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An all-fiber system for simultaneous interrogation of distributed strain and temperature sensing using spontaneous Brillouin scattering

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Abstract: We demonstrate a low loss, long range, single ended distributed optical fiber sensor to simultaneously and unambiguously measure both temperature and strain. By using the Landau-Placzek ratio and cascaded Mach-Zehnder interferometric filters, both the intensity and frequency changes in the Brillouin backscattered signal are measured. Strain and temperature measurements can then be independently resolved. A temperature resolution of 4°C, strain resolution of 290με and spatial resolution of 10m have been achieved for a sensing length of 15km.

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Recently there has been intense research in the development of distributed optical fiber temperature and strain sensors [1-4]. The ability to measure independently strain and temperature over a long range with a high spatial resolution has many applications including power utilities, oil industries and structural monitoring. It has been shown [2,5-7] that the Brillouin backscattered intensity and frequency shift exhibit both strain and temperature dependence. If the sensing fiber is subjected to both temperature and strain effects it is necessary to measure both the Brillouin intensity and frequency shift along the sensing fiber to obtain accurate information regarding temperature and/or strain.

One recently reported method of resolving both temperature and strain has been demonstrated using the Brillouin loss technique [1]. This involved using a pulsed source and a counter-propagating CW source and hence access to both ends of the sensing fiber was required. This technique required two sensing fiber lengths such that one half of the sensing fiber was subjected to both strain and temperature effects and the other half subjected to temperature effects only. These factors make this method unsuitable for certain applications, where either a single ended measurement technique is required or difficulty will be experienced in incorporating a strain free fiber which is subjected to the same temperature distribution.

This letter describes the realisation of a single-ended distributed strain and temperature sensor by measuring the intensity and frequency shift of spontaneous Brillouin backscattered light. A novel in-fiber interferometric optical filtering system is described which allows the measurement of both the intensity of the backscattered signal and its frequency shift. To compensate for fiber attenuation and splice/bend losses, the Rayleigh signal is obtained with the same spatial resolution as the Brillouin signal. The ratio of the intensities of the Rayleigh and spontaneous Brillouin signals is known as the Landau-Placzek ratio, and is independent of fiber attenuation, and splice/bend losses. This technique has been previously reported for Brillouin based distributed temperature measurements and proposed as a method to construct a combined temperature and strain sensor when combined with the known frequency dependence of the Brillouin frequency shift with strain [2].

The optical filtering system presented in this paper consists of two in-fiber Mach-Zehnder interferometers which are linked in series. The first interferometer separates the Brillouin from the Rayleigh, the second allows the frequency shift to be determined. In previous publications [2,3], Fabry Perot interferometers have been used to separate the Rayleigh and Brillouin signals but these severely attenuated the weak backscattered signals. Using a fiber Mach-Zehnder interferometer provides comparable rejection (>27dB) of the Rayleigh from the Brillouin but with a lower insertion loss (<1dB), reduced size and weight. The low insertion loss in crucial to achieve adequate signal to noise, and has resulted in a major advance in measurement accuracy over previously reported results [2,3].

The experimental configuration is illustrated in Figures 1(a) and 1(b). There are five main components to the system, the amplified narrow linewidth laser source, sensing fiber, the Mach-Zehnder interferometers, a broadband Q-switched laser source used to obtain the Rayleigh signal and the detection and averaging systems. To generate the required high peak power, narrow linewidth source, a CW distributed feedback (DFB) laser with an output power of 2.5mW was used. This was externally modulated by a $LiNbO_3$ electro-optic modulator (EOM) and amplified using an Erbium-doped fiber amplifier (EDFA1) with 26dB gain, and the residual ASE noise was filtered by a in-fiber Bragg grating (Reflectivity = 99.4%, $\Delta\lambda$ = 0.08nm, λ = 1533.4nm). The reflected signal was then amplified using another EDFA (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 1.6W, pulse width of 30ns and spectral linewidth of <100MHz. The AOM is synchronised with the EOM and pulses are generated at a repetition rate of 6600Hz. The signal was passed through a 95/5 fiber coupler (FC1), 5% of the signal was used in the control of the optical filters and the remaining signal power was then launched into the sensing fiber through a circulator (C2) as shown in Figure 1(b).

