

Large-Capacity WDM FBG Array Interrogated by OFDR for Large Strain Measurement

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Abstract: We propose a wavelength-division multiplexing (WDM) fiber Bragg grating (FBG) array designed to mitigate the spectral shadow effect, thereby enhancing multiplexing capacity. The array comprises 7 560 FBGs, which are periodically arranged across 21 distinct wavelength channels. Each FBG has an average reflectivity of 5.5% and a bandwidth of 0.113 nm. We employ an optical frequency-domain reflectometry (OFDR) system for interrogation, which enables high-density array demodulation and large-strain measurement. A convolutional localization algorithm is proposed to achieve fast and accurate addressing of each FBG. The sensing system achieves a maximum sensing-fiber length of 120 m and spatial resolution of 16 mm, along with a demonstrated strain range of 10 000 $\mu\epsilon$ and wavelength accuracy of 1.2 pm. Furthermore, a 21-fold enhancement in spectral demodulation speed is realized over identical FBG arrays. Consequently, the average demodulation time per FBG is substantially reduced from 11.25 ms to 0.53 ms. These results affirm the exceptional suitability of our system for applications demanding high precision, an extensive strain range, and substantial sensor capacity.

Keywords: Fiber Bragg grating; optical frequency domain reflectometry; large capacity; large strain measurement

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1. Introduction

Fiber Bragg gratings (FBGs), a class of passive fiber-optic devices characterized by high reflectivity, are widely employed in optical network systems [1–3]. In backscattered fiber-optic sensing systems, FBGs offer a significantly higher signal-to-noise ratio (SNR) compared with those of single-mode fibers [4–8]. Moreover, their well-defined spectral

characteristics enable highly precise wavelength shift measurement, which outperforms the irregular spectra produced by the Rayleigh scattering [9–13].

As a sensing medium superior to the conventional single-mode fiber, FBG-based sensing arrays have performance determined by both grating density and capacity. A higher grating density enables finer sensing resolution, while the larger capacity extends the sensing distance. Previous

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studies have extensively explored methods to enhance these two parameters [14].

In demodulation schemes based on optical time-domain reflectometry (OTDR), efforts have focused on reducing laser pulse widths or employing hybrid multiplexing techniques to improve spatial resolution. For instance, in 2012, Wang *et al.* [15] used an electro-optical modulator to generate 1 ns narrow pulses, enabling the interrogation of 1 000 FBGs with the 1 m spacing. In 2018, Yang *et al.* [16] applied wavelength-division multiplexing (WDM) to achieve sensing resolution of 1 m using 20 ns pulses, while increasing the multiplexing capacity to 2 000 FBGs. In 2022, Wang *et al.* [17] combined space-division multiplexing (SDM) with the WDM to achieve the total capacity of 4 000 FBGs.

In contrast, optical frequency-domain reflectometry (OFDR) offers inherently high spatial resolution, allowing straightforward demodulation of high-density FBG arrays. Research in this area has thus concentrated primarily on increasing array capacity. In 2018, Zhang *et al.* [18] demonstrated an ultra-weak FBG array with spatial resolution of 100 mm and a capacity of 5 000 FBGs for distributed strain sensing. The following year, Gui *et al.* [19] developed a dense ultra-short FBG array, further boosting the capacity to 6 680 FBGs. These advances underscored the ongoing progress in enhancing both spatial resolution and multiplexing capacity in FBG sensing systems.

Despite these achievements, two significant challenges remain. First, although WDM-enhanced OTDR systems can reduce the inter-grating spacing, they also constrain the available wavelength shift range, thereby limiting the measurable strain range. This restriction poses a particular obstacle in applications involving non-uniform strain fields or shape sensing. Second, the spectral shadow effect continues to impede system performance: upstream FBGs reflect part of the optical power, which introduces spectral distortions in downstream FBGs. These distortions degrade wavelength measurement

accuracy and effectively limit the number of usable sensors. The use of ultra-weak FBGs can partially mitigate this effect, but at the expense of a reduced SNR, introducing a fundamental trade-off in the system design.

In this work, we combine WDM FBG arrays with the OFDR. This approach not only mitigates spectral distortion and substantially increases the FBG capacity but also overcomes limitations inherent in WDM-OTDR systems, such as the restricted strain measurement range and limited sensor density. Moreover, the spectral demodulation speed of the WDM-FBG array is several times faster than that of identical FBG arrays, particularly for detecting small-magnitude physical changes. To evaluate system performance, we perform distributed temperature and strain measurement. Experimental results demonstrate that the proposed sensing system offers several key advantages, including a large strain measurement range, high wavelength accuracy, and compatibility with a large number of FBGs.

2. Experimental setup and principles

2.1 Spectral demodulation principle

The key characteristics of the fabricated WDM FBG array and a schematic diagram of the OFDR system are shown in Fig. 1.

The array comprises 21 FBGs with distinct Bragg wavelengths, arranged periodically to form 360 subarrays in total. This spatial distribution is designed to achieve two main objectives. First, the periodic arrangement allows any consecutive set of up to 21 FBGs to operate as an independent subarray. Because the spectral responses of the WDM FBGs are non-overlapping, all gratings within a subarray can be interrogated simultaneously. This feature considerably accelerates the spectral demodulation process, resulting in a multi-fold increase in speed compared to the identical FBG arrays. Second, as noted in [20], the spacing between FBGs sharing the

same Bragg wavelength must exceed the physical length of a single FBG to suppress triple-reflection noise in OFDR systems. The periodic layout inherently increases this spacing, thereby effectively reducing spectral interference. Specifically, the center-to-center separation between FBGs with the same Bragg wavelength is increased from 16 mm in an identical-wavelength FBG array to $16 \text{ mm} \times 21 = 336 \text{ mm}$ in the proposed WDM FBG array. Equivalently, the edge-to-edge spacing is increased from 8 mm to 328 mm. Importantly, this improvement is achieved without compromising the 16-mm sensing resolution.

