature and strain is achieved in a quasi-distributed manner. The environmental conditions for the temperature and strain are varied from 143.5 °C to 21.0 °C and from 1 466.3 $\mu\epsilon$ to 80.1 $\mu\epsilon$, respectively. Seventeen sets of data are recorded, and representative spectra are shown in Fig. 4. In this case, the MZI sensor exhibits the largest spectral shift, due to its higher sensitivity to the temperature. Additionally, FBG1 shows a larger spectral shift than FBG2, resulted from the combined effect of the temperature and strain, and FBG2 is only affected by the temperature.

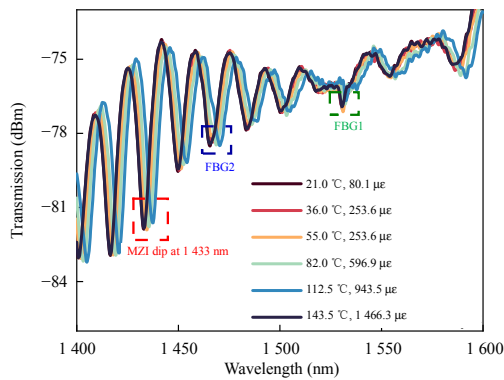
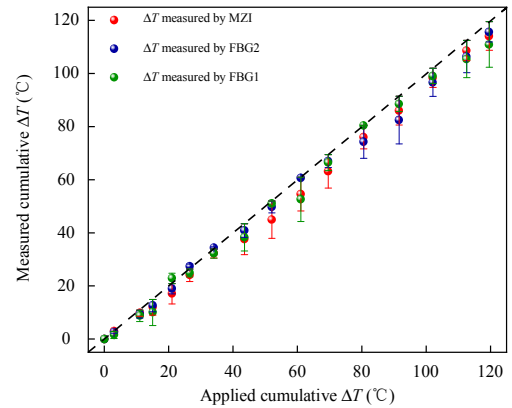


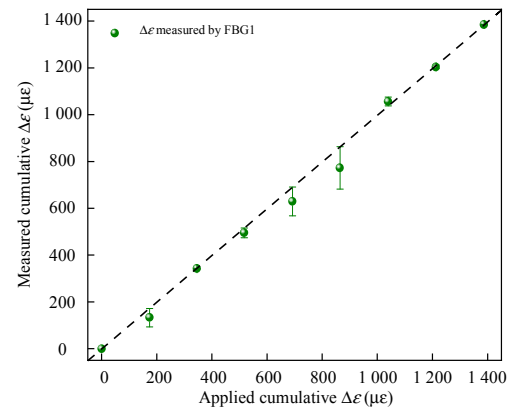
Fig. 4 Spectra for simultaneous dual-parameter sensing.

Figure 5 illustrates the relationship between the

applied and measured values, with black reference lines indicating their deviations. It is observed that the measured values are consistently lower than the applied values. For temperature measurement, the root mean square errors (RMSEs) of the MZI sensor, FBG1, and FBG2 are 4.3 °C, 4.2 °C, and 3.7 °C, respectively, while the RMSE for FBG1 strain measurement is 33.9 $\mu\epsilon$. These discrepancies are primarily attributed to experimental limitations, such as the non-uniform thermal distribution across the heating plate, instrument resolution, and mechanical friction. Additionally, despite the significant reduction in RIN of the ASE source achieved by $\lambda=830$ nm pumping (Section 2.1), the inherent non-flat spectral characteristics of the BEDF continue to introduce the non-Gaussian noise during the sensing process. To accurately quantify this effect, advanced uncertainty quantification methods beyond conventional approaches are required.



(a)



(b)

Fig. 5 Analysis of sensing performance: (a) measured ΔT vs. applied ΔT and (b) measured $\Delta\epsilon$ vs. applied $\Delta\epsilon$.

