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# 100km Distributed Temperature Sensor Based on Coherent Detection of Spontaneous Brillouin Backscatter

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**Abstract.** We report the longest sensing range of a distributed temperature change measurement along an optical sensing fibre with single-ended access. The technique is based on spontaneous Brillouin scattering and microwave heterodyne detection. The Brillouin frequency shift was used to obtain the distributed temperature change at a range of 100km with a temperature error of less than 8 °C, and a spatial resolution of 50m.

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## 1. Introduction

Long range distributed fibre sensors have attracted a great deal of interest due to their potential use for monitoring temperature and strain of underground power cables and oil pipe lines, making temperature independent strain measurements of live optical links, large scale structures such as dams and bridges and for strain mapping of large areas of land for early warning of potentially catastrophic land slippage in areas identified to be at risk. Our present interest is for monitoring terrestrial or sub-sea pipelines and for effective management it is desirable to be able to measure the strain and pressure loading of the pipeline and its contents' temperature. The main aims of such monitoring are to detect potentially weak sites that could lead to leakage or even fracture and to avoid expensive blockages occurring possible in remote sites that are not easily accessible or only accessible at great expense. Blockages are avoided by careful control of the oil temperature by providing heat and adding diluents when required, but both solutions have an economic and environmental cost. Realization of a reliable distributed temperature sensor will facilitate effective management of such pipelines and potentially convert economically marginal oil fields to viable resources to be exploited in a safe an environmentally acceptable manner. Pipelines can potentially extend many 100's of kilometres and we are therefore investigating methods to increase the range of existing distributed sensors to both reduce the total number of sensing units required to provide complete coverage and also to provide greater flexibility in selecting easily accessible sites for the sensing units.

Following the early demonstration that the Brillouin intensity was strongly temperature dependent and relatively weakly strain dependent i.e. 1 °C or $300\mu\varepsilon$ produces the same change in *intensity*, whilst 1 °C or $20\mu\varepsilon$ produces the same change in *frequency*, it is now well established that by accurately measuring both the Brillouin frequency shift and the change in its intensity, both the temperature and strain changes may be resolved separately along a link of fibre [1, 2, 3]. The best performance reported to date of *single* ended systems has been a temperature sensor capable of 3 °C temperature resolution with a spatial resolution of 20m over a range of 57km [4] and a combined temperature and strain sensor capable of 4 °C temperature resolution, and strain resolution of $100\mu\varepsilon$ with a spatial resolution of 20m over a range of 30km [5]. Since the accuracy of the intensity measurement limits the performance of such combined temperature and strain sensors at long range a number of schemes have been explored to enhance the accuracy of the intensity measurement using delayed or distributed Raman amplification [6, 7]. Other techniques such as using sensing fibres with multiple Brillouin peaks with different frequency variations with temperature as a possible means for dispensing with the requirement of an intensity measurement have been investigated but presently haven't been found to offer any significant performance advantage over the frequency/intensity technique [8, 9]. Whilst the Brillouin intensity measurements at present therefore limit the performance of combined temperature and strain sensors and is being separately addressed, in certain applications simply measuring the Brillouin frequency shift may be used alone to measure temperature or strain change provided the other parameter is well defined.

This work explores the frequency resolution that can be achieved over ranges beyond that previously investigated and we demonstrate the potential of our system as a distributed temperature sensor over a distance of 100km of unstrained single mode sensing fibre. To our knowledge, this is the longest sensing range reported to date. Brillouin scattering has been researched extensively for use in long range distributed optical sensors, where both stimulated and spontaneous Brillouin scattering techniques have been reported [10, 11]. The stimulated technique requires access to both ends, whereas access to only one end of the sensing fibre is required for a measurement based on the spontaneous Brillouin scattering technique. This is more practical for long-range sensors and we have therefore restricted our investigations to this latter technique.

