Optimized configuration for high resolution distributed sensing using Brillouin echoes

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ABSTRACT

A novel configuration has been developed to optimize the response of Brillouin echoes for distributed fibre sensing. Fully resolved measurements of the Brillouin frequency shift of a 5cm spot perturbation have been performed using a 500 ps (5cm) pulse width. The linewidth of the measured Brillouin gain spectrum remains comparable to the intrinsic linewidth for any pulse width. The high accuracy and inherent stability of the technique have been successfully verified.

Keywords: Fiber optics sensors, stimulated Brillouin scattering, distributed fiber sensor, Brillouin echoes.

1. INTRODUCTION

For at least two decades the interaction between an acoustic wave and an optical wave observed through the nonlinear process called stimulated Brillouin scattering (SBS) has attracted substantial attention in the fibre sensing community, since it turns out that SBS is particularly efficient and attractive for implementing distributed strain and temperature fibre sensors [1-3].

Brillouin scattering refers to the scattering of a lightwave by an acoustic phonon. At a relatively modest power, SBS generates a strong coupling between a pump and a signal wave that are spectrally separated by the Brillouin shift frequency and are counterpropagating in a single mode optical fibre. This frequency essentially depends on the acoustic velocity in the fibre that turns out to be sensitive to the strain and temperature environment of the fibre.

Changes in strain or temperature can be determined by locally measuring the central frequency of the Brillouin spectrum along the fibre. Information on the position is determined by the time of flight of the light propagating back and forth in the fibre. In a classical configuration such sensors can only offer a spatial resolution not better than ~1 m [4], limited by the acoustic lifetime $\tau_A \cong 10$ ns. The observed Brillouin spectrum broadens as the pulse width decreases, since the effective gain spectral distribution is given by the convolution between the pulse spectrum and the natural Brillouin gain spectrum (~27 MHz in silica fibres).

However, recently specific advanced applications have required a substantial step towards better spatial resolution while preserving the same precision in the determination of strain and/or temperature. A classical configuration does not clearly fulfill such requirements since the linewidth of the Brillouin gain spectrum (BGS) should be as narrow as possible to precisely determine the information about the strain and temperature. This requires the use of long pulses, clearly incompatible with a high spatial resolution. In a classical configuration high spatial resolutions and narrow Brillouin frequency profiles are incompatible quantities, thus impossible to achieve simultaneously.

A remarkable breakthrough was realized when it was observed that the pre-excitation of the acoustic wave by a continuous pump can lead to a high spatial resolution while keeping a sharp Brillouin gain profile [5]. In such a configuration the pulse is simply reflected on the pre-existing acoustic wave that sees its amplitude mostly unchanged by the presence of the pulse. The pulse is simply locally probing the existence of the continuous acoustic wave: this is the concept of distributed sensing using Brillouin echoes (BEDS). The technique has been used *per se* using a bright pulse on top of a continuous wave down to a 15 cm spatial resolution [6] or using a dark pulse to resolve 2 cm spots [7]. By analyzing the physical principles behind Brillouin echoes a more recent configuration has been proposed, that optimizes the response by modulating the pump using π phase pulses [8].

In this paper, we demonstrate experimentally simultaneous high spatial and temperature/strain resolutions using the optimized Brillouin echo distributed sensor based on phase pulses. A spatial resolution down to 5 cm could be easily achieved while keeping a moderate number of averaging (256). The Brillouin linewidth dependence on the pulse width

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was examined experimentally and turned out to remain unchanged and comparable to the natural linewidth of 27 MHz even for pulses much shorter than the acoustic lifetime.