2.4 Simultaneous dual-parameter sensing

Uncertainty analysis is crucial for evaluating the performance of fiber sensing systems. Conventionally, the normal distribution-based method is used to quantify the measurement uncertainty, particularly for estimating sensor errors and constructing prediction intervals (PIs) [11]. It is typically applied to a uniform error commonly associated with the linear uniform error for each contribution to the measurement deviation, generating an effective white noise for which statistical distributions are characterized by the normal or Poisson standard deviation profile. For optical source applications, the underlying assumption is that the source emitter involves usually a single electronic transition that has a Gaussian emission profile. However, this method is not applicable to complex or composite emitters such as the BEDF. This can be made worse when multiple sensors are used across networks and so the method is generally not suitable for distributed sensing networks [11]. To evaluate the stability and reliability of the fiber-optic sensing system, a data-driven SL approach based on ARB-UQ is proposed to overcome this challenge.

Bootstrapping has been used to estimate the accuracy of uncertainty arising from various models, bootstrapping off each, so to speak, as it converges to a particular uncertainty [21]. Although direct bootstrapping is not accurate on its own, its calibration using a reference value improves the accuracy, making it useful. Here, an experimental equivalent applied to data sets generated by an ensemble of experimental methods and measurement along a networked sensing optical fiber is proposed. The sensors act as self-calibrating controls to address accuracy limitations in measured data for direct dataset bootstrapping. In both the MZI and FBG cases, the asymmetry is assumed to predominantly arise from variations in the amplified spontaneous emission spectrum of the BEDF source

across different wavelengths. However, the key difference is that the MZI is continuous along the fiber and the FBGs are point sensors, suggesting that the same applied analysis may produce different levels of uncertainty.

Therefore, the constructed empirical distribution is derived from the residuals obtained during the experimental MZI and FBG measurement. Based on a non-parametric bootstrap, the method generates multiple resampled datasets to estimate and predict the uncertainty range of the system error. Unlike the conventional non-parametric bootstrapping, the resampling process employs a quantile convergence criterion to dynamically control the number of iterations. This control avoids overfitting or redundant computation and improves the efficiency and stability of the estimation. Finally, the prediction interval coverage probability (PICP) [22] metric, which measures how well the predictions fall within the formulated PI, is used for posterior validation. This metric quantifies the uncertainty in the main model's predictions and provides a basis for evaluating overall system performance. By contrast, ARB-UQ avoids distributional assumptions and is driven by experimental residual data. This approach enhances the uncertainty quantification of prediction results without altering the original model structure. It also offered good applicability and ease of system integration.

The framework of ARB-UQ used is illustrated in Fig. 6, where $q_{\alpha/2}^{(B)}$ and $q_{1-\alpha/2}^{(B)}$ represent the lower and upper quantiles of the bootstrap predictions, and ε denotes a small tolerance for convergence. Using the data in Fig. 5, 11 025 bootstrap resamples are performed to calculate the confidence intervals (CIs) and PIs for each sensor [22]. For comparison, a parallel analysis is conducted using the conventional normal distribution (ND) method. As shown in Table 1, the ARB-UQ method produces narrower CIs and PIs, indicating the higher estimation efficiency and greater precision.

The intervals estimated by the ARB-UQ method closely matches the actual measurement

(Fig. 5), with a slight tendency toward underestimation.

