Measurement of Brillouin gain spectrum with dual-frequency laser for optical fibre sensor

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In this Letter, the authors present a first measurement of Brillouin gain spectrum with dual-frequency solid-state laser. This allows a coherent detection of the Brillouin backscattered spectrum in a frequency range below the hundreds of MHz by fine-tuning of the difference between the two cross-polarised fields emitted by the laser. The photodetection at low-frequency benefits from the balanced detection technique where high dynamic range measurements are largely available. The narrow line-width of the cross-polarised field permits also the direct measurement of the Brillouin spectrum line-width. The system is demonstrated by measuring the Brillouin frequency shift with temperature when standard single-mode fibre-28 (SMF-28) and large effective area fibre (LEAF) are fully heated. This gives temperature coefficients close to theoretical expectations with values of 1.16 MHz/°C for SMF-28 and 1.15 MHz/°C for LEAF.

Introduction: The phenomenon of spontaneous or stimulated Brillouin scattering applied to optical fibre sensors has been the subject of numerous scientific investigations during last few decades thanks to its high capacities such as (i) high sensitivity to a localised temperature variation and/or deformation in the fibre, (ii) long sensing range and good spatial resolution, and (iii) potential applications for a large-scale structural health monitoring [1]. The performances of these distributed sensors are constantly improved to have the most accurate measurement of the Brillouin frequency shift (BFS) [2, 3]. There are several conventional systems allowing a distributed measurement of this BFS either in time domain [4], in frequency domain [5] or in correlation domain [6]. Some of these systems use the same laser source as a pump wave for the excitation of Brillouin backscattering and also as a local oscillator (LO) for coherent detection, which requires a high bandwidth photodetector combined with frequency down-conversion electronics [7]. To overcome this constraint, these systems have been upgraded by introducing an optical frequency translation block to shift the pump wave frequency by the Brillouin frequency difference [8]. Another solution consists in using two independent laser sources for pump wave and LO wave with a frequency difference close to the BFS value [9]. However, the uncorrelated laser diodes solution presents an inability to have high beat-frequency stability through a simple optical phase-locked loop (OPLL) [10] and a lack of frequency tunability of the frequency difference, making the adjustment of the frequency difference as near as possible to BFS quite difficult, knowing that there are fibres with several BFS. The tuning range of the frequency difference is thus limited by the OPLL parameters. We believe that a new generation of Brillouin sensors that would overcome these systems penalties is greatly needed. For this, we implement the Brillouin sensor with a dual-frequency cross-polarised laser (DFL) which offers the best compromise between compactness and large tunability. Previous work based on such configuration has been initiated in [11] with a dual-frequency cross-polarised vertical-cavity surface-emitting laser (VECSEL). The advantage of solid-state laser over VECSEL is the stability of lasing modes, particularly with temperature. In this Letter, we present first measurements of a Brillouin-fibre optic gain spectrum based on DFL. The corresponding emitted fields are cross-polarised, which facilitates their spatial separation. Besides, the frequency difference stabilisation could simply be achieved because the two optical frequencies are generated within the same laser cavity. The frequency difference between the two laser eigenstates can be tuned over the full free spectral range of the cavity. This makes it possible to be adjusted at a frequency close to the BFS of silica-based fibres. Using the heterodyne coherent detection scheme, one ends up with a beating frequency lower than 500 MHz, low enough for signal processing, with low noise and high dynamic electronics. Here, we seek to take advantage of these unique features to develop a state-of-the-art Brillouin optical time-domain reflectometer (B-OTDR) sensor.

The Letter is organised as follows: first, a description of the laser source and developed experimental set up is given. Then, we present the static measurement results of the Brillouin gain spectrum of a 40 km single-mode fibre (SMF) and a 10 km large effective area (LEAF). Finally, the measured peak-frequency shifts of the Brillouin spectrum with temperature are given for the used fibres and their respective temperature coefficients are estimated and compared to theoretical values.

Description of experimental set-up and measurement results: The originality of the proposed Brillouin optical sensor resides in the use of a single laser source generating simultaneously the pump and LO optical signals. It consists of a dual-frequency dual-polarisation laser where the frequency difference between the two laser eigenstates can be tuned to down-convert the Brillouin spectrum to an intermediate frequency through a simple coherent detection. In this section, we describe the laser source, the developed experimental set-up, and present measurement results of a Brillouin gain spectrum.

