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# Technique for measuring distributed temperature with 35cm spatial resolution utilising the Landau-Placzek ratio

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ABSTRACT

The authors report a spontaneous Brillouin-based distributed temperature sensing (DTS) system using a short pulse width laser source at 1.5μm, which permits measurements down to an accuracy of 35cm spatial resolution. This DTS system has been demonstrated utilising conventional single-mode silica fibers for a range of 1km from a single-ended source, and a temperature resolution of 4.3°C was achieved.

INDEX TERMS

Laser applications, optical fiber devices, optical fiber measurement applications, temperature measurement

## INTRODUCTION

Distributed optical fiber temperature sensors based on Brillouin scattering have been researched for a number of years. One significant advantage of using Brillouin-based backscattered systems over previous Raman-based systems is the sensitivity of the Brillouin signals to both temperature and strain using conventional single-mode silica sensing fibers. Several methods have been proposed for performing distributed sensing measurements. One popular method is the time-domain technique known as optical time domain reflectometry (OTDR) which was first demonstrated in 1976 by Barnowski and Jensen [1]. An alternative novel method for distributed sensing using a frequency-domain approach was performed by Ghafoori-Shiraz and Okoshi [2]. Using a frequency-domain approach, distributed Brillouin-based temperature and strain measurements have been performed with a spatial resolution of 3m over a 1-km sensing range [3]. The use of Brillouin scattering for OTDR measurements was demonstrated by Horiguchi and Tateda in 1989 [4]. Since then, outstanding improvements have been reported in terms of sensing range [5] and measurement time [6]. However, there has been debate as to whether the Brillouin linewidth ultimately limits the spatial resolution that can be achieved. It has been suggested that using the time-domain pulsed approach is unsuitable for distributed measurements of sub-metre resolution [7,8].

In some applications, there is a need for fine monitoring of structures over a shorter sensing range, which require sub-metre spatial resolution. Despite a short sensing range of 7.8m, a novel method using direct-frequency-modulation of a tunable laser diode and electro-optic modulator (EOM) demonstrated a remarkable sensing spatial resolution of 45cms [8]. More recently, there have now been claims of distributed strain measurements with spatial resolutions of 40cms [9] and even 25cms [10]. However, the authors of these results point out that each of the sensing fiber sections that are being interrogated must be uniformly strained and identical in length. This presupposes some knowledge of the strain distribution in the fiber which renders the approach inappropriate for most applications. Furthermore the technique suffers from the requirement that access is needed at both ends of the sensing fiber.

In this Letter, we present a high spatial resolution distributed temperature sensor based on measuring the ratio of the intensity of the spontaneous Brillouin to Rayleigh backscattered signal (Landau-Placzek ratio). This technique was initially performed for a 12.9-km sensing range with a 600m spatial resolution [11] and more recently for a 6.3-km sensing range with a 10m spatial resolution [12]. These sensors enable the temperature profile along a length of fiber to be continuously measured using the OTDR principle, whereby a pulse of light is transmitted down the fiber and the light which is backscattered within the numerical aperture of the fiber is measured. The time between sending the pulse of light and detecting the backscattered signal provides a measure of the distance along the fiber, whilst the intensity of the spontaneous Brillouin backscattered light provides the information on temperature. With the source pulse width being shorter than the acoustic damping time, the Brillouin gain spectrum broadens out, resulting in a lower peak gain but broader frequency spectrum. To the best of our knowledge, this is the first demonstration of a Brillouin-based distributed temperature sensor with a spatial resolution of less than 50cm using a single-ended source.

EXPERIMENT

There are two main components in the system in addition to the sensing fiber; a laser source to generate the Brillouin backscattered signal and a low cost filtering and detection system which comprises an all-fiber Mach-Zehnder interferometer and a sensitive InGaAs detector connected to a computer based averaging system. Figure 1 shows the experimental set-up for measuring the temperature profile along the sensing fiber. There is a need to generate a high peak power within the short pulse, to maximise the backscattered signal. The signal pulse was generated from a narrow linewidth CW distributed feedback (DFB) laser diode with an output power of 2.5mW externally modulated by using a $LiNbO_3$ EOM which has a rise time of 100ps. This signal pulse was then amplified using an Erbium-doped fiber amplifier (EDFA1) and the residual ASE noise was filtered by an in-fiber Bragg grating (Reflectivity = 99.4%, $\Delta\lambda$ = 0.08nm, $\lambda$ = 1533.4nm) in conjunction with a circulator 1 (C1). The reflected signal was then amplified using another Erbium-doped fiber amplifier (EDFA2) to overcome the loss of the acousto-optic modulator (AOM) which served to gate the pulse and filter the ASE generated by the second EDFA. The resultant signal pulse had a peak power of 4.5W and pulse width of 3.5ns. The AOM was synchronised with the EOM and pulses were generated at a repetition rate of 6600Hz. The signal was then launched into the sensing fiber through a circulator (C2).

