Long Reach Fibre Optic Distributed Acoustic Sensing using Enhanced Scattering Fibre

B. Zhu (1) *, Y. Li (2), Y.-K. Huang (2), P. Westbrook (1), K. S. Feder (1), Z. Shi (1), J. Hu(2),T. Wang (2), and D. J. DiGiovanni (1)

(1) OFS Labs, Somerset, NJ USA, bzhu@ofsoptics.com
(2) NEC Labs America, Princeton, NJ, USA,

Abstract *We report significant noise reduction in distributed acoustic sensing (DAS) link using enhanced-scatter fibre (ESF). The longest reach of 195km DAS link without inline amplifications is also demonstrated. We further present demonstration of simultaneous fibre-optic sensing and 400Gb/s data transmissions over 195km fibre using ESF. ©2023 The Author(s)*

1. Introduction

Recently, there is an increasing interest in fibre optic distributed acoustic sensing (DAS). This technology, which was initially developed for borehole monitoring in the oil/gas industry [1], soon found the wide applications in railway, power cables and highway monitoring, and seismological studies [1-3]. Future applications are expected to include traffic sensing, buildings health monitoring, and security surveillance integrated into telecom fibre networks [4].

DAS systems with a sensing range of up to 40~50km have proved adequate for borehole monitoring in the oil/gas industry. However, there are many cases that require DAS systems with a much longer sensing reach, especially new applications such as perimeter security monitoring or railway track analysis and traffic monitoring. Therefore, recent research has focused on increasing the DAS range. One way to increase the reach is inline optical amplification such as all-Raman amplification [5] and remotely pumped EDFAs [6]. Another way is to use advanced coding and digital signal processing (DSP) techniques. Chirped pulses were used to extend DAS range to 171km in single span without inline amplification [7]. Using frequency diversity method plus all-Raman multiple span amplification, 1007km reach DAS link with simultaneous 10-Tb/s data transmissions have been demonstrated [5]. A third way to increase the DAS reach is to use advanced fibre such as enhanced scattering fibre (ESF) [8-9] and large-area and ultra-low loss (ULL) fibre. Using a commercial DAS interrogator, a 125km reach DAS link was demonstrated by using OFS TeraWave™ SCUBA fibre and 5km Acoustisens® ESF without inline amplification [10].

In this work, we first report the DAS measurement results of total 153km link comprising of 143km SCUBA125 fibre and 10km AcoustiSens® ESF or 10km standard single-mode fibre (SSMF), showing more than 10 dB spectral noise reduction when using 10km ESF compared with 10km of SSMF. Next, we increase the DAS reach to a 195km link consisting of 185km SCUBA125 and 10km ESF. An average strain sensitivity as low as 59.9 pε/√(Hz) was measured in the 195km DAS link. To the best of our knowledge, this is the longest reach DAS link without the need for inline amplification. Then we demonstrate the simultaneous fibre-optic sensing and 400Gb/s DWDM signal transmission over the 195km fibre link. We show that the data transmission penalty is negligible for wavelengths outside of the reflection band of the ESF, while about 1.8dB signal-to-noise-ratio (SNR) degradation of sensing signal in co-existing system was measured.

2. Low noise long-reach DAS link using enhanced backscatter fibre

The ESF used in this work was similar to that of [9]. The reflection bandwidth of this ESF was increased to support typical commercially available DAS interrogators operating at 1540nm and 1550nm. Fig 1 (a) shows the reflection spectra of the 10km ESF with the reflection at 1550nm about 20dB above Rayleigh scattering.

We first assessed the benefit of the ESF in a 153 km DAS fibre link comprising 143km SCUBA125 fibre plus 10km ESF or 10km SSMF. Fig.1 (b) shows the schematic experimental set-up, the DAS interrogator is a phase-based DAS with advanced coding DSP technique with out-of-band (OOB) signals inserted digitally [5,11]. The pulse frame rate of the DAS was set to be 600Hz for the 153km link measurement. The SCUBA125 fibre [12] has effective area A_{eff} of 125μm^2 and 1550nm attenuation of 0.146dB/km. The end of fibre link was inserted into index matching oil to eliminate the end-face reflections. Additionally, the last 10km ESF or SSMF was put in a vibration isolated box. The performance of the DAS

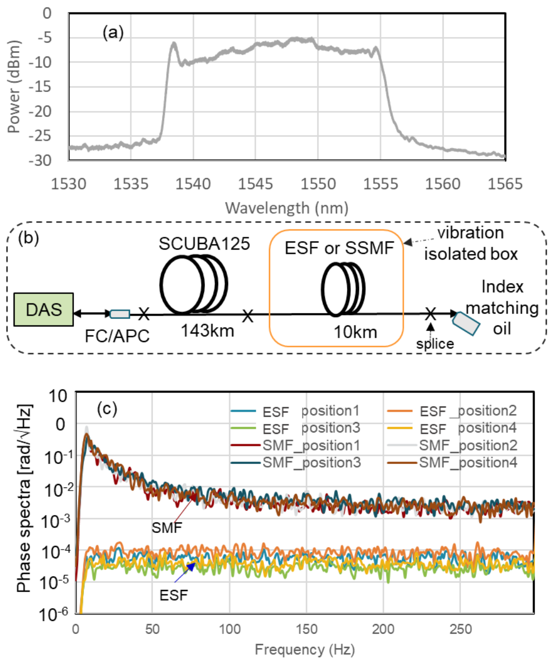

Fig. 1: (a) Reflection spectrum of ESF, (b) experimental set-up, (c) comparison of phase noise spectra.

