Simultaneous independent distributed strain and temperature measurements over 15 km using spontaneous Brillouin scattering

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ABSTRACT

Long range simultaneous distributed strain and temperature sensors have many applications for measurements in the power and oil industries and also for structural monitoring. We present an efficient technique to measure both the intensity and frequency shift at every point along the sensing fibre with a low loss filtering device utilising two in-fibre Mach-Zehnder interferometers. From these two measurements, it is possible to compute accurately the strain and temperature profile. The first interferometer was used in a double-pass configuration and served to separate the Brillouin from the Rayleigh signal, the second allowed the frequency shift to be determined. It is possible to tune the Mach-Zehnder such that the launched source signal (and hence the Rayleigh) lies at the maximum or minimum of the transfer function. The Brillouin backscattered signals for the condition of maximum and minimum throughput at the signal wavelength are summed thus obtaining a Brillouin backscattered intensity measurement independent of frequency shift. The measurement obtained when the Rayleigh lies at a minimum of the transfer function provides information of both Brillouin intensity and frequency shift variations which then allows the frequency shift to be determined. The temperature and strain resolutions were estimated to be 4°C and 290$\mu\varepsilon$ with a 10m spatial resolution over a sensing range of 15km.

Keywords: Spontaneous Brillouin scattering, distributed fibre sensing, strain measurement, temperature measurement, Mach-Zehnder interferometer

1. INTRODUCTION

The major advantage that Brillouin-based distributed sensors offer over Raman-based systems is the sensitivity of Brillouin backscattered signals to both strain and temperature. Furthermore, it is possible to design a Brillouin-based sensor which enables single-ended measurements.

It has been demonstrated that both the Brillouin frequency shift and intensity vary with strain as well as with temperature [1-4]. The relations describing both the Brillouin frequency shift and intensity variations and their responses to strain and temperature are described in the matrix of Equation (1), where $\Delta\nu$ is the Brillouin frequency shift, ΔI percentage change is the Brillouin backscattered intensity, $\Delta\varepsilon$ is the strain applied to the sensing fibre and ΔT is the temperature variation of the fibre. The strain and temperature measurands can then be evaluated by taking the inverse matrix of Equation (1) resulting in Equation (2), provided that the determinant of the Brillouin coefficient matrix does not have a value of zero. The feasibility of this technique was first demonstrated in 1997 [4].

$$\begin{pmatrix} \Delta\upsilon \\ \Delta I \end{pmatrix} = \begin{pmatrix} C_{\upsilon\varepsilon} & C_{\upsilon T} \\ C_{I\varepsilon} & C_{IT} \end{pmatrix} \begin{pmatrix} \Delta\varepsilon \\ \Delta T \end{pmatrix} \qquad (1)$$

$$\begin{pmatrix} \Delta\varepsilon \\ \Delta T \end{pmatrix} = \begin{pmatrix} C_{\upsilon\varepsilon} & C_{\upsilon T} \\ C_{I\varepsilon} & C_{IT} \end{pmatrix}^{-1} \begin{pmatrix} \Delta\upsilon \\ \Delta I \end{pmatrix} \qquad (2)$$

From Equation (2), it is possible to evaluate the errors in strain and temperature measurements and these are expressed by Equations (3) and (4) [5]:

$$|\delta\varepsilon| = \frac{|C_{IT}||\delta\upsilon| + |C_{\upsilon T}||\delta I|}{|C_{\upsilon\varepsilon}C_{IT} - C_{I\varepsilon}C_{\upsilon T}|} \qquad (3)$$

$$|\delta T| = \frac{|C_{I\varepsilon}||\delta\upsilon| + |C_{\upsilon\varepsilon}||\delta I|}{|C_{\upsilon\varepsilon}C_{IT} - C_{I\varepsilon}C_{\upsilon T}|} \qquad (4)$$

2. EXPERIMENT

To perform simultaneous distributed strain and temperature Brillouin-OTDR (BOTDR) measurements, it is necessary to design a narrow linewidth pulsed source capable of producing sufficient pulse energy to maximise the backscatter power signals. Previous experiments for performing spontaneous Brillouin-based distributed temperature sensing (DTS) have utilised Erbium-doped Q-switched fibre lasers with a bandwidth of approximately 2-3GHz [6]. In this experiment, there is a need to use a source with a smaller linewidth for accurately determining the Brillouin frequency shift.