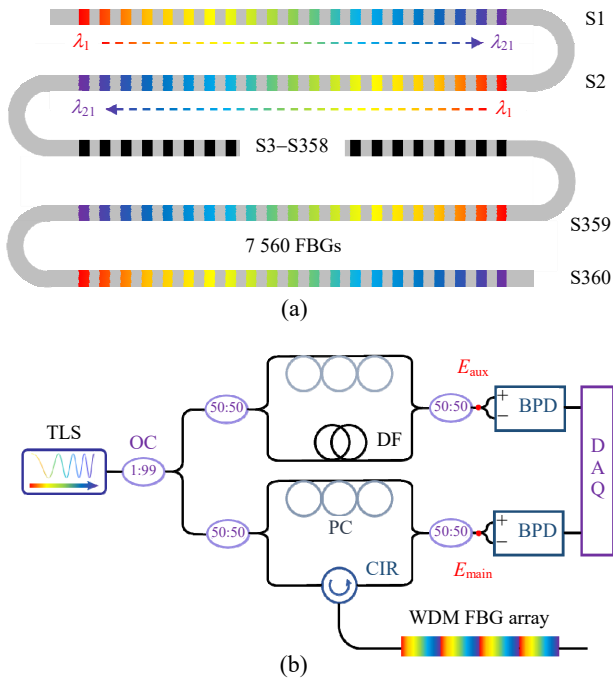


Fig. 1 Experimental system: (a) the WDM FBG array and (b) the schematic of our OFDR system (TLS: tunable laser source; OC: optical coupler; DF: delay fiber; PC: polarization controller; CIR: circulator; BPD: balanced photodetector; DAQ: data acquisition).

The OFDR system incorporates an auxiliary interferometer and employs a resampling algorithm based on cubic spline interpolation to effectively compensate for phase noise and ensure measurement accuracy. A balanced photodetector is also used to suppress common-mode noise and remove the direct current (DC) component, thus significantly enhancing the SNR and overall signal quality.

The tunable laser source (TLS) in the system outputs an optical field described mathematically as

$$E_{\text{in}} = E_0(t) \exp \left[j2\pi \left(f_0 + \frac{1}{2} \gamma t \right) t + \varphi(t) \right] \quad (1)$$

where f_0 is the initial sweep frequency and γ is the sweep speed; E_0 and φ are the time-varying light field and phase noise, respectively. The beat interference signals from the auxiliary interferometer and the main interferometer are, respectively:

$$\begin{aligned} E_{\text{aux}} &= \kappa_a \sqrt{\kappa_{a1} \kappa_{a2}} E_0^2(t) \cdot \\ &\quad 2 \cos [2\pi \gamma \tau_{\text{aux}} t + \varphi(t) - \varphi(t - \tau_{\text{aux}})] \quad (2) \\ E_{\text{main}} &= \sum_i E_i \\ &= \sum_i \kappa_m \sqrt{\kappa_{m1} \kappa_{m2}} \sqrt{R_i(t)} E_0^2(t) \cdot \\ &\quad 2 \cos [2\pi \gamma \tau_i t + \varphi(t) - \varphi(t - \tau_i)] \quad (3) \end{aligned}$$

where κ is the beam-splitting ratio of each optical coupler (OC), and its specific value is presented in Fig. 1; τ_i is the optical delay corresponding to the reflection position of the i th FBG; E_i denotes the beat-signal component contributed by the i th FBG; $R_i(t)$ is the wavelength-dependent reflectivity of the i th FBG sampled by the wavelength-swept laser. In fact, the above results implicitly make an assumption:

$$E_0(t) = E_0(t - \tau_i) \quad (4a)$$

$$R_i(t) = R_i(t - \tau_i) \quad (4b)$$

and it would be discussed in Section 3.1.

Two beat signals in (2) and (3) can be regarded as the product of three parts. The first term is determined by the optical power distribution of each OC. The second one is determined by the reflectivity at the reflection point. Since the auxiliary interferometer is transmissive, the reflectivity can be calculated as 100%. The last one is the cosine term of the beat interference, with different positions corresponding to different beat frequencies.

By using a convolutional localization algorithm, the peak of each FBG could be addressed as follows:

$$\text{findpeaks}\{F[E_{\text{main}}] * \text{rect}[f/L_{\text{FBG}}]\} \quad (5)$$

where F is the Fourier transform; $*$ represents the convolution operation; $\text{rect}[f/L_{\text{FBG}}]$ is a rectangular window function in the frequency (or distance) domain with the same width as the FBG. Each maximal point corresponds to one FBG position. Afterward, the reflection spectrum of a particular FBG can be obtained by filtering and calculating the relative amplitude:

$$R_i(t) = \left| \frac{H\{F^{-1}[w(f - \gamma\tau_i, L_{\text{FBG}})F[E_{\text{main}}(t)]]\}}{99H\{E_{\text{aux}}(t)\}} \right|^2 \quad (6)$$

where $w(f - \gamma\tau_i, L_{\text{FBG}})$ is the window function in the frequency domain with a central frequency of $\gamma\tau_i$ and a width of FBG size L_{FBG} ; F^{-1} is the inverse Fourier transform (IFFT); H is the Hilbert transform used to change the real signal into an analytic signal to extract the amplitude. We utilize BPDs with identical specifications to maintain uniformity in photoelectric conversion coefficients.

It is important to highlight that (6) isolates the spectrum of only one FBG within the array. For an array of identical FBGs, the window function width must be carefully adjusted to encompass only a single FBG, thereby preventing the interference from adjacent FBG spectra. However, for the WDM FBG array, the window function can be broadened to span the entire sub-array:

$$\sum_i^{i+20} R_i(t) = \left| \frac{H\{F^{-1}[w(f, L_{\text{sub}})F[E_{\text{main}}(t)]]\}}{99H\{E_{\text{aux}}(t)\}} \right|. \quad (7)$$

The spectral data from 21 FBGs can be captured simultaneously, so the spectral demodulation speed is significantly increased compared with those using an identical FBG array. By examining the spectral shifts and formulating a sensitivity equation, variations in external physical parameters can be effectively tracked.