system was characterised by measuring the phase noises ‘floors’ [13], strain sensitivity, and SNR. The phase noises are usually defined by the power spectral density (PSD) of the demodulation phase signal without any strain modulation of the fibre [7,13]. Usually, the square root of this PSD is stated with unit rad/√Hz. This value can be converted into the strain sensitivity with the unit ε/√Hz (or pε/√Hz) for a DAS system by $\varepsilon=\lambda\Delta\phi/(4\pi nG\xi)$ [13], where the $\Delta\phi$ is phase noise in radians, λ is the operation wavelength of sensing signal, G is the gauge length, n is the refractive index. ξ =0.78 is the strain optic coefficient. To properly assess the DAS performance, five to ten measurements were conducted in experiments, 4 positions near the end of the 10km fibre were selected for each measurement. Fig.1 (c) plots the comparison of phase noise spectra. The noise levels of the 153km DAS link using 10km ESF are almost frequency independent, while noises with SSMF is high, and especially at low acoustic frequencies(<50Hz). The averaged noises measured from 5 measurement cases (each case with 4 positions) is 34.8mrad/√Hz for the SMF sensing link, while noise density is only about 2.9mrad/√Hz when using ESF, or more than 10dB noise deduction.

Then, we spliced the 10km ESF to another ESF, 22m of which was wrapped around a piezoelectric transducer (PZT) to provide stretching modulation on the fibre (Fig.2 (a)) for SNR measurement. The PZT was driven by a 57mV sinewave signal at 100Hz and produced maximum 0.47rad phase shift. Fig. 2 (b) shows a waterfall diagram from 153km DAS link using ESF, the noise reduction regime can be identified on the diagram. Fig. 2(c) shows the phase amplitudes of 4 positions near the end of the ESF where vibration was stimulated by the PZT as a function of time. Fig.2 (d) plots the phase PSD spectra in rad/√Hz. The measured averaged phase noise is 2.8mrad/√Hz. The averaged sensitivity of 13.4pε/√Hz was achieved in this 153km DAS by using ESF. The SNR was defined as the ratio of the sensing signal power over noise power at 100Hz. The measured averaged SNR was 41.8dB. It should be noted that the sensing signal was not recovered after 153km when using 10km SSMF.

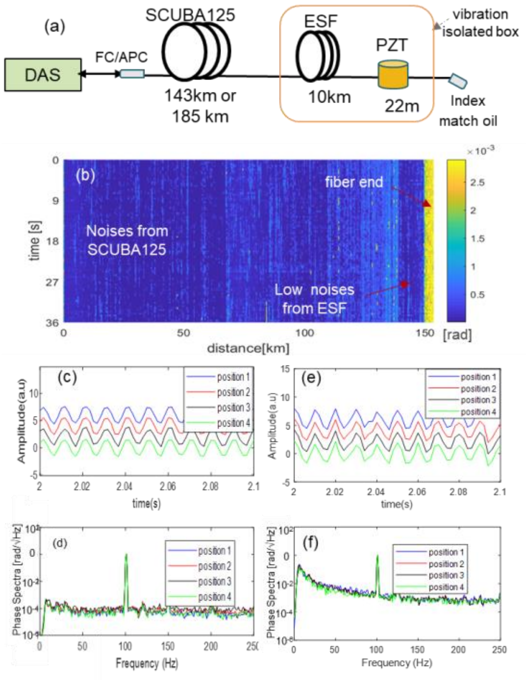

Fig. 2: (a) Experimental set-up for 153km and/or 195km DAS link, (b) waterfall diagram for 153km link, (c-d) phase amplitude and spectra from typical 153km DAS link measurements, (e-f) phase amplitude and spectra from typical 195km DAS link measurements, respectively.

We further extended the DAS reach to 195km by adding another 42km SCUBA125 fibre to the link (similar to the set-up shown in Fig.2(a)). The pulse frame rate of the DAS was adjusted to 500Hz for the 195km DAS link. The driving sinewave on the PZT was not changed. The phase amplitudes and spectra for the 195km DAS link is shown in Fig. 2 (e, f) respectively. The phase noise floor at short frequency was increased compared with that of the 153km link. The measured average phase noise was 12.5mrad/√Hz, and the averaged strain sensitivity and SNR were measured to be 59.9pε/√Hz and 28.6dB respectively.

