Laser Processed Reflector Fibre with Enhanced Backscatter for Distributed Sensing

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Abstract: Low loss point reflectors were fabricated in optical fibre by femtosecond laser writing to enhance and control the backscattering signal, for low noise and high resolution distributed acoustic sensing based on optical time domain reflectometry.

Keywords: Femtosecond laser writing; Distributed acoustic sensing; OTDR.

Rapid developments in optical fibre distributed acoustic sensing (DAS) have attracted much research interest, with applications ranging from long distance cable monitoring [1] to seismology [2]. Dynamic mapping of acoustic waves or strain using fibre Bragg gratings (FBGs) at different wavelengths for each point is often limited to ~100 points/fibre. Using low reflectivity FBGs of the same Bragg wavelength interrogated by time division techniques can overcome this, but remains vulnerable to resonance wavelength thermal drift. While intrinsic optical fibre Rayleigh backscattering can be exploited for optical time domain reflectometry (OTDR), it is weak for telecoms fibre (-82 dB for 1 ns pulse width at 1550 nm). To address these issues, we have developed an ultrafast laser processing technique to fabricate low loss point reflectors in optical fibre, with consistent and controllable reflectance.

Each reflector resembles a plane of higher refractive index, thus exhibiting a broadband reflection with minimal scattering loss. Fabrication is quick (~30 s per reflector) with no additional fibre pre/post-processing. Since most of the fibre remains unmodified, the total loss is low. The localized nature of the reflection (unlike Rayleigh scattering) allows for interferometric techniques between the point reflectors, without interference fading. We demonstrate the reflector fibres in two DAS schemes which exploit the strong backscatter signal for long range or high spatial resolution monitoring while minimising noise.

The fibre was modified by focusing 200 fs laser pulses from the second harmonic of a 1030 nm 200 kHz source (PHAROS, Light Conversion Ltd.) into SMF-28 fibre using a 0.5 NA oil immersion lens, as shown in Fig. 1(a). Each reflector was produced by scanning the beam in a rectangular raster pattern covering the core (Fig. 1(b)), with 100 scanlines 20 µm wide spaced vertically by 100 nm. The fabrication process is reel-to-reel with computer-automated winding, fibre positioning and laser writing.

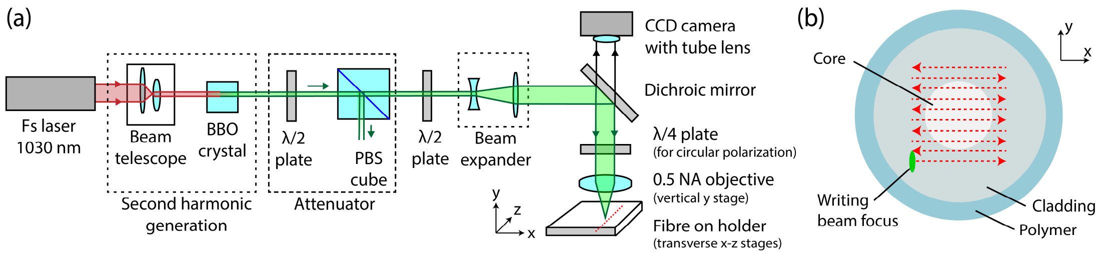

Figure 1 (a) Femtosecond laser writing set up used to inscribe point reflectors in fibre. (b) Laser scanning path forming a single point reflector covering the fibre core cross section. Scanlines are spaced 100 nm apart.

Adjusting the pulse energy between 1–5 µJ allows reflectance to be set between -63 dB and -48 dB with high consistency (standard deviation ~0.9 dB). The reflector plane thickness is ~1 µm, allowing reflectors to be spaced arbitrarily closely or far apart. An OTDR arrangement using a 1550 nm 1 ns pulse source monitors the reflector back-reflection during writing as feedback for dynamic adjustment of writing parameters. The cut-back measured insertion loss was ~0.01 dB for 100 reflectors at 1550 nm.

For the first DAS scheme in Fig. 2, four 2.5 km SMF-28 fibre samples each with 250 reflectors 10 m apart were fabricated with reflectances between -48 dB to -63 dB and interrogated by frequency multiplexed phase sensitive (φ-) OTDR [3]. The power spectral density (PSD) S_φ spectrogram extracted from the time-varying phase measurement correctly identifies the frequency and position of a piezo-electric transducer (PZT) modulated at 700 Hz (Fig. 2(c)), with -60 dB harmonic distortion, 40 dB crosstalk suppression, and 10 m spatial resolution. The strongest reflector fibre sample demonstrated -101 dB (re rad^2/Hz) phase noise over 2.5 km for 2–15 kHz in Fig. 2(d) (approx. 0.095 pε/√Hz strain noise).