2.1 Pulsed source for Brillouin measurements

The experimental configuration used to generate the pulses that are launched down the sensing fibre is shown in Figure 1. To obtain the required narrow linewidth signal, a continuous wave (cw) semiconductor distributed feedback (DFB) laser with an output power of 2.5mW and linewidth less than 100MHz was used. This signal was externally modulated to avoid spectral chirping by using a fibre-pigtailed $LiNbO_3$ electro-optic (EOM) modulator, and amplified with an Erbium-doped fibre amplifier (EDFA 1) of 26-dB gain. The amplified spontaneous emission (ASE) from EDFA 1 was filtered by an fibre Bragg grating centred at the signal wavelength of 1533.4nm (reflectivity = 99%, bandwidth = 0.08nm) through circulator C1. The reflected signal was further amplified by EDFA 2 to compensate for the high loss of the acousto-optic modulator (AOM). The AOM was synchronised with the EOM, and pulses were launched down the sensing fibre at a repetition rate of 6.6kHz through circulator C2 in Figure 4.

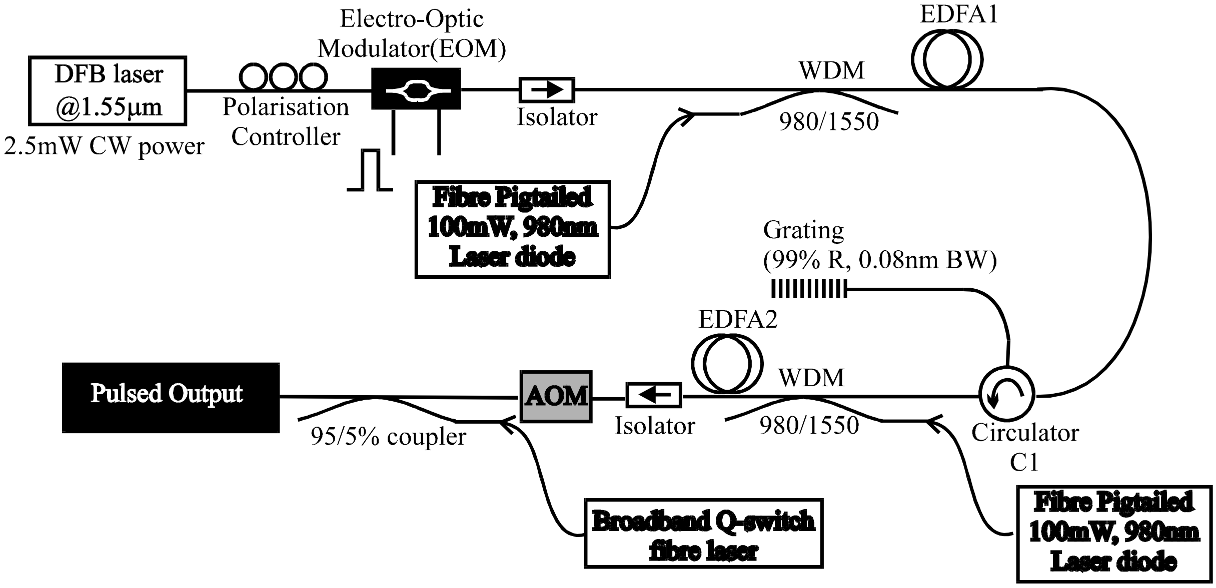


Figure 1: Experimental configuration of pulsed source used to obtain both the Brillouin and Rayleigh signals

2.2 Pulsed source for Rayleigh measurement

To obtain the Rayleigh signal required to normalise the Brillouin signals, a separate laser was used. This is due to the fact that the narrow linewidth pulsed signal used to obtain the Brillouin signals generates excessive coherent Rayleigh noise (CRN) [7]. In this experiment, a broadband Erbium-doped Q-switched fibre laser was constructed to generate broadband pulses up to 100W peak power and 34ns, with a linewidth of approximately 3nm. A fraction of the Q-switch pulses were launched down the sensing fibre through the 95/5 splitting ratio coupler and circulator C2.