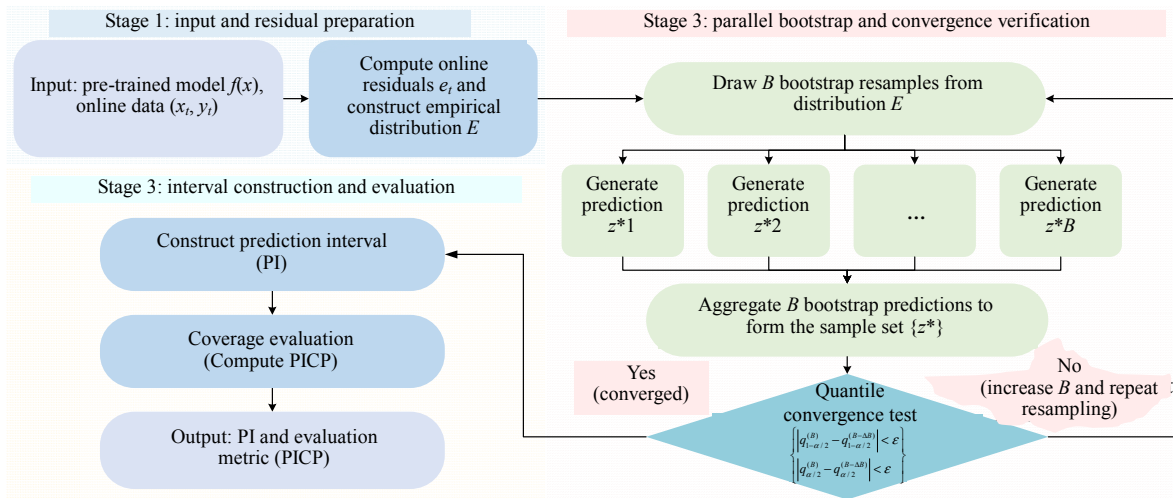


Fig. 6 Data-driven SL framework for ARB-UQ.

Table 1 Uncertainty analysis of sensors.

Sensing parameter	ARB-UQ method		ND method	
	CI	PI	CI	PI
Temperature measured by MZI	(−13.5%, −6.5%)	(−15.4%, 1.1%)	(−14.2%, 1.2%)	(−15.5%, 2.7%)
Temperature measured by FBG1	(−9.6%, −3.8%)	(−12.4%, 3.3%)	(−14.3%, 4.0%)	(−15.7%, 5.4%)
Temperature measured by FBG2	(−10.6%, −2.3%)	(−13.3%, 8.4%)	(−14.5%, 6.6%)	(−16.4%, 8.6%)
Strain measured by FBG1	(−14.0%, −1.1%)	(−11.6%, 1.7%)	(−13.7%, 6.6%)	(−17.1%, 10.0%)

The measurement uncertainty of the proposed system is less than 4.1% for temperature sensing and less than 6.4% for strain sensing, respectively. These results suggest that the uncertainty in temperature and strain measurement stays within a controllable range. It also confirms the robustness and accuracy of the proposed sensing system under complex conditions. In contrast, the ND method yields uncertainties as high as 10.5% for the temperature and 10.1% for the strain. Compared with the ND method, the ARB-UQ method reduces the uncertainty by nearly half providing a more accurate representation of the sample variability and error. This advantage is particularly relevant when analyzing data with non-Gaussian characteristics, such as skewed distributions and heteroscedasticity,

which are frequently encountered in networked fiber sensing systems. By comparison, the ND method often produces distorted interval estimates, reducing the accuracy of uncertainty evaluation.

The PICP for the strain-sensing error of FBG1 is 83.3%. For the temperature-sensing error, the PICPs of the MZI, FBG1, and FBG2 are 100%, 81.8%, and 86.6%, respectively. The higher coverage probability of the MZI sensor demonstrates the reliability and effectiveness of ARB-UQ. The relatively lower PICP of the FBG sensors is due to their inherently lower sensitivity, which exacerbates their susceptibility to spectral fluctuations and light source instabilities. These perturbations introduce error fluctuations during the demodulation process, leading to a slight expansion of measurement residuals

and a subsequent reduction in PICP. However, this does not affect the ability of ARB-UQ to evaluate overall system performance. Future improvements will focus on hardware optimization, such as refining the BEDF spectral profile by material composition optimization and the integration of deep learning algorithms for adaptive error compensation. In summary, the ARB-UQ method provides more accurate uncertainty estimates for the proposed sensing system. It also demonstrates the greater adaptability in evaluating fiber sensing performance, particularly under scenarios with unknown error distributions or complex experimental conditions.

