Higher-order acoustic modes with Brillouin optical time-domain reflectometer

M. Dossou, D. Bacquet and P. Szriftgiser

Using a discrete Fourier transform-based Brillouin optical time-domain reflectometer, the observation of distributed high-order acoustic longitudinal modes with a 20 m spatial resolution are reported. A dispersion shifted fibre is investigated and a spectrogram with up to a 44 dB dynamic range is reported. Four modes at 10.53, 10.79, 11.0 and 11.16 GHz are clearly identified.

Introduction: Thermally excited acoustic phonons in optical fibres are at the origin of longitudinal acoustic modes. By backscattering the incident light, these modes induce a stimulated Brillouin scattering (SBS) process above a given threshold of the incident light. Contrary to a standard singlemode fibre (SMF), in which mainly a single acoustic mode is observable at high frequency (>9 GHz for 1550 nm light), there are multiple Brillouin longitudinal modes in a dispersion-shifted fibre (DSF). This is notably owing to its core doping and cladding structure [1]. These modes are sometimes called 'multi-peaks', and have also been observed in microstructured fibres [2], although in that case they are rather a mix of longitudinal and transverse modes [3]. These modes are of potential interest for distributed sensing applications. Indeed, their frequency dependence on temperature or strain slightly differs from the fundamental Stokes one, which could be useful for strain/temperature discrimination [4]. Recently distributed measurements of multi-peaks in a DSF have been reported in a pump-probe configuration with a Brillouin optical time-domain analyser (BOTDA) [5]. This BOTDA displayed a very high dynamic range. Performing multi-peaks high dynamic range distributed measurements with a Brillouin optical time-domain reflectometer (BOTDR) [6, 7] is also of potential interest. This is mainly the case because with a BOTDR measurements can be made within a few milliseconds, while the BOTDA requires typically a few minutes. Additionally, the BOTDR needs access only to one end of the fibre. Distributed measurements of two peaks have been reported with a BOTDR, but no spectrogram was reported [4]. In this Letter, with a discrete Fourier transform-based BOTDR [8], we report a spectrogram displaying four peaks. A high 44 dB dynamic range is also reported for a very modest 20 times averaging and a very short 20 ms measurement time.

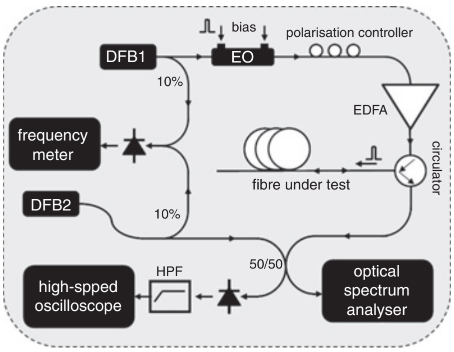

Fig. 1 *Schematic representation of experimental setup*

DFB1 is pulsed, amplified and sent to fibre under test. Backscattered light is collected through circulator, mixed with DFB2 to lower the signal frequency. The optical spectrum analyser is there for calibration purpose in continuous operating mode

Experimental setup and results: The experimental setup is depicted in Fig. 1. A first distributed feedback laser diode (DFB1, ~1548 nm) is pulsed and amplified with an erbium-doped fibre amplifier (EDFA). Around ~1 W, and $\tau = 200$ ns-long pulses are launched in a ~900 m-long DSF section. The time of flight of the backscattered light is collected with a circulator, and mixed with a second DFB (DFB2). DFB1 and DFB2 are low-noise laser diodes with a ~500 kHz full width half maximum (FWHM). A typical emission spectrum of these diodes can be found in [9]. Except for an accurate current and temperature control, both DFB1 and DFB2 are free running with no servo locking of their frequency [10]. However, a beat-note of these diodes is monitored by a frequency-meter and the absolute frequency for a spectrogram is corrected with this measurement. DFB2 is red-shifted with respect to DFB1 by ΔF (10.14 GHz presently). The beat-note between DFB2 and the SBS backscattered light occurs then at a frequency far below 10 GHz, which could easily be logged with a high speed oscilloscope (>3.5 GHz bandwidth, 8 bits vertical resolution). After an optical to electrical conversion, the signal is filtered with a 200 MHz highpass filter (HPF) and amplified. The HPF is helpful for rejecting low-frequency noise that could otherwise saturate the amplifier stage; in a future work, it could also be useful to reject the fundamental Stokes lines. Indeed, this line is potentially more intense by several orders of magnitude compared to higher order peaks. By tuning ΔF so that the main Stokes line beat-note falls in the HPF cutoff band, one could decrease the vertical scale of the oscilloscope without any saturation to take advantage of its full dynamic range. The sampling rate of the oscilloscope is 20 GHz/s.

After the HPF, the time-logged signal is numerically filtered and down-sampled by a factor 4, which results in an effective $F_S =$ 5 GHz/s sampling rate. The lowpass filter acts as a moving average over ~four points. This process results in an increase of the signal-to-noise ratio by a factor 2 and an effective 9 bits vertical resolution for the oscilloscope. The downsampled signal is sliced into segments made of N_{FFT} consecutive samples. Each segment has a 75% overlap with the previous one to optimise the spectrogram visual aspect. The spectrogram is then compounded with a concatenation of the square of the absolute fast Fourier transform (FFT) of each segment. Note that the numerical spatial resolution Δr_{num} is proportional to the segment length N_{FFT}. With no segment overlap: $\Delta r_{num} = \frac{1}{2}\frac{c}{n}\frac{N_{FFT}}{F_S}$, where c is the vacuum speed of light, n the fibre effective optical index. The 1/2 factor takes into account the fact that the light pulse has to go back and forth. For a better spatial resolution, one could think to reduce N_{FFT}, but this would be at the cost of a degraded frequency resolution because they are inversely proportional. Indeed, the Nyquist frequency F_{Nyq} is half F_S; because the data are real, the spectrum is symmetric so that only half of the points are useful after an FFT. The frequency resolution is then: $\Delta f = F_{Nyq}/(N_{FFT}/2) = F_S/N_{FFT}$. In this Letter, we have chosen $N_{FFT} = 512$ (for which $\Delta f \sim$ 10 MHz) is a good compromise. For this value, Δr_{num} is half the physical spatial resolution $\Delta r_{pulse} = c\tau/(2n) \sim 2\Delta r_{num} \sim 20$ m. Reducing the pulse duration τ for a better spatial resolution would be almost useless, unless by reducing N_{FFT}, again at the cost of an increase in Δf.

