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Signal-to-noise Enhancement of a Distributed Fibre-Optic Temperature Sensor using Optical Preamplification

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ABSTRACT

A fibre-based optical preamplifier system has been used to improve the signal-to-noise capabilities of a Brillouin-based fibre-optic distributed temperature sensor. A 17dB optical signal-to-noise improvement in a 23km sensor is demonstrated.

1. INTRODUCTION

Fibre-optic distributed temperature sensing based on backscattered spontaneous Brillouin scattering and utilizing the Landau-Placzek ratio method has previously been demonstrated [1]. The major impediment to extending the range of such a sensor is the limitation to the peak power that can be transmitted down a sensing fibre due to the onset of nonlinear phenomenon such as stimulated Brillouin scattering, stimulated Raman scattering and self phase modulation. The range of the sensor is then limited by the receiver sensitivity, which can be improved by signal averaging, which for long sensor lengths, degrades performance in terms of the measurement time required to extract the useful temperature information from the spontaneous Brillouin signal . This is further exacerbated by the increased noise which accompanies larger receiver bandwidths required for improved sensor spatial resolution.

This paper reports an experimental investigation into the use of an optical preamplifier system in a distributed fibre-optic temperature sensor as a means of improving receiver sensitivity and consequently sensor range and measurement time.

2. EXPERIMENTAL

The preamplifier configuration will be described first followed by the experimental set up.

(i) *Preamplifier configuration*

Figure 1 shows a schematic of the preamplifier configuration. A 980nm fibre pig-tailed source supplying 28mW CW power, was spliced onto a 1550/980 WDM and used to pump 9m of 200ppm erbium-doped fibre. Backscattered radiation from a sensing fibre co-propagated with the 980nm pump through the erbium fibre. The output end of the erbium fibre was spliced onto port 1 of an E-TEK three port circulator. Light was transmitted from one port to the next with about 1dB throughput loss and over 40dB isolation in the reverse direction. Thus effectively backscattered radiation was transmitted from port 1 to port 2 with low losses. Port 2 of the circulator was spliced on to a narrowband in-fibre grating with specifications of 1531.6nm centre wavelength, 0.37nm (47GHz) optical bandwidth, and > 99% reflectivity. Each end of the grating was glued to a strain rig consisting of a fixed mount and a movable micrometer stage.

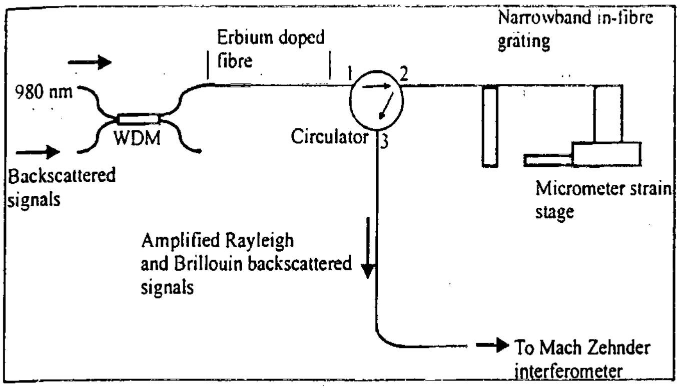

Figure 1. Schematic of preamplifier system

The amplified backscattered signal and forward amplified spontaneous emission (ASE) were reflected from the grating, isolated from port1, and emerged from port 3 of the circulator. The grating was strained to tune it to the signal wavelength thus maximising the latter while reducing the ASE gain-bandwidth from ~40nm to ~0.4nm. The output end of the grating was immersed in index matching liquid with a refractive index of ~1.46 in order to eliminate end reflections. The output port 3 was fed into an insulated single-pass Mach-Zehnder interferometer (SPMZ) with FSR = 22.3 GHz, which was thermally tuned to separate the Rayleigh and Brillouin signals [1]. In addition to separating the signals with low losses, the SPMZ also reduced the accompanying ASE power by 3dB.

