A 10 cm spatial resolution distributed acoustic sensor based on ultra low-loss enhanced backscattering fibre

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Abstract: In this work, a distributed acoustic sensor (DAS) with 10 cm spatial resolution is demonstrated. Such a high resolution is achieved by employing an ultra low-loss enhanced backscattering (ULEB) fibre as a sensing element. A conventional DAS system is modified to interrogate the ULEB fibre comprised of 50 discrete reflectors with an average reflectance of $-56\,dB$. The ULEB fibre was fabricated with an automated reel-to-reel inscription machine, modified to create more uniform reflectors with similar reflectivity in the core of the fibre. The sensing arrangement exhibits a phase noise of $1.9\,n\varepsilon/\sqrt{Hz}$ over 1 km sensing range.

1. Introduction

The past decade has witnessed a rapid adoption of distributed acoustic sensor (DAS) technology in various fields from geophysical sciences [1–3] and railway track behavior analysis [4] to hydrocarbon reservoir monitoring [5, 6] and submarine power cable condition assessment [7, 8]. Thus far, most of the research efforts in DAS technology have been devoted to addressing the requirements of the oil and gas industry which accounts for the largest share of the DAS market, requirements such as systems with a longer sensing range [9–11] and higher measurement accuracy [12–15]. Consequently, less effort has been directed towards improving the spatial resolution of DAS systems. With 1 m gauge length providing sufficient spatial resolution for DASs main target market, commercial DAS manufacturers have had little incentive to use shorter probe pulses to achieve sub-meter resolution by sacrificing the signal-to-noise ratio (SNR). This, in turn, has restricted the adoption of DAS technology in areas such as mechanical and civil engineering which require mapping dynamic strains with much higher resolution.

The most commonly used approach to obtain a high resolution map of dynamic strains along a structure is based on fibre Bragg grating (FBG) arrays [16, 17]. In this approach, several tens of FBGs with different Bragg wavelengths are used to measure strain levels at multiple points along the fibre. The number of sensing nodes in such an array, however, is usually limited to less than a hundred per fibre which may restrict the application of this approach. To address this limitation, sensing systems based on ultra-weak fibre Bragg grating (UWFBG) arrays have been developed [18–21]. UWFBG arrays, used in this approach, are comprised of several hundred low-reflectivity FBGs with an identical Bragg wavelength which, unlike conventional FBG arrays, are interrogated through time division multiplexing. Using this approach, Li et al. [22] have demonstrated a 2 km long sensing system based on an array of 960 UWFBGs with $-40\,dB$ reflectivity capable of measuring dynamic strain with frequencies as high as 12.5 kHz. Despite exhibiting a superior strain accuracy, sensing systems that rely on UWFBG array are susceptible to signal fading due to slow drift in the Bragg wavelength of the FBGs as a result of localized temperature or strain changes. Any such drifts in the Bragg wavelength of the FBGs that pushes their reflection bands beyond the operating wavelength of the seed laser will result in signal fading.

Several studies have shown that DAS systems based on phase-sensitive optical time-domain reflectometry (ϕ-OTDR) can achieve sub-meter spatial resolution by either sacrificing the sensitivity or using very high speed digitizers [23–26]. For instance, using $5\,ns$ probe pulses, Masoudi et al. [23] have demonstrate a DAS system with $50\,cm$ spatial resolution albeit with a minimum detectable strain amplitude of $40\,n\varepsilon$ at $200\,Hz$. In 2018, Chen et al. [25] used a chirped-pulse ϕ-OTDR to achieve $80\,cm$ spatial resolution over $9.8\,km$ sensing range. Although the setup achieved an excellent strain sensitivity of $245\,p\varepsilon/\sqrt{Hz}$, it relied on a $2\,GHz$ bandwidth oscilloscope and linear frequency modulation of up to $1\,GHz$ to achieve a sub-meter spatial resolution. An extreme example of this approach was demonstrated by Martins et al. [26] where an oscilloscope with $62\,GHz$ bandwidth was used to demonstrate a DAS with $2.5\,cm$ spatial resolution. Although these examples show that ϕ-OTDR can achieve sub-meter resolution along conventional telecom optical fibre, using high frequency electronics to achieve such high resolutions might be prohibitively expensive in many applications.

