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High Spatial Resolution Microwave Detection System for Long Range Brillouin-based Distributed Sensors

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Abstract: We present a microwave detection system for long range Brillouin-based sensing with a potential spatial resolution of 60cm. It was demonstrated over 30km, with temperature accuracy of 1.6°C, and spatial resolution of 2m.

1.Introduction

Distributed optical fibre sensors based on Brillouin scattering with sub metre spatial resolution capabilities have been previously reported [1, 2], but were confined to relatively short sensing lengths. Several applications such as the continuous monitoring of temperature/strain in underground power cables, live optical links and large scale structures require sensors with relatively high spatial resolution combined with long range [3, 4].

It is now well established that the Brillouin frequency shift and the change in its intensity may be used to obtain simultaneously temperature and strain change along a link of fibre [5, 6]. Coherent detection of the anti-stokes Brillouin signal has proved to be a particularly promising approach, but the long range sensor previously described [7], required electrical detection in the microwave realm, as the detected Brillouin backscatter beat signal lies between 10.5-11.5GHz. Modern photo-detectors and electronic spectrum analyzers (ESAs) can readily process such signals but the majority of ESAs are designed to maximize the frequency resolution capability i.e. have narrow resolution bandwidth, operate at relatively low intermediate frequencies (IF) and have correspondingly low video bandwidths leading to poor spatial resolution.

In our previous reported work, using such an ESA, the spatial resolution was limited to 20m [7, 8]. Our present application for monitoring temperature in power cables required a spatial resolution of 2m. To achieve this, required a higher video bandwidth and a broader resolution bandwidth than was available at an economic price. In this paper we present a microwave detection system specifically designed to achieve this order of magnitude improvement in spatial resolution. The system was tested as a distributed temperature sensor over 30km.

2. Principle of Operation

The principle of Brillouin Optical Time-Domain Reflectometry (BOTDR) and coherent detection was employed. A single laser was used both as a source for generating the probe pulse and as an optical local oscillator (OLO) for coherent detection of the backscattered anti-stokes Brillouin signal. The generated beat signal was around 11GHz, corresponding to the Brillouin frequency shift. This was mixed with a PC controlled YIG-based electrical local oscillator (ELO) and passed through a band-pass filter (BPF) centred at 1GHz, bandwidth 40MHz to generate an IF of 1GHz.

The ELO was scanned through a range of frequencies in user-defined frequency steps. The selected frequency of the ELO determined the portion of the Brillouin beat frequency spectrum that was measured: i.e. the measured component of the Brillouin beat frequency was equal to the ELO frequency plus the 1GHz IF. The IF was amplified and then rectified using a microwave diode rectifier and fed to a storage oscilloscope. The signal recorded was

proportional to the Brillouin power at the chosen frequency over the bandwidth determined by the BPF. The oscilloscope was used to average a large number of time domain traces that were then transferred to the PC.

The Brillouin spectra were built by collecting such traces over a range of frequencies determined by the YIG synthesizer. The Brillouin frequency shifts and Brillouin intensity change were then extracted from the collected data and hence the temperature/strain change was spatially resolved.

3. System Set-up and Measurements

The experimental arrangement for the coherent detection of the anti-stoke spontaneous Brillouin backscatter using the microwave detection system is shown in figure 1. The source was a tuneable laser @ 1533.2nm, with 1MHz line width, and 100µW CW output. Two Erbium doped fibre amplifiers (EDFAs) and an acoustic-optic modulator were used to generate a probe pulse of 25mW, 20ns, figure 2 which was launched into the 32km sensing fibre. An EDFA preamplifier was used to amplify the weak backscattered signal generated in the sensing fibre prior to mixing with a 1.8mW OLO. A 20GHz lightwave detector and the microwave detection system allowed the collection of time domain traces centred at the desired RF frequencies.

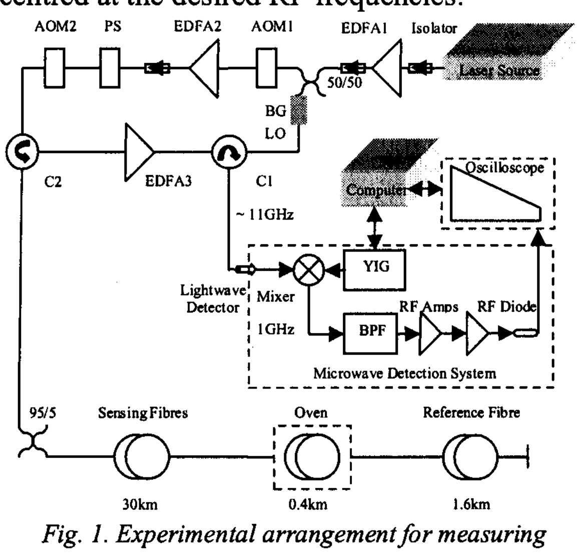

Fig. 1. Experimental arrangement for measuring Brillouin frequency shift using microwave detection system.

The sensing fibre was standard SMF in 3 sections, fusion spliced and arranged as shown in figure 1. The first 30km remained on the original spools at room temperature. The next 400m were placed in an oven at 60°C. The subsequent 1.6km was maintained at room temperature as a reference.