Dual-frequency dual-polarisation laser description: The schematic diagram of a dual-frequency dual-polarisation laser is shown in Fig. 1*a*. This laser was initially developed for RADAR clock applications [12]. It consists of an optically pumped Er/Yb solid-state laser emitting at the telecom wavelength [13, 14]. The control of the gain medium and the use of the 1-mm birefringent $LiTaO_3$ crystal allow the simultaneous emission of two cross-polarised eigenstates. An uncoated silica etalon inserted inside the cavity permits the selection of one optical mode for each polarisation. The tunability of the frequency difference between the two cross-polarised eigenstates is ensured by the two electro-optic and thermo-optic effects of the $LiTaO_3$ crystal having typical intrinsic coefficients of 1 MHz/V and 1.1 GHz/K, respectively [12, 15]. In this laser configuration, the maximum frequency difference between the two fields can reach 30 GHz. Furthermore, since the two modes arise from the same cavity, any thermal drift inside the cavity length or vibration of the mirror mounts induces equal frequency variations in both modes and results in a narrow bandwidth beat note [12]. At the laser output, the optical beam is collimated and fibre-coupled to a single-mode polarisation maintaining fibre.

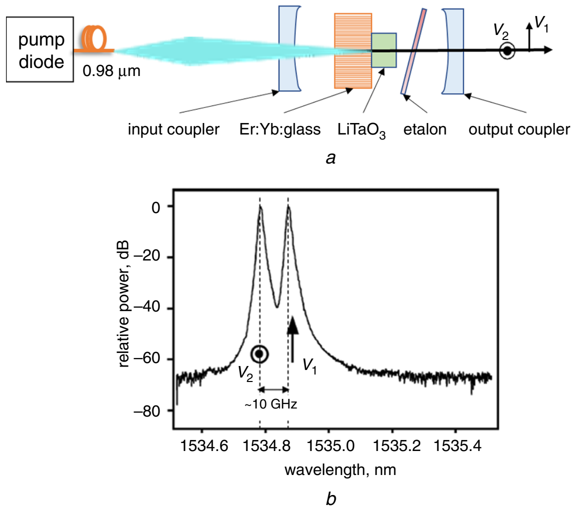

Fig. 1 *Dual-frequency dual-polarisation laser*

a Topology
b Output optical spectrum

The BFS ν_B is typically between 10.5 and 11 GHz for silica-based fibre. Fig. 1*b* shows the optical spectrum of the two modes of the laser where the frequency difference has been stabilised using the optical phase-locked loop method and external RF reference, as described in [12–15]. The power of the laser modes depends on the cavity gain profile and can be adjusted by the crystal applied voltage. Then, the two modes are chosen to promote the pump wave and at the same time to prevent the saturation of the photodiode with high LO power. The OPLL has been developed with laboratory instrument solutions where the spectral purity of the resulting beat note has been improved from a typical short-term line-width over 1 kHz in free-running conditions to a value below 200 μHz when the beat note is locked [15]. However, knowing that the use of an external reference is not important since the two laser frequencies are phase correlated. As the purpose of the locking loop is to provide long-term frequency drift compensation with an alternative procedure that does not require an external reference but based on an optical frequency locked loop. This opens the way to a more simplified and compact system compared to conventional ones. The implementation of this technique for DFLs is discussed in [12, 15]. In our experiments, it is important to precise that these results were obtained without insulation of the laser cavity compared to the laboratory environment. Thus, we were able to lock the laser at the desired beat frequency for the tenth of minutes and more.

Experimental set-up for Brillouin spectra measurement: The proposed system based on a dual-frequency laser is illustrated in Fig. 2. The DFL frequencies (ν_1 and ν_2, $\nu_1 > \nu_2$) are synchronised with an OPLL as detailed in [13] and are separated by a beam polarisation splitter, where the optical frequency ν_1 is used as a pump wave to excite the Brillouin scattering process and the optical frequency ν_2 is used as an optical LO for coherent heterodyne detection. The pump wave power is controlled by an erbium-doped fibre amplifier followed by a variable attenuator. An optical circulator is used to inject the pump wave into the fibre under test and to drive the backscattered Brillouin Stokes signal (frequency ν_S) to the detection block. A 50/50 optical coupler is used to combine Stokes signal and optical LO signal for detection with a low-speed commercial photodiode. The resulting electrical signal is then amplified with a 50 dB LNA (RF Amp) and filtered with a 825 MHz low pass filter. The amplified electrical signal is analysed with an electrical spectrum analyser in a frequency bandwidth lower than 1 GHz, where the spectrum is acquired directly by processing the fast Fourier transform of the time signal.