2. PRINCIPLE AND EXPERIMENTAL IMPLEMENTATION

The optimized implementation of BEDS is realized by propagating continuous pump and probe waves through the sensing fibre at the proper frequencies for the Brillouin interaction and by abruptly and briefly shifting the phase of the CW pump wave by π during a time much shorter than the acoustic lifetime τ_A. During this very short time the acoustic wave doesn't have time to noticeably change its phase and amplitude, so that the pump will be reflected completely out of phase during the brief π–phase shift, when compared to the normal steady-state gain situation. A destructive interference on the signal results from this pump reflection, observed as a small apparent loss on the probe waveform. This brief reflection on the pre-existing acoustic wave is called the *first echo* and its magnitude is proportional to the amplitude of the steady acoustic wave generated by the continuous counterpropagating optical waves. When the phase of the pump returns to its initial state, the normal steady state gain situation is restored. Nevertheless the acoustic wave slightly changed its amplitude and phase during the pump phase pulse and then returns slowly to its initial state during a typical time given by τ_A. This creates a small deficit in gain during this period that manifests as a trailing and decaying loss over the probe waveform. This effect is called *second echo* and is clearly detrimental for the measurement, since it gives a trailing signal that may interfere with the useful information given by the first echo at later positions. The relative importance of the second echo when compared to the first main echo decreases for shorter pulses; however solutions must be found to subtract from the probe signal the response of the 2nd echo to get unbiased information. A more detailed description of the echo response is devoted to another presentation in this conference [9].

Our BEDS experimental configuration is based on a simple modification of the classical pump and probe set-up, as depicted in Fig. 1. The pump and probe optical waves are both generated by the same source using the classical sideband technique [10] and is designed to avoid the propagation of waves showing the same optical frequency in opposite directions through the fibre. This way the optical noise is minimized and no incoherent beating resulting from Rayleigh scattering or spurious reflections is possible in the entire setup [11].

A 1552 nm 11 mW compact external cavity laser diode (Redfern Integrated Optics PLANEX™ RIO0095) was used as light source showing an enhanced coherence (linewidth =23 kHz). A coherence time substantially longer than the acoustic lifetime τ_A is required to allow an efficient build up of the acoustic wave through the stable interference obtained by mixing the continuous pump and probe. The output of the laser diode was split into two distinct channels by a polarization-maintaining coupler: in one of the channel an amplitude modulator is driven by a microwave signal in a suppressed carrier configuration. This creates sidebands which are boosted by an erbium-doped fibre amplifier (EDFA-1) to 20 dBm and launched into one end of the sensing fibre. The other channel is connected to the opposite end of the sensing fibre to launch a continuous pump wave that is periodically modulated by a phase modulator to produce very short π phase pulses. The pulse generator can generate electrical pulses with a 500 ps minimum duration that are directly applied to the phase modulator electrodes, corresponding to a minimum spatial resolution of 5 cm. The output light is controlled by a polarization controller to best align pump and probe polarizations to maximize the SBS interaction, and then boosted to 22 dBm by a second high power EDFA-2. A fibre Bragg grating filter (bandwidth 10 GHz) is placed prior to the detector to eliminate one of the sideband from the signal and any residual light from the pump.