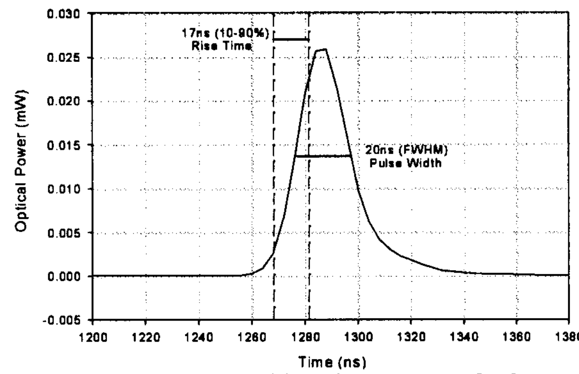

Fig. 2. Optical pulse width and rise time at the front end of the sensing fibre.

In order to validate the spatial resolution and accuracy of the system, measurements were taken between 30 and 30.8km where the central 400m length of fibre was heated to 60°C, and the remaining fibre was at room temperature of 20°C.

The temperature change along the sensing fibre was determined by analysing the frequency shift of Brillouin backscatter. Brillouin spectra were built from 15 separate backscatter traces, each averaged 2^{15} times, taken every 10MHz, starting at 10.99GHz. A Lorentzian curve was fitted to each spectrum and the peak frequency was evaluated at each point along the sensing fibre.

4. Results and Discussion

Figure 3 shows the temperature change at the heated section derived from the shift in Brillouin frequency. A temperature sensitivity of 1.07±0.07 MHz/°C was measured. This is in agreement with previously reported results [7, 9]

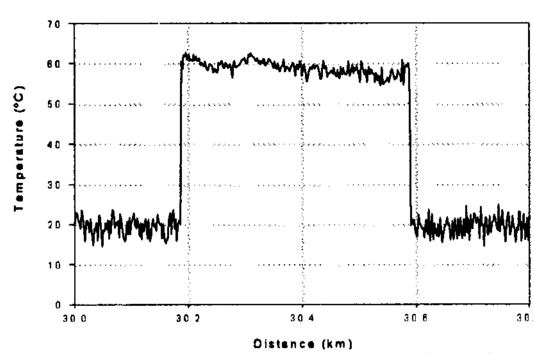

Fig. 3. Temperature change at the heated section.

The spatial resolution was limited by the rise time (~20ns) of the available modulator used to generate the probe pulse. For clarity, figure 4 shows a 10-90% rise-time that was measured at the front end of the sensing fibre and agrees with the expected performance governed by the duration of the pulse and not by the electronics of the detection system. The BPF bandwidth is currently 40MHz (~1.25m) and we believe our detection system is now potentially capable of ~60cm spatial resolution provided its bandwidth is tuned to its maximum (80MHz).

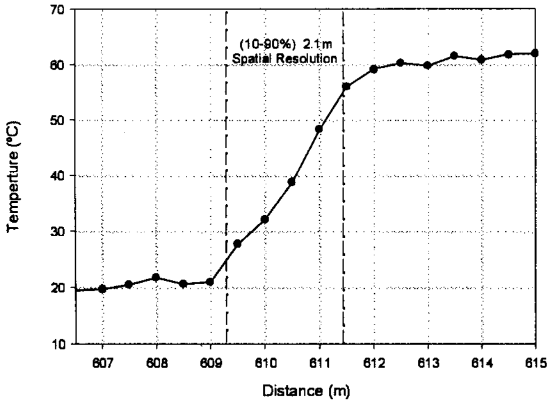

Fig.4 A (10-90%) rise-time of temperature change at 600m down the sensing fibre indicating spatial resolution of ~2m.

The sensor was able to record temperature changes of less than 1.1°C up to 20km. The error increased with distance, but was less than 1.7°C at the end of the sensing length (figure 5).

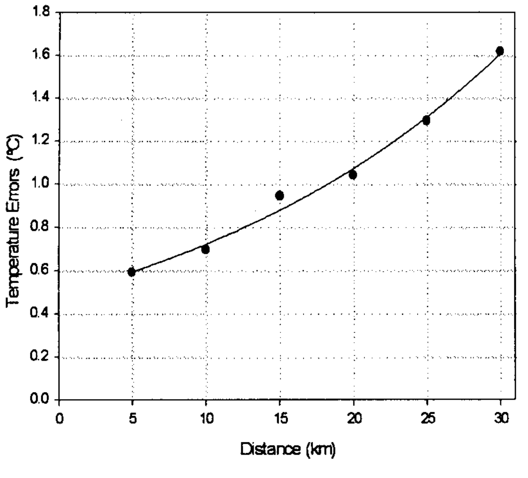

Fig. 5. The RMS temperature errors along the sensing fibre at 5km intervals average over a length of 500m.

5. Conclusion

In conclusion, a microwave detection system has been designed and tested for coherent detection of the backscattered spontaneous anti-stokes Brillouin signals for distributed temperature/strain sensors. The aim was to improve the spatial resolution of our previously reported results by an order of magnitude and this has been achieved. The RMS temperature error was ~1.6°C over a 30km range with a spatial resolution of 2m.

The design represents an important and necessary advance for constructing a commercial sensor as it dispenses with the previous need for an expensive ESA. It also promises practical high spatial resolution and accurate long range Brillouin-based distributed optical sensing systems, with potential for further improvements in spatial resolution

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