The EDFA gains at different pump powers were determined by measuring and recording the Brillouin power without amplification and that obtained with amplification at different pump powers. Grating reflected ASE spectra were collected and stored on an optical spectrum analyser.

(ii) *Distributed temperature sensor configuration*

The distributed temperature fibre-optic sensor used is shown in Figure 2. A narrowband Q-switched erbium-doped fibre laser provided a narrow linewidth source of ~1.5GHz, 18ns pulse width, centre wavelength of 1532.2nm and peak power of 9W at a repetition frequency of 500Hz. The laser output was spliced on to a 96/4 fibre coupler with the 4% port used to monitor the signal launched down the sensing fibre.

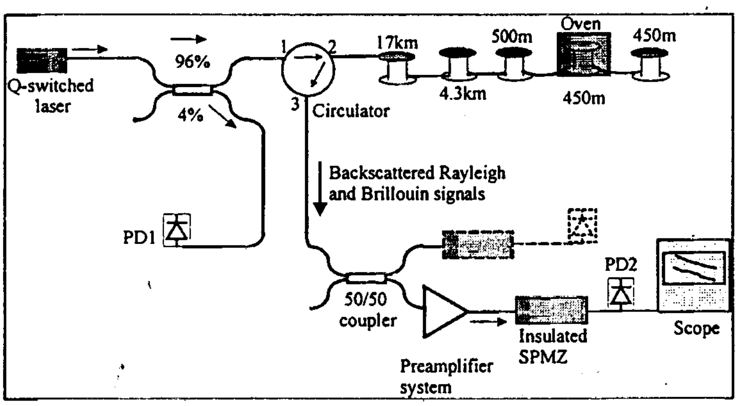

Figure 2. Schematic of experimental set up.

A peak power of 250mW was launched via a circulator into the sensing fibre. At this power, no nonlinear effects were observed.

The sensing fibre consisted of approximately 23km of standard telecommunications fibre divided into five sections having lengths of 17km, 4.3km, 0.5km, 0.45km, 0.45km. The fourth section consisting of 0.45km was placed into an oven with a measured temperature of 333K±0.1. The other four sections were kept adjacent to one another at a room temperature of 296K±0.1.

The backscattered light was divided by a 50/50 coupler with one output spliced on to the optical preamplifier system. This allowed an easy comparison to be made between optically unamplified and amplified backscattered signals albeit introducing a 3dB loss of signal. The unamplified signal was passed through the thermally tuned SPMZ to filter the Rayleigh and Brillouin signals. The Brillouin signal was detected using an electronic receiver system comprising a 125MHz dc detector of transimpedance 50kΩ and saturation power 62μW, a 20MHz low pass filter and a x32 electronic amplifier. The detected signal was averaged 8192 times, digitized and stored on computer. A similar procedure was followed for the optically amplified signals. In order to observe the effects of temperature at the far end of the sensing fibre where signal power is severely reduced, data from that region was collected separately, averaged 40960 times as opposed to 8192 times and similarly stored.

3. RESULTS AND DISCUSSION

Figure 3 shows the variation of EDFA gain with 980nm pump power for the preamplifier configuration where the input signal power was 400pW. The onset of gain saturation was observed implying that near total bleaching of the erbium fibre at the pump wavelength has been achieved at a maximum gain of ~27dB.

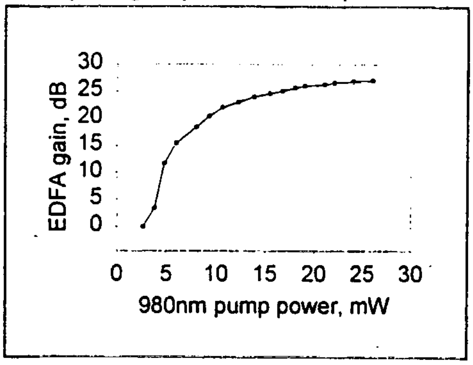

Figure 3. EDFA gain against pump.

