A multiplexed CW Brillouin system for precise interrogation of a sensor array made from short discrete sections of optical fibre

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ABSTRACT

A novel configuration for precise temperature sensing in an array of optical fibre sections is reported. The sections are chosen to have different Brillouin shifts, to enable separation of scattered light signals in the frequency domain, rather than the traditional time domain, allowing lower-noise CW operation and greater precision due to the 100% duty cycle.
Keywords: *Instrumentation, Fiber-optic sensor, Optical fibers, Brillouin scattering, temperature sensing.*

1. INTRODUCTION

Raman and Brillouin scattering are both commonly-used, truly-distributed methods of interrogating long lengths of fibre [1-4]. Brillouin scattering is narrow band in nature, and the frequency difference between incident and scattered light is a function of temperature, strain and fibre properties, particularly the core material [5,6]. Whilst a powerful tool for sensing, the instrumentation for distributed Brillouin sensing is complex, and the precision is limited by the need to use pulsed light signals. In this work, we take advantage of the fact that the Brillouin shift varies with fibre properties, allowing construction of a sensing array by splicing several different fibre together (each with significantly different Brillouin shifts), addressing the array with a continuous wave (CW) optical signal, and separating signals in the frequency domain.

2. PRINCIPLE AND APPARATUS

Brillouin scattering is usually described as the light scattered by thermally excited acoustic phonons and the Brillouin shift $\nu_B = 2nV_a/\lambda$ depends on the velocity, V_a, of the longitudinal acoustic wave, the effective refractive index, n, of the fibre and the wavelength of light λ [6]. The first two parameters are dependent on fibre composition. Our new sensing arrangement is shown in Fig.1. When the fibre sensing array is excited with a CW optical incident signal, a set of different scattered signals is generated, of optical frequency depending on the fibre type and material. For a given fibre section, however, the exact frequency of each scattered signal also reflects the physical condition of this section, particularly the temperature of, and mechanical strain in, the fibre. If the fibre sections are packaged in loosely-wound coils, to avoid strain, then a useful temperature sensing array is formed. It is only a multiplexed system, rather than being fully distributed, but the sensor is now capable of better s/n ratio, allowing far greater real-time measurement precision.
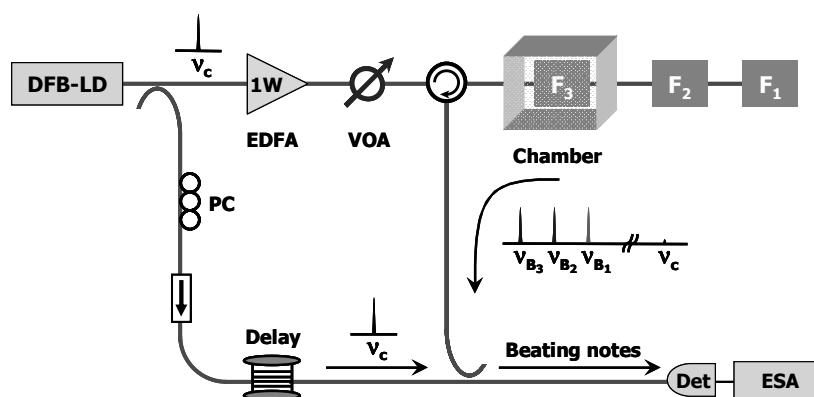

Fig.1: Schematic of apparatus for first viability tests. *EDFA is Erbium Doped Fiber Amplifier; VOA is Variable Optical Attenuator; Det is Detector and ESA is Electrical Spectrum Analyzer*
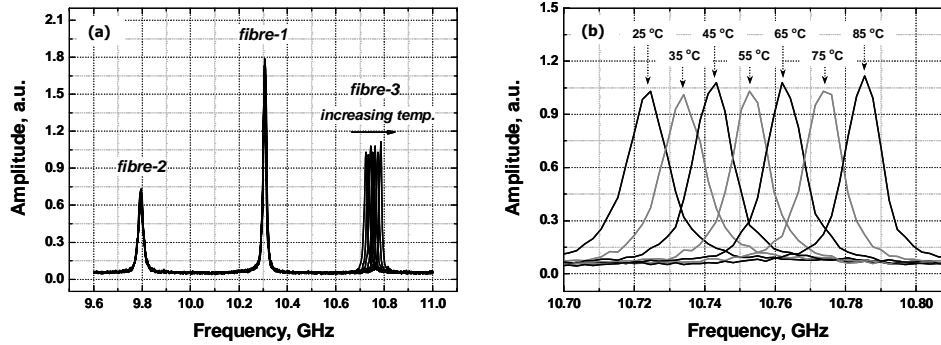
Fig.2: RF spectra of Brillouin signals from the 3 fibre sections (with expanded scales on the right hand side)

In our system, the optical signals are arranged to return to a single optical detector, along with a local oscillator signal, which is derived by tapping off part of the signal used to excite the fibre sensing array. The heterodyne output of this detector is a set of beat frequencies, each depending on the Brillouin shift of the corresponding fibre sensing section and on the frequency of the local oscillator. We shall show that not only does this form a relatively simple multiplexed sensor system, but it is also one which is capable of real-time thermal sensing with high precision.

