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Novel Distributed Fibre Sensor Using Microwave Heterodyne Detection of Spontaneous Brillouin Backscatter

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ABSTRACT

A new distributed sensing technique using spontaneous Brillouin backscatter has been demonstrated. For the first time ever, direct 11GHz heterodyne detection allows measurements of both Stokes and anti-Stokes signals. Results have been obtained for a sensing fibre length of over 10km with a spatial resolution of 20m.

1. INTRODUCTION

Several schemes have been proposed for long-range distributed optical fibre strain and/or temperature measurements. Utilising the Brillouin intensity and frequency dependences on strain/temperature effects [1-5], the possible sensing methods are classified as pump/probe method using two counter-propagating sources [6,7] or Brillouin optical time-domain reflectometry (BOTDR). In certain systems single-ended measurements must be performed, which permits only the use of BOTDR or end mirrors. There have been attempts to use both direct detection and coherent detection of the backscattered signals. In direct detection schemes, single-ended measurements of spontaneous backscattered signals were previously performed by separating the Rayleigh from Brillouin signals using optical filters such as bulk Fabry-Perot [3] and Mach-Zehnder [8] interferometers. However, the coherent detection technique theoretically allows a higher dynamic range and a faster acquisition time to be achieved. In addition, by using a narrow linewidth optical reference signal, excellent separation of the backscattered traces is possible through electrical filtering. Most of the methods reported so far have used dual frequency sources separated by the Brillouin frequency shift (approximately 11GHz at a pump wavelength of 1.5μm). This frequency shift was introduced in order to reduce the beat frequency to within the bandwidth of a conventional heterodyne receiver [9-11].

In this paper, we present a novel technique of performing heterodyne detection at a frequency of approximately 11GHz through the use of a high bandwidth receiver. With the proposed experimental configuration, a highly versatile and simple system for obtaining the Rayleigh and Brillouin backscattered traces is realised. A narrow-band source is required to produce the Brillouin signals, whereas a broadband source must be used to minimise coherent Rayleigh noise (CRN) effects in the Rayleigh backscattered signal [12]. The configuration used enables both narrow-band and broad-band pulses to be launched down the sensing fibre to obtain the respective traces. In addition, it is also possible to obtain both the Stokes and anti-Stokes Brillouin signals by merely selecting the appropriate centre frequencies since they both lie within the wide receiver bandwidth.

2. EXPERIMENT

The experimental configuration is shown in Figure 1. Radiation from a pigtailed cw laser operating at 1532.5nm with a linewidth of 1MHz is amplified to ~8mW using EDFA 1. The radiation is divided by a 3dB coupler, with half the power used to produce the optical reference signal for heterodyne detection. The remaining power is gated through a 110MHz downshifting AOM and then amplified by EDFA 2 to produce sensing pulses with peak power of up to 2W and a duration of 200ns. The pulses are launched into a 10km length of conventional single-mode silica fibre via a circulator. The backscattered traces at port 3 of the circulator are amplified using EDFA 3, before being mixed with the cw local oscillator. A 20GHz optical detector and 26.5GHz RF spectrum analyser allow observation of the beat frequencies and, when set in zero span mode, may be used to acquire time-domain traces centred at the desired RF frequency. The sensing fibre comprises four fibre sections spliced together of lengths 8800m, 500m, 500m and 500m, with the second fibre section being heated to a temperature of 340K and all other fibre sections at the room temperature of 295K.

For the chosen operating wavelength of 1532.5nm, the Brillouin frequency shift was found to be 11.00GHz for unstrained fibre at room temperature. This results in central beat frequencies of 10.89GHz and 11.11GHz for the anti-Stokes and Stokes Brillouin backscattered traces respectively due to the 110MHz downshifting AOM. The polarisation state of the local oscillator is continuously scrambled throughout the Brillouin backscattered averaging process to reduce the polarisation noise observed on the signal.

The Brillouin signal obtained does not provide absolute temperature measurements due to the dependence of the signal on fiber attenuation and localised splice/bend losses. The Brillouin signal has to be referenced to the Rayleigh backscattered signal, which is independent of temperature fluctuations. The normalising Rayleigh trace was collected using conventional, non-heterodyne detection through a 5% tap of the backscattered signal using the same optical system, but by launching broad-band ASE pulses (1 MHz laser switched off) to eliminate CRN effects on the backscattered trace.