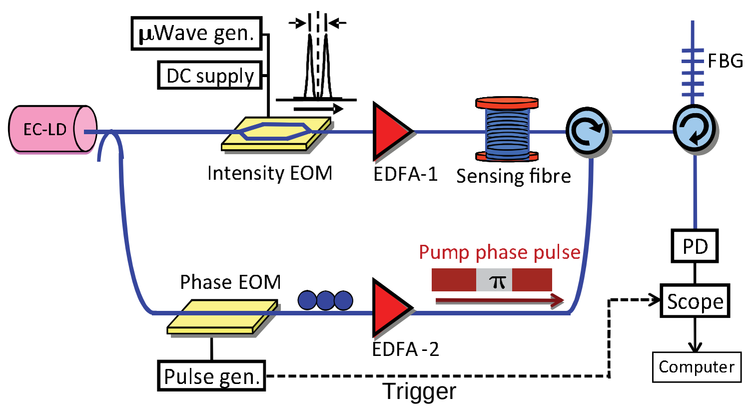
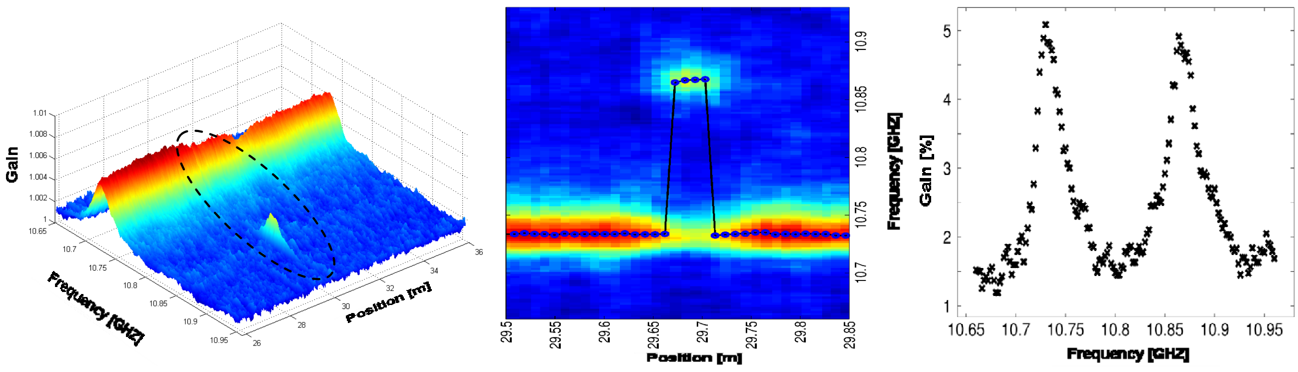


Fig. 1: Experimental setup of the optimized BEDS system: EC-LD: external cavity laser diode; EDFA: erbium-doped fibre amplifier; EOM: electro-optic modulator; FBG: fibre Bragg grating; PD: photodiode.

The Brillouin gain spectrum is determined by scanning the microwave generator around the Brillouin shift ν_B. The net Brillouin gain is then measured by converting the optical signal using a DC-1 GHz photodiode (PD). For each preset microwave frequency the signal is acquired in the time domain by a 4 GHz digital oscilloscope synchronously triggered by the pulse generator.



(a) (b) (c)

Fig. 2: (a) 3D distribution of the Brillouin gain along the sensing fibre as a function of frequency and position. (b) Enlarged top view of the 3D distribution of the Brillouin gain in the vicinity of the 5 cm fibre section. (c) Measured Brillouin gain distribution within the 5 cm section at position 29.68 m, showing the high quality of the measured spectrum and the unwanted presence of the second echo interference. Since the echo response manifests as an apparent loss the signal polarity has been inverted for clarity. Measurements were performed using a 500 ps phase pulse (true 5 cm spatial resolution) and a 256 times averaging of each temporal trace.

4. RESULTS

To test the performance of the BEDS system a sensing fibre composed of segments of two different fibres was fabricated. A 5 cm section of G652A fibre was spliced in the middle of a 40 m G652D fibre. This creates abrupt Brillouin frequency shift steps from 10.730 GHz (G652D fibre) to 10.870 GHz (G652A fibre), as a simple consequence of the difference in core doping concentration, as shown in Fig. 2a. It can be clearly observed in the figure that each fibre section is fully resolved.

Measurements were performed using 500 ps phase pulse (5 cm resolution) which is actually the shortest possible pulse handled by our electrical pulse generator. It can be clearly seen on the measurements that there is a dynamic margin and there is space for an even better spatial resolution. The SNR is much improved when compared to our previous results obtained with a 10 cm spatial resolution [8]. This comes essentially from the fact that a standard DFB laser was used for those measurements, leading to a less efficient build-up of the acoustic wave and a more noisy response.