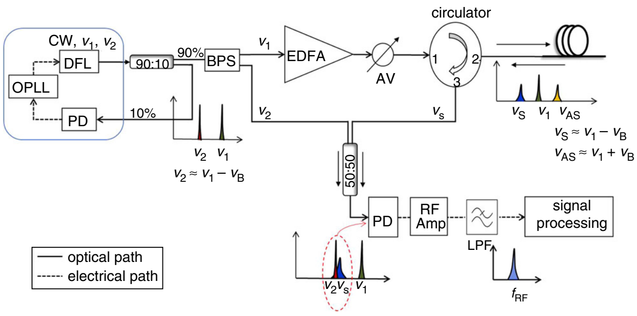

Fig. 2 *Experimental setup for characterisation of Brillouin backscattering spectrum based on dual-frequency laser. All parameters are defined in text*

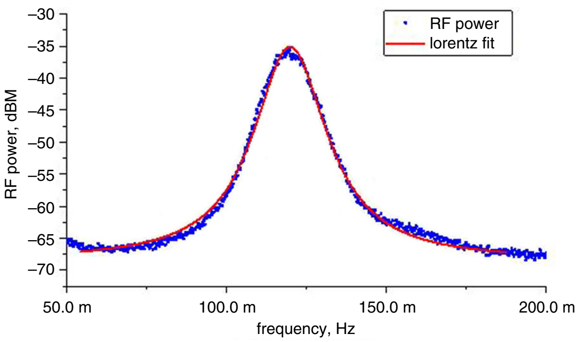

Fig. 3 *Measured Brillouin gain spectrum and Lorentzian fitted curve of SMF-28 at room temperature*

Measurement results of Brillouin gain spectrum: The process of the Stokes backscattered wave is characterised by the Brillouin gain spectrum, which has a Lorentzian shape according to (1). This is in the hypothesis that acoustic waves decrease exponentially [3]

$$g_B(\nu) = g_{B_0} \frac{\left(\frac{\Delta\nu_B}{2}\right)^2}{(\nu - \nu_{B_0})^2 + \left(\frac{\Delta\nu_B}{2}\right)^2} \tag{1}$$

where g_{B_0} is the Brillouin gain coefficient at the Brillouin frequency peak ν_B and $\Delta\nu_B$ is the full width at half maximum (FWHM) of the gain spectrum. The spontaneous Brillouin spectrum of a 40 km SMF-28 and a 10 km LEAF have been characterised in a climate-controlled room for an injected pump power of 20 mW and an optical LO power of 100 μW. Fig. 3 shows the measured and fitted Brillouin spectrum for the 40 km SMF-28 when the DFL beat frequency has been locked at 10.83 GHz. The measured peak frequency of the spectrum is around 120 MHz, which corresponds to a typical BFS value of 10.8 GHz for such fibre. For spectrum characterisation purposes, a Lorentzian fit gives a Brillouin line-width of 9.32 MHz, which is consistent with our expectations [16], since the diffusion process is in stimulated mode (or amplified spontaneous diffusion) where the critical power is 3 mW.

The Brillouin spectrum of the 10 km length LEAF is shown in Fig. 4. The multi-peak Brillouin spectrum corresponding to the different acoustic modes of the fibre has been measured. As only frequency values of Brillouin peaks are sought in this characterisation, the electrical filter, which influences only on the peak powers, has not been changed. Only three peaks of Brillouin backscattering signal are identified at frequencies of 743.1, 1140, and 1360 MHz. The frequency interval between the first and the second peak is about 400 MHz, which is compliant with typical LEAF values. The second and third peaks are attenuated by the low-pass filter where the fourth peak is filtered and being drowned in the noise floor.

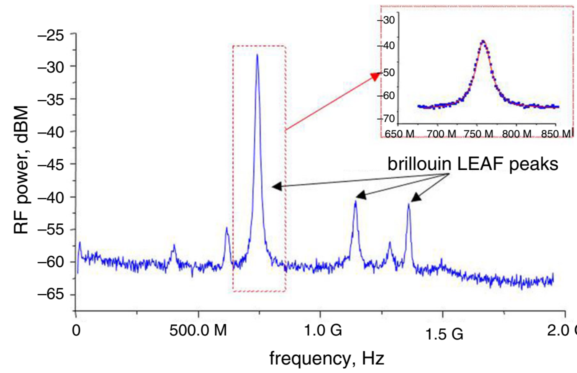

Fig. 4 *LEAF multi-peaks frequency Brillouin gain spectrum at room temperature*

The other peaks of the spectrum are linked to signal distortion, probably due to inter-peak coupling. The Lorentzian fit of the first Brillouin peak gives a line-width of 7.76 MHz describing an amplified diffusion process. It is important to notice that the high phase stability of the two laser eigenstates gives a measured beat note line-width of a few kHz in free-running mode [12]. This allows a precise measurement of the Brillouin gain line-width compared to other state-of-the-art solutions. Thus, direct measurement of the FWHM Brillouin line-width is obtained with a dual-frequency laser based on B-OTDR that can be used to evaluate temperature/strain variation.