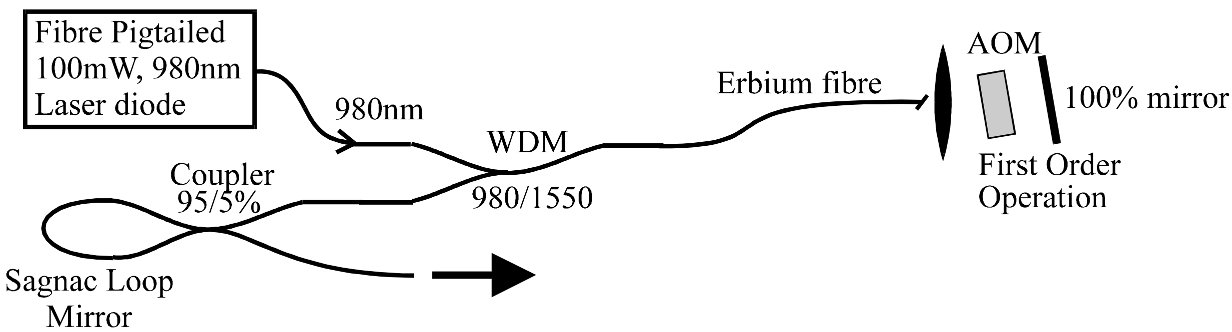
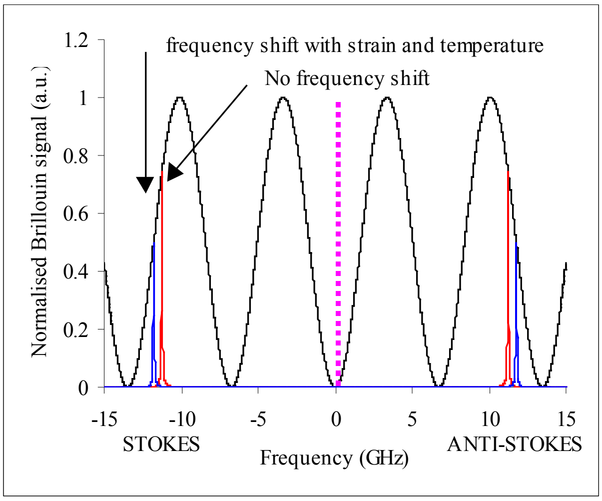


Figure 2: 1.5μm broadband Erbium-doped Q-switched fibre laser used to obtain the Rayleigh signal

