Distributed optical fibre sensing at 1.65μm using a Q-switched fibre laser

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ABSTRACT

It is becoming increasingly vital to monitor telecommunication links during operation and installation process. By using a high peak power source and the optical time domain reflectometry (OTDR) technique operating at the wavelength region of 1.6μm, it is possible to monitor conventional C-band Erbium-doped fibre amplifier (EDFA) systems whilst transmitting data, and to characterise losses at the higher wavelengths of extended bandwidth systems designed around the L-band EDFA systems. We describe a compact design based on Raman shifting the output of an Erbium-doped Q-switched fibre laser operating at 1.5μm for obtaining a pulsed source at 1.6μm. This source was used for an OTDR measurement and also as a source for a 1.65μm Raman-based distributed temperature sensor, in contrast to distributed temperature sensors normally operating at 1.5μm. OTDR measurements at 1.65μm provide more accurate determination of macro and micro-bend losses than at 1.5μm as such losses increase with wavelength. The temperature measurement extracted from the anti-Stokes Raman signal at 1.5μm was made over a sensing range of 10.1km, with a spatial resolution of 10m and temperature resolution of 4°C.

Keywords: Q-switched laser, Erbium-doped fibre laser, temperature measurement, fault location, distributed sensing

1. INTRODUCTION

Distributed fibre sensing operating at the wavelength of 1.5μm region has been extensively researched, particularly for long range systems. One popular method for single-ended measurements of distributed sensing is using the optical time domain reflectometry technique, and these sensors have been demonstrated for use in fault location and loss distribution measurements [1]. However, there is currently great interest in developing systems for use in monitoring links used for live optical data transmission at the conventional C-band Erbium-doped fibre amplifier (EDFA) systems at 1.5μm. It is therefore useful to set the wavelength used for sensing purposes different to the 1.5μm region used for data transmission.

There is also interest in expanding the C-band EDFA systems to incorporate the use of L-band EDFA operating in the 1560-1620nm wavelength region. It is useful to be able to monitor the integrity of a complete fibre length during and after installation of such systems,

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using a single-ended measurement technique. The installation of these cables require critical design issues as fibres are more susceptible to bend losses at higher wavelengths. OTDR diagnostic tools operating at a higher wavelength region are therefore becoming essential.

In this paper, a simple technique of performing OTDR sensing at a higher wavelength of 1.6μm is described. The main difficulty in generating pulsed fibre laser sources at this wavelength region is due to the fact that there is presently no suitable gain medium for doped fibres at this wavelength. Although semiconductor laser diodes have been developed at 1.6μm, the continuous wave (cw) output powers available from these diodes are still limited to a few mW [2]. The technique we describe to generate pulses at 1.6μm is by utilising the high peak powers available from 1.5μm Q-switched Erbium-doped fibre lasers to generate pulses at the first order Stokes wavelength through stimulated Raman amplification. Such a source was built and used for the demonstration of three distributed sensors; a long-range 1.6μm OTDR sensor, an extended OTDR sensor and a 1.6μm Raman-based distributed temperature sensor.

2. 1.6μm PULSE GENERATION

The experimental configuration for the generation of 1.65μm pulse signal is illustrated in Figure 1. A 1.5μm Q-switched fibre laser was constructed which had the AOM operating in first order to achieve high-Q state. A Sagnac loop mirror was used as one end reflector of the cavity. It consisted of a 95/5 coupler with two arms spliced together, providing a mirror reflectivity of 19%. The pulse signal at 1.53μm had a peak power of 100W and pulse width of 34ns, as shown in Figure 1.

The output from this 1.5μm laser was then fed into a Raman generation fibre length that consisted of a single 390m drum of conventional single-mode silica fibre. This length was selected to optimise the generation of the first order Stokes signal whilst minimising the transfer of energy to higher order Stokes signals.