2.2 Spectral shadow effect

The result in (3) is derived under ideal conditions, in which the fiber transmission loss and

reflections from upstream FBGs are neglected. In practice, the beat signal detected by the photodetector for the i th FBG should be

$$E_i^* = \prod_{j=1}^{i-1} (1 - R_j(t)) \exp(-\alpha l_i) E_i \quad (8)$$

where α is the transmission loss of the fiber and l_i is the effective propagation length from the array input to the i th FBG. As the number of upstream FBGs increases, the spectrum becomes increasingly distorted because of the spectral shadow effect.

The simulated spectral evolution of the first 2 000 FBGs is shown in Fig. 2(a) for an identical FBG array and in Fig. 2(b) for a WDM FBG array, both with -30dB reflectivity. As the number of FBGs increases, the central-wavelength reflectivity gradually decreases until a central dip appears. At this point, the spectrum is considered distorted, and the corresponding FBG can no longer function as a normal sensing unit. For the identical FBG array, this distortion becomes visible at the 750th FBG. By FBG#2000, the main peak intensity drops to that of the side peaks.

In contrast, the WDM FBG array exhibits a markedly different behavior. Even for the last FBG, only the reflection intensity is attenuated, whereas the overall spectral profile remains largely intact. Furthermore, the simulation uses only five wavelength channels; a typical OFDR system with a scanning range of tens of nanometers can accommodate substantially more channels, enabling much larger array scales.

Moreover, we perform a theoretical analysis of the trade-offs among reflectivity, grating capacity, and wavelength measurement accuracy. Figure 2(c) shows the maximum number of FBGs that can be accommodated within a single wavelength channel at different reflectivity levels. We define a relative intensity parameter as the ratio of the reflectivity at the central wavelength to that of the highest side peak or distortion peak. The onset of spectral distortion, marked by the appearance of a central dip,

is identified by a sharp change in this parameter, which sets the upper capacity limit for a given reflectivity. For instance, the capacity increases from 50 FBGs at -20 dB to 5 000 at -40 dB.

Although lowering the reflectivity increases the capacity, it also increases the wavelength measurement uncertainty and reduces sensing accuracy, because weaker FBG reflections are more susceptible to the intrinsic Rayleigh-scattering

background in the fiber, which superimposes a random noise spectrum onto the FBG response and introduces demodulation errors. Taking the Rayleigh scattering intensity in a standard single-mode fiber as -60 dB, the standard deviation results for wavelength measurement at different reflectivity levels are presented in Fig. 2(d), representing the fundamental lower limit of the wavelength error for such sensing systems.

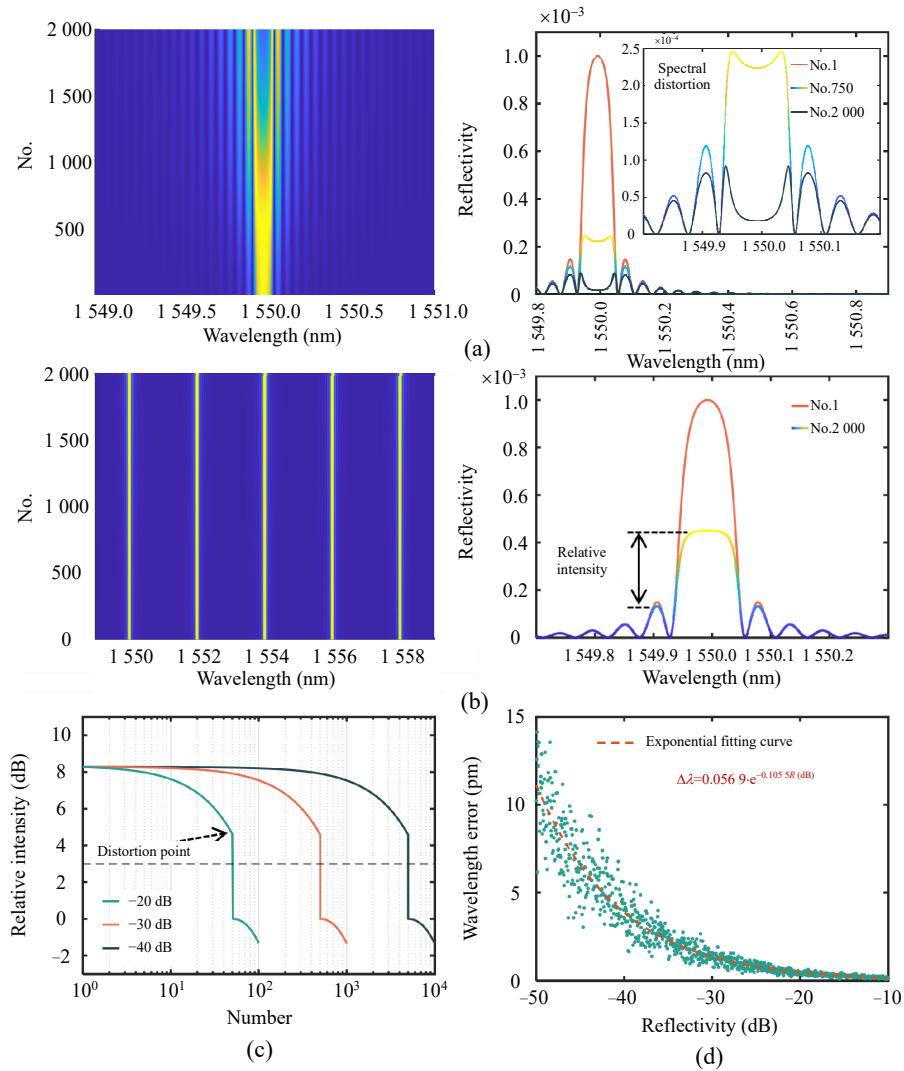


Fig. 2 Spectral distortion caused by spectral shadow effect in (a) an identical FBG array, (b) a WDM FBG array, (c) the upper limit of the FBG capacity, and (d) the wavelength measurement errors at different reflectivity levels.

