Highly-sensitive distributed birefringence measurements based on a two-pulse interrogation of a dynamic Brillouin grating

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ABSTRACT

A method for distributed birefringence measurements is proposed based on the interference pattern generated by the interrogation of a dynamic Brillouin grating (DBG) using two short consecutive optical pulses. Compared to existing DBG interrogation techniques, the method here offers an improved sensitivity to birefringence changes thanks to the interferometric effect generated by the reflections of the two pulses. Experimental results demonstrate the possibility to obtain the longitudinal birefringence profile of a 20 m-long Panda fibre with an accuracy of ~10^{-8} using 16 averages and 30 cm spatial resolution. The method enables sub-metric and highly-accurate distributed temperature and strain sensing.

Keywords: Fibre optics, optical fibre sensors, Brillouin scattering, distributed fibre sensor, birefringence.

1. INTRODUCTION

For many years birefringence has been one of the properties of optical fibres that has been extensively used for sensing purposes. While a high birefringence is intentionally imposed during the fabrication of polarisation-maintaining fibres (PMF), birefringence can also be highly affected by external environmental perturbations, thus giving the possibility to perform sensing of quantities such as temperature, strain, electric current, hydrostatic pressure, and others[1-10]. Although there exist several techniques for birefringence measurement, most of them can only measure the average birefringence value, thus limiting those methods only to discrete sensing applications. For birefringence-based distributed sensing, several techniques based on reflectometry have been proposed in the literature: e.g. phase- or polarisation-sensitive Rayleigh based reflectometry in time or frequency domain (φOTDR, OFRD, POTDR, POFDR)[1-4], Brillouin optical time-domain reflectometry (BOTDR)[5], and dynamic Brillouin gratings (DBG)[6]. Those methods provide either direct or indirect measurements of the local fibre birefringence. One of the advantages of direct measurement methods such as DBGs[6-10] is that they can attain very high spatial resolution over longer distances. In particular, OFDR can enable a very sharp spatial resolution (down to a few millimetres), however it requires a sophisticated detection scheme and intense signal processing; on the other hand, DBGs enable centimetre resolution using standard and simple time-domain measurements.

In this paper a novel interrogation method of dynamic Brillouin gratings is proposed and experimentally demonstrated for distributed sensing purposes based on birefringence measurements. The method consists in generating a DBG along a PM fibre and reading it with two consecutive short pulses. The response (reflection) of the BDG to the two reading pulses results in an interference pattern that maps the longitudinal variations of the fibre birefringence with very high precision and sub-metric spatial resolution. The method is experimentally demonstrated measuring the distributed birefringence profile of a 20-m Panda PM fibre with an uncertainty of ~10^{-8}, obtained with 30 cm spatial resolution and 16 averages.

2. MEASUREMENT PRINCIPLE

The method here proposed for distributed sensing based on birefringence measurements consists in generating the DBG along a given polarisation axis of a PM fibre (e.g. the *x*-axis of the fibre) and reading it with two consecutive short pulses aligned with the orthogonal polarisation axis (e.g. *y*-axis). As schematically shown in Fig. 1, the DBG reflection of the two pulses will sum up and interfere in photodetection, leading to a time-domain trace that highly depends on the phase mismatch between the two reflections. This phase mismatch can be tightly related to birefringence

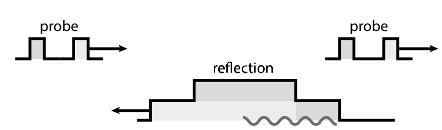

Figure 1. Measurement principle. A DBG is generated and then interrogated using two consecutive short pulses. The response of the DBG corresponds to the sum of the two reflected field.

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variations along the fibre. The principle can be better understood considering the impulse response $h_R(t)$ of the dynamic Brillouin grating, which can be written as:

$$h_R(t) = \frac{c}{2n}\kappa^*(ct/2n)\exp[-it\Delta\Omega_{DBG}(ct/2n)]\,, \tag{1}$$

where $\kappa^*(ct/2n)$ is the DBG coupling coefficient at a fibre location $z = ct/2n$, $\Delta\Omega_{DBG}(ct/2n)$ is the offset between the frequency of the probing pulses and the local resonance peak frequency of the DBG, c is the speed of light and $n = (n_{slow} + n_{fast})/2$ is the average of the refractive indices between the slow and fast axes of the fibre. Note that in the above expression, it has been assumed that the grating frequency matches exactly the Brillouin frequency (i.e. the DBG pumps are separated by the Brillouin frequency of the fibre).