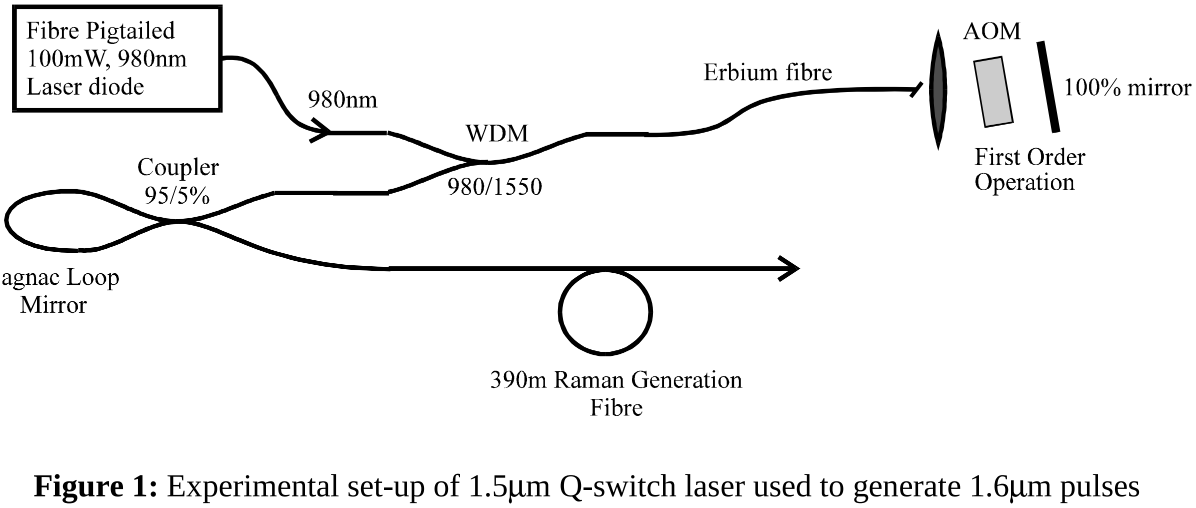

Figure 1: Experimental set-up of 1.5μm Q-switch laser used to generate 1.6μm pulses

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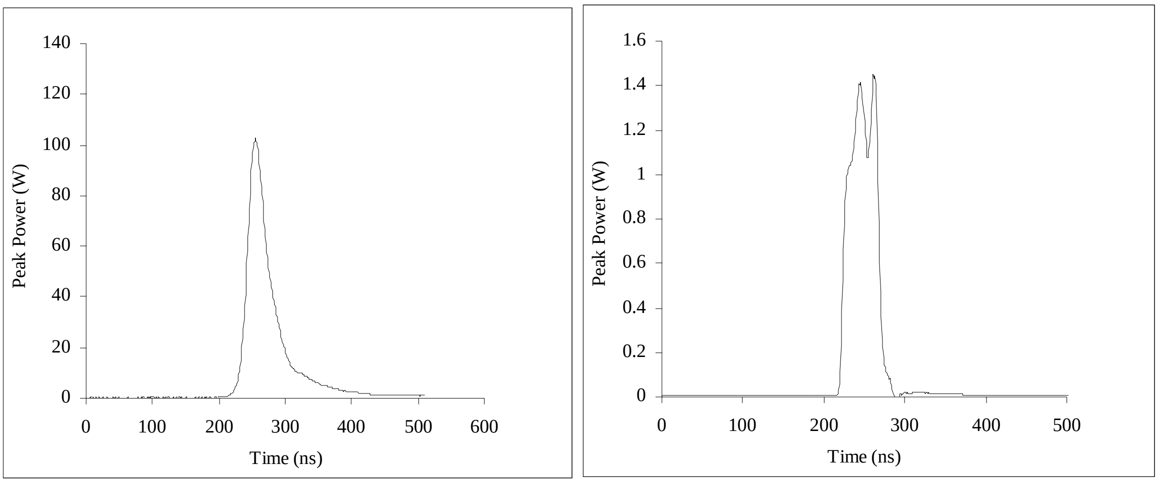
Figure 2 shows the pulse profiles of both the 1.5μm pulse from the output of the Q-switched fibre laser, and the resultant 1.6μm pulse after the Raman generation fibre. The pulse was filtered from the residual pump by incorporating a bandpass filter centred at 1.65μm with a 3dB bandwidth of 25nm. The resulting pulse had a peak power of 1.4W and pulse width of 45ns.