Overall, the WDM FBG array can deliver the larger capacity while maintaining the same measurement accuracy. Alternatively, it can provide higher measurement accuracy while maintaining the same capacity.

2.3 Demodulation of the WDM FBG array

The specific sensing workflow of the WDM FBG array is shown in Fig. 3. The process begins with identifying the position of each FBG within the

phase-noise-compensated reflection signal (further details regarding phase noise compensation in the OFDR can be found in [21]). Using the convolutional localization algorithm, each peak in the resulting convolution output corresponds to the precise location of an individual FBG [see (5)].

Next, based on different environmental conditions, an appropriate filter window is selected for spectral demodulation. When the wavelength shift is minimal (changes in the ambient temperature), all FBGs within a subarray can collectively sense. This approach significantly enhances the spectral demodulation speed compared to those of identical FBG arrays. In scenarios where the wavelength shift exceeds the central wavelength interval between adjacent FBGs (significant strain), the spectrum of each FBG must be separated and analyzed individually. Thanks to the wide wavelength scanning range of the tunable laser source (TLS), the OFDR system achieves a large strain measurement range and a distinct advantage over OTDR-based methods. Once the spectral information for each FBG position is acquired, the sensitivity equation can be constructed, facilitating accurate distributed sensing.

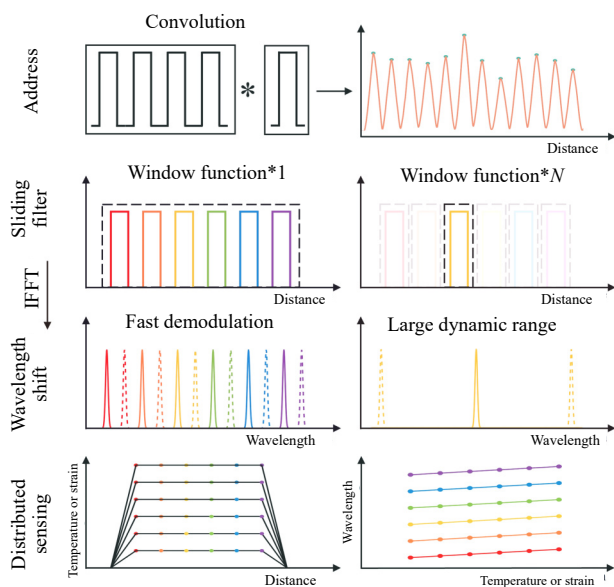


Fig. 3 Sensing flow chart of the WDM FBG array as sensing fiber interrogated by the OFDR.

3. Experimental results

3.1 Characteristics of the WDM FBG array

The localization results of the WDM FBG array using the OFDR are presented in Fig. 4(a). The measured array length is approximately 120 m, with both the FBG size and spacing of 8 mm, perfectly aligning with the predefined fabrication parameters. The convolutional localization algorithm, as described in (5), is employed to accurately determine the positional information of each FBG, which is indicated by the green dots in Fig. 4(a).

The distance-wavelength distributions of selected FBGs are obtained by using the filtering algorithm outlined in (7) and the short-time Fourier transform (STFT), respectively, and shown in Figs. 4(b) and 4(c). For clarity, the reflectivity in Fig. 4(b) has been normalized to highlight the periodicity of the FBG distribution. The close agreement between the two methods confirms the highly precise periodic arrangement in the WDM FBG array.

The measured reflectivity results for all FBGs are presented in Fig. 4(d). As the number of FBGs increases, the reflectivity exhibits a clear decreasing trend. The average reflectivity decreases from 5.5% to 2.3%. Figure 4(e) displays the 3 dB spectral bandwidth of each FBG. It is evident that all FBGs exhibit highly consistent spectral bandwidths. The average bandwidth is 0.113 nm with a standard deviation of 4.5 pm, demonstrating the high consistency of the FBG array once again.

Here, we will explain the validity of the assumptions in (4). The tunable laser source (TSL-710, Santec, Japan) employed in this study is configured to operate within a wavelength range of 1 520 nm to 1 580 nm, encompassing the entire spectral range of the FBGs. It provides the minimum wavelength resolution of 0.1 pm and scanning speed of 60 nm/s. Under this scanning speed, the laser resides at each wavelength long enough for light to

propagate through approximately 167 m of the fiber. As a result, for fiber lengths shorter than 167 m, the propagation time of light can be safely neglected when calculating the FBG spectra. Since the total length of the WDM FBG array used in this study is

well within this limit, the assumption is valid. However, for fibers longer than 167 m, the measured spectra must be corrected by introducing a wavelength shift to account for deviations caused by the propagation delay of the laser.