The detection systems used in recent distributed Brillouin temperature sensors operated with the use of an expensive, high loss bulk Fabry-Perot interferometer [11]. In this experiment, a double pass configured in-fiber Mach-Zehnder interferometer was used to spectrally separate the Brillouin signal from the Rayleigh signal [13]. This low-loss interferometer provided in excess of 26dB extinction of the Rayleigh signal from the Brillouin and was locked using a peltier cooler in thermal contact with one arm of the device. The sensing fiber was 1km in total, consisting of three sections of conventional single-mode silica fiber (NA=0.12, cutoff=1.2μm) spliced together with lengths of 600m, 200m and 200m respectively. The spontaneous Brillouin backscattered signal was then measured using a detector and transimpedance amplifier with a bandwidth of 100MHz and sensitivity of 0.1mV/nW. Signal averaging was performed by connecting a digital oscilloscope to a PC, and $2^{17}$ averages were obtained within 26 minutes.

RESULTS

Figure 2 shows the plot of the spontaneous Brillouin backscattered signal taken at a distance of 550m down the sensing fiber. The second drum (200m) was heated to a temperature of 67°C, an increase of 44°C from the room temperature of 23°C. It can be seen from the plot that there is a clear rise in the heated section. In addition, the signal at the end of the sensing fiber is well above the noise floor, indicating that measurements may be made for sensing lengths exceeding 1km. Although it is possible to generate higher pump peak powers with the available source, distortion of the backscattered trace due to self-phase modulation and/or stimulated scattering is readily observed if the peak pump power exceeds a certain threshold and would lead to erroneous results. The Brillouin signal obtained cannot be used to measure absolute temperature due to the dependence of the signal on fiber attenuation and localised splice/bend losses. In order to make absolute measurements, the Brillouin signal has to be referenced to the Rayleigh backscattered signal which is independent of temperature fluctuations. To minimise coherent effects, the Rayleigh signal was obtained by using a broadband pulsed source in place of the DFB laser diode. The ratio of the Brillouin and Rayleigh signals is known as the Landau-Placzek ratio and provides a temperature dependent signal which is corrected for splice/bend losses and fiber attenuation, and this ratio is shown in figure 3. The RMS noise on the Landau-Placzek ratio was calculated to provide information on the temperature resolution of the trace, which corresponded to 4.3°C. Figure 4 shows an expanded trace of the step in Brillouin backscattered signal for sections at 67°C and 23°C, to illustrate the spatial resolution. This was analysed to be of 34.2cms from the 10/90% fall time using the mean values of the heated and unheated sections in this region, and agrees with the theoretical predictions. The seemingly larger fall time in figure 2 as compared to figure 4 is due to the oscilloscope sampling rate falling to accommodate a longer viewed length.

## CONCLUSION

The results demonstrate the highest spatial resolution reported to date using a DTS system based on the intensity dependence of spontaneous Brillouin scattering. A temperature resolution of 4.3°C with a spatial resolution of 35cm for a range of 1km was achieved, using a pulsed source which produced 4.5W peak power at 1.5μm with a pulse width of 3.5ns at a repetition rate of 6600Hz. To achieve such spatial resolution necessitates that the bandwidth of the Brillouin signal has increased to that of the pump pulsed source. The system has the advantage of requiring access to just one end of the sensing fiber. Although this source was used for monitoring temperature variations through measuring the Brillouin backscattered intensity, these results now indicate the potential to perform combined distributed temperature and strain measurements [11,14] with a very high spatial resolution provided the frequency shift can be resolved with similar spatial resolution.

