3048

Coherent Detection of Spontaneous Brillouin Scattering Combined with Raman Amplification for Long Range Distributed Temperature and Strain Measurements

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ABSTRACT

Brillouin intensity and frequency measurements achieved temperature and strain to be unambiguously resolved with resolutions of 3.5°C and 85με at 50km. Frequency only measurements, achieved temperature or strain resolution of 1.7°C and 35με at 100km.

Distributed Optical Sensors, Simultaneous Temperature and Strain Measurements, Spontaneous Brillouin S cattering, Optical Raman Amplification.

1. INTRODUCTION

The dependence of the Brillouin frequency shift on strain and temperature has been previously reported as the basis for strain and temperature sensors [1] but is unable to discriminate between the two measurands. A development of this idea, was to use the Brillouin Optical Time-Domain Reflectometry (BOTDR) technique, in which both Brillouin frequency shift and change in power are used to obtain temperature and strain change simultaneously along a link of standard single mode fibre (SMF); however the range and measurand resolution are mainly limited by the accuracy of the power measurement due to the weak signal [2]. The probe power cannot simply be increased to overcome this problem due to the onset of non-linear effects. The most significant of these in long range sensors has recently been shown to be due to modulation instability (MI) [3]. MI leads to a broadening of the probe pulse spectrum, which eventually leads to significant spectral overlap of the Brillouin and Rayleigh signals. We have investigated other techniques to measure temperature and strain simultaneously that avoid the Brillouin power measurement, such as multiple Brillouin peaks [4], and combining spontaneous Raman intensity with Brillouin frequency measurements [5], but have found to-date that the intensity and frequency method provides the best resolution for sensing ranges beyond 30km. We have therefore addressed the possibility of compensating for fibre loss by using in line Raman amplification. Initial results using direct detection of the Brillouin signal [6] achieved s/n improvement of (~8dB). In this study we combine the benefits of Raman amplification with coherent detection of the Brillouin spectrum. Coherent detection offers improved sensitivity over direct detection and also permits simple determination of both the Brillouin frequency shift and power change for unambiguously resolving temperature and strain measurements. Experiments were conducted to investigate and optimize the signal probe pulse and Raman pump powers and demonstrate the improvement in the temperature and strain resolution of long range sensors that can be achieved with Raman amplification.

2-EXPERIMENTAL DETAILS

The experimental arrangement for utilizing Raman amplification with coherent detection of the anti-Stokes spontaneous Brillouin backscatter is shown in figure 1. The source generating both the local oscillator and the probe pulse was a tuneable laser @ 1533.2nm, with ~1MHz linewidth. Two-cascaded erbium doped fibre amplifiers (EDFAs) generated a peak probe power up to ~80mW, and pulse width of 50ns with a repetition rate of ~1kHz, and this was launched into the sensing fibre. A third EDFA was used to amplify the weak backscattered signal prior to mixing with an optical local oscillator (LO). The fibre Bragg grating (BG1) (λ_g=1533.11nm, $\Delta\lambda_g$=0.12nm, reflectivity=99.4%) was used to filter the anti-Stokes Brillouin signal from the Rayleigh and spontaneous Raman scattering and to allow efficient mixing of the LO with the anti-Stokes signal. BG2 (λ_g=1533nm, $\Delta\lambda_g$=1nm, reflectivity=99.2%) was used to filter ASE and reflected the anti-Stokes signal for double pass amplification. A 95/5 coupler was used to tap 5% of the probe and backscattered light for pulse monitoring (PM) and detection of the Rayleigh backscatter (R) respectively. A 20GHz optical detector and a microwave detection system [7] was used to collect time domain traces centred at the desired RF frequencies. The Raman pump signal at 1450nm with ~1.5nm line width and up to 1W of CW output power was coupled to the probe pulse using a (1450/1550nm) wavelength division multiplexer.