(a) (b)

Figure 2: Pulse profiles for (a) 1.5μm pulse at output of Q-switched fibre laser and (b) 1.6μm pulse through stimulated Raman scattering process

3. 1.6μm LONG-RANGE OTDR SENSOR

The experimental configuration used to construct a long-range 1.6μm OTDR sensor is shown in Figure 3. The 1.6μm pulses generated through stimulated Raman scattering were filtered by the 1.65μm bandpass filter, before being launched down 100km of sensing fibre through a 66/34 splitting ratio coupler. The Rayleigh backscattered signal was then collected through the coupler and averaged 4096 times.

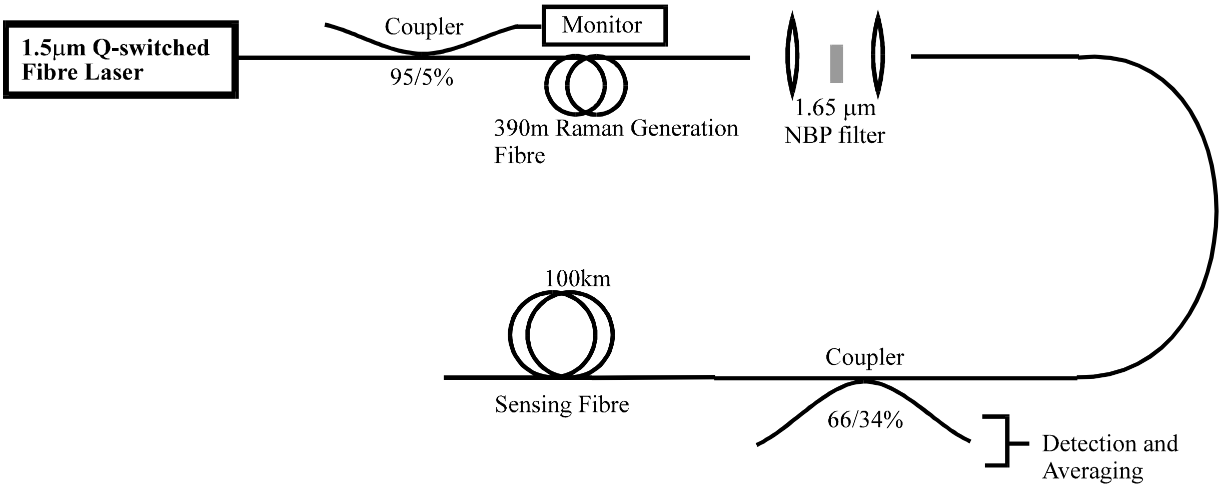


Figure 3: 1.6μm OTDR distributed sensor

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Figure 4(a) shows the Rayleigh backscattered signal over the 100km sensing fibre length. It can be observed that the signal begins to reach the noise floor at approximately 80km from the front end of the sensing fibre.

