Enhanced Performance of a Temperature Compensated Sub-Metre Spatial Resolution Distributed Strain Sensor

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Abstract— We demonstrate a scheme which allows for temperature corrected distributed strain measurements with improved spatial and strain resolutions and reduced data collection time. The technique utilizes the combination of frequency based BOCDA with Brillouin intensity measurements for a fully temperature compensated strain sensor with a strain resolution of 56με and spatial and temperature resolutions of 10cms and 0.95**°C**.

***Keywords*- distributed sensing, Brillouin scattering, Raman scattering**

I. INTRODUCTION

Optical fibre sensors utilizing Brillouin scattering have been previously reported for measuring temperature and strain [1]. In situations where both strain and temperature are influencing factors, Brillouin frequency measurements alone are insufficient to unambiguously determine the strain. Brillouin Optical Correlation Domain Analysis (BOCDA), whilst offering unrivalled high spatial resolution of the Brillouin frequency shift [2], requires an additional measurement to allow temperature and strain effects to be separated. This paper provides a solution to this problem by combining BOCDA with an independent distributed measurement of temperature, based on the determination of the intensity of the anti-Stokes Brillouin scattering (B-OTDR) with very much higher spatial, temperature and strain resolutions than previously reported, table 1, in order to produce an improved high spatial resolution, fully temperature compensated strain sensor.

Ref.	Spatial Resolution	Temperature Resolution	Strain Resolution
[1]	20m	4°C	100με
[3]	10m	6°C	150με
[4]	5m	3.5°C	85με
[5]	1.3m	3°C	80με
[6]	32m	8.8°C	220με
[7]	10m	4.1°C & 27°C	140με & 570με

Table 1, lists the achievements of previous techniques with spatial, temperature and strain resolutions respectively

In BOCDA a frequency swept laser output is split into two. One of which is frequency shifted by an amount close to the expected Brillouin frequency shift, and launched into the opposite end of the sensing fibre to the other un-shifted beam. A strong Brillouin interaction results in a localized region of the fibre corresponding to zero delay between the counter-propagating beams of light. Peak Brillouin frequency corresponding to this localised region is obtained by scanning the frequency of the frequency shifter. By delaying the phase of one beam relative to the other, the position of the localised Brillouin interaction region can be swept all along the fibre. This is normally achieved by incorporating a delay fibre outside the sensing fibre, which essentially translates any change in the sweeping frequency of laser into the phase change necessary to move the interrogation point along the sensing fibre._ For the BOCDA based measurements, the spatial resolution (Δz) and measurement range corresponding to the interval between correlation peaks (Δd) are given by the following equations [2]:

$$\Delta z = \frac{\Delta d . \Delta \nu_B}{\pi . \Delta f} \quad ; \quad \Delta d = \frac{V_g}{2 f_m} \tag{1}$$

where f_m is the modulation frequency, Δf is the frequency variation achieved when the laser wavelength is swept at frequency f_m , $\Delta \nu_B$ is the linewidth of the Brillouin spectrum and V_g is the velocity of light in the fibre.

Previously, we reported the use of spontaneous Raman scattering to provide this temperature compensation. Despite using high peak pulse powers, the spatial resolution we achieved was limited to 24 cms even with averaging times of 40 minutes, due to the very weak nature of the spontaneous Raman scattering [8]. In order to more fully exploit the high spatial resolution capability of BOCDA, we have investigated the benefit of combining the Brillouin anti-Stokes measurement with the Brillouin frequency based BOCDA technique. The known temperature dependence of 0.36%/°C [1] and small strain dependence of –9 x 10^{-4} %/με [9], of the Brillouin anti-Stokes intensity was then used to allow for strain to be determined from the BOTDR and BOCDA information. In order to discriminate temperature and strain, the change in Brillouin frequency shift from BOCDA and intensity from B-OTDR can be expressed in matrix form, which on solving allows for the temperature compensated strain to be ascertained, as given by equation 2.

