Evaluation of a high spatial resolution temperature compensated distributed strain sensor using a temperature controlled strain rig

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ABSTRACT

We demonstrate a scheme which allows for temperature corrected distributed strain measurements under environments involving simultaneous application of strain and temperature, with enhanced spatial (5 cms), strain (66με) and temperature resolutions (1.9°C). The technique utilizes the combination of frequency based BOCDA with Brillouin intensity measurements.

Keyword: Brillouin scattering, distributed fiber sensors

1. INTRODUCTION

In situations where both strain and temperature are simultaneously influencing the same section of the sensing fiber, Brillouin frequency measurements alone are insufficient to unambiguously determine the strain. A solution to this problem has been previously provided [1], but to date has only been tested for sensing rigs where sections have either been heated or strained. This is due to the difficulty of heating an extended strain region. With the advent of techniques allowing high spatial resolution, albeit over shorter sensing lengths, the concept of discriminating temperature and strain can be tested for regions of sensing fiber which are simultaneously strained and heated in an environmental chamber. 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 a distributed measurement of the power of the anti-Stokes Brillouin scattering (B-OTDR) with very much higher spatial resolution than previously reported, table 1, in order to produce an improved high spatial resolution, fully temperature compensated distributed strain sensor. High spatial resolution Brillouin intensity measurements require very short pulses with high peak powers. Such a requirement ties in well for short range distributed sensing as much higher peak pulses are permissible before non linear deleterious effects such as self phase modulation, cross phase modulation, stimulated Raman scattering become significant.

Ref.	Spatial Resolution	Strain Resolution	Temperature Resolution	Range
[1]	20m	100με	4°C	30 Km
[3]	5m	85με	3.5°C	50 Km
[4]	1.3m	80με	3°C	6.3 Km

Table 1. 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. The 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 along the sensing fibre. This is normally achieved by incorporating a delay fibre outside the sensing fibre, which essentially translates any change in the sweeping frequency of the 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]:

$$\Delta z = \frac{\Delta d.\Delta v_B}{\pi.\Delta f} \quad ; \quad \Delta d = \frac{V_g}{2f_m} \qquad (1)$$

where f_m is the modulation frequency, Δf is the laser frequency excursion achieved when the laser wavelength is swept at frequency f_m, Δv_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, investigating separately heated and strained regions of fibre, but the spatial resolution was limited to 24 cms [5] even with an averaging time of 40 minutes, due to the weak nature of Raman anti Stokes scattering. In order to more fully exploit the high spatial resolution capability of BOCDA, we investigated the benefit and robustness of combining the Brillouin anti-Stokes measurement, which is a stronger signal compared to Raman anti Stokes, with the Brillouin frequency based BOCDA technique. Using BOCDA and B-OTDR to discriminate temperature and strain requires the values of Brillouin frequency change obtained from BOCDA and intensity change from B-OTDR for temperature and stain. This is expressed in the form of matrix, which on solving allows for the temperature compensated strain to be ascertained.

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

This equation relies on the assumption that the coefficients describing the change in frequency or power with strain or temperature are constant as the other parameter is varied. The validity of this assumption is the subject of a separate investigation to be reported. The temperature compensated strain resolution can be estimated from equation 2 using previously determined experimental values of Brillouin coefficients [1, 6].

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

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

2. EXPERIMENT

The experimental set up, with detail of the sensing fiber layout is shown in fig. 1.