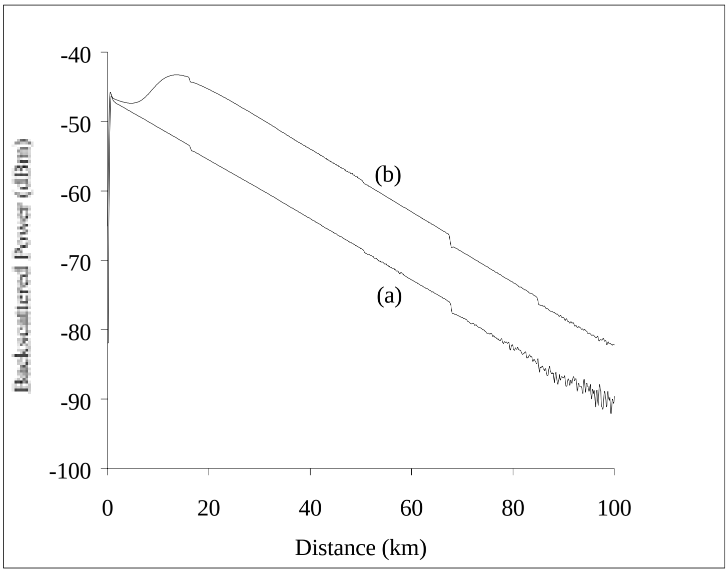

Figure 4: Rayleigh backscattered traces at 1.6μm for (a) without Raman amplification and (b) with delayed Raman amplification

4. EXTENDED RANGE OTDR SENSOR USING DELAYED RAMAN AMPLIFICATION

By using Raman amplification, it is possible to increase the dynamic range of 1.6μm OTDR systems. The use of Raman amplification to amplify a 1.66μm laser diode pulse by 24.8dB has recently been reported whereby the signal was amplified before being launched down the sensing fibre [3]. However, it is also possible to increase the dynamic range of OTDR systems by proving delayed Raman amplification at some distance down the sensing fibre. This technique has been recently described and demonstrated for a 1.6μm OTDR sensor [4].

The ability to achieve a greater dynamic range with this system may be explained as follows. Consider initially the situation in which both the pump and OTDR probe pulses have the same pulse width and peak powers, the depletion of the pump pulse at some distance along the sensing fibre will double the energy of the probe pulse. As such, the amplification achieved depends on the amount of energy available to amplify the probe pulse, which is determined by the peak intensity and pulse width of the pump pulse. The stimulated Raman threshold of the pump pulse limits the amount of energy that may be launched down the sensing fibre. Although the OTDR pulse width is limited by the system spatial resolution requirements, the pump pulse width may be considerably larger. This enables a large amount of energy to be transferred to the signal pulse. This process of amplification is achieved without significant noise penalty as a result of the directionality of the Raman gain, and is therefore ideally suited for backscattered measurements. In addition, this OTDR system operating at the pump and Stokes wavelengths of 1.53μm and 1.65μm respectively minimises the fibre attenuation during propagation as these wavelengths are in the low loss window of silica-based optical fibres, providing an ideal system for long lengths of sensing fibre. An example of setting an initial delay of 35ns between the pump and probe pulses (Figure 5) results in the backscattered signal shown in Figure 4(b). It can be observed that the signal only reaches the noise floor at approximately 100km, and the splice loss after 80km down the sensing fibre is visible.