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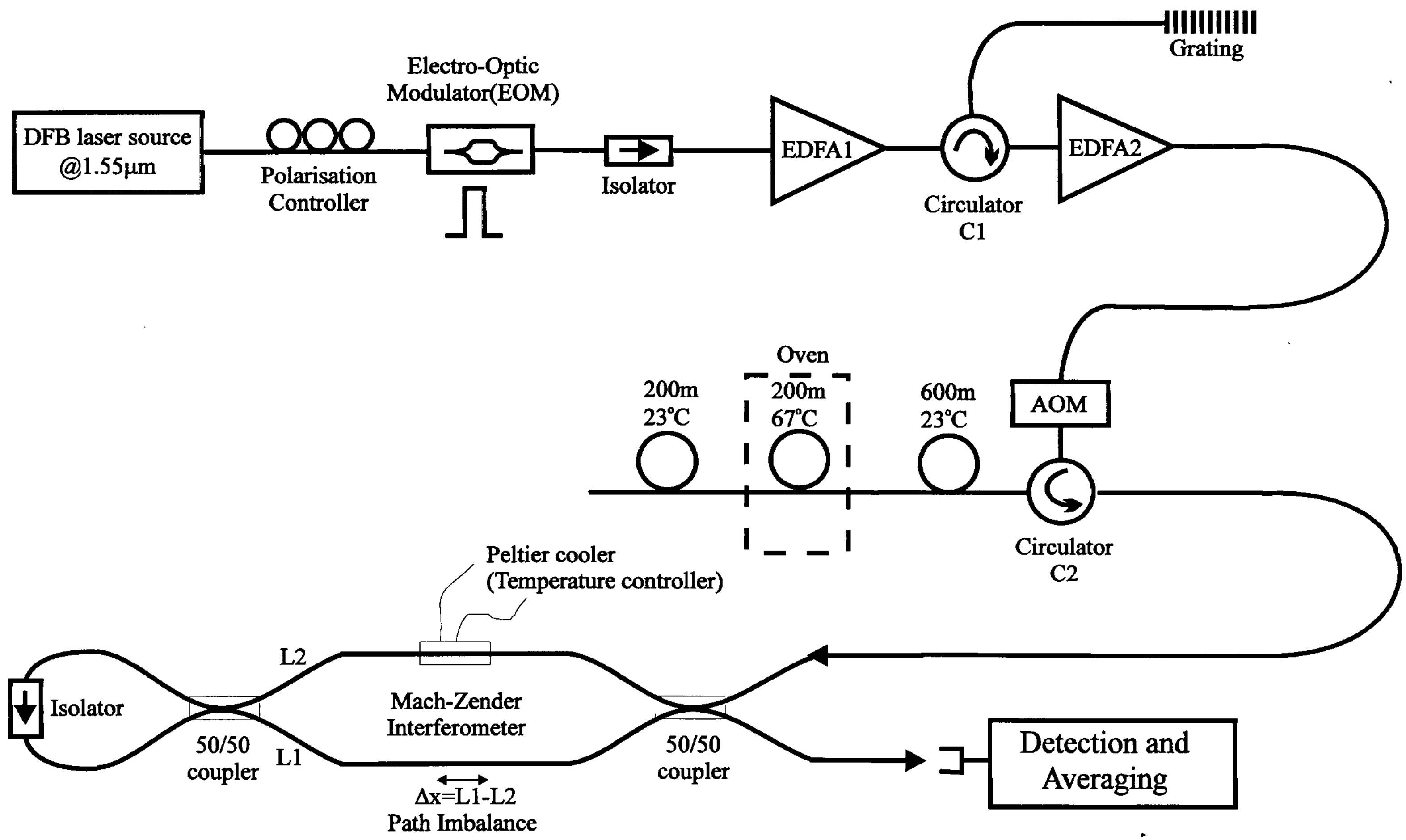
CAPTIONS

Figure 1 – Experimental set-up for the short pulsewidth source

Figure 2 – Brillouin backscattered signal illustrating the signal rise due to a heated section at 67°C, before the signal was compensated for splice losses

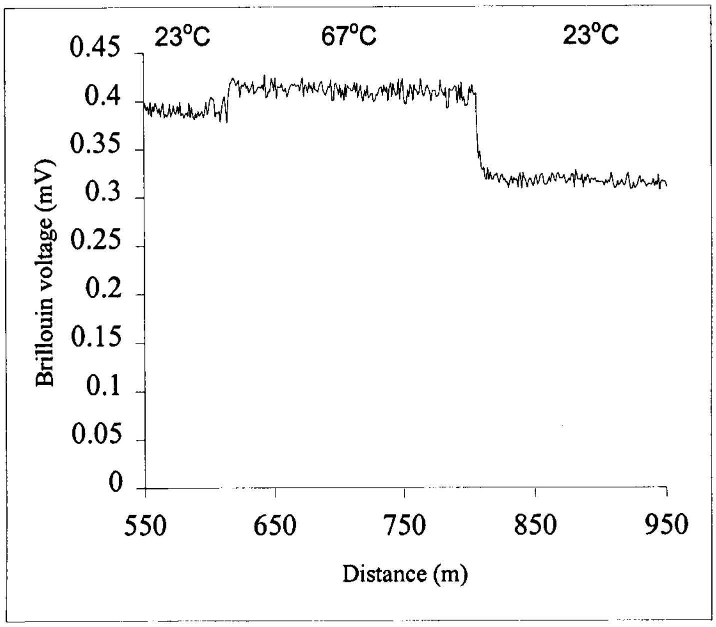
Figure 3 –Landau-Placzek ratio which shows the splice loss compensated by dividing the Rayleigh to Brillouin signals