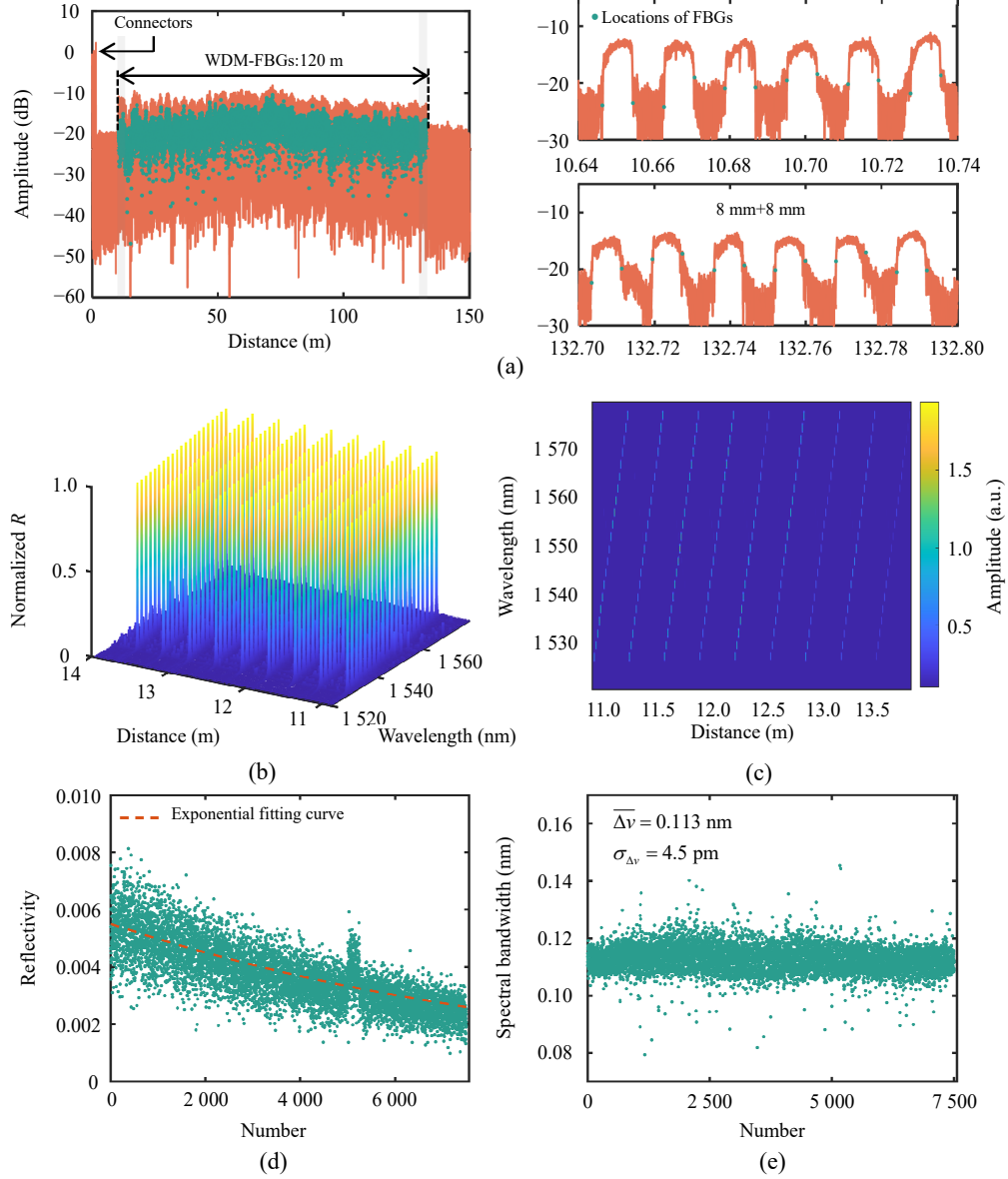


Fig. 4 Measurement results of the WDM FBG array: (a) distribution in the distance domain, (b) spectra of FBGs at different positions (normalized reflectivity), (c) distance-wavelength map using STFT, and (d) reflectivity and (e) spectral bandwidth of the FBGs.

The spectra of the first and last subarrays are presented in Figs. 5(a) and 5(b), respectively. It is evident that the reflection intensity of the downstream FBGs is significantly reduced, primarily due to power reflections from the upstream FBGs, which is consistent with the results

presented in Fig. 2(b). Additionally, the spectral distributions of FBGs with three distinct wavelengths are extracted, as illustrated in Fig. 5(c) (the spectral distributions for all 21 wavelengths are presented in the Fig. S1, Supplementary files). Minor variations in the central wavelengths of FBGs

at different positions are observed, which can be attributed to fabrication tolerances. Moreover, all FBGs exhibit a slight redshift in their central wavelengths at 90 m, which is likely attributable to

the unexpected localized strain. The spectra in this region deviate from the strong reflection wavelength range of the upstream FBGs, resulting in a localized increase in reflectivity, as shown in Fig. 4(d).

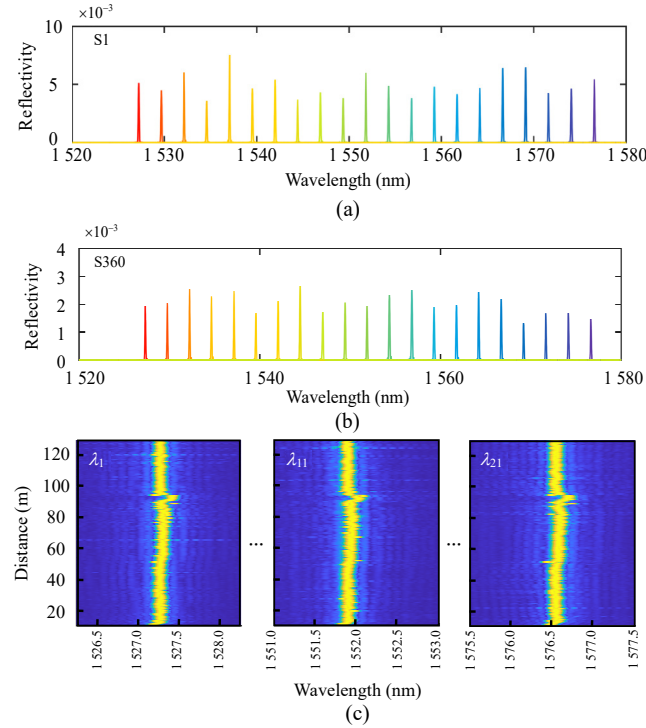


Fig. 5 Spectral characteristics of the WDM FBG array: (a) the reflection spectrum of the first subarray S1, (b) the reflection spectrum of the last subarray S360, and (c) distance-wavelength distributions of three representative wavelength channels, λ_1 , λ_{11} , and λ_{21} .

