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Simultaneous Distributed Measurements of Temperature and Strain using Spontaneous Raman and Brillouin Scattering

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Abstract: We report on a novel method for simultaneous distributed measurement of the temperature and strain in an optical fibre based on spatially resolving the anti-Stokes signals of both the spontaneous Raman and Brillouin backscattered signals.

Keywords: Distributed Optical Sensors, Simultaneous Temperature and Strain Measurements, Spontaneous Brillouin and Raman Scattering.

1. INTRODUCTION

Over the last 15 years, Brillouin scattering has been widely investigated as a basis for fibre distributed temperature and strain measurements. One of the earliest reports [1] focussed on the determination of the Brillouin frequency shift for measuring temperature and strain, and subsequent research has focussed on techniques for improving the accuracy with which this frequency shift could be measured. Recent work in this respect has been to improve the spatial resolution of such frequency measurements and the most significant advance in this respect has been the correlation based continuous wave technique proposed and developed by the University of Tokyo under Professor Hotate's direction [2]. Measurement of a single parameter however is unable to discriminate the two measurands, temperature and strain, and our work has therefore focussed on investigating methods to separate and unambiguously resolve both temperature and strain with particular emphasis on long range systems. We initially verified that the Brillouin intensity was temperature dependent [3] but that the intensity was relatively weakly dependent on strain [4] ; i.e. 1°C or 300με produces the same change in intensity, whilst 1°C or 20με produces the same change in frequency. The Brillouin Optical Time Domain Reflectometry technique was thus developed, in which both the Brillouin frequency shift and change in power are used to obtain temperature and strain change simultaneously along a length of fibre [5-7]. However in attempting to develop long-range sensors, it was found that the accuracy of the intensity measurement limits the performance of a combined temperature and strain sensor [7]. Other techniques have therefore been explored to provide an alternative to relying on the Brillouin intensity for separating temperature and strain. One elegant solution recently proposed was to use sensing fibres with multiple Brillouin peaks that exhibit different frequency variations with temperature [8]. Our investigations however indicated that it was just as troublesome to measure the differential frequency with the required precision and presently we have been unable to demonstrate any significant performance advantage over the frequency/intensity technique. In this paper we present a new technique to measure both measurands simultaneously that uses both the Raman and Brillouin anti-Stokes backscattered signals. Using this technique, a temperature resolution of ~3.5°C and strain resolution of ~80με with 5m spatial resolution was achieved over 6.3km sensing range.

2. PRINCIPLE OF OPERATION

The principle of this technique is based on optical time domain reflectometry using a single pulsed light source operating at 1533nm and spatially resolving both the Brillouin anti-Stokes frequency shift at 1533nm and the intensity of the Raman anti-Stokes signal at 1450nm. The Raman signal is sensitive to temperature but not to strain and the temperature along the fibre can be determined and is the basis of conventional Raman based distributed temperature sensors. With knowledge of the temperature of the fibre, the strain can then be computed from the Brillouin frequency shift information. The intensity of the anti-Stokes Raman signal is more sensitive to temperature, 0.8%/°C [9], than the anti-Stokes Brillouin signal, 0.3%/°C. This to some extent compensates for it being more than an order of magnitude smaller than that of Brillouin signal. To accurately predict the temperature changes, the Raman signal has to be referenced to a temperature independent signal measured with the same spatial resolution. In commercial Raman based distributed temperature sensors, a second source is normally used to generate the Rayleigh signal at the Raman shifted wavelength. For experimental convenience we used the Raman signal recorded prior to heating the fibre as our reference for normalisation and hence compensation for splice and fibre losses. The temperature profile can be obtained using the measured Raman intensity change as follows:

$$\Delta T_R(L) = \Delta I_R(L)\ C_R^T \qquad (1)$$

Where L is the distance along the fibre, $\Delta I_R(L)$ is the normalized change of Raman intensity, and C_R^T is the temperature coefficient of the Raman intensity change. The Brillouin frequency shift is dependent on both the temperature and strain. Using the now known temperature $\Delta T_R(L)$, the strain profile along the fibre is given by:

$$\Delta\varepsilon(L) = \frac{\Delta\nu_B(L) - C_{B\nu}^T \Delta T_R(L)}{C_{B\nu}^\varepsilon} \qquad (2)$$

Where $\Delta\nu_B(L)$ is the Brillouin frequency shift along the sensing fibre, $C_{B\nu}^T$ and $C_{B\nu}^\varepsilon$ are the temperature and strain coefficients for the Brillouin frequency shift respectively. These coefficients are taken to be 1.07MHz/°C for $C_{B\nu}^T$ and 0.05MHz/με for $C_{B\nu}^\varepsilon$ [7].

3. EXPERIMENTAL SET-UP AND MEASUREMENTS

The experimental set-up for measuring temperature and strain simultaneously is shown in figure 1.