Initially, to validate the basic principle, 3 loosely-coiled optical fibres of different type (**fibre-1**: 50 m of bend-insensitive fiber; **fibre-2**: 15 m of dispersion-compensated fiber; and **fibre-3**: 50 m of dispersion-shifted fiber) were spliced to form a simple sensor array (Fig.1). The incident light source was a CW DFB semiconductor laser diode (NEL type NLK1556STG, of wavelength 1551 nm, linewidth ~1 MHz), amplified with a erbium-doped fibre amplifier, with a saturated output power of 30 dBm, giving a launch power of ~1 W into the circulator. Light exits from the 2nd port of the circulator into the sensing array, and the return backscatter signal exits from the third port. This is mixed with some of the light from the CW source laser on a high-speed (> 10 GHz) analogue optical receiver (New Focus InGaAs, PIN/transimpedance receiver, type NFO-1544-A with NEP=33pW/Hz$^{-1/2}$). The resulting electrical beat frequencies from the detector were then viewed using a conventional electrical spectrum analyzer (type HP 8563E).

The display of the spectrum analyzer (Fig.2-a) shows several RF frequency spectra, taken as the temperature of the 3rd fibre (Brillouin shift ~10.9 GHz at 25^{0}C) is changed from 25^{0}C to 85^{0}C, whilst the other 2 fibres were held constant. The Brillouin shift change of fibre 3, derived using the spectrum analyzer, is shown in Fig.3. The scale factor for the thermally-modulated fibre is ~1MHz per ^{0}C, whereas the signals from others stay, as expected, at constant frequency.

The amplitude of the Brillouin scattering peaks from each fibre varies, as a result of the different gain and pump power in each. Ideally the sensing segments should all have a similar gain, being just under the Brillouin threshold to
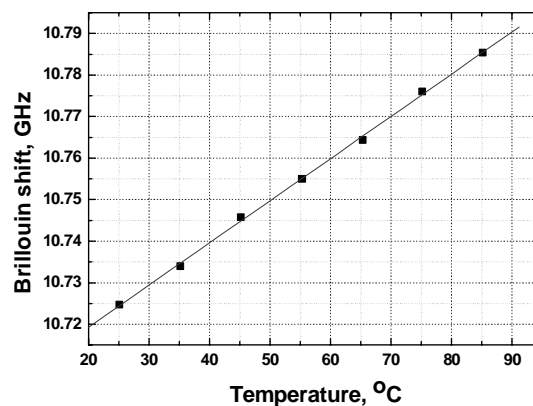

Fig.3: Plot of Brillouin shift versus temperature of fibre section 3, taken from ESA data.

avoid signal depletion or dynamic oscillations in the system. A fluctuating pump power in a fibre segment will reduce accuracy, so we chose fibre lengths, so as to operate just below the Brillouin threshold with the pump power from our saturated amplifier. As the fibres had different materials and core sizes, the length of each segment was different.

Please note that, in Fig.1, fibre which takes light directly from the laser has a delay coil of ~1km length, much longer than the laser coherence length, in order to suppress any noise due to (Mach-Zehnder type) interference with any stray un-shifted light from the pump. There will also be a small residual level of un-shifted (elastically scattered) stray light because the components do not have ideal behaviour, and therefore such light can return from the 3rd port of the circulator and interfere, on the detector, with the by-passed pump light used as our local oscillator signal.
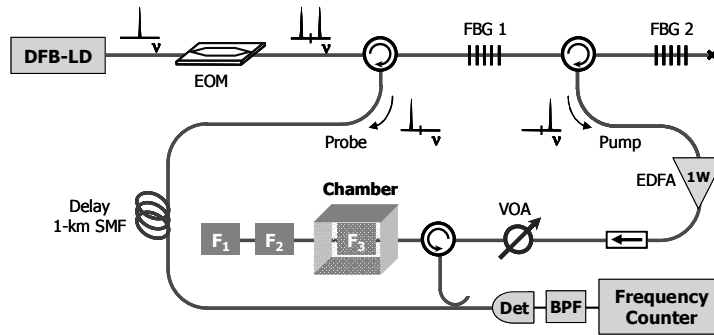

Fig.4: Schematic diagram of the real-time frequency measurement system (2nd electrical mixing down stage not shown).