The sensing fiber consisted of 15km of conventional telecommunications single mode silica fiber. The first length of sensing fiber was a 9km drum (D1), followed a section of 0.46km drum D2. Fiber drum D2 was placed in an oven and subjected to a temperature of 53°C, an increase in temperature of 30°C from the temperature from other drums of fiber at room temperature (23°C). Drums D4 and D5 consists of a continuous length of fiber. Between D4 and D5 there was a 120m section of fiber which was loosely reeled on to 11 pairs of pulleys. Weights were then added on one of the ends of the 120m length of fiber to provide a strain. The change in length of the fiber was measured and to determine the average strain over the 120m. The backscattered signal was collected through the circulator (C2) and filtered through the two Mach-Zehnder interferometers.

The first Mach-Zehnder (MZ1) was used in a double-pass configuration with a path imbalance of 9.2mm (FSR = 22GHz) introduced between the two arms of the interferometer. This provided maximum rejection of the Rayleigh signal from the Brillouin to minimise the effect of coherent Rayleigh noise (CRN) which has a detrimental effect on the strain and temperature resolution. The output of this first Mach-Zehnder was then connected to the second Mach-Zehnder (MZ2) which was in a single-pass configuration and with a path imbalance of 28.6mm (FSR = 7GHz). The second Mach-Zehnder was used to convert the Brillouin frequency shift to an intensity change. When the Rayleigh signal frequency lies at a minimum of the transfer function, the Brillouin signals corresponding to zero strain lie at approximately 80% transfer function maximum. The Mach-Zehnder was tuned by monitoring the output port of the Mach-Zehnder whilst launching the laser signal from the 5% arm of the 95/5 coupler (FC1). It is possible to tune the Mach-Zehnder such that the laser signal frequency (and hence the Rayleigh frequency) lies at the minimum or maximum of the transfer function. The Brillouin backscattered signals for the condition of minimum and maximum throughput at the signal wavelength are summed thus obtaining a measurement of the Brillouin backscattered intensity which is independent of frequency shift. The measurement obtained when the Rayleigh frequency lies at a minimum of the transfer function provides a measure of both changes in Brillouin intensity and frequency shift. As the Brillouin intensity has been measured independently of frequency (by summing the two outputs), the Brillouin frequency shift can be calculated.

The backscattered traces were obtained from the output of the single pass Mach-Zehnder using a InGaAs photo-detector and a preamplifier which has a sensitivity of 10mV/nA and an electrical bandwidth of 3MHz. The backscattered traces were averaged 65536 times with an averaging time of 15 minutes. Figures 2(a) and 2(b) show the output of the single pass Mach-Zehnder when the Rayleigh signal frequency has been tuned to the minimum and maximum of the transfer function. Figure 2(c) shows the sum of Figures 2(a) and 2(b) which represents the Brillouin signal dependent only on intensity variations. The attenuation and splice/bend losses are compensated for by dividing the Brillouin signals by the Rayleigh signal. To obtain the Brillouin frequency shift along the sensing fiber, Figure 2(a) is normalised to the Brillouin signal dependent only on intensity variations. Known constants relating the Brillouin frequency shift and intensity to strain and temperature were used in conjunction with the sets of data obtained to solve two simultaneous equations to produce strain and temperature profiles [8], as shown in Figure 3 and Figure 4. The temperature resolution and strain resolutions were estimated from the r.m.s noise of the signals to be 4°C and 290με with a spatial resolution of 10m. The slope on the strained region is due to friction on the pulleys.

In summary, we have demonstrated a long-range single-ended distributed fiber optic simultaneous strain and temperature sensor. The intensity dependence of the Brillouin signal due to variations in strain and temperature are measured by summing the two outputs from the single-pass Mach-Zehnder; and the Brillouin frequency shift dependence is measured by obtaining the output from one arm of the single-pass Mach-Zehnder and compensating for Brillouin intensity changes. Using the Landau-Placzek ratio to compensate for splice and bend losses, variations in strain and temperature could be independently identified. The sensor has been demonstrated for a length of 15km, and a temperature resolution of 4°C, strain resolution of 290με and a spatial resolution of 10m has been achieved. In practical applications, this single-ended sensor has the potential to offer long-range monitoring over tens of kilometers, particularly in systems whereby only one end of the sensing fiber is accessible.