3. Distributed fibre-optic sensing and 400G data transmission over 195km fibre

Fig.3 show the schematic for our co-existing sensing and 400G DWDM transmission experiment. Two 400Gb/s channels using 400ZR+ transceivers with 75GHz channel spacing were combined with an ASE source (1535.2-1563.94nm) cascaded with a channelized WSS as loading channels. The DWDM channels were amplified by a high-power booster EDFA and combined with the DAS signal via a 90/10 coupler. In the measurement, the WSS was used to block the ASE channels at DAS channel and 400G channels (inset of Fig.3). After 195km transmission and low noise receiver amplifier, a 400G DWDM signal was selected by de-multiplexer (DeMux), then sent to the receiver of the 400ZR+ transceiver. The detail 400Gb/s DWDM transmission set-up and measurement procedures are similar to reference [14]. The pulse frame rate of the DAS was set at 500Hz, The OOB signals have reduced amplitudes for the trade-offs between DAS performance and fibre nonlinearity cross-talks to co-propagating 400G channels due to cross-phase modulation [11]. The driven RF signal on PZT was kept the same. The DAS performance was evaluated with and without DWDM data channels to study the crosstalk. The examples phase amplitudes, and spectra of the measurements are plotted in Fig. 4 (a-b) and (c-d) with and without DWDM data transmission respectively. The measured average noises, strain sensitivities and SNR are summarized in table 1 including those for 153km and 195km DAS only link. The SNR of DAS signal was degraded about 1.8dB when all DWDM data channels turned on.

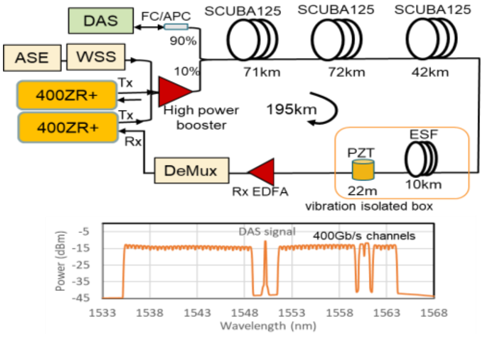

Fig. 3: Experimental set-ups for DAS and 400G DWDM transmission over 195km link, Inset transmitters spectra

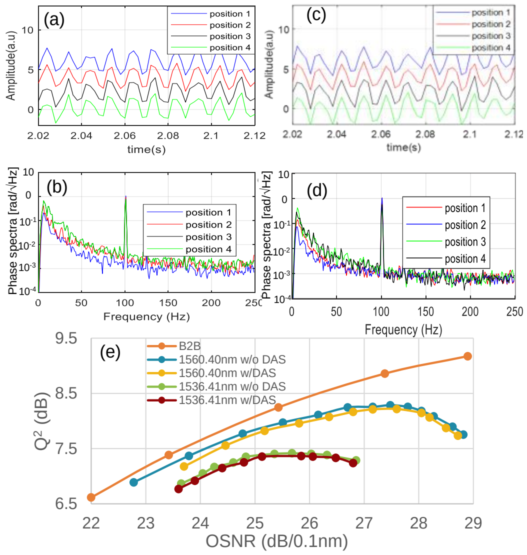

Fig. 4: Phase amplitudes and spectra 195km DAS link with (a-b) and without (c-d) DWDM data channels respectively; (e) Q^2 vs OSNR at channels 1536.41nm and 1560.40nm with/ without sensor signal.

The performance of data transmissions was characterized by measuring bit-error-rate (BER), then converted to Q^2 -factor. The Q^2 factors of 400G channels at 1560.40nm and 1536.41nm as a function received OSNR are plotted in Fig.4 (e) showing negligible penalty from DAS signal and from the reflection of ESF at out-band. For out-band channels, the averaged OSNR was ~ 25.9dB/0.1nm, and the minimum Q^2-factor was 6.7dB, which is below FEC threshold. The system penalty on 400Gb/s at in-band of reflection was not measured as BERs were above the FEC threshold. The in-band penalty of about 6.7dB was observed in 200Gb/s DWDM system [9] with similar reflection of ESF. Nevertheless, simultaneous fibre sensing and 400G DWDM data transmission over 195km has been demonstrated. It should be noted that the reflection bandwidth of ESF can made less than 5nm, or the centre of reflection of the ESF can be fabricated in or out of the typical transmission band, so the data bandwidth can be increased and the crosstalk between sensing and data channels can be mitigated.

Tab. 1: Measured average results of DAS systems using ESF and data transmissions.

	phase noises (mrad/√Hz)	Strain senstivity (pε/√Hz)	SNR (dB)
153km DAS link	2.8	13.4	41.8
195km DAS link	12.5	59.9	28.6
195kmDAS with Data	15.6	74.8	26.7
195kmDAS w/o Data	13.0	62.3	28.5

4. Conclusions

We have demonstrated a significant reduction in phase noise of DAS signals using ESF, and more than 10dB noise reduction was found in a 153km DAS link with 10km ESF compared with that with 10km SSMF. The longest DAS link of 195km without inline amplification have also been reported. In addition, simultaneous fibre sensing and 400G DWDM transmission over 195km fibre link have been demonstrated and crosstalk between DAS signal and DWDM channels have been studied.

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