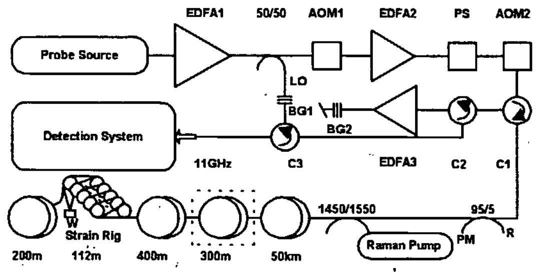

***Figure 1**: Schematic diagram of the experimental set-up.*

The sensing fibre was arranged as shown in figure 1. The first 50km remained on the original spools at room temperature. The next 300m was loosely coiled and placed in an oven to allow heating whilst ensuring zero strain. The subsequent 400m were used as a reference and maintained at room temperature with zero strain. The following 112m section was passed around 8 pairs of pulleys and loaded by placing weights suspended at the end of the fibre. The last 200m was used as a second reference length and maintained at room temperature with zero strain. The Brillouin spectra were built from 20 separate backscatter traces, each averaged 2^{15} times, and taken every 10MHz, starting at 11.05GHz. Each individual spectrum was fitted to a Lorentzian curve to identify the peak of the Brillouin frequency shift. The Brillouin power was measured by numerical integration of the Brillouin spectral components and normalized using a measurement at room temperature/zero strain, to account for the fibre/splice loss. The changes in the Brillouin frequency shift were also referenced to the room temperature/zero strain values. The Brillouin frequency shift and power change are related to temperature and strain as follows:

$$\Delta\nu = K_\varepsilon^\nu \Delta\varepsilon + K_T^\nu \Delta T \qquad (1)$$

$$\Delta P = K_\varepsilon^P \Delta\varepsilon + K_T^P \Delta T \qquad (2)$$

Where K_T^ν and K_ε^ν are temperature and strain coefficients governing frequency shifts with previously ascertained values of 1.07MHz/°C and 5MHz/100με respectively [2]. K_T^P and K_ε^P are the coefficients for power variations with respect to temperature 0.36%/°C and strain -0.09%/100με respectively [2]. Provided ($K_\varepsilon^\nu K_T^P - K_\varepsilon^P K_T^\nu \neq 0$), the temperature and strain along the sensing fibre can be written as [8]:

$$\Delta T = \frac{K_\varepsilon^\nu \Delta P - K_\varepsilon^P \Delta\nu}{\left|K_\varepsilon^\nu K_T^P - K_\varepsilon^P K_T^\nu\right|} \qquad (3)$$

$$\Delta\varepsilon = \frac{K_T^P \Delta\nu - K_T^\nu \Delta P}{\left|K_\varepsilon^\nu K_T^P - K_\varepsilon^P K_T^\nu\right|} \qquad (4)$$

and the temperature and strain errors as

$$\delta T = \frac{\left|K_\varepsilon^P \delta\nu\right| - \left|K_\varepsilon^\nu \delta P\right|}{\left|K_\varepsilon^\nu K_T^P - K_\varepsilon^P K_T^\nu\right|} \qquad (5)$$

$$\delta\varepsilon = \frac{\left|K_T^P \delta\nu\right| - \left|K_T^\nu \delta P\right|}{\left|K_\varepsilon^\nu K_T^P - K_\varepsilon^P K_T^\nu\right|} \qquad (6)$$

where $\delta\nu$ and δP are the RMS error of Brillouin frequency and power respectively.

A preliminary investigation of non-linear spectral broadening effects was performed with and without Raman amplification by measuring the optical spectrum of the emerging probe pulse at the end of a 100km length of fibre for various probe and Raman pump powers. It was found that the maximum usable probe power, without Raman pump was around 80mW. Above this, spectral broadening of the probe pulse, previously shown to be due to MI [3], was observed. MI leads to overlap of the Brillouin and Rayleigh signals once the probe spectra has broadened to a significant fraction of the Brillouin frequency shift and, dependent on the precise filtering arrangements, causes either an apparent reduction in the temperature sensitivity of the power measurement or loss of signal. Both effects lead to deterioration in resolution performance. The onset of MI occurs at a lower probe pulse power in the presence of Raman gain. Spectra were collected for different combinations of probe and pump powers and the resolution of the Brillouin frequency measurement was determined at 100km.

The Raman gain was measured using an input probe pulse of 10mW and comparing the output amplified pulse to that of the un-amplified pulse at the far end of the 100km sensing fibre for Raman pump powers from 0 to 1W in steps of 200mW.

Initial temperature measurements along 100km using Brillouin frequency shift was performed, in such measurements, two fibre sections of 500m and 1.3km at sensing range of 47 and 100km were placed in an oven at temperature of 80°C respectively.

Distributed temperature and strain measurements were then made over a 50km sensing range. Using the optimum probe and pump power combination, both the Brillouin frequency shift and power were measured along the sensing length and the RMS errors evaluated every 10km over a distance of 500m.

3. RESULTS AND DISCUSSION

The overall single pass gain at 1W Raman pump power was measured to be ~17dB and due to pump attenuation is mostly achieved within the first 25km. The gain showed the expected linear increase with pump power.