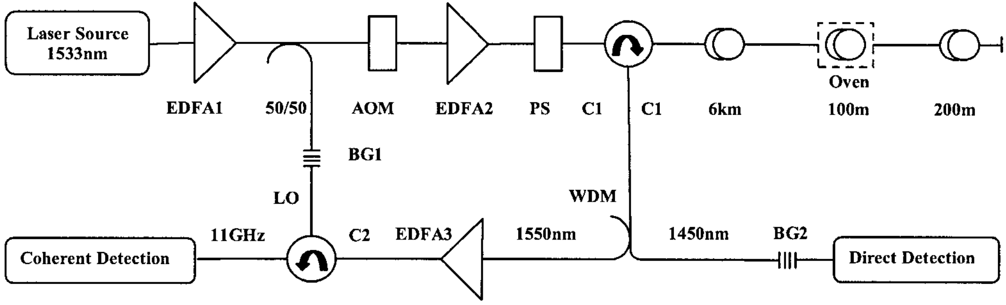

Figure 1: Experimental set-up for measuring both Raman intensity and Brillouin frequency shifts. EDFA, erbium-doped fibre amplifier; AOM, acoustic-optic modulator; BG, fibre Bragg grating; PS, polarisation scrambler; C, circulator; LO, Local oscillator.

The source was a narrow linewidth (a few MHz) tuneable laser source at 1533nm. Erbium doped fibre amplifiers, *EDFA1* and *EDFA2* were used in conjunction with an acousto-optic modulator (AOM) to generate a probe pulse of 1W, 50ns which was launched into 6.3km of standard single mode silica fibre. This was made up of three fibre sections of fibre, fusion spliced together and arranged as shown in figure 1 to be used as the sensing fibre. The first 6km remained on the original spools at room temperature and zero strain; the next 100m was strained by applying tension during the winding process, and placed in an oven at 60°C. The subsequent 200m were subject to room temperature (20°C) and zero strain as a reference. Two detection systems were employed; a direct detection system was used to spatially resolve the Raman anti-Stokes intensity, and coherent detection was used to spatially resolve the Brillouin frequency shifts.

In the direct detection measurement of the Raman signal, a (1550/1450) WDM was used to provide some initial filtering of the 1533nm Rayleigh signal from the anti-Stokes Raman signal. The Rayleigh signal was ~30dB bigger than the Raman anti-Stokes, so a fibre Bragg grating (BG2) centred at 1533nm with 1nm bandwidth (reflectivity = 99%, $\Delta\lambda$ = 1nm, λ = 1533nm) were placed before the detector to provide further rejection of the backscattered Rayleigh light. The Raman anti-Stokes signal was averaged 2^{15} times. In the coherent detection of the frequency of anti-Stokes spontaneous Brillouin signal, the backscattered signal was first amplified using EDFA3 and then combined with a local oscillator using a circulator and a fibre Bragg grating BG1. The Bragg grating (reflectivity = 99.4%, $\Delta\lambda$ = 0.12nm, λ = 1533.11nm) was centred at the Brillouin frequency. This arrangement allowed transmission of the local oscillator whilst filtering the Brillouin signal from the backscattered signal. It avoids the usual 3dB loss associated with using a 50/50 coupler. The amplified, filtered Brillouin anti-Stokes signal and local optical oscillator were then optically heterodyned on the face of a 20GHz lightwave detector generating a beat signal equal to the Brillouin shifted frequency (plus a 110MHz shift due to the AOM). The microwave detection system has been previously described [10] but essentially allows the collection of time domain traces centred at the desired RF frequencies. Brillouin spectra were built from 20 separate backscatter traces, each averaged 2^{15} times, taken every 10MHz, starting at 11.05GHz. A Lorentzian curve was fitted to each spectrum and the peak frequency was evaluated at each point along the sensing fibre. Initially, the Brillouin frequency shift due to the applied strain was measured at room temperature and then, the 100m strained section was heated in the oven to 60°C and the Brillouin frequency shift due to the combined effect of both temperature and strain was measured.

4. ANALYSIS AND DISCUSSIONS

A plot of the Raman backscatter intensity measurement at 1450nm over the entire 6.3km length of sensing fibre is shown in figure 2; the heated section is clearly visible. The trace was then normalised using a trace obtained prior to heating the fibre. Figure 3 shows on an enlarged scale the temperature profile obtained from the normalised Raman trace and using the known Raman anti-Stokes temperature coefficient of 0.8%/°C.

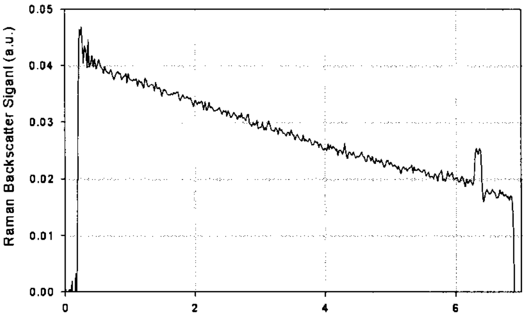

Figure 2: Raman anti-Stokes intensity trace along the sensing fibre, the heated section is clearly visible at 6.3km.