Figure 4 – Results showing the step change between 67°C and 23°C to illustrate the 35cms spatial resolution



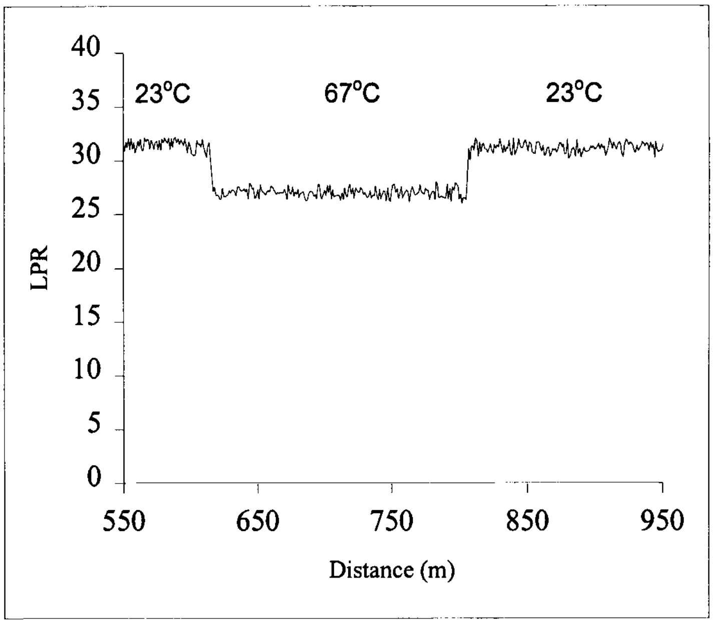
DFB laser source
@1.55μm
Polarisation
Controller
Electro-Optic
Modulator(EOM)
Isolator
EDFA1
Circulator
C1
Grating
EDFA2
AOM
Circulator
C2
Oven
200m
23°C
200m
67°C
600m
23°C
Peltier cooler
(Temperature controller)
L2
L1
Isolator
50/50
coupler
Mach-Zender
Interferometer
Δx=L1-L2
Path Imbalance
50/50
coupler
Detection and
Averaging


**FIGURE 1**



23°C
67°C
23°C
Brillouin voltage (mV)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
550
650
750
850
950
Distance (m)


**FIGURE 2**



23°C
67°C
23°C
LPR
40
35
30
25
20
15
10
5
0
550
650
750
850
950
Distance (m)


FIGURE 3

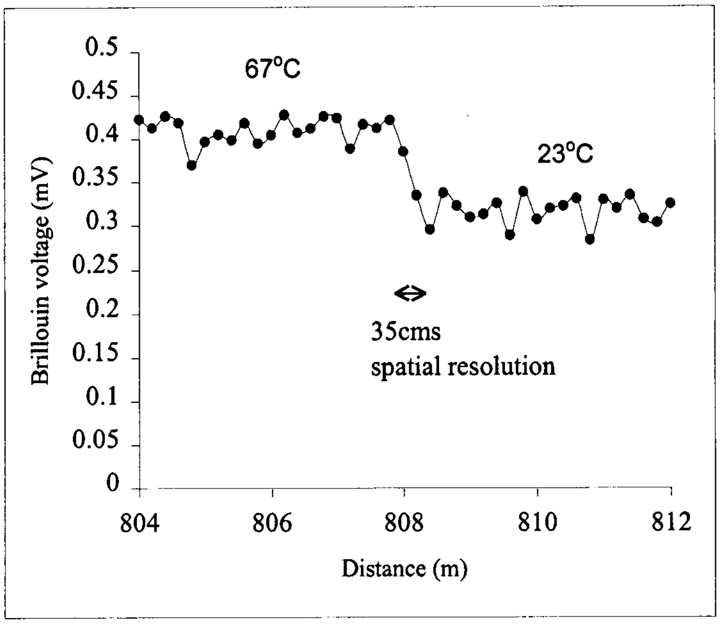

0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Brillouin voltage (mV)
67°C
23°C
35cms
spatial resolution
804
806
808
810
812
Distance (m)

FIGURE 4