BFS temperature dependence: The BFS dependence with temperature and/or strain is the physical parameter that is exploited in distributed fibre sensors. The dependence of this shift is quantified by the associated sensitivity coefficients of the considered fibre

$$\delta\nu_B = C_T\Delta T + C_\epsilon\Delta\epsilon \tag{2}$$

where C_T and C_ϵ are, respectively, the sensitivity coefficients of temperature and strain, ΔT and $\Delta\epsilon$ are changes in temperature and strain, respectively. For a wavelength around 1550 nm, the coefficients related to BFS are typically $C_T \approx 1$ MHz/°C and $C_\epsilon \approx 0.05$ MHz/$\mu\epsilon$ for SMF-28 [16]. For the LEAF, these coefficients are of 1.19 MHz/°C and 48 kHz/$\mu\epsilon$ for peak 1 and 1.22 MHz/°C and 50 kHz/$\mu\epsilon$ for peak 2 [17]. To determine these coefficients with the proposed system, each fibre (SMF-28 and LEAF) has been completely heated in a controlled temperature oven from 24 to 30°C by a step of 1°C.

Fig. 5 shows the measurement results for the 40 km length SMF-28 when the beat frequency of the DFL has been stabilised at 10.83 GHz. The linear behaviour of the dependence of the frequency shift with the temperature is observed. As expected, the central frequency of the spectrum shifts towards the high frequencies with the increase of the fibre temperature. The sensitivity coefficient C_T has been estimated according to the BFS with temperature. A recording temperature error of 0.4°C is considered, which is linked to the maximum difference between the oven probe and an external probe positioned at the surface of the spooled optical fibres. This means that a relative error of 0.4°C around an external probe measured temperature is considered. This error is represented by horizontal error bars in the figures. Then, the uncertainty on the recorded values is estimated from a triangular distribution function with a 95% confidence interval. This distribution is determined from the minimum and maximum values of the coefficient C_T between two consecutive temperature points according to the error bars. The estimated sensitivity coefficient is obtained by considering the extreme error case and is of 1.16 MHz/°C ± 65 kHz/°C for SMF-28, which agrees well with the theoretical expectation.

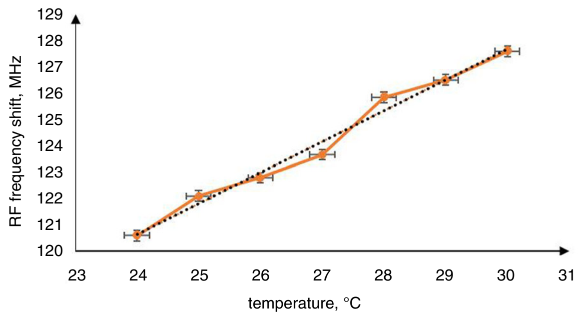

Fig. 5 *BFS with temperature for SMF-28*

For the LEAF characterisation, only the first two peaks are considered and the DFL's beat frequency has been stabilised at 9.83 GHz giving a first photo-detected Brillouin peak frequency close to 740 MHz and the second peak around 1140 MHz. As for SMF-28, the Brillouin multi-peak frequency shift related to LEAF has the same behaviour with temperature. Fig. 6 shows a quasi-linear increase of the two first peaks with the increase of the fibre temperature. The estimated sensitivity coefficients for these peaks are, respectively, of 1.15 MHz/°C ± 31kHz/°C and 1.35 MHz/°C ± 37 kHz/°C. These coefficients are in good agreement with those presented in [17].

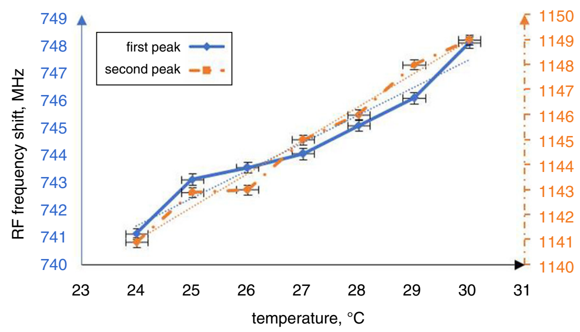

Fig. 6 *Multi-peak BFS with temperature for LEAF*

Conclusions: We characterise the Brillouin gain spectrum using a dual-frequency and dual-polarisation laser for the next-generation of distributed optical sensing systems. The advantages of this system are: (i) the two laser frequencies are phase correlated leading to a low noise sensor and (ii) the wide tunability of the frequency difference allowing to adjust the frequency difference to BFS. The Brillouin spectra of SMF-28 and LEAF have been characterised to validate the proposed system. The averaged spectra have shown a high stability over time and allows the direct measurement of the Brillouin line-width. The BFS with temperature has been characterised for both fibres for which the expected linear relationship has been observed. For SMF-28, the measured temperature coefficient is around a value of 1.16 MHz/°C, while for LEAF, it is 1.15 MHz/°C for the first peak frequency and 1.35 MHz/°C for the second one. These temperature sensitivity coefficients of both fibres are in good agreement with the published data.

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

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