When two very short optical pulses are used to interrogate the DBG, the reflected signal amplitude can be described by the sum of the delayed impulse responses, as:

$$s(t) = h_R(t) + h_R(t-\tau) \propto \exp[-it\Delta\Omega_{DBG}(ct/2n)]\{1 + \exp[i\tau\Delta\Omega_{DBG}(ct/2n)]\}\,, \tag{2}$$

where τ is the separation between pulses, and $\Delta\Omega_{DBG}$ has been assumed constant in the interval $\{t-\tau, t\}$. The detected intensity in the time domain leads to a varying pattern related to the birefringence variations:

$$I(z) = |s(ct/2n)|^2 \propto cos^2\left(\frac{\tau\Delta\Omega_{DBG}(z)}{2}\right). \tag{3}$$

This expression indicates that the local detuning induced by local birefringence variations results in intensity variations that can be measured using simply time-domain reflectometry, with a spectral sensitivity that depends on the separation τ between pulses.

3. EXPERIMENTAL SETUP

Figure 2 shows the experimental setup implemented to validate the proposed method for distributed fibre sensing based on birefringence measurements. In the upper part of the figure, a DFB laser is split into two branches using a PM splitter to generate the two pumps generating the DBG. The light in the top branch is used to generate *pump 1*; which is essentially at the laser nominal wavelength and is amplified by an Erbium-doped optical amplifier (EDFA) to a power level of ~25 dBm. This pump is then launched into the *x*-polarisation axis of a 20 m-long Panda PM fibre. The light in the lower branch is used to obtain a two-sideband pump (*pump 2*); which is generated by using an electro-optic modulator (EOM) driven by an RF frequency corresponding to the Brillouin frequency shift of the Panda PM fibre. The two sidebands are then amplified by an EDFA to reach a power similar to pump 1. Pump powers have been tuned during the experiment to avoid detrimental effects, such as nonlinearities and depletion. Using a polarisation beam combiner, pump 2 is also launched into the *x*-polarisation axis of the PM fibre. Note that since pump 2 contains two spectral components, two distinct Brillouin gratings are generated inside the fibre moving into opposite directions. Only one of these gratings is here interrogated for distributed birefringence measurements.

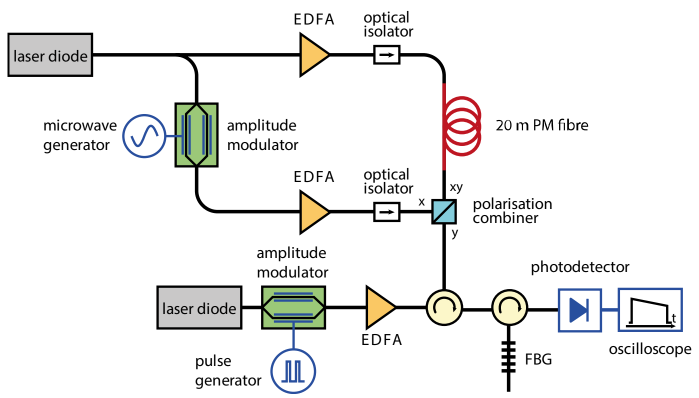

Figure 2. Experimental setup for distributed birefringence measurements, based on the reading of a 20 m-long DBG in a Panda PM fibre using two pulses of 300 ps separated by 3 ns (this defines a 30 cm spatial resolution).

In the second part of the setup the two-pulse probe signal is generated. For this, the frequency of another DFB laser is tuned to match the resonant frequency of one of the Brillouin gratings but along the *y*-polarisation axis. Two consecutive pulses of 300 ps and separated by 3 ns are generated using an EOM, driven by a pulse generator. Pulses are then amplified by an EDFA, and sent into the PM fibre through the PBC that aligns the polarisation of the probe along the *y*-axis of the PM fibre. Note that the probe co-propagates with pump 2, and therefore considering the phase-matching condition between probe and the generated DBG, the probe will be reflected by the DBG at a higher optical frequency (shifted by the Brillouin frequency of the fibre). The signal reflected from the BDG is then filtered and sent into a receiver stage, composed of a 10 GHz FBG filter and a photodetector with a 5 GHz bandwidth connected to an oscilloscope.