Other interrogation techniques such as optical frequency-domain reflectometry (OFDR) have also been used to obtain a high-resolution map of dynamic strains along sensing fibres [27–30]. In this approach, the strain distribution along the sensing fibre is obtained by extracting the phase of the Rayleigh backscattered light from OFDR traces and calculating the changes in the value of the differential phase between adjacent points along the fibre. This interrogation technique has been used to demonstrate DAS with a spatial resolution as low as $10\,cm$ over a sensing range of $200\,m$. The main limitation of OFDR interrogation technique, however, is its trade-off between the measurement accuracy and spatial resolution [31].

Recently, a new class of specialty optical fibres has been developed that can enhance the backscattered signal by more than $20\,dB$ above the naturally occurring Rayleigh backscattered signal. The enhancement in the intensity of the backscattered signal has been achieved by either forming a continuous grating along the fibre [32] or inscribing individual reflectors at fixed intervals in the core of the fibre [33]. In 2020, Zhang et al. [34] have shown that the spatial resolution of a conventional DAS system that operates based on ϕ-OTDR interrogation technique can be reduced to as low as $20\,cm$ if a continuous grating enhanced backscattering (CGEB) fibre is used as a sensing medium. In the following year, Xiong et al. [35] have used CGEB fibre to demonstrate a DAS system with $28\,cm$ resolution, but over a much longer sensing range of up to $920\,m$. Despite these successful demonstrations, since the intensity of the backscattered light in a CGEB fibre is proportional to the duration of the probe pulse, DAS systems based on CGEB fibre still encounter the same trade-off between the spatial resolution and SNR. Additionally, the enhancement in the intensity of the backscattered signal in CGEB fibre comes at the cost of higher attenuation level which, in turn, affects the sensing range of the sensor. Enhanced backscattering fibres based on point reflectors, on the other hand, does not suffer from the aforementioned trade-offs. This class of fibres, which are also known as ultra low-loss enhanced backscattering (ULEB) fibres, combines the advantages of UWFBG array and CGEB fibre to form a sensing medium that is capable of boosting the backscattered signal by more than $20\,dB$, has an extremely low excess loss (down to $0.01\,dB$ excess loss per 100 reflectors [36]), and is wavelength independent. So far, ULEB fibres have been used to extend the sensing range and measurement precision of conventional DAS systems [36,37]. In this letter, a ULEB fibre with 50 reflectors, spaced $10\,cm$ apart, is used to demonstrate a high-resolution DAS based on $\phi-$OTDR interrogation technique. It is shown that such an arrangement can achieve a sensing range and measurement accuracy of $1\,km$ and $1.9\,n\varepsilon/\sqrt{Hz}$, respectively.

2. Principle

The sensing principle of the DAS setup, used in this study, is based on using a Mach-Zehnder interferometer (MZI) with a fixed path-imbalance to measure the phase difference between adjacent points along the sensing fibre. The role of the interferometer is to mix the backscattered light from different points on the sensing fibre by splitting the backscattered signal into two paths and combining them back with a fixed temporal delay. For an interferometer with a path difference of ΔL, the intensity at the output of the interferometer is given by [23]:

$$I = A + B\cos(\beta\Delta L + \Delta\Phi) \tag{1}$$

where β is the propagation constant of the probe pulse, $\Delta\Phi$ is the phase difference between two separate points on the fibre, and A and B are determined by the intensity of the backscattered light. Since the gauge-length of the sensing arrangement, used in this study, is dictated by the spatial separation between the reflectors in the ULEB fibre, the path-imbalance of the MZI should be fixed to twice the distance between the reflectors. In order to avoid phase fading while extracting the phase information from Eq. (1), a symmetric 3×3 coupler can be used at the output of the interferometer. The data from three arms of the 3×3 coupler can then be combined to yield [38]:

$$\Delta\Phi = 0.78 \times \varepsilon\ell\frac{4\pi n}{\lambda} \tag{2}$$

where ε is the induced strain at a given section of the sensing fibre, ℓ is the length of that section, n is the effective refractive index of the fibre, and λ is the wavelength of the seed laser. Equation (2) shows that the phase-difference between the backscattered light from two adjacent reflectors has a linear relationship with the induced strain between those reflectors.