Figure 2 illustrates the improvement in the temperature resolution based on the frequency shift measurement at 100km down the sensing fibre as a function of pump power. It is seen that although the probe power has to be reduced to avoid MI as the Raman pump power is increased, there is a net improvement in temperature resolution as the Raman pump power is increased. The optimum combination was found to be 10mW and 1W of probe and pump power respectively.

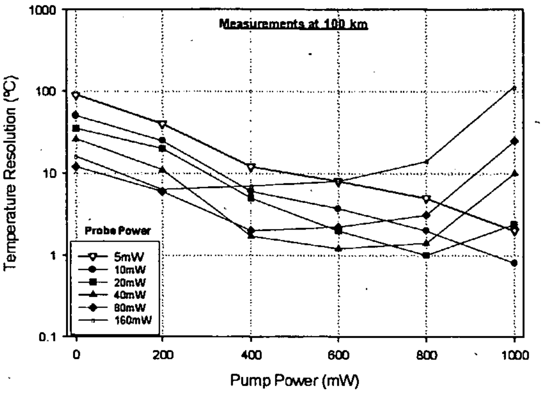

Figure 2. Temperature resolution versus Raman pump power.

Figure 3 shows the Brillouin frequency shift and the corresponding temperature change measurements along 100km sensing fibre. The two spikes correspond to the heated sections are clearly visible at 47 and 100km down the sensing fibre. A temperature resolution of ~1.7ºC with 20m spatial resolutions was achieved at 100km.

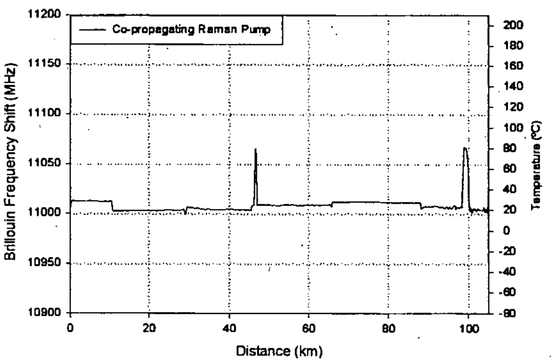

Figure 3. The Brillouin frequency and temperature change over 100km sensing length.

Figure 4a shows the measured Brillouin frequency shift and the measured Brillouin power along the sensor length of 50km using the co-propagating Raman pump configuration with the optimized probe and pump power of 10mW and 1W respectively. The amplified power trace is shown with a maximum occurring around 25km. It is evident that the signal power at the far end is greater than at the front end, showing that the Raman gain more than compensates for the two way fibre loss of 20dB (50kmx2x0.2dB/km) and splice losses.

The frequency measurement in figure 4a indicates the boundaries between different fibre sections where the difference in frequency shift along the fibre at room temperature is attributed to differences in either the winding tension or intrinsic fibre properties.

The frequency measurements in figure 4b show the shift due to both heated and strain sections at 60ºC and 1850με close to the far end of the sensing fibre respectively.

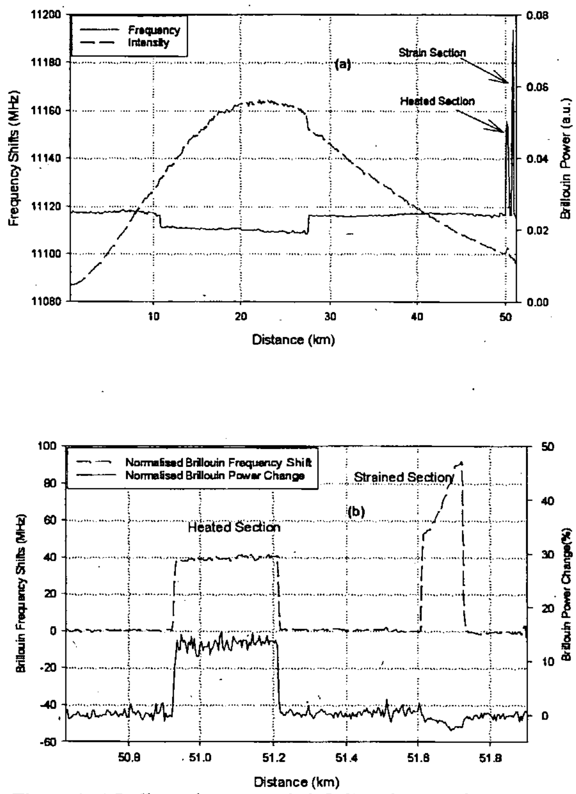

Figure 4. a) Brillouin frequency shift (left) and power change (right) along the entire sensing fibre. b) Detail of the frequency shift (left) and the normalized power change (right) at both heated and strain sections at the far end of the sensing fibre.