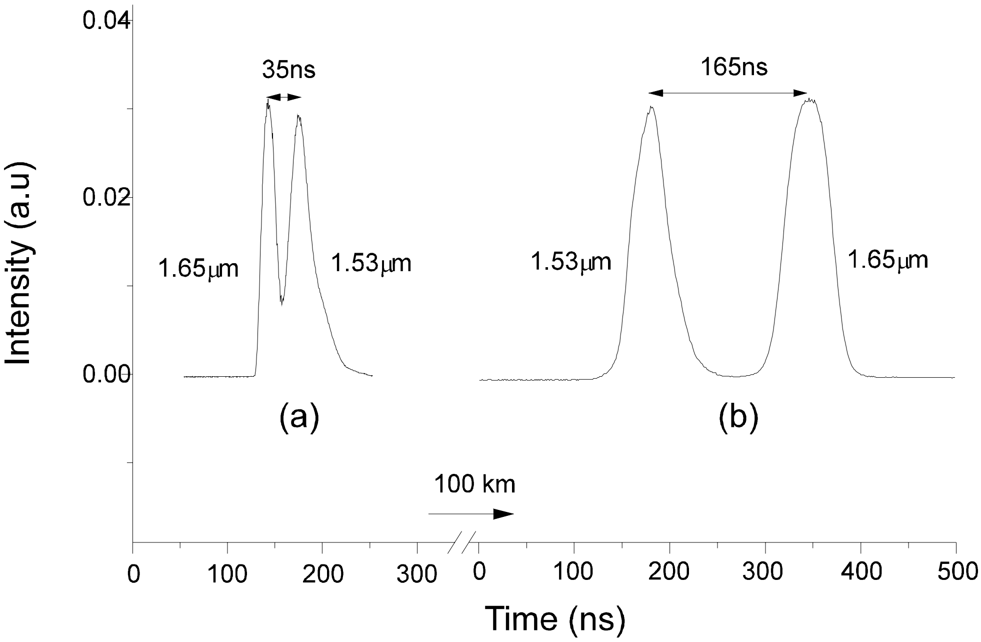

Figure 5: Relative delay between the pump and probe pulses at the wavelengths of 1.5μm and 1.6μm respectively. (a) shows the delay at the front end of the sensing fibre and (b) shows the delay at the far end of the 100km sensing fibre

5. 1.6μm RAMAN-BASED DISTRIBUTED TEMPERATURE SENSOR

In this section, a Raman distributed temperature sensor (DTS) system operating at the wavelength of 1.65μm is described. Optical fibre temperature sensors based on spontaneous Raman scattering at the wavelength region of 1.5μm have been the subject of research for a number of years [5,6]. Previous Raman-based systems typically operate with a pump light in the wavelength region of 1.5μm and sensors cannot be used in active optical transmission systems. By utilising the 1.65μm pulsed source which has been described earlier, it is possible to operate a DTS system by launching the 1.65μm pulsed source down the sensing fibre and obtaining the anti-Stokes spontaneous Raman backscattered signal.

A schematic diagram of the experimental set-up is shown in Figure 6. The generated Stokes 1.65μm pulses generated after the 390m telecommunications fibre were separated from the residual 1.53μm pump pulses by a bandpass filter centred at 1.65μm, to produce pulses with 1.5W of peak power and 40ns pulse width. The broadband nature (25nm) of these pulses is ideal for OTDR as coherent effects are reduced to a minimum. The pulses were then launched into the sensing fibre through a 1.6μm/1.5μm wavelength division multiplexer (WDM). The sensing fibre was 10.1km in total, consisting of four sections of standard single-mode telecommunications fibre, D1, D2, D3 and D4 spliced together with lengths of 8.6km, 500m, 500m and 500m respectively. Section D3 was placed in an oven and heated to 59^{o}C. The

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Raman backscattered signal was measured using an InGaAs PIN detector in conjunction with a transimpedance amplifier with a bandwidth of 3MHz and sensitivity of 11mV/nW. The detected signal was electrically amplified with a 30dB gain amplifier and averaged 2^{19} times. A narrow bandpass filter (FWHM 25nm) centred at 1.53μm was placed before the detector to filter the anti-Stokes signal from the backscattered Rayleigh signal. This filter had a transmission of 80% at 1.53μm.