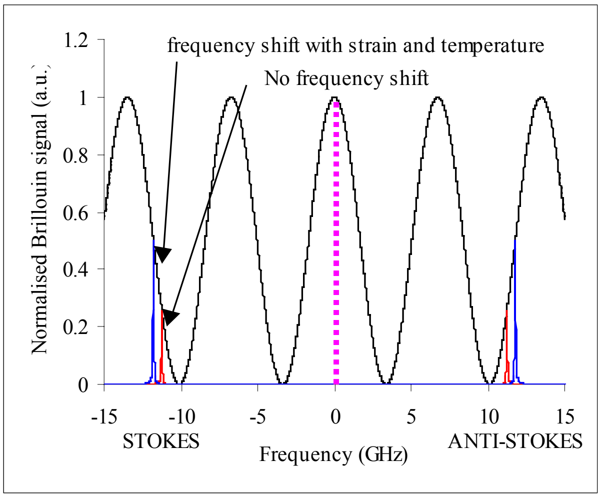
2.3 All-fibre optical filtering system

The optical filtering system consisted of two fibre-based Mach-Zehnder interferometers cascaded together. The first Mach-Zehnder (MZ1) was used in a double-pass configuration with a path imbalance of 9.2mm (FSR = 22GHz) introduced between the two arms of the interferometer. This provided maximum rejection of the Rayleigh signal from the Brillouin to minimise the effect of coherent Rayleigh noise (CRN) which has a detrimental effect on the strain and temperature resolution. The output of this first Mach-Zehnder was then connected to the second Mach-Zehnder (MZ2) which was in a single-pass configuration and with a path imbalance of 29mm (FSR = 6.8GHz). The second Mach-Zehnder was used to convert the Brillouin frequency shift to an intensity change. When the Rayleigh signal frequency lies at a minimum of the transfer function, the Brillouin signals corresponding to zero strain lie at approximately 70% transfer function maximum. The Mach-Zehnder was tuned by monitoring the output port of the Mach-Zehnder whilst launching the laser signal from the 5% arm of the 95/5 coupler shown in Figure 4. It is possible to tune the Mach-Zehnder such that the laser signal frequency (and hence the Rayleigh frequency) lies at the minimum or maximum of the transfer function. The Brillouin backscattered signals for the condition of minimum and maximum throughput at the signal wavelength are summed thus obtaining a measurement of the Brillouin backscattered intensity which is independent of frequency shift. The measurement obtained when the Rayleigh frequency lies either at a minimum or maximum of the transfer function provides a measure of both changes in Brillouin intensity and frequency shift. Normalising this signal by the intensity of the Brillouin signal allows the frequency information to be computed.

Figure 3(a) and 3(b) illustrates the Brillouin signals from the output of the double-pass Mach-Zehnder being filtered by the second interferometer. As the strain or temperature is increased, both the Stokes and anti-Stokes Brillouin frequency shift increases away from the Rayleigh signal frequency.



(a)



(b)

Figure 3: Brillouin frequency shift variation due to applied strain temperature when the laser monitor signal is tuned to (a) the minimum of the single-pass Mach-Zehnder transfer function (b) the maximum of the single-pass Mach-Zehnder transfer function

2.4 Spontaneous Brillouin-based sensor

The overall sensor configuration is illustrated in Figure 4. The sensing fibre consisted of 15km conventional telecommunications single-mode silica fibre. The first length of sensing fibre was a 9km drum (D1), followed a section of 0.46km drum D2. Fibre drum D2 was placed in an oven and heated to a temperature of 53°C, an increase in temperature of 30°C from the temperature of other fibre drums at room temperature of 23°C. This was then followed by drum D3 spliced to drum D2. Drums D4 and D5 consisted of a continuous length of fibre. Between D4 and D5 there was a 120m section of fibre which was loosely reeled on to 11 pairs of pulleys. Weights were then added on one of the ends of the 120m length of fibre to provide a strain. The change in length of the fibre was measured to determine the average strain over the 120m. The backscattered signal was collected through the circulator C2 and filtered through the two Mach-Zehnder interferometers. The backscattered traces were obtained from the output of the single pass Mach-Zehnder using a InGaAs photo-detector and a preamplifier which had a sensitivity of 10mV/nA and an electrical bandwidth of 3MHz, and the backscattered traces were averaged 65536 times.