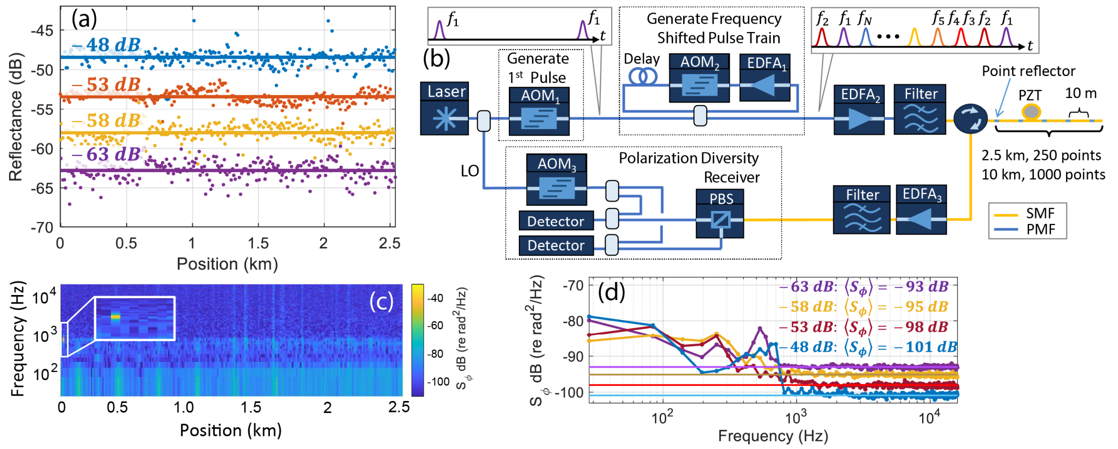

Figure 2 Test scheme 1: (a) Reflectance of point reflectors in 4 fibre samples. (b) φ-OTDR setup using 10 frequency-shifted temporally spaced interrogation pulses. (c) PSD spectrogram along the –48 dB reflectance fibre with PZT modulated at 700 Hz near start. (d) Phase noise PSD for each point reflector fibre. Solid lines indicate mean noise between 2–15 kHz.

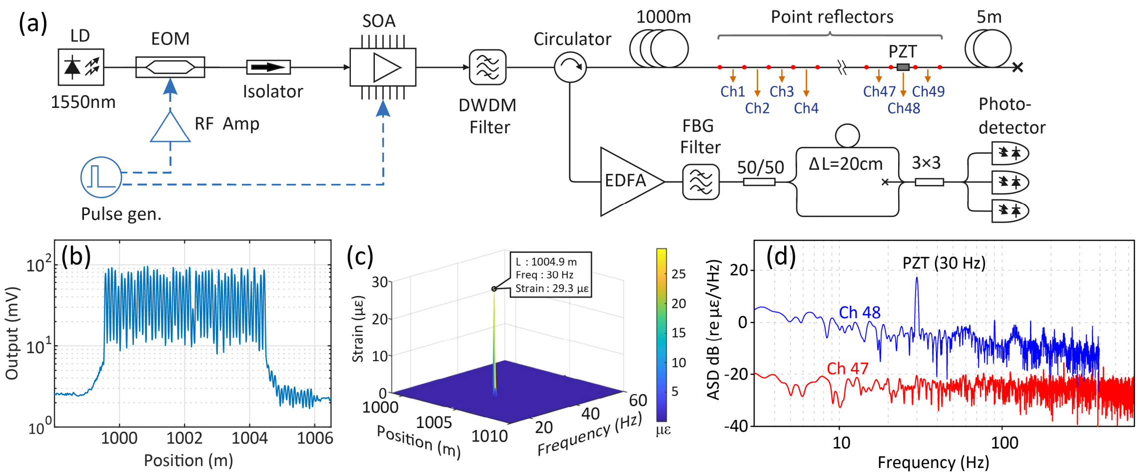

Figure 3 Test scheme 2: (a) High spatial resolution DAS set up based on interfering back-reflections from adjacent reflectors using 0.5 ns 1550 nm pulses. Red dots indicate reflector points. (b) OTDR trace of test fibre with 50 reflectors at 10 cm spacing, average reflectance -56 dB. (c) Mapped strain spectrogram of fibre showing PZT-modulated strain location. (d) Strain ASD for channel 48 (with PZT modulated at 30 Hz) and neighbouring channel 47 (before the PZT).

The second OTDR scheme in Fig. 3 aims to achieve a high spatial resolution by interrogating a fibre with 50 reflectors (mean reflectance -56 dB) spaced 10 cm apart using 0.5 ns 1550 nm pulses and then interfering the back-scatter of adjacent reflectors using a Mach-Zehnder interferometer, with the output sampled at 1.25 GS/s. Using a modulated PZT, the mapped strain output spectrogram in Fig. 3(c) confirmed a 10 cm spatial resolution, while the strain amplitude spectral density (ASD) in Fig. 3(d) showed a 1.9 nε/√Hz noise floor (averaged from 1 Hz –1 kHz), with 21 dB channel crosstalk suppression.

In summary, we have demonstrated a femtosecond laser writing process to fabricate point reflectors in optical fibre over several kilometres with adjustable reflectance (-63 to -48 dB) with high consistency (0.9 dB std. dev.), which was successfully applied in low noise phase sensitive OTDR and high spatial resolution distributed acoustic sensing schemes.

References

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