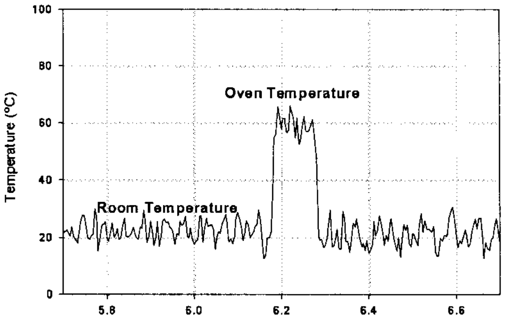

Figure 3: The temperature profile after normalisation, measured using the Raman anti-Stokes intensity.

The temperature change was calculated to be 39°C, and the rms resolution was measured to be ~3.5°C. The peak Brillouin beat frequency as a function of distance around the strained section at room temperature and at 60°C is shown in figure 4.

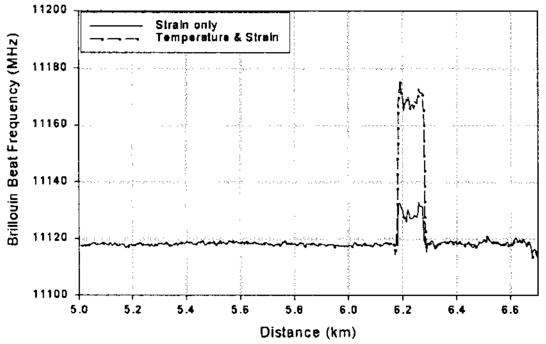

Figure 4: Brillouin beat frequency measurements for the strained fibre at room temperature, and at 60°C.

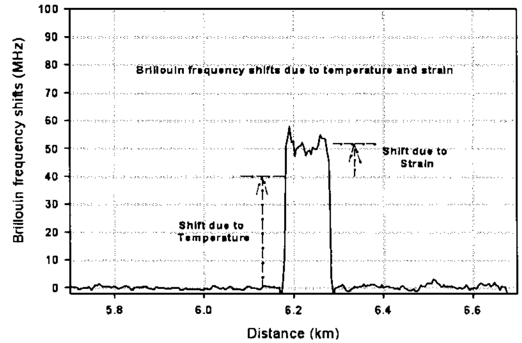

Figure 5: The Brillouin frequency shift for the heated and strained fibre relative to the unheated, unstrained fibre.

Figure 5 shows the Brillouin frequency shifts for both heated and strained section relative to the unheated and unstrained fibre. The strain in the fibre is not necessarily the same as in the unheated case due to the possible presence of thermally induced strain from the drum on which the fibre is coiled. The frequency shift was around ~55MHz. The temperature was determined to be 39°C from the Raman measurements and from this the strain using equation 2 was calculated to be $265\mu\varepsilon$. This compared to the measured strain of $260\mu\varepsilon$ prior to heating the fibre. The derived strain profile is shown in figure 6; the rms strain resolution was determined to be ~$80\mu\varepsilon$.

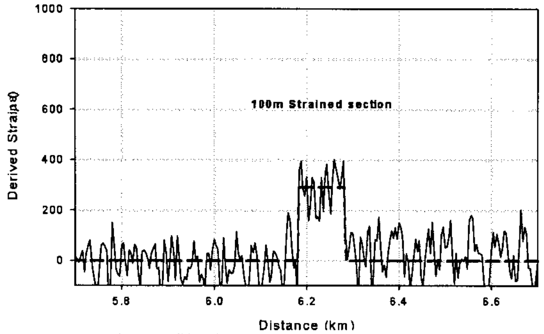

Figure 6: Strain profile derived based on the data of figure 3 & 5.

The noise on the temperature and strain measurements mainly arise from the noise associated with the Raman intensity measurement and maybe reduced by increasing the number of averages. Some of the noise is also thought to arise from contamination of the Raman signal with coherent Rayleigh noise. Improved filtering and further attenuation of the Rayleigh contamination would help to reduce this noise. The contribution to the temperature and strain errors from errors in the determination of the Brillouin frequency shift is small in comparison to the noise on the Raman intensity measurements; the RMS frequency error was evaluated at 6km over a range of 100m, and converted to the corresponding temperature and strain errors. It was calculated to be less than 0.35MHz, which is equivalent to temperature error of less than 0.33°C and strain error of less than 7µε. The spatial resolution (5m) was limited by the response time of the acoustic optical modulator used in this experiment.

5. CONCLUSIONS

We report our preliminary investigations of a novel technique of measuring temperature and strain simultaneously using the anti-Stokes spontaneous Raman and Brillouin signals generated from a single light source. The Raman anti-Stokes intensity was used to measure the temperature and is independent of the strain, and this combined with the Brillouin frequency shift measurement allows the strain information to be determined. A temperature resolution of ~3.5°C and strain resolution of ~80µε with spatial resolution of 5m for a range of over 6km were demonstrated using this technique. These results are encouraging and demonstrate the feasibility of the technique; further investigations are required to quantify the relative advantages of combining the Brillouin frequency measurement with the measurement of the intensity of the spontaneous Raman signal instead of the intensity of the spontaneous Brillouin signal to measure strain and temperature.

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