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Figure Captions:

Fig. 1(a). - Experimental configuration for generating the high peak power, short pulse width source

Fig. 1(b). - Sensor configuration for simultaneous strain and temperature measurement

Fig. 2. - Brillouin backscattered signal from the single-pass Mach-Zehnder when the Rayleigh signal frequency has been tuned to (a) minimum and (b) maximum of the transfer function, (c) the sum of (a) and (b)

Fig. 3 - Resolved profile along the sensing fiber for (a) strain distribution (b) temperature distribution

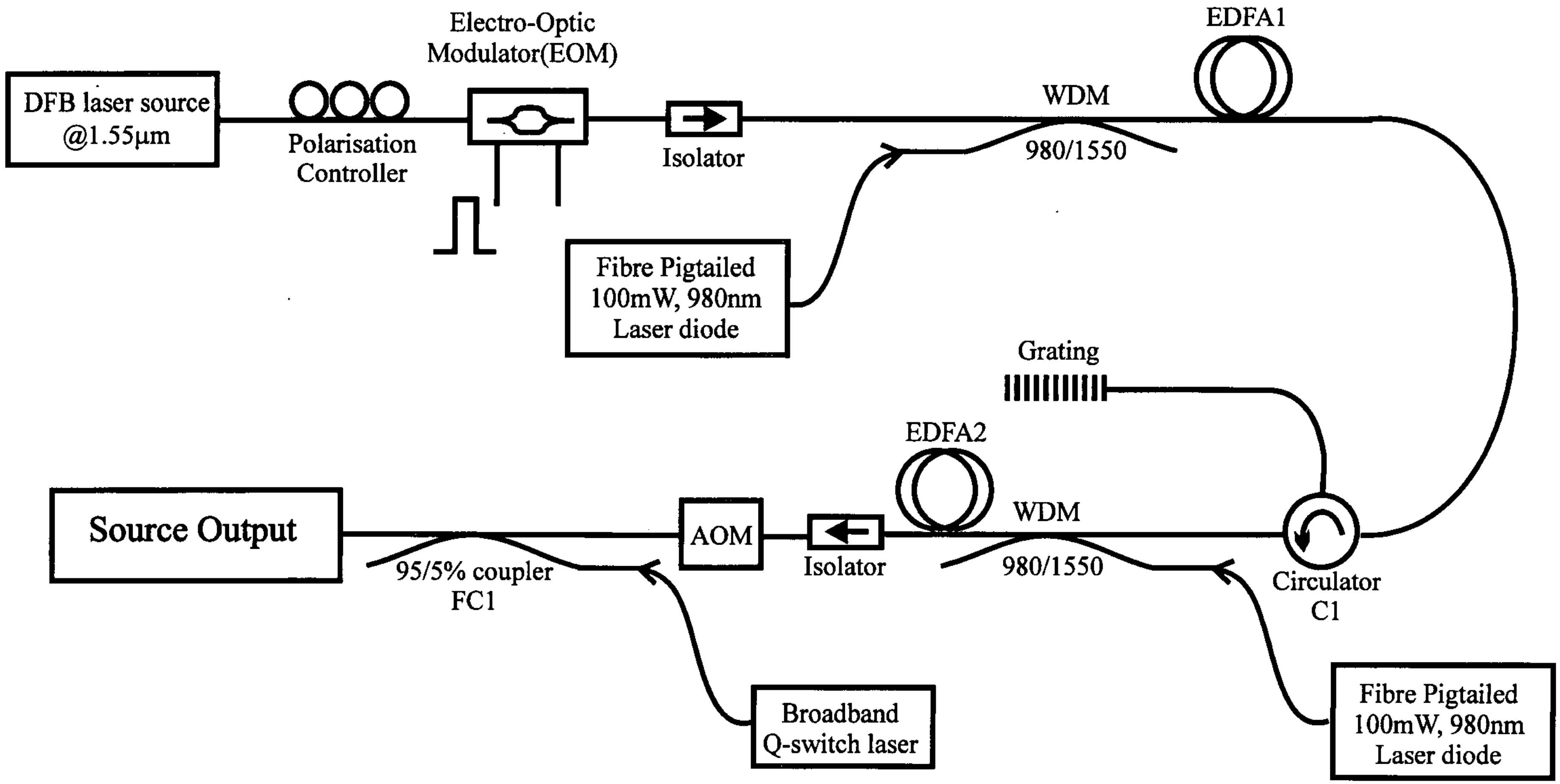
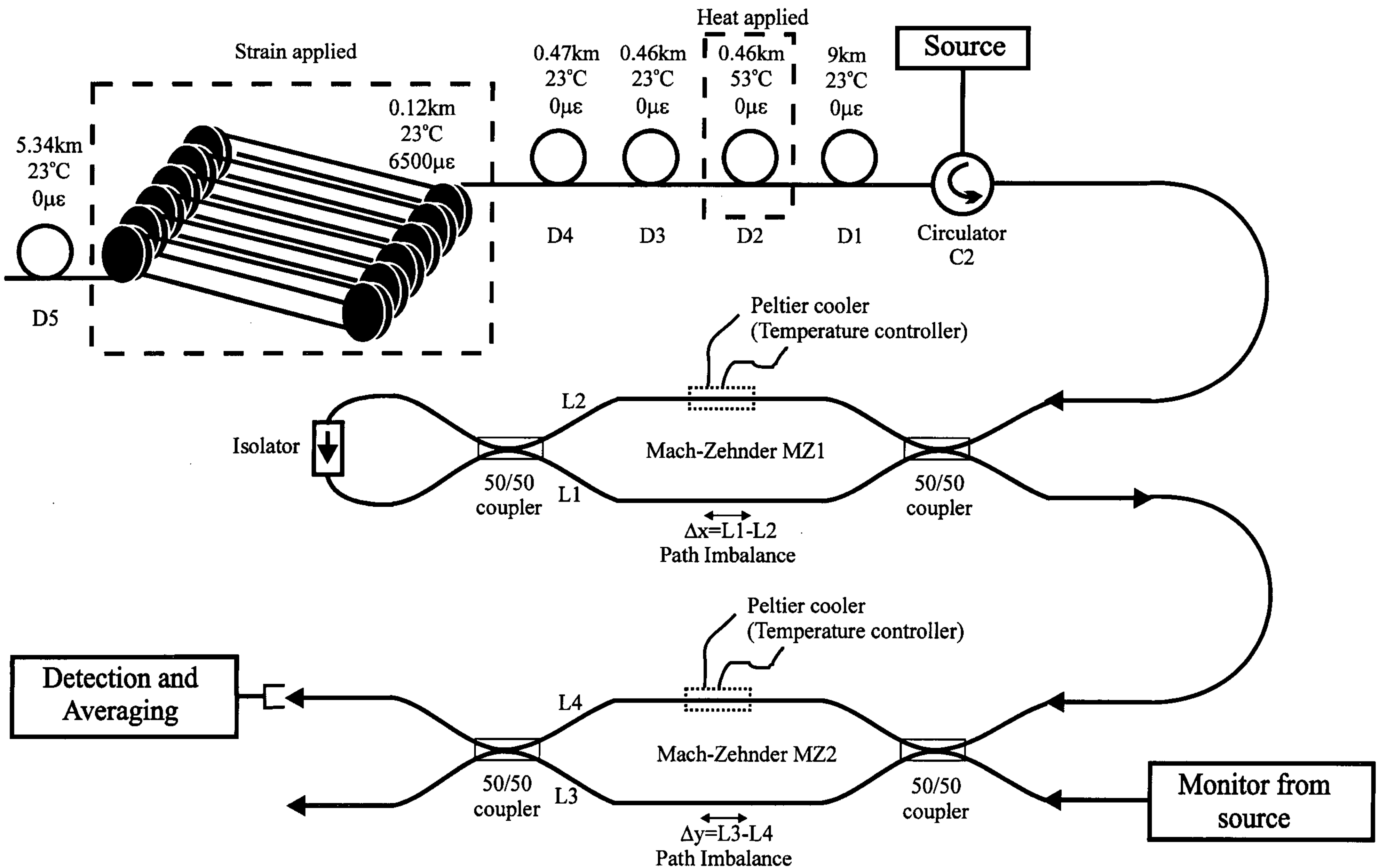