3. Experiment

3.1. Sensing Setup

The sensing arrangement is shown in Fig. 1. A narrow linewidth DFB laser diode ($\lambda = 1550\,nm$, $\Delta\nu = 100\,kHz$) is used as a seed laser. The laser output is intensity modulated by an electro-optic modulator (EOM) to generate $500\,ps$ probe pulses with $25\,kHz$ repetition rate. To increase the extinction ratio of the probe pulses, a semiconductor optical amplifier (SOA) is employed as a pulse picker followed by a dense wavelength division multiplexing (DWDM) filter with $100\,GHz$ bandwidth to limit the forward amplified spontaneous emission (ASE) of the SOA. As a high-speed optical switch, the SOA plays an important role in generating a high extinction-ratio probe pulse with short pedestal. The probe pulse with $5\,mW$ peak power is launched into the fibre under test (FUT) via circulator C1.

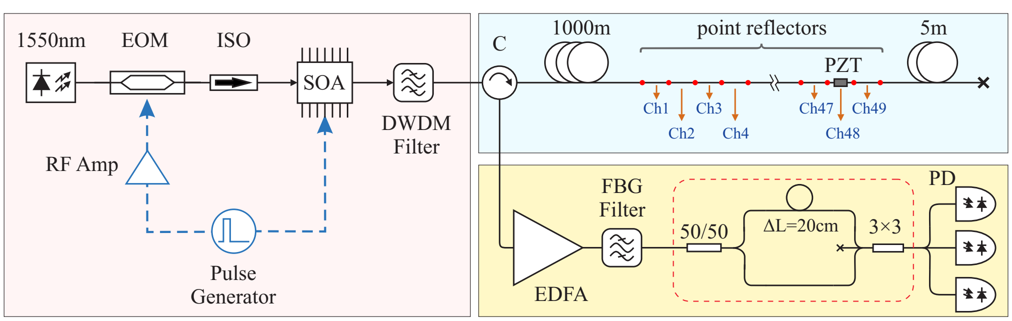

Fig. 1. Sensing setup of high-resolution DAS based on ULEB fibre. EOM: Electro-optic modulator; ISO: isolator; SOA: Semiconductor optical amplifier; DWDM: Dense wavelength division multiplexing; PZT: Piezo-electric actuator; C: Circulator; EDFA: Erbium-doped fibre amplifier; FBG: fibre Bragg grating; IMZI: Imbalanced Mach–Zehnder interferometer; PD: Photodetector; Data Acq.: Data acquisition unit. The red dots along the sensing fibre represent the point reflectors.

A 5 m long ULEB fibre with 50 point reflectors is spliced to 990 m long standard single-mode fibre (SSMF) to form the FUT. A 50 mm long piezoelectric stacks (Thorlabs: PK4FXH3P2) is attached to the ULEB fibre between its 48$^{\text{th}}$ and 49$^{\text{th}}$ reflectors, i.e. the second to last channel of the ULEB fibre, to generate test signals. An extra 5 m of SSMF is added after the ULEB fibre to separate it from the far-end of the FUT.

At the receiving arm of the sensing system, the backscattered signal from the FUT is first amplified by an Erbium-doped optical amplifier (EDFA) and filtered by an FBG filter (λ_B = 1550.1 nm, $\Delta\lambda$ = 0.2 nm, Reflectivity = 99%) to minimize the ASE. The amplified backscattered light is then passed through a MZI with 20 cm path imbalance to mix the back-reflected signals from adjacent reflectors. Finally, the mixed signal at the output of the interferometer is detected by three amplified photodetectors ($BW = 600\,MHz$, $TIA = 40\,k\Omega$) and sampled with a 500 MHz bandwidth PCIe digitizer at a rate of 1.25 GS/s. The captured data is then analyzed using Arctan demodulation algorithm [23] to extract the phase information.