An averaging of 256 waveforms per frequency step was used, resulting in a total acquisition time of about 8 min. Most of this time is associated to the slow setting time of the microwave generator and the data transfer to the computer. The actual amount of time strictly needed to fully analyze the fibre (considering 256 averages and 256 frequency steps) is less than 10 s. Fig. 2b also shows the calculated Brillouin frequency shift as a function of position (solid line), around the 5 cm fibre section. The central frequency of the Brillouin gain was determined by fitting the raw data to a Lorentzian distribution. The uncertainty was about 0.5 MHz corresponding to a temperature accuracy of about ± 0.5°C and strain accuracy of about ± 8.75 με. We could experimentally confirm that the linewidth of the measured spectrum obtained by BEDS is essentially independent of the pulse duration, as illustrated in Fig. 3.

As shown in Fig. 2c an important residual peak at the frequency of the long leading segment (10.730 GHz) is observed in the local measured spectrum, even though the pulse is entirely contained in the short segment (10.870 GHz) at that particular position. This peak is a consequence of the second echo and can clearly lead to a misinterpretation of the observed Brillouin response.

Its amplitude is fairly important despite the ultra short phase pulse, since it results from the sum of all the secondary echoes accumulated along the long homogenous section of the leading fibre. This unwanted response must be eliminated from the measured data to correctly retrieve the local Brillouin signature contained in the measured spectrum.

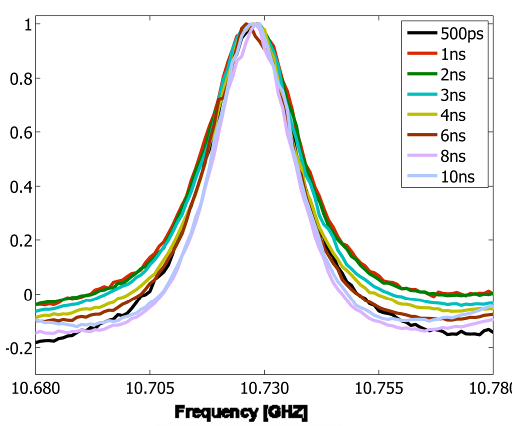


Fig. 3: Spectral distribution of the Brillouin gain measured locally by the Brillouin echo of a π-phase pulse, for a broad range of pulse width shorter than the acoustic lifetime, showing that the measured linewidth is unchanged and equal to the natural linewidth $\Delta\nu_B$=27 MHz.

We could determine two approaches to suppress the interference of the second echo:

1. By deconvolving numerically the time traces: the impulse response of any BEDS sensor is analytically determined [9] and in particular the contribution of the 2nd echo to this impulse response can be unambiguously extracted. This contribution can then be removed from the time traces by a simple step-by-step single pass algorithm.
2. By turning off the pump immediately after the pump phase pulse: no more light from the pump can be reflected after the pulse end and no trailing light is present. This solution was successfully tested [8] for a phase pulse in a differential measurement configuration by subtracting the traces obtained with the phase pulse turned on and off, successively, and was recently adapted for a bright pulse [12]

Tests are carried out to identify the most efficient between these 2 solutions.

5. CONCLUSION

Brillouin echo distributed sensing (BEDS) has proved to be a powerful solution to realize sub-metric spatial resolutions in Brillouin distributed measurements. Thanks to a model giving a general solution an optimized configuration could be defined using π-phase pump pulses that was experimentally tested down to a spatial resolution of 5 cm, with a clear margin for further improvement. Major difficulties are related to the restoring of the acoustic wave that manifests as a secondary trailing echo in the response. In the near future the main effort will be placed in defining technical solutions to suppress the interference of this echo. The range must also be extended, being yet limited to less than 1 km using a continuous pump, as a result of the large integrated gain leading to pump depletion. We are confident that BEDS system will become a key and powerful configuration for the next generation of Brillouin fibre distributed sensors.

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