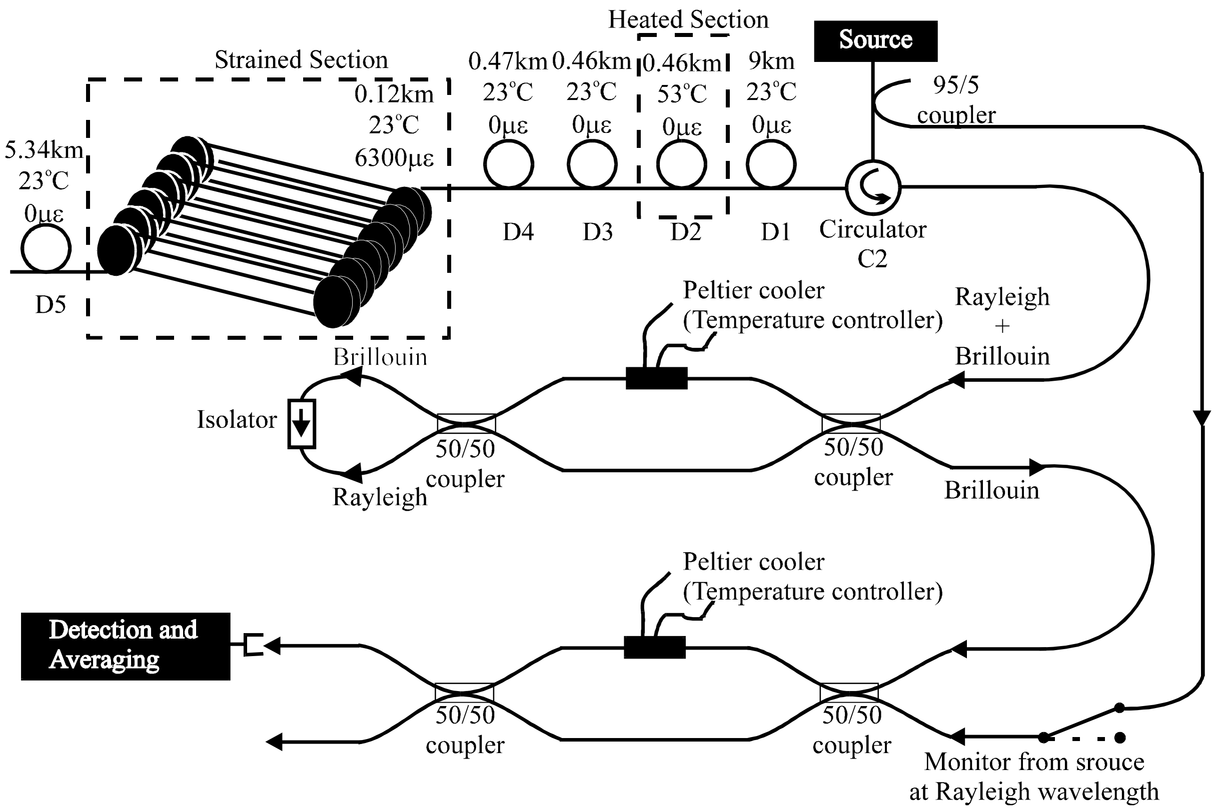


Figure 4: Combined spontaneous Brillouin-based distributed strain and temperature sensor

3. RESULTS

Figure 5(a) and 5(b) show the output of the single pass Mach-Zehnder at 8.8km down the sensing fibre, when the signal at the Rayleigh frequency has been tuned to the minimum and maximum of the transfer function. Figure 5(c) shows the sum of Figures 5(a) and 5(b) which represents the Brillouin signal dependent only on intensity variations. The attenuation and splice/bend losses were compensated for by dividing the Brillouin signals with the Rayleigh signal. Using the broadband Q-switched fibre laser, the Rayleigh signal obtained at the same distance down the sensing fibre is shown in Figure 6.