The backscattered spontaneous Brillouin system may be spatially resolved using either direct or coherent detection. Direct detection requires optical filtering of the Brillouin component from the Rayleigh signal and this has been achieved using Fabry-Perot interferometers, low loss fibre Mach Zehnder interferometers, fibre Bragg gratings or a combination of the two. In our coherent detection system, the 11GHz Brillouin signal is separated using a combination of optical and electronic filters and this has been found to minimize the contamination of the Brillouin signal with Rayleigh and improve the overall SNR which translates to an increased range [4]. In coherent detection, the Brillouin backscattered signal is mixed optically with a strong optical local oscillator (OLO) effectively amplifying the much weaker Brillouin signal. An efficient means of combining the backscattered signal with the OLO was achieved using a fibre Bragg grating and avoided the usual 3dB loss. The same laser is used to generate the OLO and the probe pulse and hence the intermediate frequency (IF) after optical mixing is approximately equal to the Brillouin shift (~11GHz). This beat frequency lies within the bandwidth of the 20GHz detector and this is electronically mixed down to an IF of 21.4MHz. We believe that this is a more robust and more easily implemented solution than using a lower bandwidth detector (typically a few 100'sMHz) and generating a OLO locked to the probe pulse frequency and at a frequency such that the beat frequency lies within the bandwidth of the detector.

## 2. Experimental Details

The experimental arrangement for coherent detection of the anti-Stokes spontaneous Brillouin backscatter is shown in figure 1. The source is a tuneable laser @ 1533.2nm, with ~1MHz line width. Two-cascaded erbium doped fibre amplifiers (EDFAs) generated a probe pulse with peak power of 85mW, and pulse width of 500ns. The probe power was limited to 85mW to avoid unwanted non linear effects arising from the influence of self phase modulation/modulatin instability. AOM1 generated the pulse and AOM2 gated out the interpulse ASE generated by EDFA2 (both have an extinction ratio >50dB) operated in first order. Without such gating, Rayleigh scattering from the ASE would contaminate the Brillouin as the signal is derived from a length of fibre equivalent to the spatial resolution, whereas the ASE is collected from the entire sensing fibre. The pulse was fed into the 103km single mode sensing fibre. A third EDFA was used to amplify the weak backscattered signal prior to mixing with 1.8mW OLO. The mixing of the two optical signals was achieved by using the circulator C1 and a Bragg grating. In this arrangement the Brillouin backscattered signal is reflected by the grating (Reflectivity= 99.4%,$\lambda g = 1533.1nm, \Delta\lambda = 0.12nm$) and separated from much of the amplified spontaneous emission (ASE) generated by EDFA3. The grating provides further attenuation of Rayleigh scattering of any residual ASE from EDFA1 and EDFA2. The grating also allows the OLO to pass through and combine with the reflected Brillouin signal via the circulator and optically heterodyned at the face of the 20GHz photodetector. This configuration avoids the usual 3dB loss associated with combining the two signals with a coupler. The electrical signal from the photodetector was measured using an electrical spectrum analyzer (ESA) operated in zero scan mode to allow the collection of time domain traces centred at the desired RF frequencies.

The sensing fibre used was standard telecommunications single mode silica fibre with the following characteristics: loss of 0.199dB/km, effective area of 80$\mu$m$^2$, and dispersion of 17 ps/nm.km @ 1550nm. The total sensing length was made up of 8 sections of fibre fusion spliced together and arranged as shown in figure 1. The first 11km, 19km, 17.2km, 19km, 22.3km and 11km remain on the original spools at room temperature. The next 1.3km was placed in an oven at 60 °C, and the final 2.2km was maintain at room temperature as a reference. The temperature change along the sensing fibre was determined by analysing the frequency shift of the anti-Stokes Brillouin backscatter signal. Brillouin spectra were built from 15 separate backscatter traces, each averaged $2^{15}$ times, and taken every 10MHz, starting at 10.94GHz. A Lorentzian curve was fitted to each spectrum and the peak frequency was evaluated at each point along the sensing fibre. In order to validate sensor performance and accuracy, measurements were taken between 98 and 102km at oven temperatures of 20 °C, 40 °C and 60 °C.