3.2. ULEB Fibre Inscription Setup

The ULEB fibre, used in this test, was fabricated using an automated reel-to-reel fibre inscription setup, a schematic of which is shown in Fig. 2(a). An objective lens was used to focus the output of a femtosecond laser with pulse duration and energy of 200 fs and 4 μJ, respectively, on the target fibre. Data from a CCD camera was used to automatically align the fibre at the focal point of the objective lens using a multi-axis stage. A pulley arrangement was used to control the fibre tension during the inscription procedure. An *in-situ* OTDR system was used to allow measuring the optical signal during inscription. This allowed to control the reflectivity level at each reflector and achieve a consistency of ±2 dB.

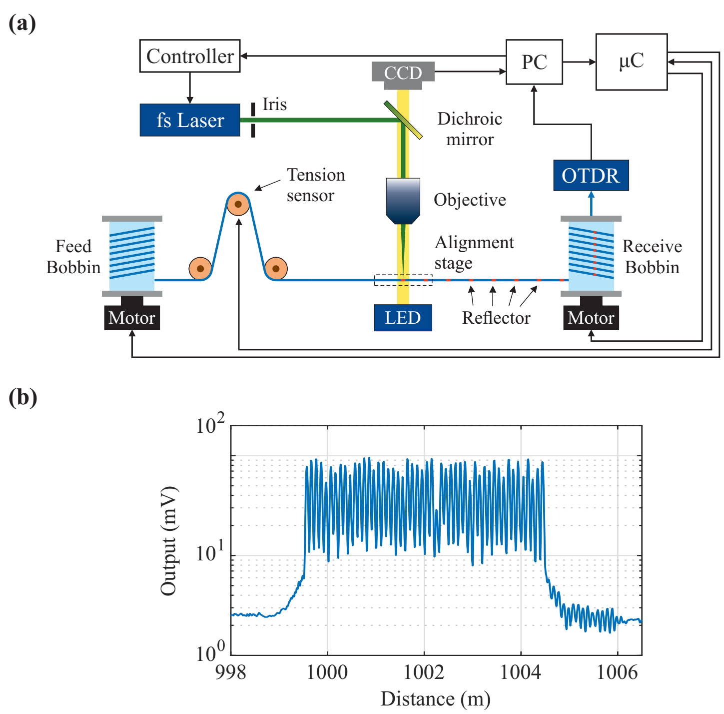

Fig. 2. (a) Schematic of the reel-to-reel, automated, fibre inscription set up. (b) The OTDR trace of the ULEB fibre at the far-end of the FUT exhibiting 50 reflectors with an average reflectivity of 14 dB above the intensity of the Rayleigh backscattered light.

The inscription setup was used to write 50 point reflectors with an average reflectance of $-56\,dB$ and a spatial separation of $10\,cm$ in the core of a SSMF through its polymer coating. With each pair of reflectors constituting a single sensing channel, the ULEB fibre, used in this test, had 49 measurement channels. With an inscription speed of under 2 minutes per reflector which includes fibre alignment, reflector inscription, and rewinding, the number of reflectors used for this study was reduced to 50 to keep the fibre fabrication time under 2 hours.

