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Optical fibre sources, amplifiers and special fibres for application in multiplexed and distributed sensor systems

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ABSTRACT

The paper describes how active fibre devices and special fibres can enhance the performance of multiplexed and distributed sensing systems. The use of active fibres, such as rare-earth-doped types, can act as powerful CW or pulsed sources, as wavelength-tunable sources, high-power amplifiers and as low-noise detector preamplifiers. Thus many arrangements for sensor-multiplexing, or distributed sensing, which may appear unattractively lossy on first consideration, may become perfectly viable with the insertion of active devices. The paper also reviews possible applications of special fibres in multiplexed and distributed sensors. The use of such fibres can greatly enhance the performance of sensor systems and even allow the construction of new types of optical sensor which were not previously possible with conventional fibres.

1. INTRODUCTION

Optical fibre active devices have found application in communications systems as laser sources, optical power amplifiers, all-optical repeaters and pre-detector optical amplifiers (ie optical pre-amplifiers). In addition, they have future promise as pulse shapers, filters with optical gain, and as non-linear elements. Many of these devices can also be used to great advantage in multiplexed and distributed optical fibre sensing systems, as the primary design problem to be overcome is the high attenuation that can occur in large passive networks.

With the use of high-power optical fibre sources, high-gain optical amplifiers and low-noise optical pre-amplifiers, the number of multiplexed sensors that can be addressed by a single source and detector may be increased dramatically and, in addition, the acceptable length of sensing fibre in a distributed network can be increased markedly. Indeed, with care in the choice of suitable locations for amplifiers, the acceptable size of a sensor network can be increased to the limits set, not by the usual signal/noise limitations, but by either the need to avoid undesirable oscillation (either true lasing, or problems with prolonged pulse echoes) or by the eventual signal degradation and non-linearity arising from multiple stages of amplification. In addition, for long sensor lengths, the effects of fibre dispersion may limit the permissable range of high resolution systems.

Of course, for a large network, with many amplifiers, care will need to be taken to ensure accurate sensor referencing, as optical amplifiers will, modify both the signal intensity and the spectral power distribution of an optical signal.

This paper discusses some of the basic methods by which active devices can improve the capability of multiplexed and distributed sensors, even using relatively simple configurations and goes on to speculate on more advanced architectures. It will also sound a note of caution regarding the new problems which might be met in practice. We shall commence our discussions by describing the optical-time-domain reflectometer (OTDR) and showing the improvements in performance which are achievable with the inclusion of optical amplifiers.

We shall also consider the potential of tuned fibre sources for use in sensors. These are attractive for addressing wavelength-selective devices, such as fibre gratings, in multiplexed networks.

Within the context of distributed systems, the paper will also include discussions of some of the special fibres that have been produced at Southampton University, and which may have particular attractions in sensing cables.