Figure 4 shows the grating reflected ASE spectra with a major peak and smaller side lobes. The FWHM bandwidth was approximately 0.37nm or 47GHz. At this bandwidth and with the grating tuned to maximize the reflected backscattered signals, the approximate power loss of each of the amplified Stokes and anti-Stokes spontaneous Brillouin components was < 0.5dB. Hence the total Brillouin power loss due to a grating of bandwidth ~0.37nm was < 0.5dB. Also, the temperature error caused by the effect of a Brillouin intensity change along the grating due to the Brillouin frequency shift [2] for a 37°C temperature change is negligible at about 0.2°C.

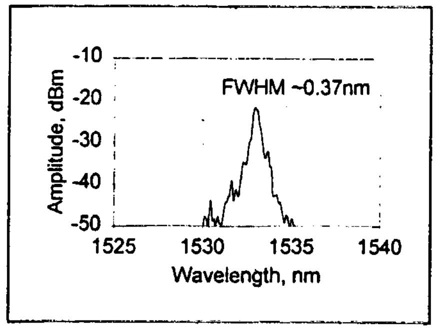

Figure 4. Grating profile.

A measure of the electrically detected root mean square voltage noise without any signal and averages, with and without optical preamplification, is shown in Figure 5. Without any preamplifier, the root mean square (RMS) voltage noise without any averages was approximately 12.5mV. With preamplification, the RMS voltage noise was approximately 100mV. The former was attributed to transimpedance amplifier noise while the latter was predominantly due to ASE-ASE beat noise.

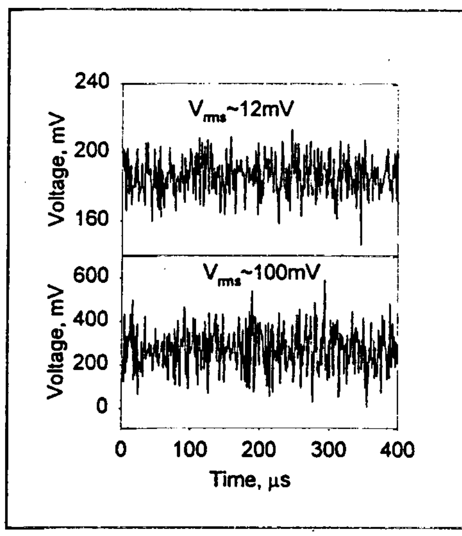

Figure 5. RMS noise of detection system without (top) and with (bottom) preamplification.

Fig. 6 (a) and (b) show the full range unamplified and amplified Brillouin signals respectively. Both were averaged 8192 times. In the unamplified case, the signal was very noisy and was just discernable up to about 10km. Beyond this, the receiver sensitivity was too poor and the signal was masked by the transimpedance amplifier noise. In contrast, the amplified Brillouin signal was discernable over the full range of the sensing fibre. The average RMS voltage noise has been calculated as 1.3mV. This agrees well with a value of 1.1mV expected for 8192 averages on the dominant ASE-ASE beat noise with a nominal RMS voltage noise of ~100mV (Fig. 5).

Fig. 7 (a) and (b) show the unamplified and amplified Brillouin signals at the heated section of the sensing fibre. Both signals were averaged 40960 times. This reduced the RMS voltage noise of the unamplified Brillouin signal from 12.5mV to 52μV (1.4nW). There was no indication of any temperature change. The expected optically unamplified Brillouin power at the fibre end was approximately 500pW assuming a 10dB two-way loss (calculated from Fig. 6 (b)) and a front end power of approximately 5nW (see Fig. 6 (a)). An optical signal-to-noise ratio, SNR_o, of approximately -5dB was calculated.