Using the normalized frequency shift and percentage power change of figure 4b for the region around the heated and strain sections, the derived temperature and strain profile were obtained using equations (3) and (4) and are shown in figure 5. It can be seen that there is a little cross-talk between strain and temperature. The variation in strain over the strained region is attributed to the friction in the pulley system. The RMS noise on the frequency shift and the power traces over the 300m heated section were measured to be ~0.57MHz and ~1.30% respectively. Using such values, the corresponding temperature and strain resolution were calculated using equations (5) and (6). A temperature resolution of 3.5ºC and a strain resolution of 85με respectively were calculated. When just the Brillouin frequency shift is used to measure temperature/strain resolutions of ~0.53ºC and ~12με were achieved respectively.

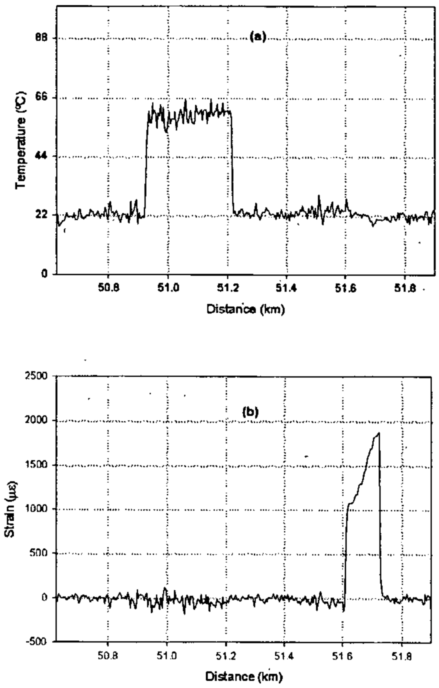

Figure 5. a) Derived temperature. b) Derived strain based upon the measured data in figure 4b.

The frequency and intensity resolutions were also evaluated at 10km intervals averaged over a length of 500m; these values were used to derive the temperature and strain resolutions, results are shown in figure 6.

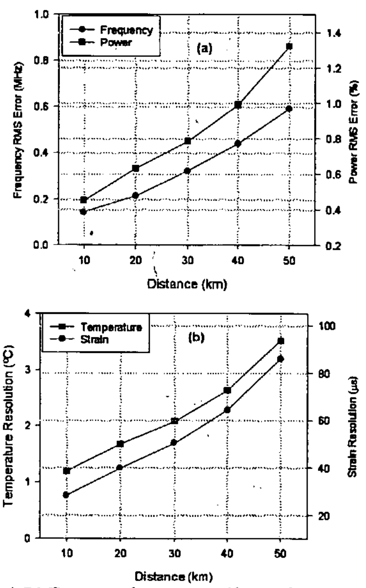

Figure 6. a) RMS error taken every 10km in frequency (left) and power (right). b) Derived temperature resolution (left) and strain (right) based upon the measured data of figure 6a.

4. CONCLUSION

We have explored and demonstrated the use of CW Raman amplification to improve the resolution of temperature and strain measurements separately resolved in long range sensors based on coherent detection of the spontaneous Brillouin backscattered signal. The Brillouin frequency shift was resolved to within ~0.57MHz at 50km increasing to ~1.8MHz at 100km, with 5 and 20m spatial resolution respectively. This corresponds to a temperature and strain resolution of ~0.53°C and ~12με and/or ~1.7°C and ~35με for situations where one parameter is known.

It was found that the noise on the power trace is still responsible for more than 90% of the temperature and strain errors, indicating that the power measurements remain the limiting factor on the accuracy of the simultaneous temperature and strain measurements. However the performance has been improved using Raman amplification. The single pass Raman amplification over the sensing length was measured to be ~17dB at 1W. The cw Raman pump amplifies both the outgoing probe pulse and the backscattered signal leading to an improvement of 34dB. This improvement is partially offset by the need to reduce the probe pulse from 80mW to 10mW (-9dB) to avoid MI, leading to an overall improvement in backscattered optical Brillouin signal power of 25dB from the far end of the sensing length. This technique benefits from combining the advantages of optical Raman amplification, coherent detection and spontaneous Brillouin measurements, which led to temperature and strain resolutions of 3.5°C and 85με at a sensing range of 50km with a spatial resolution of 5m. It also maintains the advantage of requiring access to just one end of the sensing fibre.

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