2.5 Sensor array expansion

To further evaluate system performance and quantify sensing hysteresis, we perform an expanded sensor array test. The array consists of twenty FBGs with different central wavelengths and one BEDF MZI. These FBGs are fabricated via femtosecond laser point-by-point inscription, featuring a grating length of 5 mm, a spectral bandwidth of ≤ 0.5 nm, a reflectivity of $>60\%$, and a side-mode suppression ratio of >15 dB. This design enables simultaneous sensing of the temperature and strain across twenty-one spatially separated nodes. The light source configuration remains the same as that in Fig. 2. In this experiment, an oven and a hot plate are used as two different temperature controllers, where different sensors are exposed to separate thermal fields simulating variations in the field. Together with the strain-loading fixture, this arrangement simulates a complex quasi-distributed sensing environment. The total cascaded fiber length is more than 20 m. The temperature range of the oven is 15.3°C – 107.9°C , and that of the hot plate is 35.0°C – 135.5°C . The applied strain varies from $0\ \mu\epsilon$ to $1116.6\ \mu\epsilon$. The transmission spectra of the sensor array are shown in Fig. 7(a), with an inset provided to show the magnified region of FBG-12 to FBG-20. The minimum wavelength spacing between adjacent FBGs exceeds 3 nm, ensuring that

shifts induced by the temperature and strain do not cause the spectral crosstalk. The elevated attenuation observed between $\lambda=1100$ nm and 1400 nm originates from the intrinsic high absorption and Rayleigh scattering of the fiber, coupled with the cumulative insertion losses of the cascaded sensors. Since the interrogation relies on tracking wavelength shifts rather than intensity variations, this attenuation does not compromise the sensing sensitivity or the system's ability to perform accurate multi-parameter demodulation. Specifically, FBG-10 and FBG-12 are used as reference units and not modulated by physical parameters. They are placed near the oven and the hot plate, respectively. FBG-2 is subjected only to the strain, while FBG-5 and FBG-8 are mounted on the hot plate and affected by both the temperature and strain. The remaining FBGs are arranged inside the oven and influenced only by the temperature. To illustrate the sensor responses clearly and maintain conciseness, results from selected FBGs are plotted in Figs. 7(b) and 7(c). The selection is based on their central wavelengths, so that the displayed cases cover the overall spectral range as fully as possible. Figure 7(b) shows that during changes in the temperature and strain, the spectrum of reference FBG-12 fluctuates by less than 0.04 nm. This value quantifies the upper bound of the baseline drift caused by the thermal drift of the system and other environmental factors. In the same figure, the other four FBGs exhibit the consistent sensitivity during both heating and cooling, with $R^2 > 0.990$. Similarly, Fig. 7(c) presents the strain response of FBG-2 and the temperature response of the MZI. Based on these data, the maximum hysteresis error of the sensors is calculated, which characterizes the hysteresis behavior of the sensing system. The maximum hysteresis error is below 1% for the temperature measured by the MZI, below 8% for the temperature measured by the FBGs, and below 5% for the strain measured by the FBGs. Furthermore, FBG-5, FBG-8, and the MZI are used for temperature and strain demodulation, as shown in Fig. 7(d). The results

indicate that the demodulated values match closely with the applied values across the entire measurement range. In addition, the demodulation results of different sensors for the temperature and strain show good consistency. It can be observed that all data points are tightly distributed along the 1:1 reference line. No excessive systematic

deviation with respect to the measurement range is observed from the error bars. The error bounds are consistent with the PIs provided by the ARB-UQ method (Table 1). These results demonstrate the excellent sensing performance of the proposed system and further confirm the accuracy and reliability of ARB-UQ.