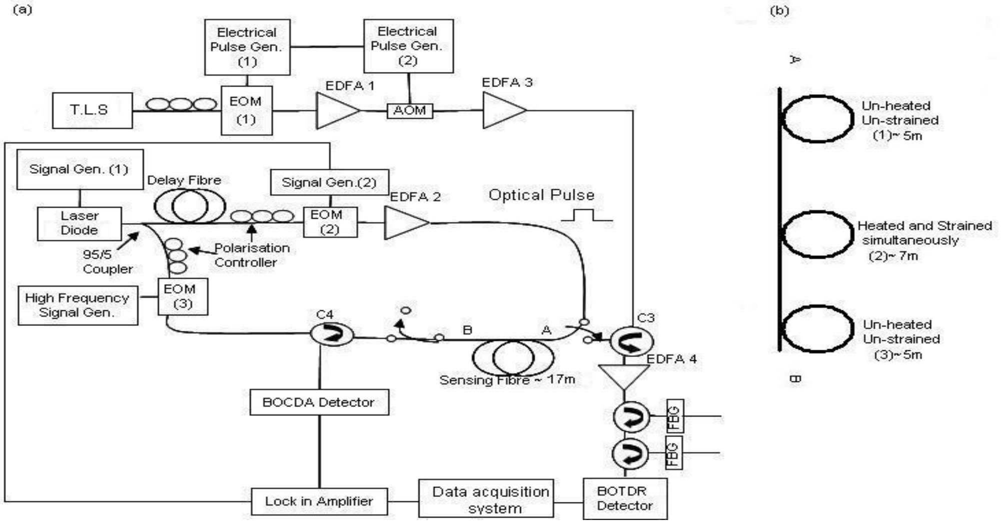

Figure 1. (a) The experimental configuration for a temperature compensated distributed strain sensor system; (b) Layout of the 17m sensing fibre.

The sensing fiber comprised 17m of standard single mode fiber with an effective area~ 80μm^2, loss ~ 0.20dB/km and dispersion ~17 ps/km nm at 1550 nm. The injection current of the laser diode (linewidth ~ 5 MHz, 1550nm) was modulated to achieve a frequency excursion Δf of 8.8GHz with sinusoidal sweep rates f_m of 2.14504 MHz – 2.1466 MHz (frequency step~ 0.03 kHz) in order to enable a single correlation peak to be scanned over the fibers from section 1, 2 and 3 respectively. The output from a tuneable laser source (T.L.S) linewidth ~ 100 KHz, 1534nm, was fed through a cascaded arrangement of electro-optic modulator (EOM) , erbium doped fiber amplifier (EDFA) and an acousto-optic modulator (AOM), resulting in 0.3 – 0.5ns, 5W 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.

3. RESULTS AND DISCUSSION

Figure 2, shows a summary of the BOCDA results. Figure 2(a), shows the two Brillouin gain spectra (BGS) corresponding to three different sections of the sensing fiber. The black trace shows the BGS corresponding to section 1 and 3, which remained un-heated and un-strained, while the red trace corresponds to section 2 which was simultaneously subjected to a temperature of 70°C and a nominal strain of 1285με. Fig. 2 (b) shows the change in Brillouin frequency shift of 101MHz emerging as the correlation peak is swept from section 1 to section 2.

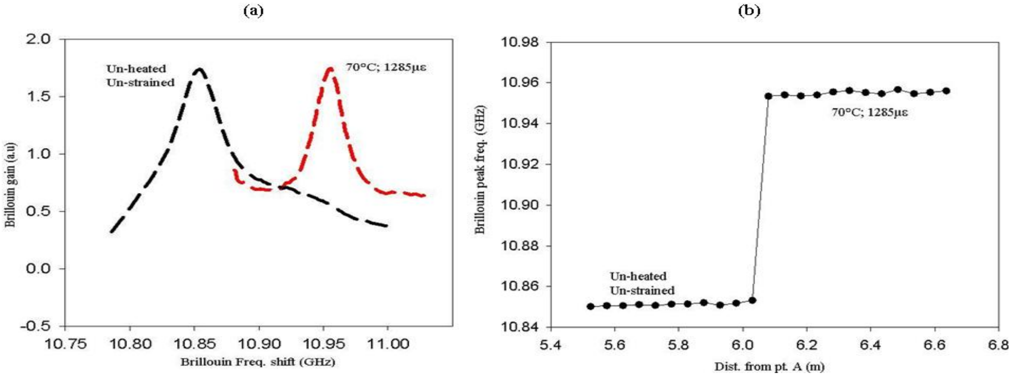

Figure 2. (a) The Brillouin peak shown in black trace corresponds to the un-heated, un-strained sections of 5m each, while the Brillouin peak shown in red represents the 7m section of fiber simultaneously subjected to a temperature of 70°C and a nominal strain of 1285με; (b) The step change in Brillouin peak frequency when scanning the correlation peak from the un-heated, un-strained section to the section of fiber simultaneously subjected to a temperature of 70°C and a nominal strain of 1285με.

The measured spatial resolution, figure 2(b), equalled the expected theoretical value of 5cm with a frequency resolution of 1MHz.

Figure 3 depicts a normalized B-OTDR plot with the insert showing a spatial resolution of 5cms.