## 3. Results and Discussion

A plot of the peak frequency as a function of distance is shown in figure 2 over the entire 103km sensing fibre. The sharp spike at 100km corresponds to the 1.3 km heated section at 60 °C. The different fibre sections exhibit different Brillouin frequency shifts at room temperature. This is attributed to differences in fibre properties or fibre winding tensions. Figure 3 shows an enlarged scale of the measured Brillouin frequency shifts from 98 to 102km whith the 1.3km section at 100km heated to 20, 40, and 60 °C. A temperature sensitivity of 1.07MHz/ °C was measured, and this is in agreement with previously reported results [3, 4, 5].

To estimate the resolution, the RMS frequency errors along the sensing fibre were evaluated every 10km over a range of 2km, and converted to the corresponding temperature error. The results are shown in figure 4. The sensor was able to resolve temperature changes of less than 0.5 °C up to 60km. The RMS error increased with distance but was less than 2 °C at 80km, and at the end of the sensing fibre the error was less than 8 °C. The spatial resolution of this sensor was 50m corresponding to the pulse width used in this experiment. The time taken for trace averaging and data analysis was approximately 100 minutes. This may readily be reduced using higher pulse repetition rate and a faster data acquisition system. For 100km sensing range, the theoretical time limit for collecting this data allowing for just the transit time of the pulse and backscattered signal is only ~8.2 minutes. As the sensing length increases to such lengths, it becomes relatively easier to approach this theoretical time limit. Analysis of the Brillouin intensity measurements proved to be too noisy for useful measurements for ranges >80km. To achieve a fully combined distributed sensor beyond 80km requires further improvements in the intensity resolution and we are presently exploring Raman amplification within the sensing fibre to enhance the signal to noise [6].

## 4. Conclusion

In conclusion, using microwave heterodyne detection of spontaneous Brillouin backscatter, we have achieved an 8 °C temperature resolution, and a spatial resolution of 50m over 100km of single mode fibre. The temperature resolution is limited by detector noise and so further improvement in accuracy could be obtained by increasing number of time domain traces averaged. The result is promising for practical high accuracy long range Brillouin-based distributed optical sensing systems.

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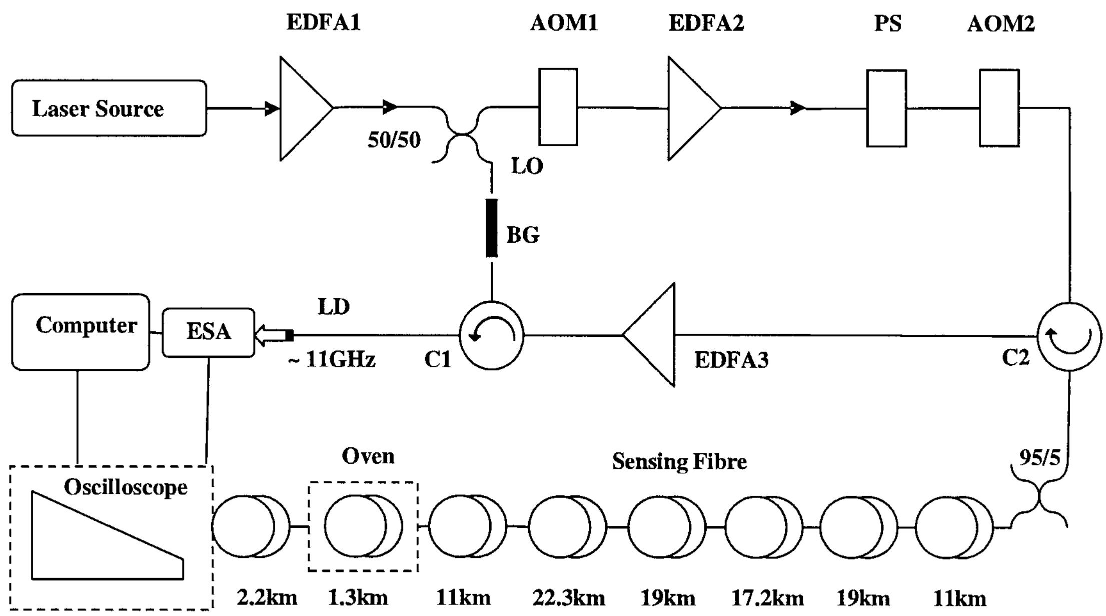
(i) **Figure-1** Experimental arrangement for measuring Brillouin frequency shift. EDFA=erbium-doped fibre amplifier, AOM=acousto-optic modulator, PS=polarization scrambler, LO=local oscillator, BG=Bragg grating, C=circulator, LD=lightwave detector, ESA=electrical spectrum analyzer.