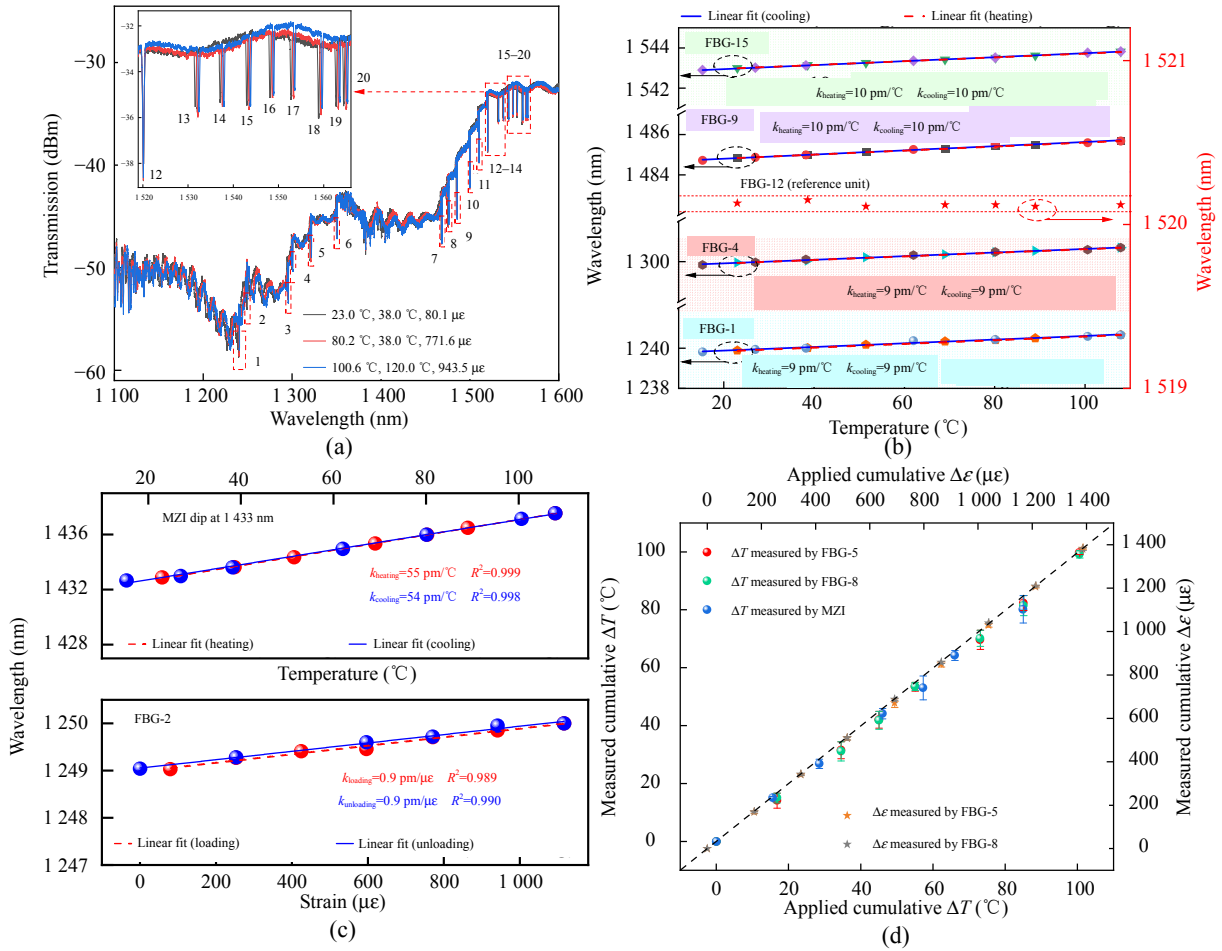


Fig. 7 Performance of the BEDF based sensing system: (a) sensing spectra over the λ of the 1100 nm–1600 nm range, (b) the FBG thermal response plotted as λ vs. T along with the reference FBG fluctuation, (c) the MZI thermal response plotted as λ vs. T and the FBG strain response plotted as λ vs. the applied strain ϵ , and (d) temperature and strain demodulation.