$$\begin{bmatrix} \Delta \nu_B \\ \Delta I_{B_{A.S}} \end{bmatrix} = \begin{bmatrix} C^{\varepsilon}_{B\nu} & C^{T}_{B\nu} \\ C^{\varepsilon}_{BI} & C^{T}_{BI} \end{bmatrix} \begin{bmatrix} \Delta \varepsilon \\ \Delta T \end{bmatrix} \quad \Rightarrow \quad \Delta \varepsilon = \frac{C^{T}_{BI} \cdot \Delta \nu_B - C^{T}_{B\nu} \cdot \Delta I_{B_{A.S}}}{C^{\varepsilon}_{B\nu} C^{T}_{BI} - C^{\varepsilon}_{BI} C^{T}_{B\nu}} \tag{2}$$

where $C^{\varepsilon}_{B\nu}$ and $C^{T}_{B\nu}$ are the coefficients for the Brillouin frequency shift due to strain and temperature, while C^{T}_{BI} and

C^{ε}_{BI} are the coefficient for the Brillouin anti-Stokes intensity change with temperature and strain respectively. Equation 3 estimates the error on strain computed using equation 2.

$$|\delta(\Delta\varepsilon)| = \frac{|C^{T}_{BI}||\delta\Delta\nu_B| + |C^{T}_{B\nu}||\delta\Delta I_{B_{A.S}}|}{|C^{\varepsilon}_{B\nu}C^{T}_{BI} - C^{\varepsilon}_{BI}C^{T}_{B\nu}|} \qquad (3)$$

$\delta\Delta\nu_B$ and $\delta\Delta I_{B_{A.S}}$ are the RMS errors on the Brillouin frequency and anti-Stokes intensity measurements respectively.

II. EXPERIMENT

The sensing fiber comprised 131m of standard single mode fiber with an effective area~ $80\mu m^2$, loss ~ 0.20dB/km and dispersion ~17 ps/km nm at 1550 nm. The experimental set up, with detail of the sensing fiber layout is shown in fig. 1. The injection current of laser diode (2) (linewidth ~ 5 MHz, 1550nm) was modulated to achieve a frequency variation Δf of 8.8GHz with sinusoidal sweep rates f_m of 1.07252 MHz – 1.07330 MHz and 1.10922 MHz – 1.11000 MHz (frequency step~ 0.03 kHz) in order to enable a single correlation peak to be scanned over the fibers from section 1, 2, 3 and 4 respectively.

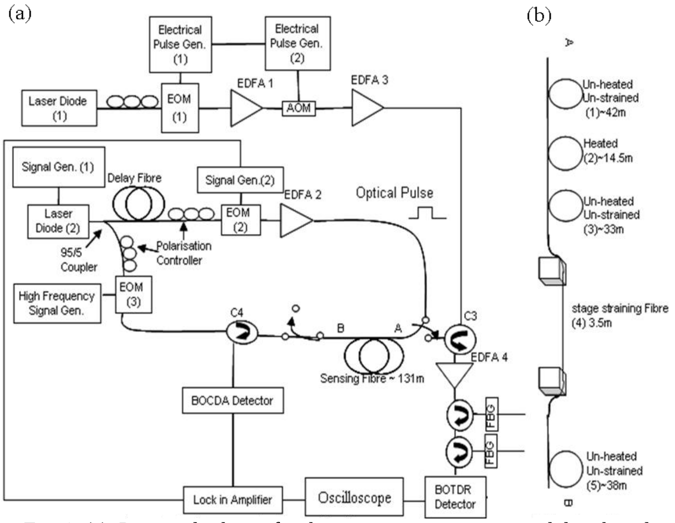

Fig. 1. (a) Proposed scheme for the temperature compensated distributed strain sensor system; (b) Layout of 131m sensing fibre.

The output from laser diode (1) (linewidth ~ 5 MHz, 1549nm) was fed through a cascaded arrangement of electro optic modulator (EOM) , erbium doped fiber amplifier (EDFA) and acousto optic modulator (AOM), resulting in 0.5 - 1ns, 1W peak power pulses, which were subsequently launched into the 131m sensing fiber. The spontaneous Brillouin anti-Stokes back-scattered signal was amplified using a 30dB gain optical amplifier and filtered using two narrow (~3.5GHz) fibre Bragg gratings. The amplified signal was detected using a 200MHz APD.