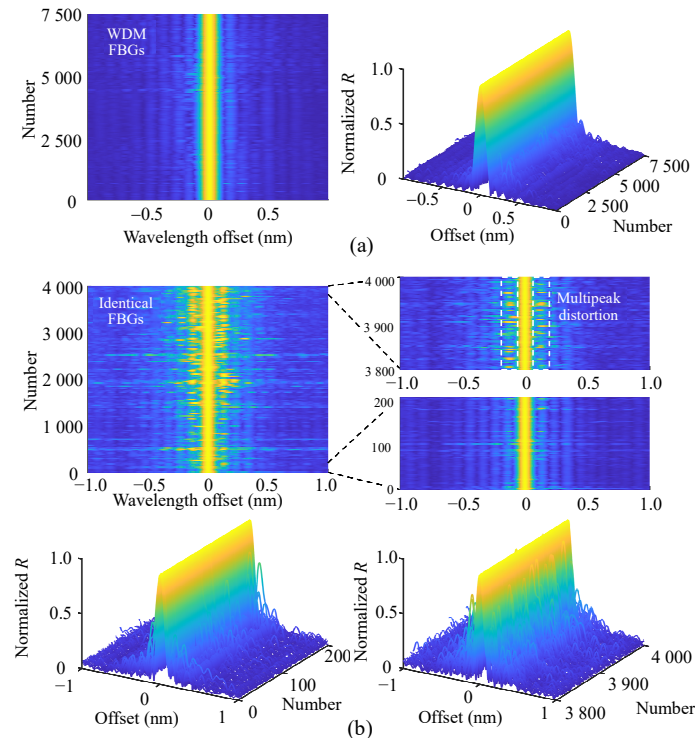


Fig. 6 Spectral distribution (normalized reflectivity) of (a) the WDM FBG array and (b) the identical FBG array.

To assess the spectral robustness of the WDM FBG array, we perform comparative spectral measurement on a conventional identical FBG array with the capacity of 4 000. Herein, we primarily focus on changes in the spectral shape. To enable the precise comparison, all spectra are pre-processed by aligning the spectral peak to the center and normalizing the intensity, thereby minimizing the influence of fabrication-induced variations in the central wavelength and absolute reflectivity. The processed spectra are shown in Fig. 6.

The WDM FBG array exhibits minimal changes in spectral shape, even at a capacity of 7 560, as shown in Fig. 6(a). In contrast, the identical FBG array maintains a stable spectral shape in the initial sections but experienced additional reflection peaks as the capacity increases, leading to significant spectral deterioration, as shown in Fig. 6(b). These findings underscore the effectiveness of the integrated WDM design in enhancing the spectral distortion resistance of FBG arrays.

3.2 Sensing performance

A significant advantage of the WDM FBG array is its adaptability, enabling the measurement strategy to be customized for applications requiring either rapid demodulation or a wide strain measurement range.

To evaluate the fast demodulation capability of the system, temperature measurement experiments are conducted. The end of the WDM FBG array is placed in a water bath thermostat, where the temperature is incrementally increased from 25 °C to 75 °C in 5 °C steps. At each temperature, measurement is repeated ten times, and the average value is used to determine the central wavelength of each FBG. The standard deviation of the measured wavelength is considered as the measurement error. During these experiments, wavelength shifts are carefully monitored, and the execution time for the spectral demodulation process is recorded. The results of the distributed temperature measurement are presented in Fig. 7.

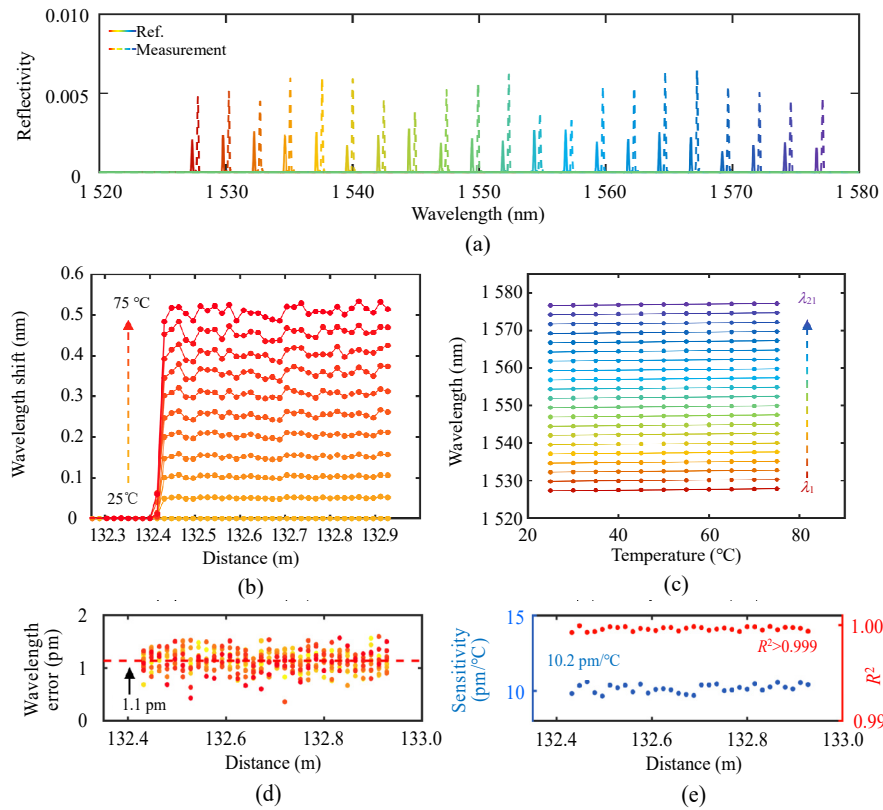


Fig. 7 Distributed temperature measurement results: (a) spectral shifts at different states, 25 °C for the reference (solid line) and 70 °C for the measurement (dashed line), (b) distributed wavelength shift results at different temperatures, (c) temperature sensitivity curves for FBGs with different central wavelengths, (d) wavelength measurement error, and (e) sensing sensitivity and R^2 of linear fit.