2. IMPROVEMENTS TO OTDR SYSTEMS

2.1. The conventional OTDR system (see Figure 1)

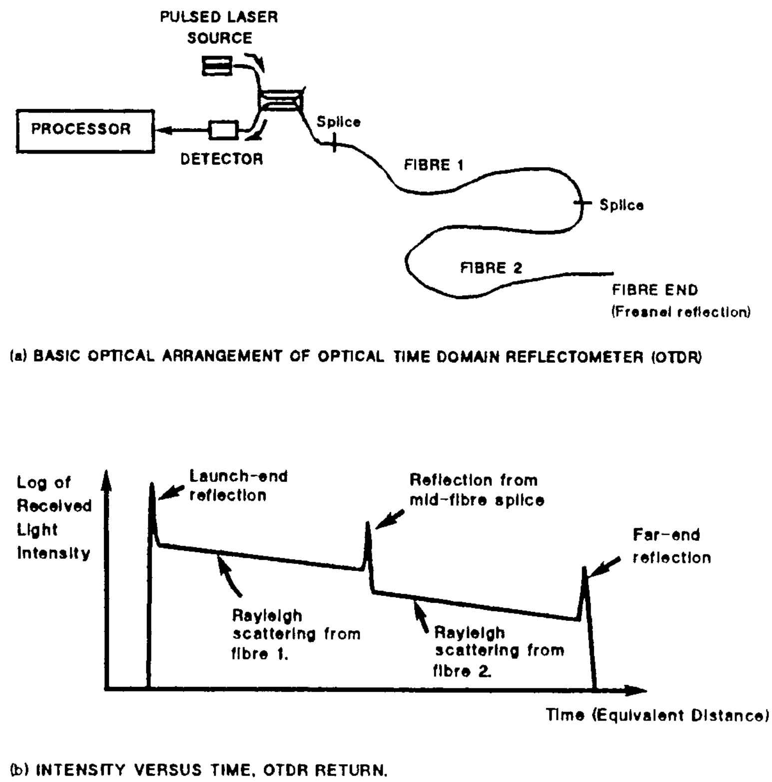


Figure 1 Concept of the basic optical time domain reflectometer

The optical time domain reflectometer (OTDR) is the most common instrument used to measure the properties of optical fibres and networks. It was first devised by Barnoski and Jensen[1], as a means of interrogating optical fibre to determine the location of imperfections and breaks. It operates in a similar manner to a radar system, but would be more exactly described as a guided wave LIDAR system. A short pulse of light, usually from a semiconductor laser, is launched into a fibre via a directional coupler. As the pulse propagates, it continually scatters light as a result of minute inhomogeneities (Rayleigh scattering) in the vitreous material of the fibre, or by Fresnel reflections from breaks or other discontinuities. A portion of the scattered light is guided back, via the other arm of the directional coupler, to the detection system. The two-way time of flight, of the returned scattered signal, is related to the distance along the fibre and the received scattered signal amplitude is a function of the pulse energy launched, the velocity in the guide, the scattering coefficient and the two way attenuation in the guide.

In addition, scattered light must be coupled back into reverse-travelling guided modes in the fibre. In general, a fraction, S, of total scattered power is coupled back. The time-varying received backscattered signal, is then given[2] by:-

$$P_s(z) = 0.5ES(z)\alpha_s(z)V_g \exp\left\{-\int_0^z[\alpha_f(z') + \alpha_b(z')]dz'\right\} \tag{1}$$

where E is the pulse energy launched into the sensing fibre section, α_s is the scattering component of the fibre attenuation coefficient, α_f and α_b are the forward and backward total attenuation coefficients and V_g is the group velocity of the optical guide. The integral expresses the two-way attenuation in the guide to the point at a distance z along the fibre, where the scatter occurs. Separate values for forward and backward attenuation are used to allow for cases (such as in tapered fibre sections) where the forward and backward attenuations may not necessarily be identical. The factor of 0.5 is included to account for the 3 dB loss in the directional coupler in the return direction. As with a conventional radar system, the distance, z, is directly related to the two-way time of flight, t, of the light, given by:-

$$t = 2z/V_g \tag{2}$$

Therefore, the temporal variation of the detected signal may be used to determine the variation of either the attenuation or scattering coefficients of the fibre. (If both vary, ambiguities will, of course, arise, a fact often overlooked by users of OTDR instruments.)

In order to give an idea of the received power levels for OTDR,it will be instructive to insert typical[3,4] values in the equations above. A typical launch energy level for OTDR is 10 nJ (e.g., a laser of 100 mW peak pulse power with 100 ns duration). A multi-mode fibre will have a typical back-scatter capture fraction, S, of 0.01, a scattering coefficient, α_s, of the order of 10^{-5} cm^{-1},and a guided wave velocity, V_g, of 2 x 10^{10} cm s^{-2}. This provides an initial received power of the order of 10^{-5}W from the earlier sections of fibre. After a two-way traverse through a fibre section with a 25 dB one-way attenuation, the received power from the end of the section will be reduced to 10^{-10}W. In many common circumstances, the main change in the OTDR signature (apart from the experimental reduction due to attenuation) will be due to a change in scattering coefficient, α_s, (assuming constant attenuation, α, and constant backscatter capture ratio, S). Then:-

$$P_s(t) = A\alpha_s \exp(-\alpha V_g t) \tag{3}$$

where A is constant (neglecting any variation in loss between the two directions of propagation). Alternatively, the change may be due to a change in attenuation with constant scattering coefficient and constant S. Then:-

$$P_s(z) = B \exp\left[-\int_0^z 2\alpha(z)dz\right] \tag{4}$$

where B is a constant and:-

$$\frac{d[P_s(z)]}{dz} = - P_s(z)2\alpha z \tag{5}$$

Thus, to summarize the above results, scattering variations are observed by directly-proportional amplitude changes from the OTDR signature. In order to observe attenuation variations, the OTDR signature must be differentiated and normalised by dividing by the instantaneous scattered level. (Alternatively, changes in the gradient of a graph of log $P_s(z)$ versus z can present an indication of the attenuation versus length characteristics, provided that α_s is constant).

The main disadvantage of the simple OTDR system is that the signal return is exceedingly weak and requires significant signal averaging. In addition, if it is desired to achieve a good spatial resolution, extremely short optical pulses must be launched and a high speed optical receiver is necessary. A spatial resolution of 10 cm corresponds to a two-way propagation delay of only 1 nanosecond in optical fibre so pulse widths of less than this are required from the source, and receiver bandwidths of several hundred megahertz are necessary to resolve the return signal.