III. RESULTS AND DISCUSSION

Fig. 2, shows a summary of the BOCDA results. Fig. 2(a), shows the three Brillouin gain spectrum (BGS) corresponding to three different sections of the sensing fiber. Traces red and blue, show the BGS corresponding to section 2 and section 4, subjected to a temperature of 52°C and a nominal strain of 1044.4με respectively, whilst the black trace shows the BGS corresponding to unheated (25°C) and unstrained sections 1,3 and 5 of the 131m sensing fiber. Fig. 2 (b) and (c) show the change in Brillouin frequency shift of 28MHz and 47MHz, emerging as the correlation peak is swept from section 1 to section 2 and section 3 to section 4, resulting in Brillouin frequency coefficients of 1.04 MHz/°C and 4.5 MHz/100με respectively.

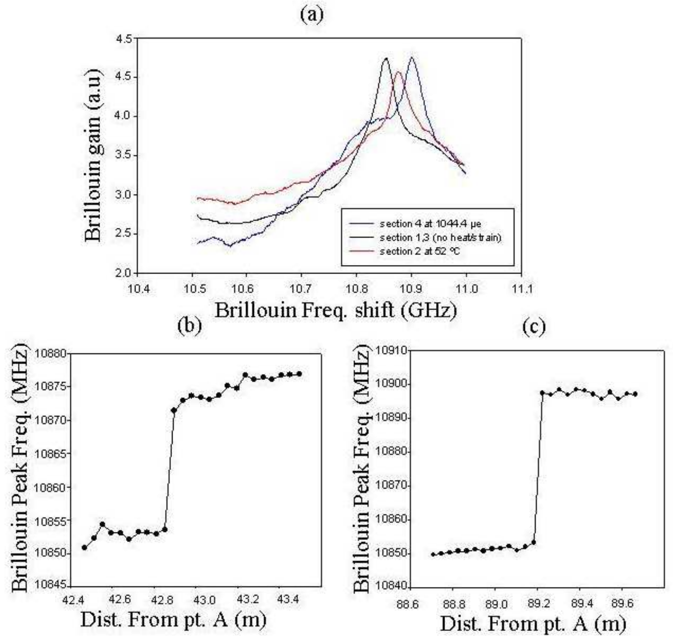

Fig. 2. (a) The Brillouin peaks corresponding to the strained, unheated/unstrained, and heated Sections of the 131m sensing fibre;, (b) the step change in Brillouin peak frequency when scanning the correlation peak from the unheated to heated Section and (c) from the unstrained to strained Sections.

The spatial resolution (10/90% response) was measured to be 10cm for the heated section and 9cm for the strained section, with a frequency error ($\delta\Delta\nu_B$) of 1.7MHz. The spatial resolutions were in close agreement with the theoretically calculated values of 10.1cm (heated section) and 9.7cm (strain section), using equation 1 and 2 respectively. The drift in the heated section in fig. 2(b) was due to a temperature gradient over the hot plate.

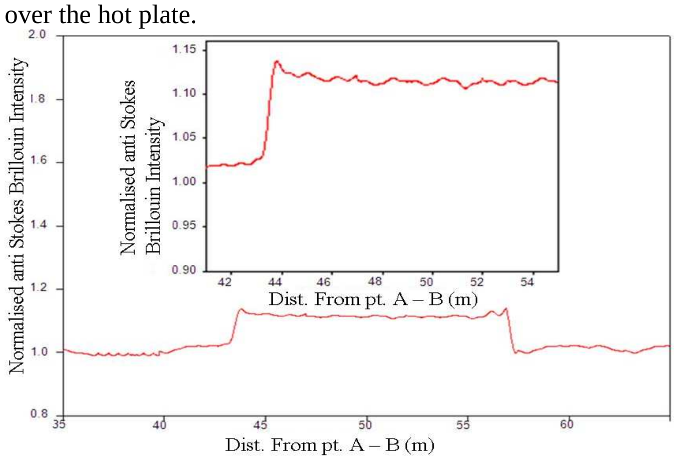

Fig. 3 The normalised B-OTDR plot of the fiber in section 2 heated to 52°C, with the insert showing the normalised Brillouin intensity of the heated section

Fig.3 depicts a normalized B-OTDR plot with the insert showing the normalized Brillouin intensity of the heated section and Fig.4, shows a spatial resolution of 7cms, evaluated using the 10/90 response of a step change in temperature, between the heated section at 52°C and unheated section at 25°C. The r.m.s intensity noise $\left(\delta\Delta I_{B_{A.S}}\right)$ of the heated section shown in insert of Fig. 3 was measured to be 0.34%, which translates into a temperature resolution of 0.95°C. An improved data acquisition system allowed 2^{23} averages to be collected in a little over a minute compared to 40 minutes in our previous result obtained with R-OTDR [9].