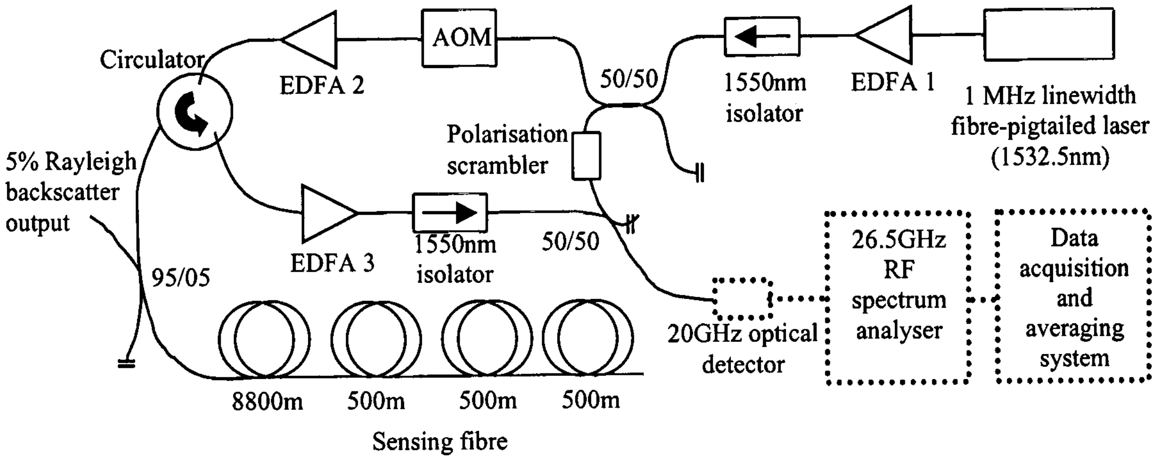

Figure 1. Experimental configuration for microwave coherent detection distributed Brillouin sensor

3. RESULTS

With the RF spectrum analyser set at 10.89 GHz and zero span, the anti-Stokes Brillouin trace observed after 65536 averages is shown in Figure 2a. The temperature change of 45K in the second fibre section results in a Brillouin frequency shift increase of ~50MHz as well as a slight increase in intensity of the backscattered signal. Figure 2a shows a pronounced dip corresponding to the 500m heated section, consistent with a shift in anti-Stokes peak frequency away from 10.89GHz. By tuning the centre frequency of the spectrum analyser such that the peak power at the heated section is maximised, the Brillouin frequency change due to temperature is measured. As expected, the anti-Stokes backscatter trace (Figure 2b) at the shifted frequency of 10.94GHz shows a substantial peak at the heated section. There is still a backscattered trace visible for the unheated fibre sections at this frequency due to the Brillouin linewidth being of the order of 50MHz. The power of the launched pulses was maintained such that there is equal Stokes and anti-Stokes backscattered powers before obtaining these results.