Electro-Optic
Modulator(EOM)
EDFA1
DFB laser source
@1.55μm
Polarisation
Controller
Isolator
WDM
980/1550
Fibre Pigtailed
100mW, 980nm
Laser diode
Grating
EDFA2
Source Output
AOM
Isolator
WDM
980/1550
95/5% coupler
FC1
Circulator
C1
Broadband
Q-switch laser
Fibre Pigtailed
100mW, 980nm
Laser diode

FIGURE 1(a)



Heat applied
Strain applied
Source
0.47km
23°C
0με
0.46km
23°C
0με
0.46km
53°C
0με
9km
23°C
0με
0.12km
23°C
6500με
5.34km
23°C
0με
D5
D4
D3
D2
D1
Circulator
C2
Peltier cooler
(Temperature controller)
L2
Isolator
Mach-Zehnder MZ1
50/50
coupler
L1
50/50
coupler
Δx=L1-L2
Path Imbalance
Peltier cooler
(Temperature controller)
Detection and
Averaging
L4
Mach-Zehnder MZ2
50/50
coupler
L3
50/50
coupler
Monitor from
source
Δy=L3-L4
Path Imbalance

FIGURE 1(b)

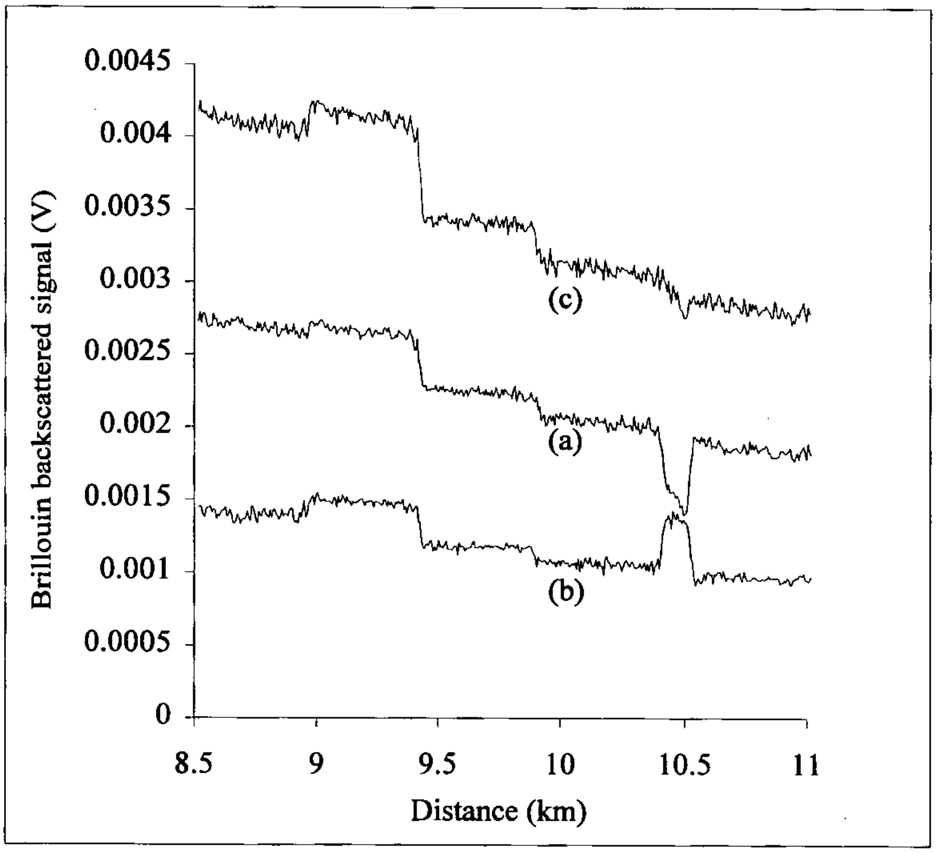

0.0045
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
Brillouin backscattered signal (V)
(c)
(a)
(b)
8.5
9
9.5
10
10.5
11
Distance (km)