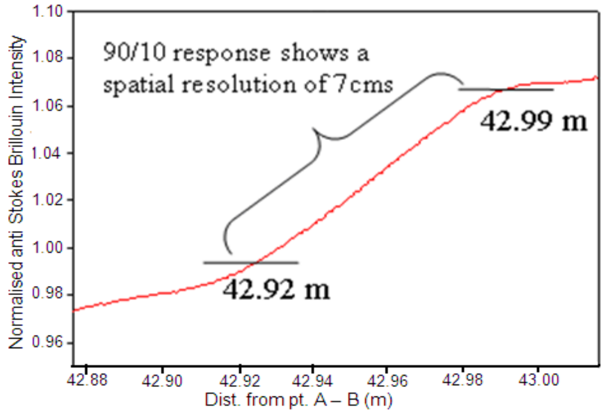

Fig. 4 Depicting a 10/90 step response for the transition from unheated (1) to heated (2) fibre, indicating a spatial resolution of 7cms.

The intensity change for the five different temperatures is plotted in fig. 5. The slope corresponding to coefficient of intensity change with temperature extracted from the equation of a linear fit was 0.36%/ °C, which is in agreement with previously reported value [1].

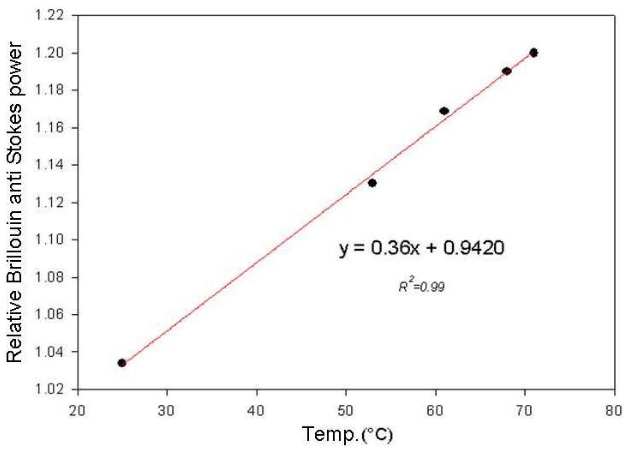

Fig. 5. The % intensity change of Brillouin anti-Stokes signal versus temperature.

The frequency error ($\delta\Delta\nu_B$) of 1.7MHz on the Brillouin frequency based strain measurements corresponds to a strain resolution of 38µε in the absence of temperature uncertainty. To ascertain the strain resolution under conditions where the temperature effects are also present, equation 3 is used to compute the strain resolution. Combined errors of the Brillouin frequency $(BOCDA\sim\ \delta\Delta\nu_B = 1.7MHz)$ and Brillouin intensity $\left(B-OTDR\sim\ \delta\Delta I_{B_{A.S}} = 0.34\%\right)$ with coefficients $C_{B\nu}^{\varepsilon} = 4.5MHz/100\mu\varepsilon$; $C_{B\nu}^{T} = 1.04MHz/^{\circ}C$; $C_{BI}^{T} = 0.36\%/^{\circ}C$; $C_{BI}^{\varepsilon} = 9\times10^{-4}\,\%/\mu\varepsilon$, yield a temperature compensated strain resolution of 56µε for a strain sensor of 131m long with a sub metre spatial resolution of10cm.

IV. CONCLUSION

A high spatial resolution temperature compensated strain sensor has been demonstrated using BOCDA combined with B-OTDR. With the use of the stronger Brillouin anti-Stokes signal as compared to the previously used Raman anti-Stokes, the signal to noise for intensity based temperature measurements was improved nearly 5 fold i.e., from 1.6% [9] to 0.34%. This permitted both the strain and spatial resolutions of the temperature compensated strain to be reduced from 97µε and 24cms [9] to 56µε and 10cms. Due to an improved data acquisition system the data collection time for the averaged B-OTDR trace was reduced from 40 minutes to a little over 1 minute. This improvement in response time provides new opportunities for monitoring cyclic loading of smart composite structures which often undergo considerable heating during the strain cycles.

References

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