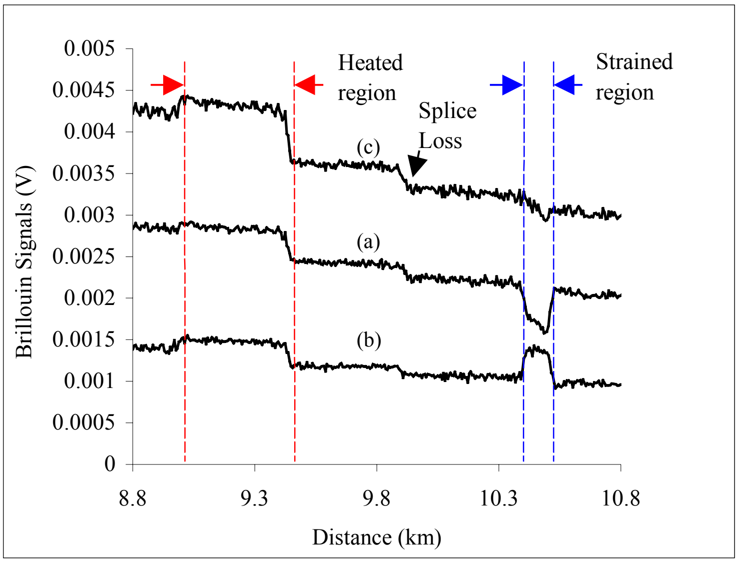


Figure 5: Brillouin backscattered signals at the output of the single-pass Mach-Zehnder when the signal at the Rayleigh frequency has been tuned to (a) the minimum and (b) the maxiumum of the single-pass Mach-Zehnder transfer function. Trace (c) is the sum of traces (a) and (b)

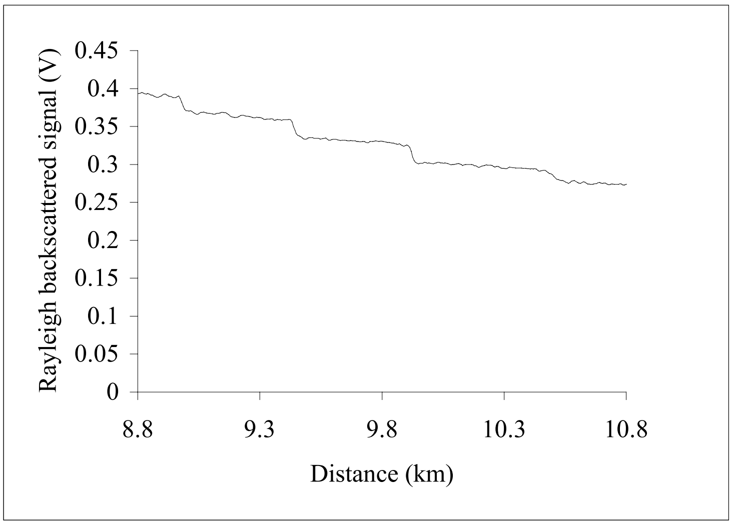


Figure 6: Rayleigh backscattered signal generated by using a broadband Erbium-doped Q-switched fibre laser

To obtain the Brillouin frequency shift along the sensing fibre, Figures 5(a), 5(b) and 5(c) are normalised to the Rayleigh signal and these plots are shown in Figure 7. As Figure 7(f) is the result of Figure 5(c) normalised to the Rayleigh signal, it is dependent only the Brillouin intensity variation and the percentage variation is shown in Figure 9(a). The dashed lines indicate the theoretical evaluated profile. As the Brillouin intensity has been measured independently of frequency (by summing the two outputs), the Brillouin signals can be calculated to be dependent only on the Brillouin frequency shift by referencing either Figure 7(d) or Figure 7(e) to Figure 7(f). The intensity variation is then converted to the frequency shift values by using the single-pass Mach-Zehnder transfer function shown. In Figure 8, I_2 is the Brillouin signal normalised to intensity changes when the fibre is subjected to strain/temperature whereas I_1 is for no strain/temperature effects. The resultant Brillouin frequency shift is shown in Figure 9(b).