FIGURE 2

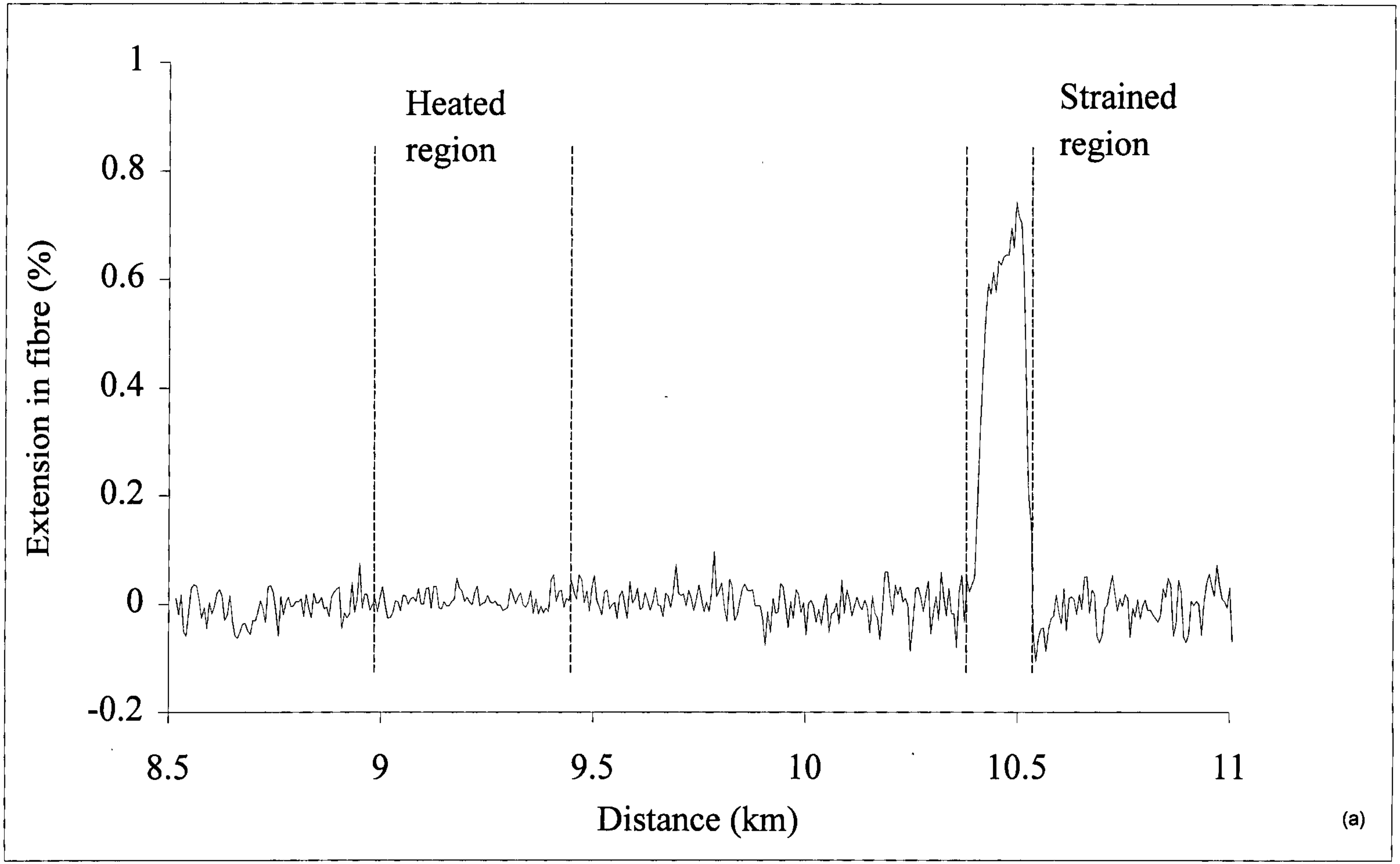

1
0.8
0.6
0.4
0.2
0
-0.2
Extension in fibre (%)
Heated region
Strained region
8.5
9
9.5
10
10.5
11
Distance (km)
(a)