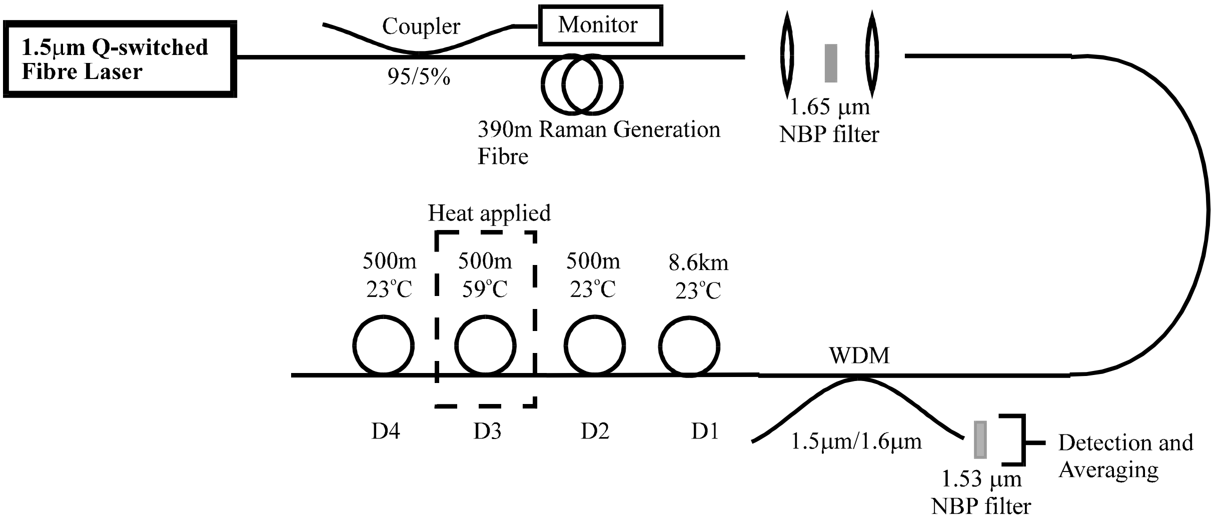

Figure 6: Experimental configuration for 1.6μm Raman-based distributed temperature sensor

The anti-Stokes Raman backscattered signal is shown in Figure 7. Figure 8 shows in detail the three sections of 500m test fibres indicating the splice positions at the far end of the sensing fibre after 8.6km. The plot shows a clear rise in the Raman signal indicating the heated section.

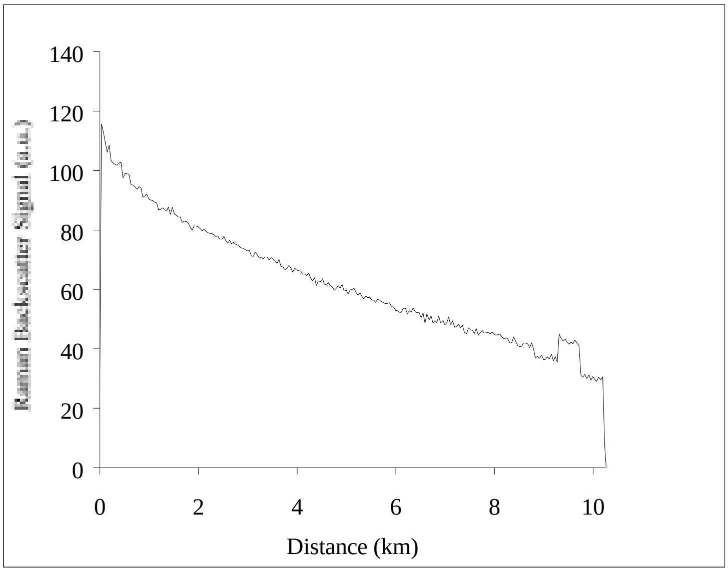

Figure 7: Anti-Stokes Raman backscattered signal for the whole length of sensing fibre

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This signal cannot be used to provide an absolute temperature value due to its dependence on fibre attenuation and splice/bend losses. To accurately predict temperature changes the Raman signal has to be referenced to the temperature-independent Rayleigh signal that must therefore be measured with the same spatial resolution. The Rayleigh signal obtained is shown in Figure 8. The ratio of the Rayleigh and Raman signals provides a temperature dependent signal which is independent of splice/bend losses and corrected for fibre attenuation. Figure 9 shows this ratio for the same three sections of test fibres. The root mean square (r.m.s.) noise on the ratio was measured to be 2.2×10^{-3}, which corresponds to a temperature resolution of 4°C. The spatial resolution was measured to be 10m, which was limited by the detector bandwidth of 3MHz. Using the Raman anti-Stokes temperature sensitivity of 0.8%/K [6], the temperature change was calculated to be 36K, and this was in agreement within the experimental accuracy of the measured fibre temperature change.