(ii) **Figure-2** Brillouin frequency shifts along the sensing fibres (left). The temperature change (right) is around 60 °C at the heated section at 100km down the sensing fibre.The different Brillouin frequency shifts at room temperature of different fibre sections is due to differences in fibre properties.

(iii) **Figure-3** (left) Brillouin Frequency shift at different applied temperatures at the heated section,(right) the correspond temperature change.

(iv) **Figure-4** The RMS temperature errors along the sensing fibre at 10km intervals averaged over a length of 2km.

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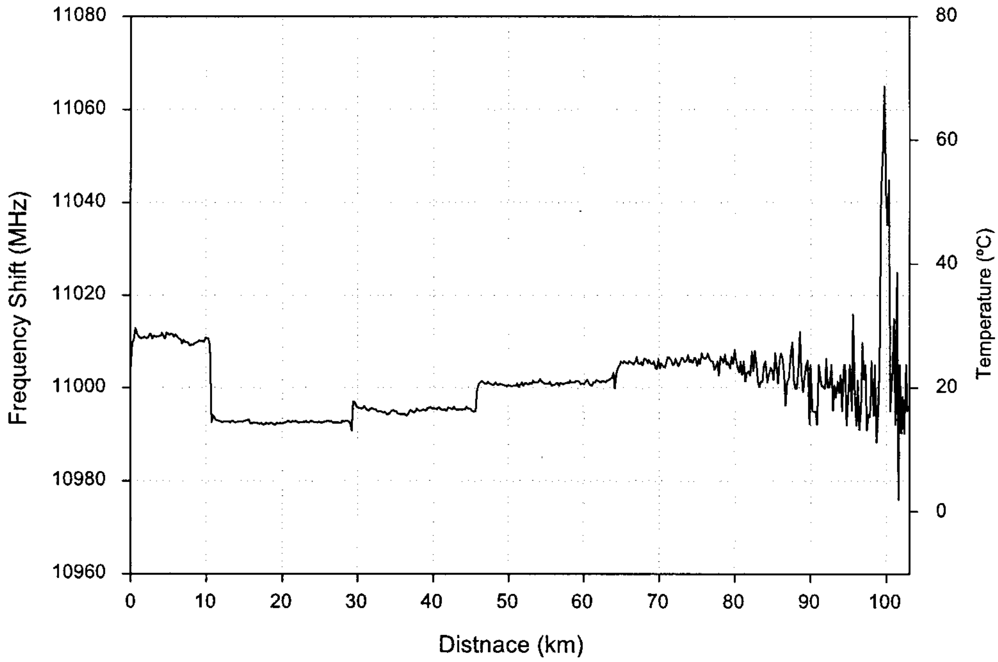
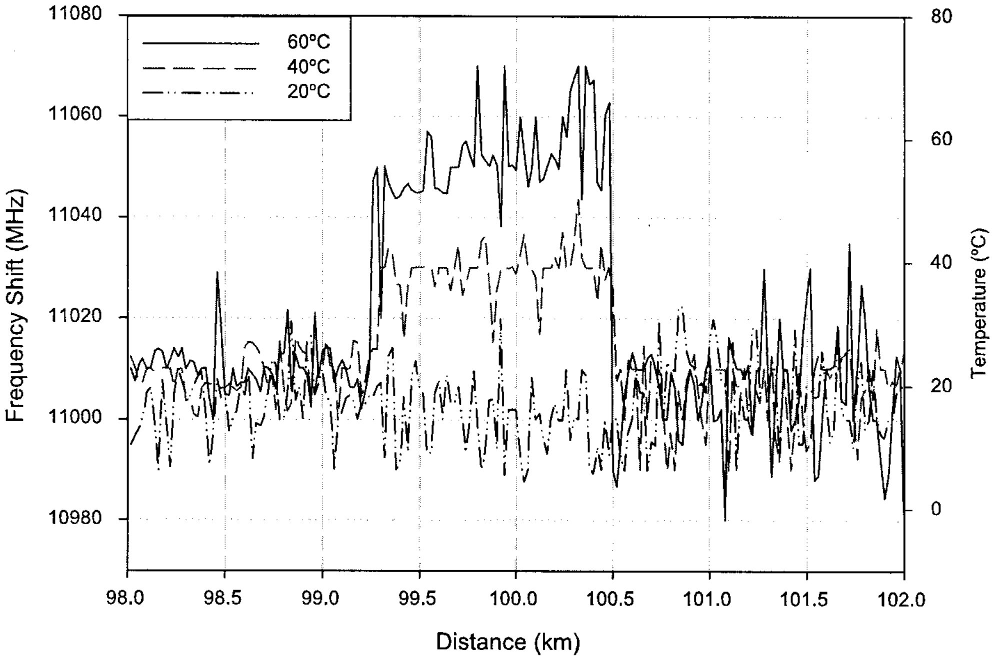