4. EXPERIMENTAL RESULTS

To verify the correct operation of the BDG, the optical spectrum of the light reaching the FBG input is measured using a continuous-wave (CW) probe, as shown in Fig. 3. Besides the DBG reflection, it is possible to observe that a large fraction of pump 1 leaks into detection, presumably due to polarisation crosstalk in the polarisation beam combiner. In addition, the Rayleigh scattering generated by the two sidebands of pump 2 and by the CW probe can also be observed in the figure. It is however worth noticing that the DBG reflections are spectrally very well separated from pump waves, so that any residual signal that could interfere with the measurement of the DBG reflection can be easily filtered out by the 10 GHz FBG in detection.

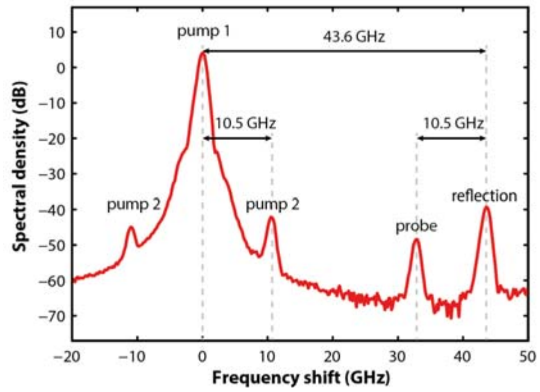

Figure 3. Measured optical spectrum of waves interacting in the DBG generation and reading. To clearly identify the DBG reflection, spectrum is measured with a CW probe.

Figure 4(a) shows the measured time-domain trace resulting from the interference between the DBG reflections of the two pulses. The trace shows sharp and high-amplitude oscillations due to the large phase shifts induced by birefringence variations and accumulated within a back-and-forth propagation of 30 cm (given by the 3 ns separation between pulses). The drop in the reflection intensity along the fibre (i.e. the envelope of the pattern) can be explained by the depletion of pump 1 caused by the CW Brillouin interaction with pump 2. To verify that the oscillations are indeed given by birefringence variations and keep static along the fibre, the measurement has been repeated after swapping the two ends of the PM fibre. For better comparison, the reflection intensity trace measured with swapped fibre ends is shown in Fig. 4(b) with an inversed temporal axis. The two interference patterns match very well each other, demonstrating that the intensity variations depicted in the traces are indeed due to local changes in the fibre birefringence.

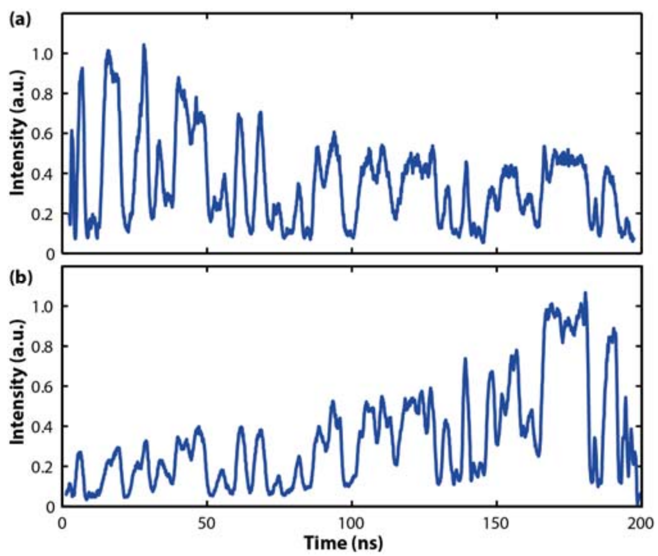

Figure 4. Reflection for two 300 ps pulses separated by 3 ns for (a) direct and (b) reversed fibre connections. The signal temporal axis of the trace measured with reversed fibre connections in (b) has been reversed for better comparison.