Many distributed and multiplexed sensors have been constructed using the OTDR as a basis[3-10]. There is a particular research emphasis on achieving enhanced spatial resolution and increased operating range in future sensors, particularly for application areas in "Smart Skins" for structural and other monitoring in aerospace applications. We shall now examine ways in which the performance of the basic OTDR system may be improved using special fibre devices.

2.2. Enhancement of the OTDR using a single fibre amplifier

An optical fibre amplifier can be inserted in the optical circuit of the OTDR as shown in Figure 2. The position of the amplifier is such that both the outgoing pulse from the laser source and the weak returning backscattered signal from the fibre are amplified in the same device. This has a dramatic effect on the performance of the system.

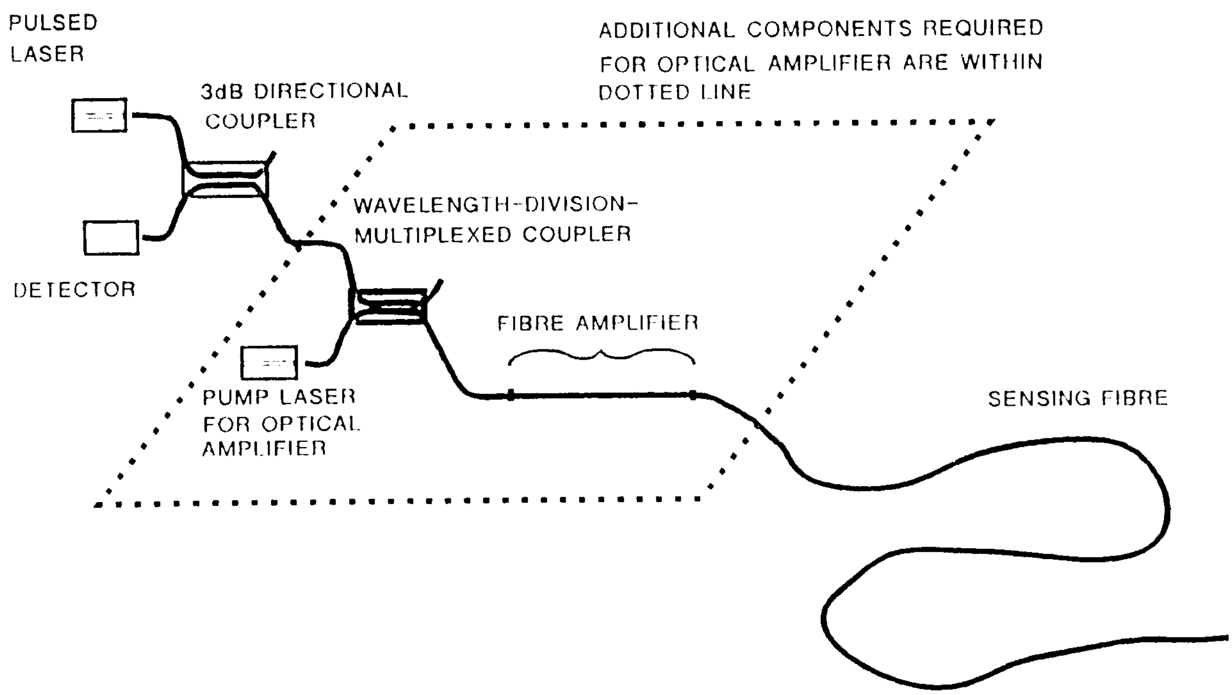


Figure 2 Schematic of OTDR system, using a fibre amplifier stage.

The outgoing laser pulse power could, in principle, be amplified up to 1000 times in a typical erbium fibre amplifier (30 dB gain at 1500 nm), since in low-duty-cycle pulsed mode the small signal gain can be approached. Thus, a semiconductor laser source of 20 mW power could be boosted to launch 10 watts into the fibre, allowing for 3 dB loss in the 3 dB coupler. For short laser pulses of higher input power, much higher output powers of several hundred Watts are possible from the amplifier, as a result of the high energy storage possible in the device. In practice, the power output may be limited by other considerations, such as the onset of stimulated Raman scattering, particularly if monomode fibres are measured, and additional factors such as eye safety.