4. Results and Discussion

Figure 2(b) shows the OTDR trace of the ULEB fibre at the far-end of the FUT. All 50 reflectors with an average reflectance of $-56\,dB$ can be seen in this diagram. 98% of the reflectors exhibited a relatively uniform reflectivity with less than $3\,dB$ variation. Only one reflector had lower than expected reflectance (28^{th} reflector with $-60\,dB$ reflectance). The oscillation in the OTDR trace that occurs after the reflectors over the spatial interval of $1005\,m - 1006\,m$ can be linked to the pedestal of the probe pulse. Since electrical pulses applied to the SOA for pulse picking were $10\,ns$ long, limited by the speed of the pulse generator, the optical pulses used for interrogating the FUT had $9.5\,ns$ pedestal. Despite $25\,dB$ extinction ratio between the main optical pulse and its pedestal, the interaction between $95\,cm$ pedestal and 9 reflectors give rise to the oscillatory pattern on the OTDR trace.

Figure 3(a) shows the waterfall diagram of the sensing system at the far-end of the sensing fibre. The location and profile of a $30\,Hz$ vibration, which was used as the test signal, can be clearly identified at $L = 1004\,m$ on the diagram. The color bar on the diagram indicates the strain level imposed on the fibre in $\mu\varepsilon$. The fast Fourier transform (FFT) of the strain level along the FUT is shown in the spectrogram of Fig. 3(b). The $30\,Hz$ modulation at $1004.9\,m$ with peak strain level of $29.3\,\mu\varepsilon$ can be identified on this diagram.

Fig. 4(a) shows a 2D cross-section of the waterfall diagram at a fixed location on the FUT, corresponding to the 48^{th} channel of the ULEB fibre, as a function of time. In order to quantify the spatial resolution of the sensor, a 2D cross-section of the spectrogram at $f = 30\,Hz$, is shown in Fig. 4(b). The rising edge of the strain profile, shown in this plot, is $8\,cm$ which is less than the $10\,cm$ spatial resolution of the system dictated by the spacing between the reflectors. This

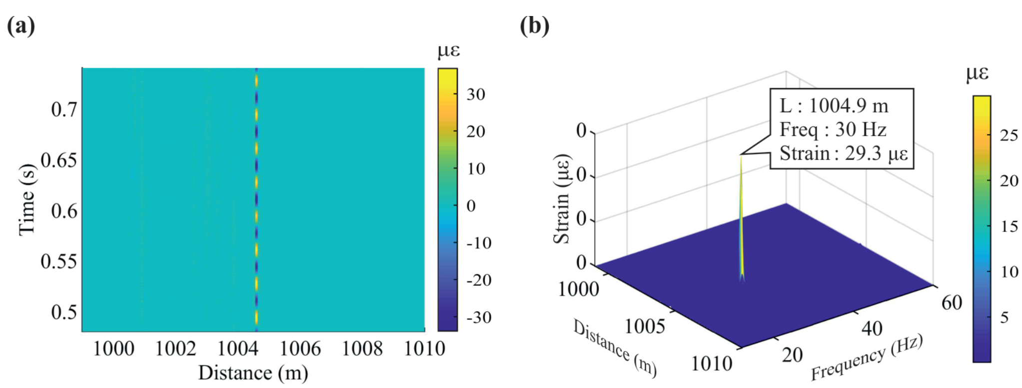

Fig. 3. a) Waterfall plot of the sensing system at the far end of the sensing fibre. The horizontal axis represents the distance along the sensing fibre while the vertical axis represents the elapsed time. b) Spectrogram of the system output mapping strain level at the last $25\,m$ of the FUT as a function of frequency. c) 2D cross-section of the waterfall plot showing the strain variation at the the 48^{th} channel of the ULEB fibre as a function of time. d) 2D cross-section of the spectrogram plot, taken perpendicular to the frequency axis at $f = 30\,Hz$, demonstrating the spatial resolution of the system.