To obtain a measurement of the distributed profile of the fibre birefringence, the interference pattern along the fibre has been measured as a function of the probe wave frequency, which is scanned in a range of 1 GHz with steps of 20 MHz. The result of this scanning process is shown in Fig. 5(a), where each horizontal row in the figure corresponds to a longitudinal trace similar to the one shown in Fig. 4(a). It can be seen that as the probe frequency changes, the reflection intensity at a given fibre location, resulting from the interference of the two DBG reflections, turns out to change significantly. This is because the frequency detuning introduces a change in the wave vector mismatch that can considerably change the interference pattern, thus providing a high sensitivity to the method.

In order to retrieve the local birefringence variations along the fibre, the longitudinal peak frequency variations are obtained by fitting the local spectrum of the interference pattern obtained at each fibre position. This way the frequency detuning required to compensate local birefringence variations along the fibre can be obtained, as shown in Fig. 5(b). This figure shows the distributed profile of the relative frequency detuning required to compensate birefringence variations (vertical axis on left-hand side), which is straightforwardly converted into relative birefringence variations (vertical axis on right-hand side) around the average birefringence of $2\cdot10^{-4}$. The measured profile shows birefringence changes close to $\pm2\cdot10^{-6}$, which correspond to variations of about 1% with respect to the average birefringence value. Measurements show both short- and long-period periodic variations, which is definitely an unprecedented observation. The uncertainty of the birefringence measurements has been estimated by calculating the standard deviation of the obtained birefringence value at each fibre position. This has led to an estimated birefringence uncertainty of $\sim1.8\cdot10^{-8}$, which, using known temperature and strain coefficients for a similar Panda fibres (55.8 MHz/K and 0.9 MHz/$\mu\varepsilon$)[8], corresponds to temperature and strain uncertainties of 70.4 mK and 4.3 $\mu\varepsilon$, respectively. Although this is a very high accuracy for a Brillouin-based system, it is believed that this uncertainty could have been partially affected during the experiment by additional birefringence fluctuations induced by small thermal variations (in the order of a few mK or tens of mK) affecting the fibre.

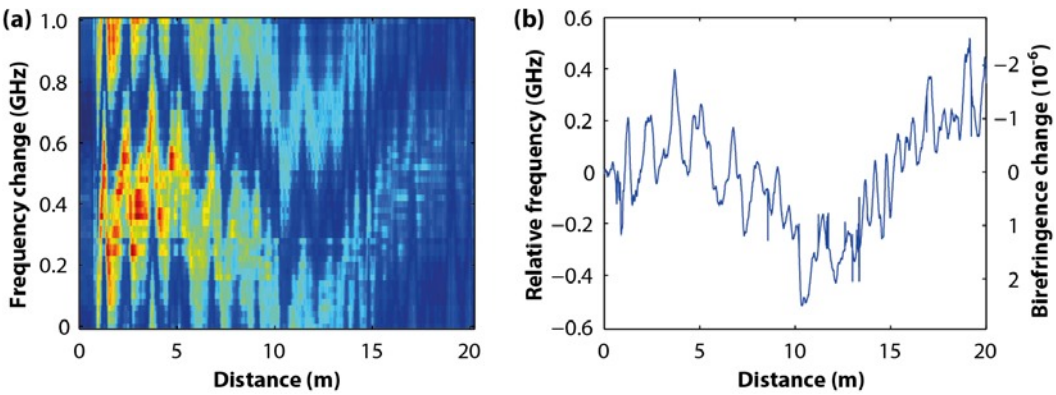

Figure 5. Measuring birefringence variation along the 20 m fibre. (a) Dependence of the DBG reflected signal on the scanned optical frequency. (b) Retrieved frequency detuning along the fibre and corresponding birefringence variation.

In conclusion, a novel method for sub-metric and highly-accurate distributed sensing based on birefringence measurements has been proposed. Results show the high sensitivity of the method as a consequence of the interference pattern generated by the DBG reflection of two short consecutive pulses. The technique opens up the possibility for sensitive DBG interrogation using trains of consecutive pulses, as well as phase-sensitive optical pulse coding techniques. Unprecedented performance in terms of fully distributed strain and temperature sensing, and discrimination can also be readily envisaged.

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