**Figure 2.** Brillouin frequency shifts along the sensing fibres (left). The temperature change (right) is around 60 °C at the heated section at 100km down the sensing fibre.The different Brillouin frequency shifts at room temperature of different fibre sections is due to differences in fibre properties.

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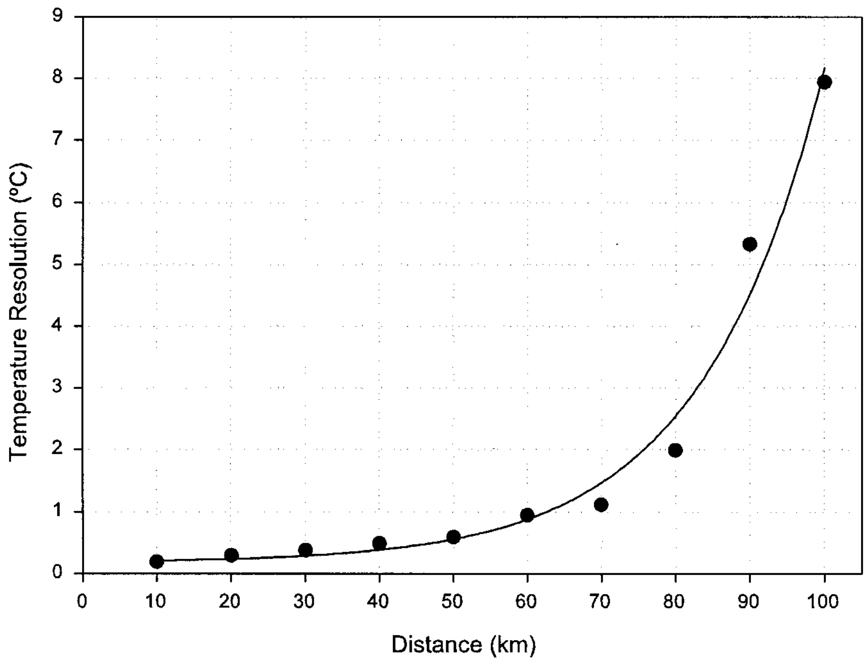


**Figure 4.** The RMS temperature errors along the sensing fibre at 10km intervals averaged over a length of 2km.