3. Discussion & conclusions

The $\lambda=830 \text{ nm}$ pumping has successfully unlocked the spectral bandwidth of the BEDF, covering telecom windows from the O- to L-bands. However, the performance limit of the sensing system is currently dictated by the output power density and spectral flatness, as evidenced by the intensity fluctuations observed in Fig. 1(a). Future advancements should focus on both gain medium

engineering and system-level optimizations to address these constraints. This requires precise control over the formation of active centers and structural defects during both preform fabrication and fiber drawing. The process involves optimizing the glass host composition (e.g., tailoring the concentrations of Al and Si relative to Bi) and carefully controlling the thermal history and redox conditions [23]. These steps allow the selective

maximization of specific broadband-emitting active centers while suppressing quenching clusters. Integrating such material-level control with system-level strategies, such as hybrid pumping or gain-flattening filters, is essential for achieving the ultra-flat and high-power ASE output, thereby establishing the foundation for superior SNRs in next-generation sensing systems. Although the current BEDF exhibits the moderate output power, its ultra-broadband emission fulfills the critical requirement for simultaneously interrogating a highly sensitive MZI and a large-scale FBG array within a single optical path. This capability is beyond the reach of conventional erbium-doped fiber sources in the realm of quasi-distributed and simultaneous dual-parameter sensing.

The current sensing system is capable of supporting a significantly larger number of FBGs than the twenty presently deployed. Given the system's broad operational bandwidth ($\lambda=1100\text{ nm}–1600\text{ nm}$) and the observed spectral shifts under the specified environmental conditions, the system could theoretically accommodate up to 166 FBGs using wavelength-division multiplexing. This estimation is based on the 500 nm operating bandwidth and the experimental observation that the total wavelength shift induced by both the temperature ($\Delta T=105\text{ }^{\circ}\text{C}$) and strain ($\Delta \varepsilon=1116.6\text{ }\mu\text{e}$) remains within 2.5 nm. By allocating a 3 nm spectral window per FBG sensor to provide a safety margin against the crosstalk, the capacity is calculated as $500\text{ nm}/3\text{ nm}\approx 166$. This capacity enables real-time monitoring at 167 distinct spatial locations (comprising 166 FBG point sensors and the continuous MZI segment). The measurable parameters encompass any physical quantity to which the FBGs exhibit the sensitivity. Additionally, the MZI can be flexibly configured to function either as a primary sensor or as a temperature compensation unit. In practical large-scale applications, however, the actual capacity may be further constrained by physical factors such as

spectral guard bands to prevent the inter-channel cross-talk, cumulative insertion losses, and the maintenance of a sufficient SNR across the ultra-broadband spectrum. The proposed system is primarily constrained by the available spectral bandwidth, as the link power budget remains sufficient to support high-density multiplexing. The proposed system is capable of achieving centimeter-level spatial resolution, although the actual resolution depends on the sensor gauge length and specific deployment configurations.

Table 2 provides a comparison with similar sensors, emphasizing the innovations and advantages of the proposed scheme. In [24] and [25], researchers processed FBGs using physical or chemical methods, which improved their performance. However, these methods are limited by extra processing steps and single-point sensing. Furthermore, [19] and [26] introduced composite sensing structures, which led to the improved sensor sensitivity. But the required femtosecond laser processing or coating techniques limited the broad applicability of these approaches. In [27], we demonstrated that the BEDF source could support single-point strain sensing for an O-band FBG. This highlights the potential of the BEDF source in expanding the sensor's operating bandwidth. Additionally, [5] and [18] analyzed the effects of packaging and refractive index modulation depth on FBG performance. They also emphasized the importance of quasi-distributed sensing. Arrays composed of multiple FBGs were widely adopted. However, the sensor capacity remains limited by the bandwidth of the light source. All these works assume a normal distribution fit and some effort in improving individual sensor performance – there is no consideration of the cumulative error or system error that is responsible for the asymmetric uncertainty in real systems, especially those with the added wavelength sensitive gain and loss variations. In this context, this study provides new insights and effective response strategies suited for sensing