The spatial resolution was evaluated using the 90/10 response of a step change in temperature, between the un-heated (23.6°C), un-strained section 1 and the simultaneously heated (70°C) and strained (1285με) section 2. The r.m.s intensity noise $\left(\delta\Delta I_{B_{A.S}}\right)$ of the heated section, of Fig. 3 was measured to be 0.71%, which translates into a temperature resolution of 1.9°C, in the absence of strain uncertainty. The frequency error ($\delta\Delta\nu_B$) of 1MHz on the Brillouin frequency based strain measurements corresponds to a strain resolution of 21με 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. The combined errors of the Brillouin frequency, $\delta\Delta\nu_B = 1\text{MHz}$ and Brillouin intensity, $\delta\Delta I_{B_{A.S}} = 0.71\%$ with coefficients $C^{\varepsilon}_{B\nu} = 4.5\text{MHz}/100\mu\varepsilon$; $C^{T}_{B\nu} = 1\text{MHz}/^{\circ}\text{C}$; $C^{T}_{BI} = 0.33\%/^{\circ}\text{C}$; $C^{\varepsilon}_{BI} = -8.4 \times 10^{-4}\ \%/\mu\varepsilon$, yield a temperature compensated strain resolution of 66με for a strain sensor of 17m long with a sub metre spatial resolution of 5cm.

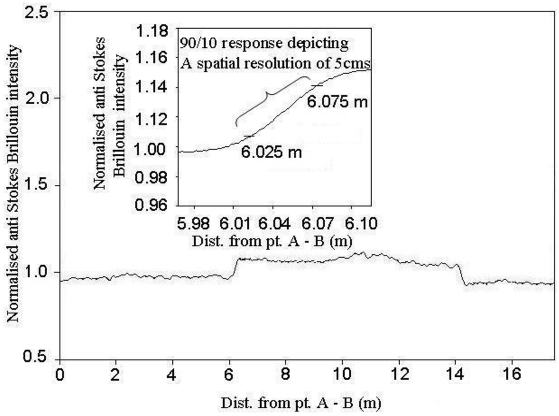

Fig. 3 The normalised B-OTDR plot of the 17 m sensing fiber, with the insert showing a 90/10 step response for the transition from unheated, unstrained section (1) to the simultaneously heated (70°C) and nominally strained (1285με) section (2) of the sensing fibre, indicating a spatial resolution of 5cms.

4. 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 2.3 times i.e., from 1.6% [4] to 0.71%. This permitted both the strain and spatial resolutions of the temperature compensated strain to be reduced from 97με and 24cms [9] to 66με and 5cms. The time domain trace was averaged 2^{16} times and collected using an improved data acquisition system which reduced the data collection time from 40 minutes to a little under 1 minute. This potentially provides new opportunities for monitoring cyclic loading of smart composite structures which often undergo considerable heating during the strain cycles.

5. References

[1] Maughan S.M., Kee H.H. and Newson T.P., ‘‘Simultaneous distributed fibre temperature and strain sensor using microwave coherent detection of spontaneous Brillouin backscatter’’, Meas. Sci. Technol. 12 834–842 (2001)

[2] Song K.Y., He Z. and Hotate K., ‘‘Distributed strain measurement with millimeter-order spatial resolution based on Brillouin optical correlation domain analysis’’, Opt. Lett. 31, 2526-2528 (2006)

[3] Alahbabi M.N., Cho Y.T. and Newson T.P., ‘‘Long-range distributed temperature and strain optical fibre sensor based on the coherent detection of spontaneous Brillouin scattering with in-line Raman amplification’’, Meas. Sci. Technol. 17, 1082-1090 (2006)

[4] Alahbabi M.N., Lawrence N.P., Cho Y.T. and Newson T.P., ‘‘High spatial resolution microwave detection system for Brillouin-based distributed temperature and strain sensors’’, Meas. Sci. Technol. 15, 1539-1543 (2004)

[5] Belal M., Cho Y.T., Ibsen M. and Newson T.P., ‘‘A temperature compensated high spatial resolution distributed strain sensor’’, Meas. Sci. Technol. 21 (2010)

[6] De Souza K., Wait P.C. and Newson T.P., “Characterisation of the strain dependence of the Landau Placzek ratio for distributed sensing.” Elec. lett. 33 (7) 615 - 616 (1997)