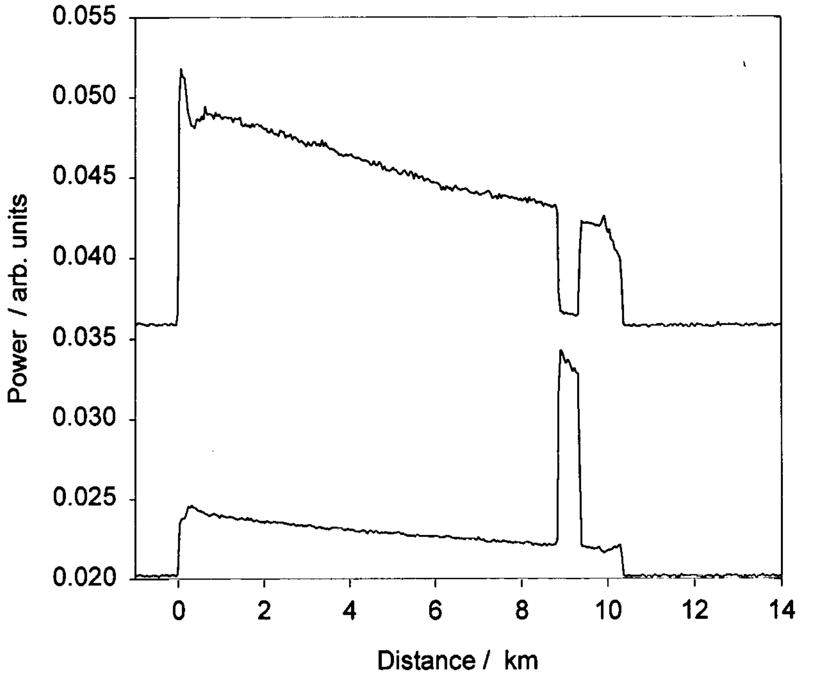

Figure 2. Anti-Stokes Brillouin backscattered traces (bandwidth 5MHz) at (a) 10.89GHz and (b) 10.94GHz

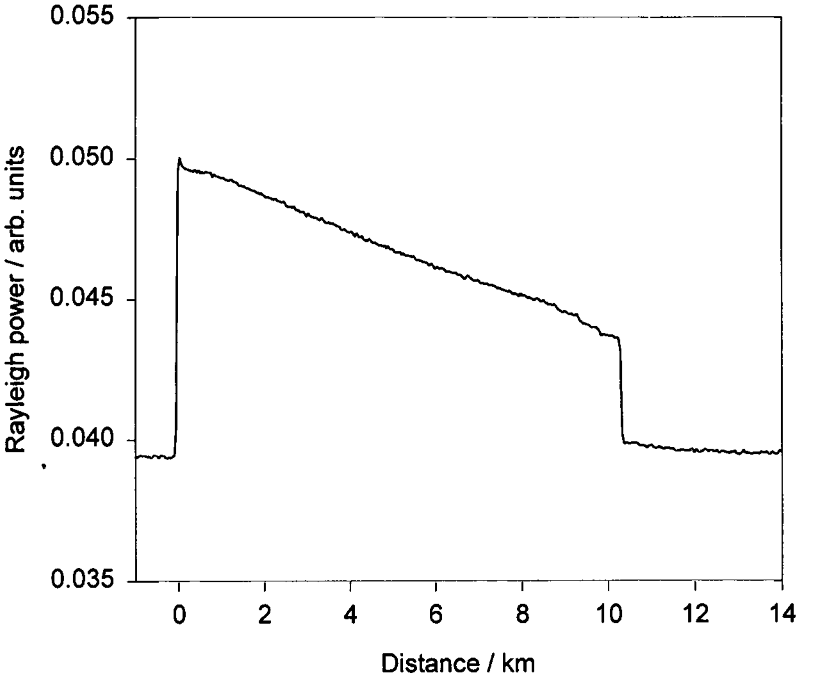

Figure 3. Rayleigh backscattered trace using a broad-band source

Although the length of the sensing fibre is only ~10km, the signal-to-noise ratio is sufficiently high that distributed measurements may be made for longer sensing ranges. The system is highly sensitive to Brillouin frequency shift as a result of either temperature or strain effects due to the narrow frequency resolution bandwidth of the spectrum analyser (5MHz). This can be seen by the peaks and troughs being reversed between Figures 2a and 2b, implying each has a slightly different peak frequency.

4. CONCLUSIONS

A direct 11GHz-band heterodyne detection spontaneous Brillouin distributed sensing technique has been demonstrated at a wavelength of 1532.5nm. Distributed measurements with a spatial resolution of 20m were obtained over a sensing length of 10km. The arrangement is simple, avoiding the need for optical separation of the Brillouin backscattered signal from the Rayleigh signal, and also versatile since broad-band pulses may be generated for direct detection of the Rayleigh backscattered trace. Since both reference wave and sensing pulses are derived from the same source, the frequency difference between backscattered and local oscillator is stable. Operation of the pulsing AOM in first order provides a good extinction ratio and allows separation of Stokes and anti-Stokes signals by twice the acoustic frequency, allowing the onset of stimulated scattering to be easily observed. To measure only the Brillouin intensity variations, traces could be collected and averaged over a frequency range greater than the anticipated Brillouin frequency changes due to temperature and strain, ie. approximately 100MHz for temperature variations of 100K and strain variations of up to 2000$\mu\varepsilon$ [5]. By measuring both the Brillouin frequency shift and peak powers, simultaneous strain and temperature sensing can be achieved.

5. REFERENCES

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