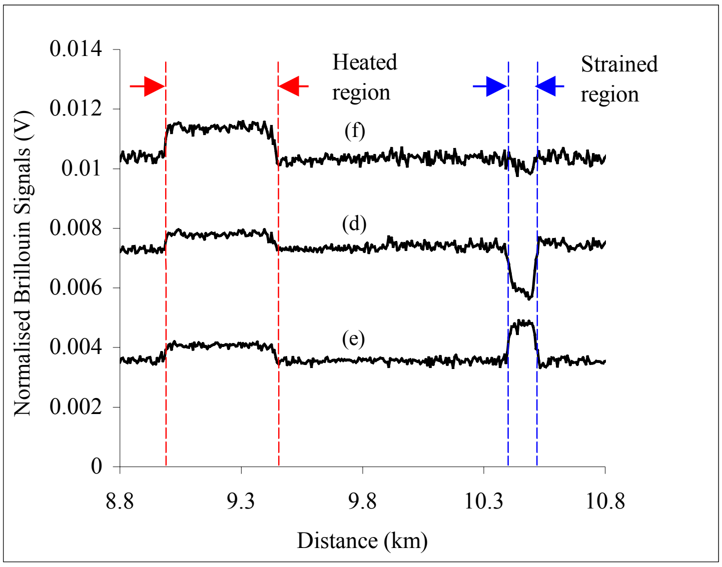


Figure 7: Brillouin signals normalised to the Rayleigh signal for (d) normalised trace of Figure 5(a), (e) normalised trace of Figure 5(b) and (f) normalised trace of Figure 5(c)

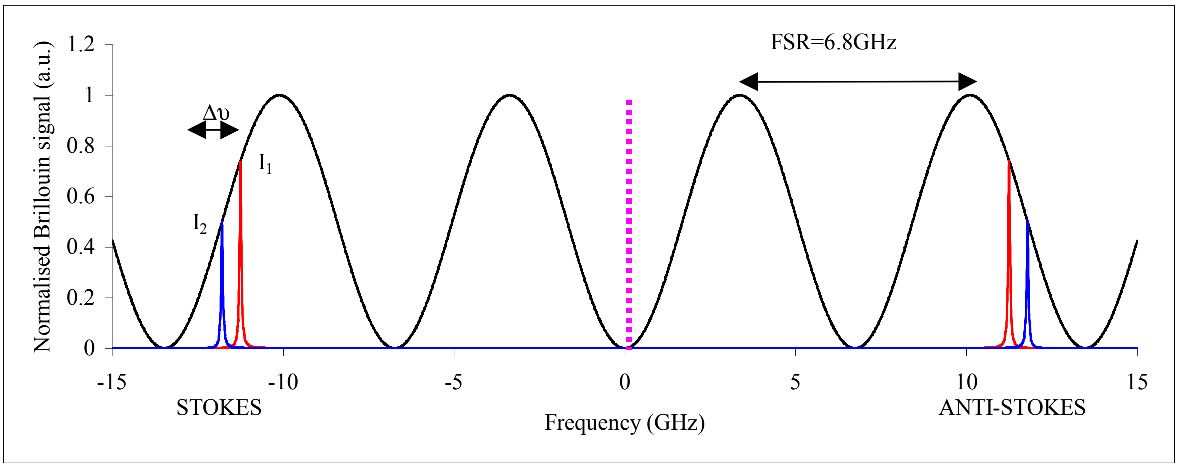
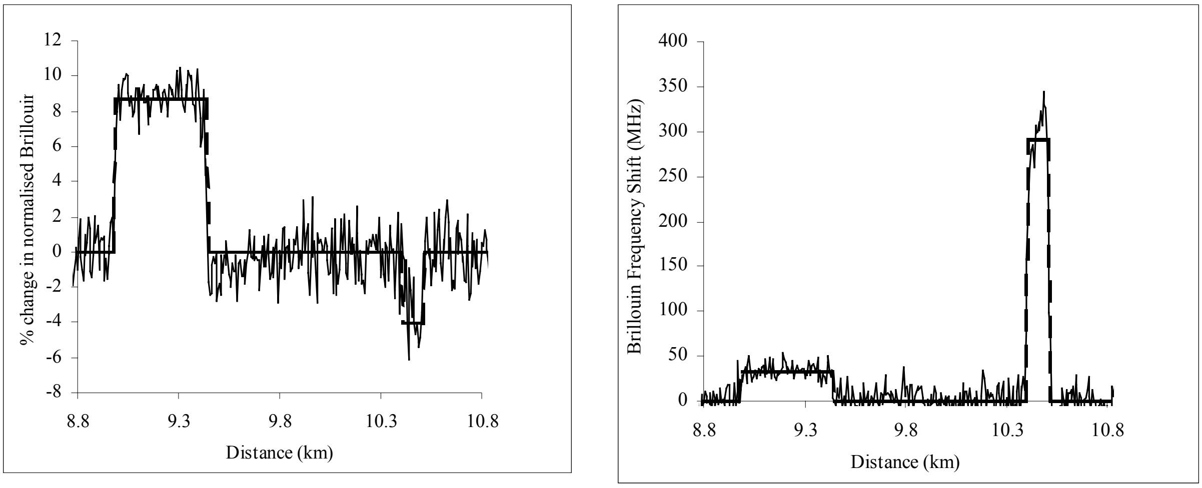