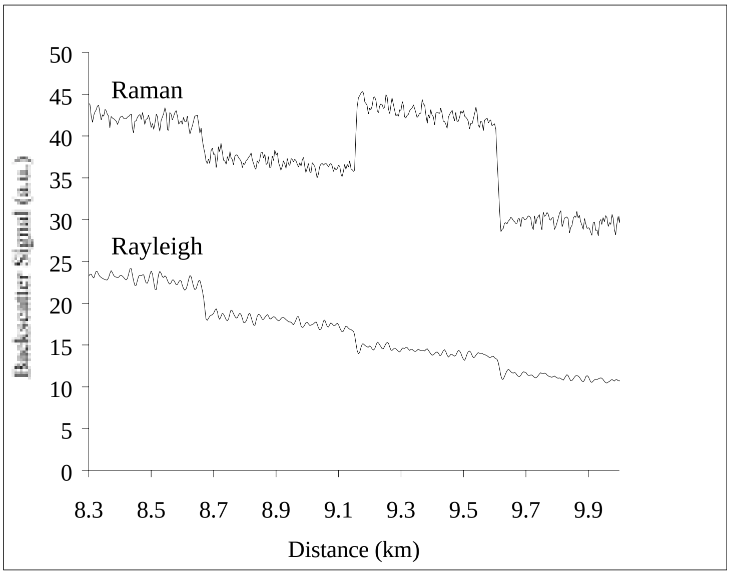

Figure 8: Rayleigh and Raman backscattered signals at far end of sensing fibre

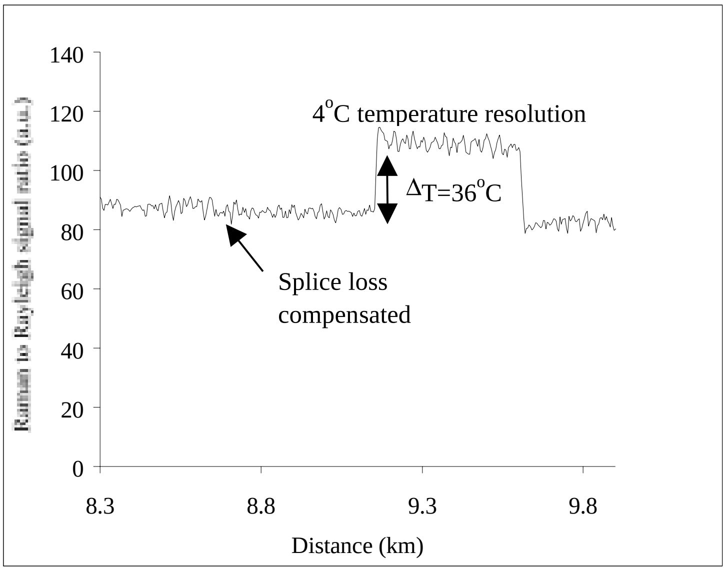

Figure 9: Ratio of Raman to Rayleigh backscattered traces, with splice/attenuation losses compensated

6. CONCLUSIONS

The simple and compact construction of a Q-switched Erbium-doped fibre laser at 1.53μm has been utilised to produce a high peak power pulsed source at 1.65μm. This source was then used for a variety of sensors based at 1.6μm including an OTDR system and an extended range sensor using delayed Raman amplification. Although this latter technique has only been demonstrated for an OTDR system based on Rayleigh backscattered measurements, it has wide applications for other forms of distributed measurements, such as distributed strain and temperature measurements based on Brillouin and Raman scattering processes. The ability to achieve the limiting threshold value of the amplified signal pulse at some distance down the sensing fibre will enable a new range of extended range distributed sensors to be developed.

Finally, the 1.65μm source was demonstrated for use in a spontaneous Raman based DTS system. This allows distributed temperature monitoring of existing live optical transmission cables to be used. A temperature resolution of 4°C with a spatial resolution of 10metres for a range of over 10km was demonstrated. Further improvements in temperature and spatial resolution could be obtained by increasing the available peak power of 1.65μm sources. Since a backscattered trace is required, such a system is presently confined to unrepeated and unamplified communication links.

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