As shown in Fig. 7(a), the system effectively tracked minimal wavelength shifts across all FBGs in a subarray. A key performance metric is the dramatic reduction in single-FBG demodulation time: from 11.25 ms in a standard array to 0.53 ms in the WDM array. This efficiency gain reduces the computational load of spectral demodulation in the OFDR system and improves the overall processing speed. Additionally, the heating causes the central wavelengths of FBGs to shift out of the upstream high-reflectivity bands of FBGs, raising the overall reflection peak intensity. The associated wavelength shifts and the linear sensitivity curves of 21 FBG sensors are presented in Figs. 7(b) and 7(c), respectively. The high accuracy and linearity demonstrated confirm the WDM FBG array's suitability as an effective quasi-distributed sensing fiber.

Measurement errors for the sensing units at each temperature step are presented in Fig. 7(d), with an average error of approximately 1.1 pm. The temperature sensitivity and corresponding linear fitting results for each sensing unit are presented in Fig. 7(e). The average temperature sensitivity is calculated to be 10.2 pm/°C, with an R^2 value exceeding 0.999, indicating excellent linearity. Theoretically, FBGs with larger central wavelengths are expected to exhibit slightly higher temperature sensitivity; however, this trend is not clearly observed in practice. This discrepancy may be attributed to limitations in wavelength measurement accuracy and minor variations in the effective refractive index introduced during the fabrication process. Based on the observed average wavelength error and temperature sensitivity values, the temperature measurement accuracy of the system is estimated to be approximately 0.1 °C.

Following the temperature experiments, distributed strain measurement tests are conducted to evaluate the system performance under a large strain range. A 400 mm fiber segment is affixed to a displacement stage, where strain was incrementally

increased from 0 $\mu\epsilon$ to 10 000 $\mu\epsilon$ in steps of 1 000 $\mu\epsilon$ by adjusting the stage elongation. At each strain level, the measurement is repeated ten times, and the central wavelength of each FBG is calculated, along with the standard deviation of the results. The outcomes of the distributed strain measurement are presented in Fig. 8.

In the experiment, the large wavelength variation requires that each FBG spectrum is isolated individually to eliminate crosstalk between channels and ensure accurate wavelength tracking. Notably, the FBG array can detect minute fiber displacements induced in the distance domain, as shown in Fig. 8(a), overcoming the signal-to-noise degradation caused by the positional mismatch in conventional single-mode fibers under high strain. Consequently, the FBG array offers superior long distance sensing accuracy compared to conventional fibers [22].

For the WDM FBG array, the spectra of FBGs belonging to the edge wavelength channels may redshift beyond the wavelength scanning range, making them undetectable in the distance domain. As shown in Fig. 8(a), four such FBGs with different wavelengths ($\lambda_{18}\sim\lambda_{21}$) are missing. This, however, does not affect the effectiveness of our convolutional localization algorithm, which remains fully capable of accurately locating all remaining FBGs.

The spectral changes of an FBG with an initial central wavelength of λ_1 under varying strain conditions are presented in Fig. 8(b). Alongside the redshift of the central wavelength, fluctuations in the peak reflectance intensity are also observed. These intensity variations result from the interplay between the reflective band and the spectral shift: as the spectrum shifts into the stronger reflective band of upstream FBGs, the intensity decreases, whereas it increases when the spectrum enters weaker reflective bands. This behavior is consistent with the findings observed in Fig. 7(a).

The distributed wavelength shifts and corresponding sensitivity curves are shown in Figs. 8(c) and 8(d), respectively. As with the temperature measurement, FBGs near the wavelength edges cease to be detectable once their central wavelengths shift beyond the scanning range. The overall distributed strain measurement performance is analogous to that of temperature measurement. Figure 8(e) (the upper panel) presents

the measurement error of each FBG sensing unit across applied strain levels, yielding an average error of about 1.2 pm. The lower panel displays the strain sensitivity and linear fitting results for each unit, showing the average sensitivity of 1.3 pm/ $\mu\epsilon$ and R^2 exceeding 0.999, confirming excellent linearity. Based on these results, the strain measurement accuracy of the system is estimated to be approximately 1 $\mu\epsilon$.