The improvement in the signal-to-noise of the detected preamplified Brillouin signal is clearly visible in Fig. 7(b). An increase in Brillouin power at the heated section was observed. The mean RMS voltage noise is 470μV

(12nW). This agreed well with the noise expected by performing 40960 averages on 100mV RMS noise (see Fig. 5). A similar analysis of the SNR gives a mean value of SNR_o = 12dB. Lastly, the improvement in SNR_o due to optical preamplification was approximately 17dB (12 +5) which can be shown to be theoretically correct.

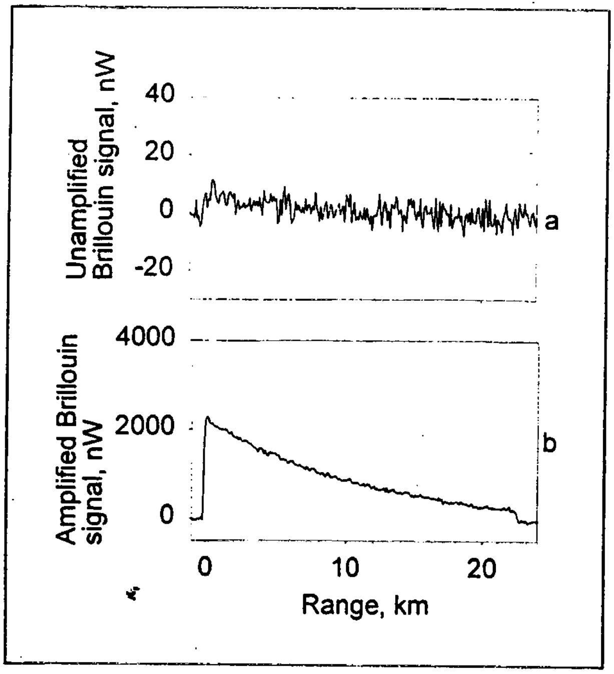

Figure 6. Unamplified (plot a) and optically amplified (plot b) Brillouin signal over the whole range, averaged 8192 times.

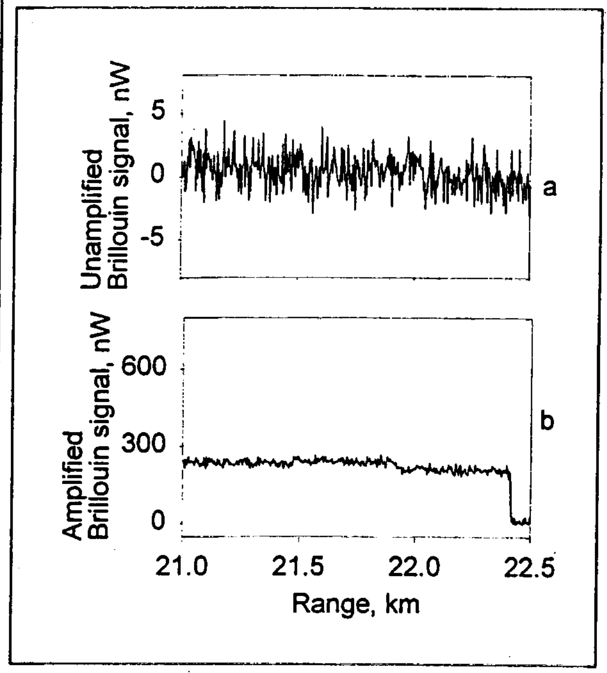

Figure 7. Optically amplified Brillouin signal at far end of fibre sensor, averaged 40960 times. Temperature resolution limited by receiver noise.

4. CONCLUSION

A fibre-based preamplification system with 27dB of gain has allowed a 17dB improvement in the optical signal-to-noise ratio SNR_o over a fibre sensor of 23km. Such an improvement corresponds to a range improvement of 40km assuming a 2-way fibre loss of 0.4dB/km at 1550nm. The main source of noise was due to ASE-ASE beat noise.

REFERENCES

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