100km Distributed Temperature Sensor Based on Coherent Detection of Spontaneous Brillouin Back-scatter

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Abstract: We report the longest distributed temperature sensor based on microwave heterodyne detection of the frequency of the anti-stokes Brillouin signal. At a sensing range of 100km, the temperature accuracy was 8°C, with a spatial resolution of 50m.

1. Introduction

Long range distributed fibre sensors attract a lot of interest due to their potential usage for monitoring temperature/strain of underground power cables, live optical links and large scale structures. Brillouin frequency shift and change in its intensity may be used to obtain simultaneously temperature and strain change along a link of fibre [1, 2]. However the accuracy of intensity measurement limits the performance in long range sensors [3]. Brillouin frequency shift measurement may be used alone to measure temperature or strain change provided one parameter is well defined [4, 5]. In this work we describe measuring temperature change over a distance of 100km of standard single mode sensing fibre assuming zero strain. 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. The stimulated technique requires access to both ends, whereas access to only one end of the sensing fibre is required for spontaneous measurement and is generally more practical for long-range sensors.

Direct and coherent detection have both been used. Direct detection requires optical filtering of the Brillouin component from the Rayleigh - signal, whereas electrical filtering is employed in coherent detection, which improves SNR and provides greater dynamic range [5]. 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.

2. Experimental Details

The experimental arrangement for coherent detection of the anti-stoke spontaneous Brillouin backscatter is shown in figure 1.

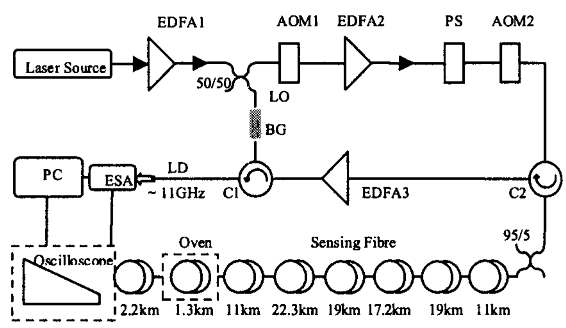

Fig. 1. Experimental arrangement for measuring Brillouin frequency shift.

The source is a tuneable laser @ 1533.2nm, with 1MHz line width. Two-cascaded erbium doped fibre amplifiers (EDFAs) generated a peak probe power of 85mW, and pulse width of

500ns, which is launched into the 103km sensing fibre. A third EDFA was used to amplify the weak backscattered signal prior to mixing with 1.8mW OLO. A 20GHz optical detector and electrical spectrum analyzer (ESA) allow the collection of time domain traces centred at the desired RF frequencies.

The sensing fibre was standard telecommunications single mode silica fibre with the following characteristics: loss of ~0.199dB/km, effective area of $60\mu m^2$, and dispersion of 17 ps/nm.km @ 1550nm. The total length was made up of 8 sections 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. The subsequent 2.2km was subject to 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, 60°C.

3. Results and Discussion

A plot of the peak frequency as a function of distance is shown in figure 2 over the 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, either due to differences in fibre properties or fibre winding tensions. Figure 3 shows the measured Brillouin frequency shifts at 20, 40, and 60°C.

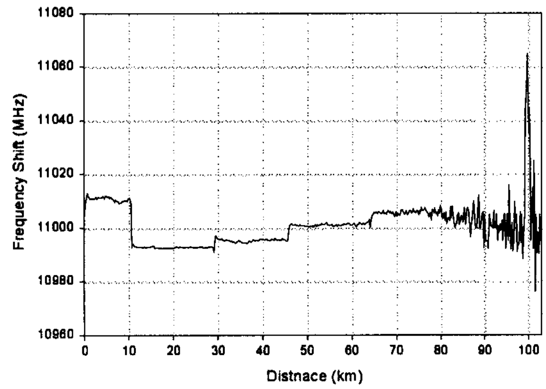

Fig. 2. Brillouin frequency shifts along the sensing fibres. The shift is around 40MHz at the heated section at 100km down the sensing fibre.

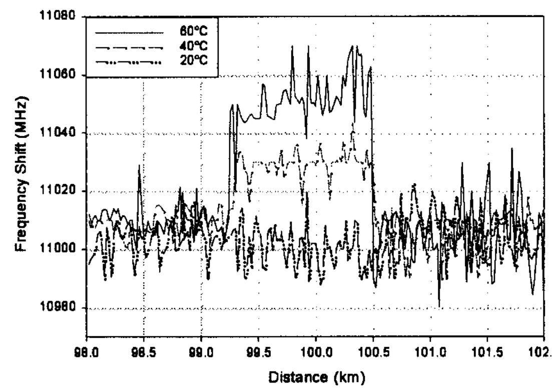

Fig. 3. Brillouin Frequency shift at different applied temperatures at the heated section.

A temperature sensitivity of 1.07±0.07 MHz/°C was measured, and this is in agreement with previously reported results [2, 3, 5]. The RMS frequency errors along the sensing fibre were evaluated every 10km over a range of 2km, and were converted to the corresponding temperature error. The results are shown in figure 4.

The sensor is able to record 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.

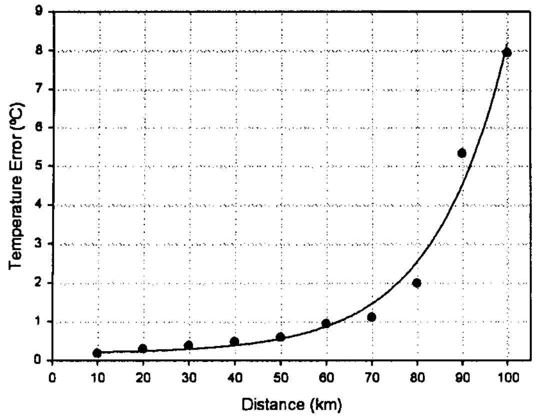

Fig. 4. The RMS temperature errors along the sensing fibre at 10km intervals average over a length of 2km.

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. The theoretical time limit for collecting this data allowing for just the transit time of the pulse and backscattered signal is only 8 minutes. As the sensing length increases to such lengths, it becomes relatively easier to approach this theoretical time limit.

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 can 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.

References:

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