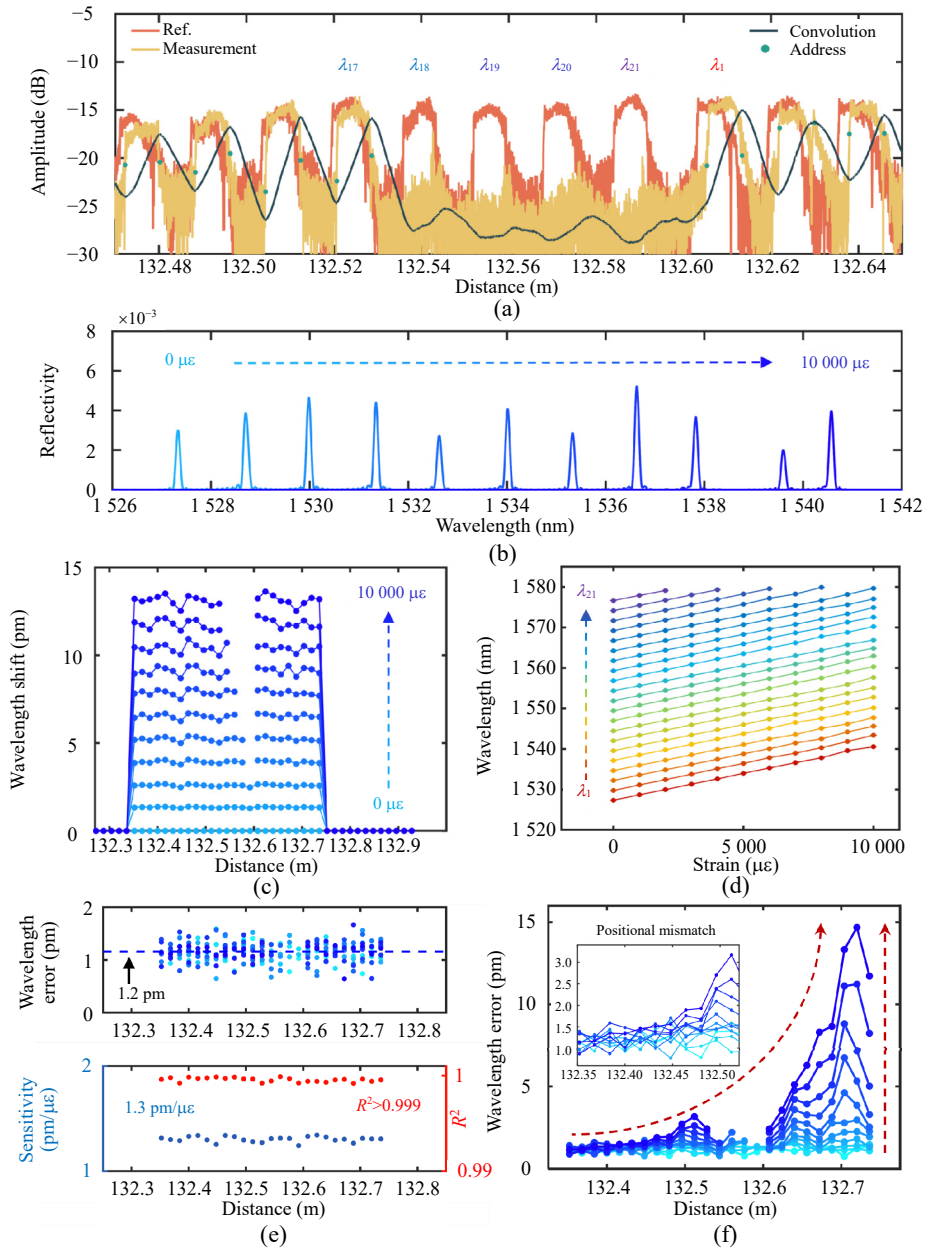


Fig. 8 Distributed strain measurement results: (a) distance-domain localization results under large strain, (b) spectral shifts of a representative FBG under strains from 0 $\mu\epsilon$ to 10 000 $\mu\epsilon$, (c) distributed wavelength shifts at different strain levels, (d) strain sensitivity curves for FBGs with different central wavelengths, (e) the wavelength measurement error, strain sensitivity, and R^2 of linear fitting, and (f) wavelength measurement errors without positional mismatch compensation.

For comparison, Fig. 8(f) shows the wavelength measurement errors without positional mismatch compensation, that is, when the convolutional localization algorithm is not used to reposition the sensing units under strain. Two clear trends emerge: first, the error increases with the strain magnitude, because larger strain induces the greater fiber displacement and reduces the signal-to-noise ratio (SNR) of the demodulated spectrum; second, the error increases with the distance, due to accumulated positional mismatch along the fiber. These results underscore both the effectiveness of the proposed algorithm and the inherent advantage of FBG arrays over single-mode fibers for high-accuracy sensing.

3.3 Discussion

Below are additional notes on our experimental design in this paper, along with considerations of applications:

1) In the OFDR system, longer-distance measurement is particularly vulnerable to the phase noise, which can significantly degrade the quality of distributed measurement results. Therefore, the experiment purposely focuses on testing the performance at the end of the WDM FBG array, using these measurement results as a representation of the overall system performance across the entire fiber.

2) The capacity of 7 560 achieved in this study is not the maximum possibility with WDM FBG arrays. Theoretically, the capacity limit is determined by the product of the capacity of a conventional identical FBG array and the number of multiplexed wavelengths.

3) As highlighted in the paper, the large strain measurement range primarily arises from the extensive scanning range of the TLS and the capability of the OFDR to distinguish spectra from fibers of arbitrary lengths. Consequently, in practical applications, the TLS scanning range should be

carefully adjusted based on the Bragg wavelength and the estimated maximum strain value.

4) When the spectral offset is the primary focus rather than the detailed spectral characteristics, the frequency-domain cross-correlation method offers an effective alternative [23]. This method not only reduces algorithmic complexity but also significantly enhances processing speed, making it well-suited for practical applications.

4. Conclusions

The proposed WDM FBG array system, interrogated by the OFDR for quasi-distributed sensing, exhibits exceptional performance across multiple dimensions. It achieves a large strain measurement range of 10 000 $\mu\epsilon$, along with high measurement accuracy of 0.1 $^{\circ}\text{C}$ in temperature and 1 $\mu\epsilon$ in strain. Furthermore, the system supports the multiplexing capacity of up to 7 560 FBGs while preserving the high SNR inherent to FBG-based sensing. By effectively overcoming limitations of conventional approaches, such as the restricted multiplexing capacity, limited sensing resolution, and narrow strain measurement range, this work presents a robust and innovative solution for distributed fiber optic sensing. These advances pave the way for significantly enhanced performance in a wide range of practical applications.

Supplementary files

The supplementary files can be downloaded from the webpage of this article in *Photonic Sensors* (<https://www.sciopen.com/journal/1674-9251>).

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Declarations

Conflict of Interest Qizhen SUN is an editorial board

member for Photonic Sensors and was not involved in the editorial review, or the decision to publish this article. All authors declare that there are no competing interests.

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Use of AI Statement None.

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