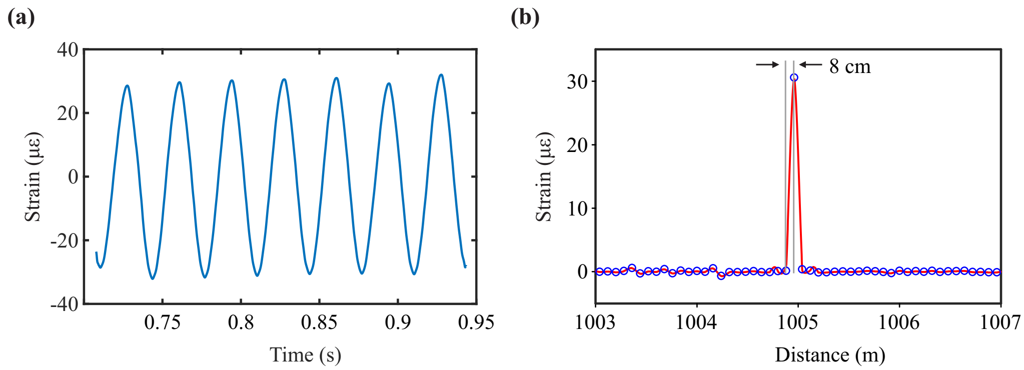

Fig. 4. a) 2D cross-section of the waterfall plot showing the strain variation at the the 48th channel of the ULEB fibre as a function of time. b) 2D cross-section of the spectrogram plot, taken perpendicular to the frequency axis at $f = 30\,Hz$, demonstrating the spatial resolution of the system.

discrepancy is due to the mismatch between the sampling rate of the digitizer that is used to capture the backscattered light and the spacing between the reflectors along the ULEB fibre. With $1.25\,GS/s$ sampling rate, the digitizer acquire one sample every $8\,cm$. Hence, the rise time of the signal appears to be less than the $10\,cm$ spacing between the reflectors.

In order to assess the noise floor and cross-talk of the sensing arrangement, amplitude spectral densities (ASDs) of the strain levels at the last three channels of the ULEB fibre are shown in Fig. 5(a). The ASD of the strain level at the 48th channel of the ULEB fibre, the channel which is stimulated by the PZT actuator, is represented by the blue trace. The peak at $30\,Hz$ shows the frequency and amplitude of the test signal. The yellow trace shows the ASD of the strain at the 47th channel of the ULEB fibre, a sensing channel before the PZT that has not been disturbed. The noise floor of the system, calculated by averaging the noise from $10\,Hz$ to $1\,kHz$, shows a phase noise of -29.23 (re rad/$\sqrt{Hz}$) which corresponds to a strain noise of $1.9\,n\varepsilon/\sqrt{Hz}$. The noise floor is identified by the dashed line on the figure. To assess the cross-talk between the adjacent sensing channels, the ASD of the 48th channel (the channel attached to the PZT) is compared with that of the 49th channel which is represented by the red trace on the plot. The analysis of the frequency peaks on the two traces shows a cross-talk of less than $21\,dB$. With an excess loss of $0.01\,dB$ per 100 reflectors, our analysis shows that replacing the SSMF at the front-end of the FUT with ULEB fibre with $10\,cm$ spacing will not have any notable impact on the noise and cross-talk levels of the sensing system. With previous studies showing the capability of DAS system in measuring $33\,n\varepsilon/\sqrt{Hz}$ vibration along a ULEB fibre at the far-end of $152\,km$ SSMF with total round-trip loss of $60\,dB$ [37], $1\,dB$ excess loss from $1\,km$ long ULEB fibre with $10\,cm$ spacing will have no substantial effect on the sensitivity of the system.

The intra-channel noise and inter-channel cross-talk, observed in the result, can be associated with the pedestal of the probe pulse as discussed earlier. The interaction of the pedestal with other reflectors along the ULEB fibre causes additional light reflection which gets added to the reflected light from the main pulse and causes distortion. Hence, by reducing the duration of pulse picking signal to better match the width of the probe pulse, it is possible to significantly reduce both the noise floor of the system and the cross-talk between different channels. Additionally, the mismatch between the sampling rate of the digitizer and the spatial resolution of the sensing fibre may contribute to the overall noise floor of each sensing channel.