Figure 3(a)

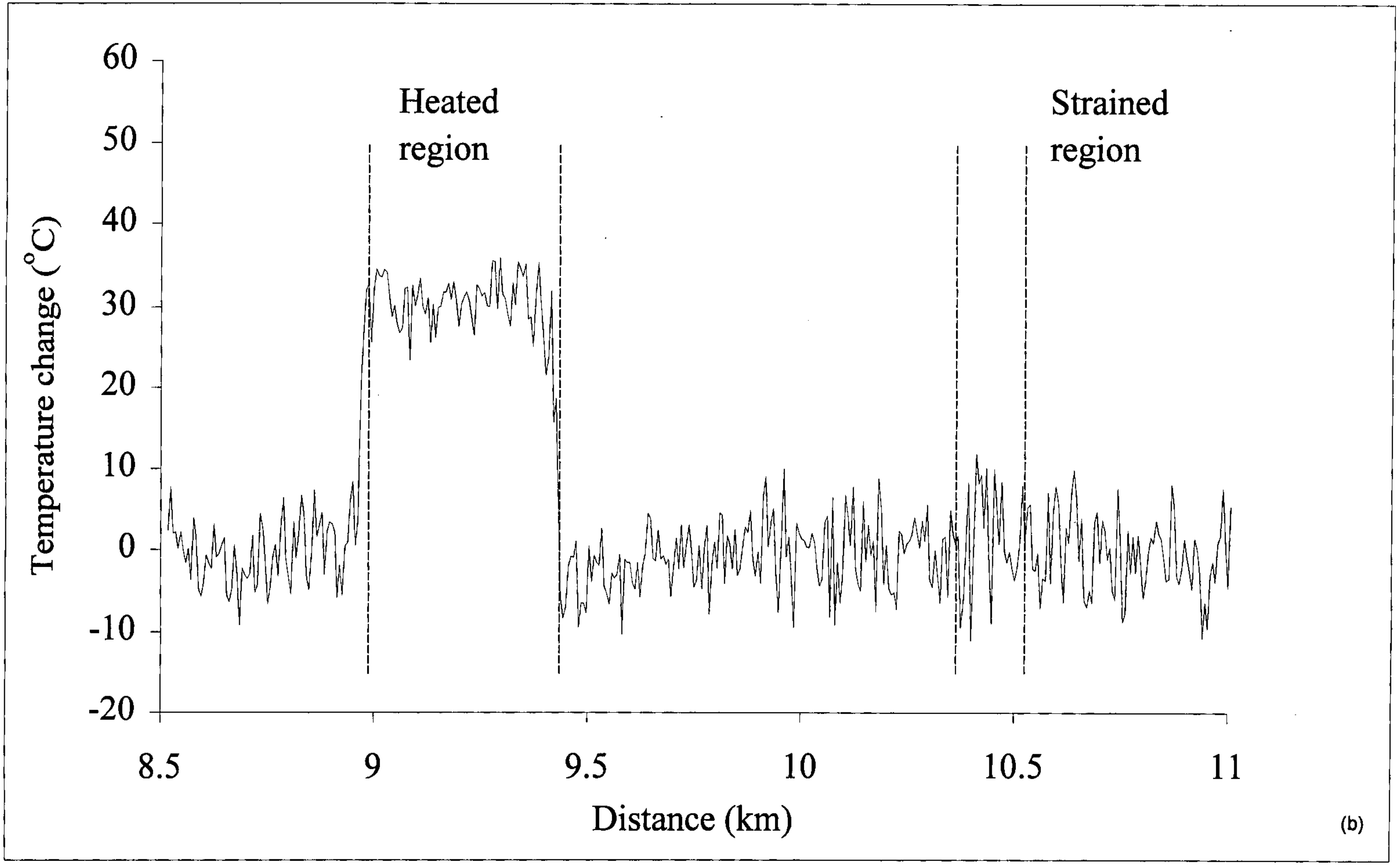

Heated region
Strained region
Temperature change (°C)
60
50
40
30
20
10
0
-10
-20
8.5
9
9.5
10
10.5
11
Distance (km)
(b)

Figure 3(b)