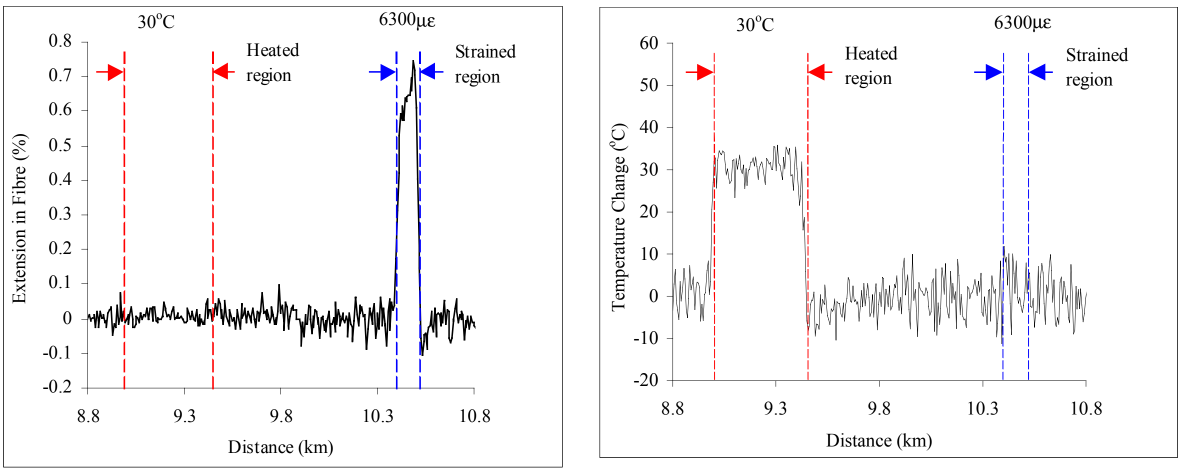
Figure 8: Evaluating the Brillouin frequency shift by taking using the information of the Brillouin intensity which has been referenced to compensate for Brillouin intensity variations



(a) (b)

Figure 9: (a) Percentage change in normalised Brillouin backscattered intensity (b) Brillouin frequency shift evaluated using the signal dependent on both intensity and frequency shift variations referenced to the signal dependent only on intensity variations

Known constants that relate the Brillouin frequency shift and intensity to strain and temperature were used in conjunction with the sets of data obtained to solve two simultaneous equations to produce strain and temperature profiles as described in Equation (2), and the results are shown in Figure 10(a) and 10(b). The temperature resolution and strain resolutions were estimated from the r.m.s noise of the signals to be 4°C and 290με with a spatial resolution of 10m.



(a) (b)

Figure 10: Resolved profiles along the sensing fibre for (a) strain variations (b) temperature variations

4. CONCLUSION

In summary, a single-ended long-range distributed strain and temperature sensor has been demonstrated based on spontaneous Brillouin scattering. This sensor potentially allows useful monitoring over tens of kilometres in systems whereby only one end is accessible. The combination of a double-pass configured Mach-Zehnder and a single-pass Mach-Zehnder interferometer linked in series allowed a low-loss optical filtering system capable of separating the Brillouin intensity and Brillouin frequency shift traces along the sensing fibre. With this information, variations in strain and temperature were identified independently. The sensor demonstrated had a temperature resolution of 4^{o}C, strain resolution of 290με and a spatial resolution of 10m.

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