In order to assess the linearity of the system, the sensing setup was used to measure the strain level at channel 48 of the ULEB fibre while increasing the drive voltage applied to the PZT from $0.5\,V$ to $20\,V$. The measurements, represented by blue circles in Fig. 5(b), exhibited a

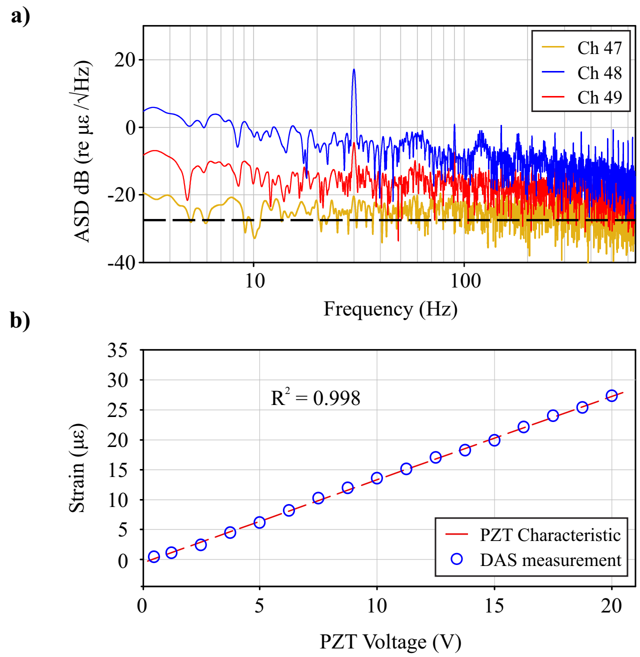

Fig. 5. a) Amplitude spectral density (ASD) of the strain levels at the last three channels of the ULEB fibre. The blue trace represents the ASD of the strain level at the 48^{th} sensing channel where the PZT actuator is located. The yellow and red traces represent the ASD of the strain level at 47^{th} and 49^{th} channels of the ULEB fibre, respectively, i.e. the sensing channels just before and just after the PZT. The dashed line at the bottom of the plot represents the noise floor of the sensor. b) The peak strain level measured by the DAS system (blue circles) for 30 Hz sinusoidal test signals at various amplitudes from 0.5 V to 20 V. The red dashed line represents the response of the PZT transducer, characterised separately with a Michelson interferometer.

high correlation ($R^2 = 0.998$) with the response of the PZT transducer which was characterized separately using a Michelson interferometer (dashed red line). In addition, the response of the system to vibrations across a wide frequency range from 0.1 Hz to 5 kHz was assessed confirming the linear response of the sensing arrangement.

5. Conclusion

In summary, a high resolution DAS system based on ULEB fibre is demonstrated. It is shown that, unlike conventional sensing systems that are based on SSMF or CGEB fibres, the DAS systems that use ULEB fibre as a sensing medium do not experience the trade-off between the spatial resolution and SNR. A ULEB fibre with 50 reflectors and an average reflectance of $-56\,dB$ is used to demonstrate a DAS with 10 cm spatial resolution at the far-end of 1 km sensing fibre. To fabricate a ULEB fibre with consistent reflectivity, an automated reel-to-reel fibre inscription setup with an *in-situ* OTDR feedback system is developed. A simple sensing arrangement based on a digitizer with 600 MHz bandwidth and an imbalanced MZI is used to achieve this resolution.

The sensor exhibited a high degree of linearity, a $1.9\,n\varepsilon/\sqrt{Hz}$ ASD noise floor, and a maximum channel cross-talk of less than 21 dB. The spatial resolution of the measurement, achieved in this work, was limited by the sampling rate and bandwidth of the digitizer. Using a digitizer with 3 GHz bandwidth and 100 ps probe pulse with sech-squared profile, it is possible to push the spatial resolution of ULEB-based DAS to as low as 1 cm.

Funding. Royal Society (CHL/R1/180350); Natural Environment Research Council (NE/S012877/1, NE/T005890/1); Royal Academy of Engineering (PoC1920/21, RF1415/14/6).

Disclosures. The authors declare no conflicts of interest.

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Data availability. Openly available at 10.5258/SOTON/D2116.

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