networks. Compared to other composite sensing structures, the proposed system features a simplified fabrication process and can be assembled through simple splicing. The sensing system addresses the technical gap in quasi-distributed and simultaneous multi-parameter sensing. Additionally, the BEDF removes the need for an external broadband light source. Most importantly, this work introduces a robust ARB-UQ framework that advances the system performance to complement individual sensor approaches. Instead of merely pursuing higher sensitivity or improved fabrication, the

framework leverages adaptive residual bootstrapping to deliver reliable interval estimates. In this way, uncertainty quantification becomes a central dimension of sensing system optimization. Specifically, the ARB-UQ framework effectively captures the heteroscedastic and skewed noise signatures of the BEDF by deriving empirical distributions directly from experimental residuals. This non-parametric approach bypasses the limitations of rigid Gaussian assumptions, ensuring reliable measurement precision for sensors operating in complex and environmentally sensitive networks.

Table 2 Performance comparison of similar sensors.

Sensing scheme	Temperature sensitivity (pm/°C)	Strain sensitivity (pm/με)	Simultaneous measurement	Quasi-distributed structure	Operating band	Ref.
HiBi-FBG	10	0.8	No	No	C+L	[24]
Four FBGs	–	0.9	No	No	O+C	[27]
Uniform FBG	12	0.7	Yes	No	C	[25]
MZI+FBG	20/10	0.5/0.7	Yes	No	S+C	[19]
FPI+FBG	1/10	3/0.9	Yes	No	C+L	[26]
Ultra-weak FBGs	–	1.0	No	Yes	C	[5]
Two FBGs	11	1.1	Yes	Yes	C	[18]
MZI+20 FBGs	56/13 (max.)	0.9	Yes	Yes	O–L	This work

Moreover, the accurate error interval prediction provided by the ARB-UQ yields significantly low uncertainty for the system, with temperature and strain measurement uncertainties maintained below 4.1% and 6.4%, respectively. This relatively low uncertainty makes our system competitive among similar studies [28]. This quantification is crucial as it formally defines the impact of the BEDF source's spectral irregularities on the overall sensing performance. Future work will focus on enhancing the scalability and adaptability of this framework. A key objective is to transition from passive quantification to active error compensation by integrating the ARB-UQ with advanced time-series models, such as long short-term memory (LSTM) or transformers. Such an approach would enable the real-time mitigation of dynamic noise patterns and environmental fluctuations, potentially eliminating the negative impact of source-induced instability. This evolution establishes a robust foundation

for intelligent and self-calibrating quasi-distributed sensing networks tailored for complex IoT and flexible electronics applications.

In summary, our study presents a quasi-distributed sensing system with an efficient and flexible architecture. The BEDF source enables effective extension of the sensor array's operating bandwidth into the O-, E-, and S-bands. Accurate temperature and strain sensing at 21 spatial locations demonstrates the system's suitability for large-scale deployment. Importantly, given that the broadband source is the origin of the asymmetry within the network, we have demonstrated for the first time a robust data-driven SL approach that improves the ultra-broadband sensing system performance by addressing the errors arising from an environmentally sensitive gain medium, in contrast to a rare-earth shielded environment. Such a method can be generically applied to other exposed systems to allow operations that would normally be

prohibited by such sensitivity. This is on top of the advantages provided for networked systems bringing together significantly mismatched technologies and making them work. The ARB-UQ method demonstrates more accurate results in uncertainty assessment compared to the traditional methods. This method enables the efficient evaluation of the sensing performance, with uncertainties in the temperature and strain as low as 4.1% and 6.4%, respectively, confirming the system's robustness and reliability. Additionally, the all-fiber configuration further allows flexible adjustment of coverage via the inter-sensor cascade length. Consequently, the proposed system is well-suited for intelligent flexible electronics and IoT applications.

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Declarations

Conflict of Interest Tingyun WANG, John CANNING, and Gangding PENG are the editorial board members for Photonic Sensors and were not involved in the editorial review, or the decision to publish this article. The authors declare that they have no other competing interests.

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Use of AI Statement None.

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