Having demonstrated the viability of the method, we then constructed a 2nd system (Fig.4), where we mixed down the Brillouin-shift heterodyne signals with a local oscillator (This L.O is a modulation sideband of the pump source after filtering out the carrier and other sidebands with fibre gratings) and fed the baseband signal to a frequency counter, to enable more precise readout of mean frequency, and hence temperature. If the signal were a perfect sinusoid, then the precision, as a fraction of the initial~10 GHz signal, would be ~10^{-10} with only 1 s measurement time! Unfortunately, in practice, such high precision is not achievable, as errors may occur due to: (a) random variations in mean frequency, as a result of the finite Brillouin linewidth (b) frequency variations of the laser source and of the oscillator used to mix-down the Brillouin signals, and (c) intensity noise, from laser-source RIN, receiver noise or photon noise, all of which, if severe, can combine to cause occasional missed or even spurious additional cycle counts. We believe the errors for the DFB laser frequency fluctuations are, however, likely to be small, as ~1.4nm wavelength shift required to cause 10 kHz error.

In the system of Fig.4, it was convenient to do the 1st heterodyning stage (mixing down from the high Brillouin-shift frequencies) at optical frequencies, as this allows use of a low-frequency optical receiver, having lower cost and superior spectral noise density to a 10GHz one. Mixing directly in the detector to baseband frequencies, was found to
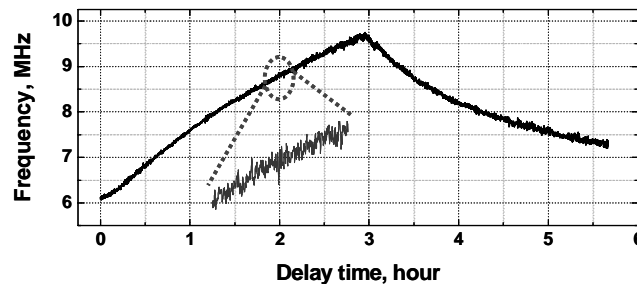

Fig.5: Frequency of mixed-down signals as measured on counter, during slow heating and cooling cycle, with temperature excursion of ~ 3.5 K.

give significant low frequency noise, so we mixed in two stages, first optically to an intermediate detected RF frequency ~145 MHz, then electrically to a 0 --> 15 MHz baseband (low-pass filter), before being passed to the frequency counter. For clarity, this 2nd electrical down-conversion stage is not shown in Fig.4. (Please note that an alternative arrangement to this counting system would be to sample the signal and use a digital processor, to perform the well-known method of fast Fourier transform analysis, and/or other appropriate signal processing algorithms [7] to find the mean frequency). If we wish to detect the temperature of the other fibres, this can be done by extending the narrow-band post-detection system to include local oscillators, mixers etc to detect other Brillouin bands, as done in a conventional radio receiver.

As we lacked a precision oven to control the temperature of the fibres to within 0.001 K, we determined the noise-limited precision of the method by placing the fibre in a container of high thermal capacity, surrounded by thermal insulation, to allow only very gradual thermal variation. We then slowly swept the fibre temperature over a very small interval of order 3.5 K, by first applying thermal energy via a resistive heater and then allowing it to cool, and we logged the counter frequency as a function of time, as shown in Fig.5. We found typical short-term fluctuations of order $\pm$ 10 kHz RMS, equivalent to a temperature variation of approx. $\pm$ 10 mK, from the scale factor in our earlier measurement, an excellent value considering the short (1 second) acquisition time for each reading. However, at times, some additional slightly-larger fluctuations appear. We are still investigating the cause of these.

The maximum number of fiber segments in the array depends on the desired temperature range, as spectral overlapping must be avoided. For a 100K change, the Brillouin frequency will shift about 100 MHz, and it is possible to fabricate fibre with Brillouin centre frequencies with ~ 1.5 GHz frequency total spread. We believe therefore that ~10 different fiber segments are feasible over the 1.5 GHz frequency range, once guard bands have been included to allow for the finite Brillouin linewidth. Clearly more fibre segments are possible, if a smaller temperature range is required.

3. CONCLUSION

We have demonstrated the initial feasibility of addressing an array of fibre sensors with a novel CW Brillouin method. Initial results suggest that real-time temperature measurements, with a noise-limited precision of order $\pm$ 10 mK RMS, in a very short update period of 1 second, is possible.

4. ACKNOWLEDGEMENTS

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