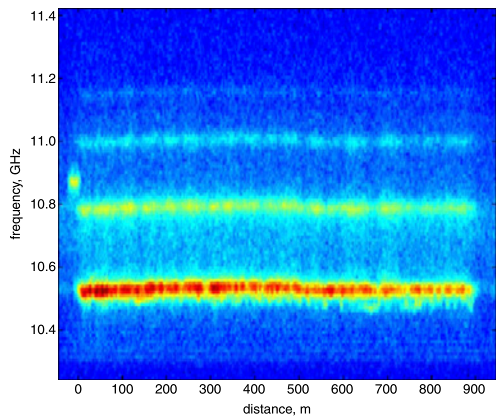

Fig. 2 *Experimental spectrogram of 900 m DSF fibre acquired with BOTDR*

Four higher-order acoustic modes are clearly visible. Beginning and end of fibre are clearly resolved. Bright point at 0 m and 10.87 GHz corresponds to SMF section used to connect DSF to BOTDR

The signal is acquired 20 times with a 1 kHz pulse frequency rate. The total acquisition time is then 20 ms. The acquisition is made in a sequence mode, i.e. once a new acquisition has begun, the signal is acquired at each pulse (without missing one), and stored in the oscilloscope memory as a segment. Each segment will give a spectrogram; the final spectrogram is an average of all of them. Fig. 2 shows a typical acquisition. Besides the fundamental Brillouin mode at 10.53 GHz, three higher-order modes at respectively 10.79, 11.0 and 11.16 GHz are clearly visible. Strain and temperature dependence of the DSF is already known [4]. To show that our spectrometer gives the expected resolving spatial power, instead of heating or stretching a fibre section, we have shown both ends of the spectrogram. The frequency and the amplitude of the fundamental mode have then been fitted. The results are shown in Fig. 3. One can clearly see sharp rising and falling amplitude edges. For instance, for the rising edge, there is an increase in amplitude of ∼24 dB over a time span corresponding to ∼18 m, in good agreement with the expected resolution. To complete the study, Fig. 4 shows an average over 20 m of the spectrogram cross-sections from 40 to 60 m. The dynamic reaches 44 dB.

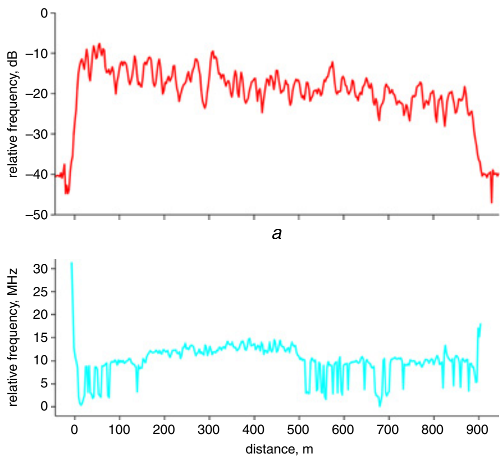

Fig. 3 *Relative power of fundamental mode and relative frequency for same mode*

a Relative power
b Relative frequency

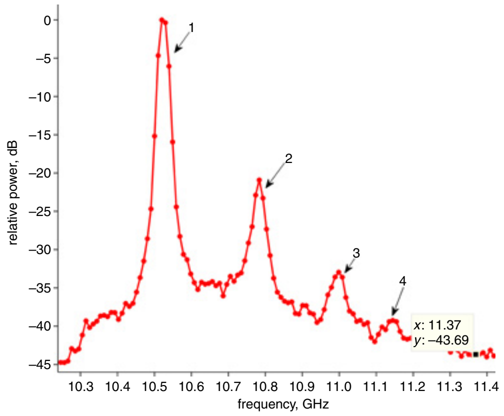

Fig. 4 *Average cross-section of spectrogram over 20 m from 40 to 60 m*

Conclusion and perspectives: We have reported a full spectrogram with four acoustic modes with a BOTDR. A very high 44 dB dynamic range is also reported which is to date and to our knowledge the best dynamic range for a BOTDR. Presently, the acquisition time is 20 ms (1 kHz pulse rate, average 20 times). The overall process, including data transfer, processing and displaying takes typically 1 or 2 s. This time could be optimised to be almost negligible with an acquisition card (instead of an oscilloscope) followed by an adequate field-programmable gate array (FPGA). For a 1 km-long fibre, the pulse frequency could be increased to ∼30 kHz, which would correspond to a sub-millisecond acquisition time. The SBS Stokes line, and higher-order modes are potentially sensitive to some fibre geometry fluctuation [11, 12]. A high dynamic range simultaneously with a ∼1 ms acquisition and processing time could lead to new applications for distributed sensors. As the BOTDR needs access to only one end of the fibre, it could be used, for instance, for real-time monitoring of the fibre geometry during the drawing process.

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One or more of the Figures in this Letter are available in colour online.

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