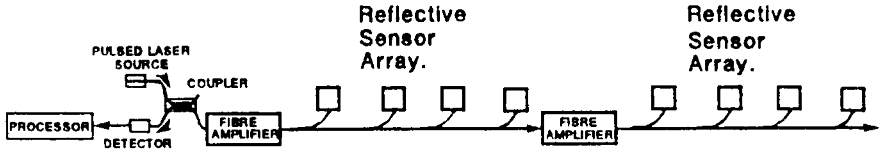
The effect on the returning backscattered signal is also highly significant. Firstly, the amplifier provides gain before the lossy 3dB directional coupler, and hence provides an immediate 3 dB optical power improvement in the detectable signal limit. However, for high bandwidth signals, the performance of the detector in combination with an optical fibre preamplifier, has generally a far superior detection limit than the detector alone. This advantage becomes particularly marked if the detector has a narrow band filter to remove amplified spontaneous emission (ASE) outside the wavelength band required. This band must include any source- laser frequency fluctuations (including also the modulation sidebands corresponding to the desired spatial resolution to be covered).

The advantages of the optical preamplifier are most marked when the detection bandwidth is high, as, particularly above 100 MHz bandwidth, the thermal noise of conventional detection systems tends to rise rapidly, whereas for the optical preamplifier system the design of an appropriate optical filter to remove out-of-band ASE becomes progressively easier. An example of the detection limit improvement that can be achieved with an erbium fibre amplifier at 1 GHz is given in the paper by Laming et al[11]. At 1 GHz, an improvement of 7 dB in receiver sensitivity is possible. In the OTDR system, when the 3 dB gain due to amplification before the 3 dB coupler is included, a total potential receiver sensitivity improvement of 10 dB is anticipated. At frequencies above 1 GHz, as might be used for ultra-high resolution measurement, the potential improvement factor is much greater.

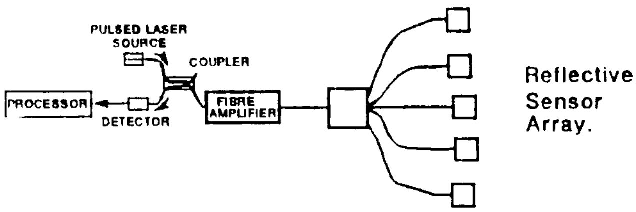
If one adds all the potential improvement factors there is a possible overall improvement of up to 10,000 times (40 dB), permitting the same performance to be achieved over a fibre sensor with an additional 20 dB one way loss. However, care must be taken to avoid problems of spontaneous oscillation due to optical feedback (caused by, for example, reflections from the source laser and detector and from coherent Rayleigh backscatter in the sensing fibre) and the maximum possible improvement may therefore be less than this in practice. In addition, care must be taken to ensure that the gain of the amplifier does not change significantly during the period when the backscatter signal is returning, (or, if it does not, compensate for gain changes that occur). Provided the launched pulse does not seriously deplete the excited-state population (by virtue of its short duration), there is not likely to be a serious population-change problem with the much weaker backscattered signals, as even the time-averaged signal power is much less than that of the launched laser signal.

2.3. Optical amplifiers in OTDR - addressed multiplexed sensor arrays

The potential improvements in sensor multiplexing systems are enormous when optical amplifiers are incorporated. A major problem with passive fibre branching networks is the rapid build-up of losses, firstly the inevitable losses due to power division and, secondly, the additional losses in imperfect components (connectors, splices and power splitters). Incorporation of optical amplifiers in judicious locations in the network can compensate for losses, either as, or before, they occur, preferably always boosting the optical power before it has become too weak. Thus a good signal/noise ratio is maintained in the propagating signals throughout the network. Examples of some possible arrangements are shown in Figure 3. The simplest form of sensor which may be addressed is a binary (on/off) reflective sensor. Multiplexing is achieved by virtue of different optical path length (and hence optical delay differences) to each reflective point. The allocation of several binary sensing lines to a single sensor could produce a multi-bit digitally encoded sensor, such as a shaft encoder, extending the capability of simpler systems of this nature by allowing many such sensors to be addressed.



Schematic of OTDR-Addressed Array of Reflective Sensors, Using Linear Branching Highway.



Schematic of OTDR-Addressed Array of Reflective Sensors, Using Star-splitter Configuration.

Figure 3 Active sensor networks suitable for addressing with OTDR systems. (Note: The networks can be expanded greatly, using more amplifiers. Combinations of branching and star couplers may be used. For simplicity of drawing, only very small numbers of sensors have been shown).

One potential useful application, requiring large numbers of multiplexed sensors is, for polling of consumer premises for automatic remote reading of utility meters (gas, water and electricity). The problem so far has been the enormous network losses. However, use of optical amplifiers may overcome these, allowing the addressing of large communities from a single central monitor station.

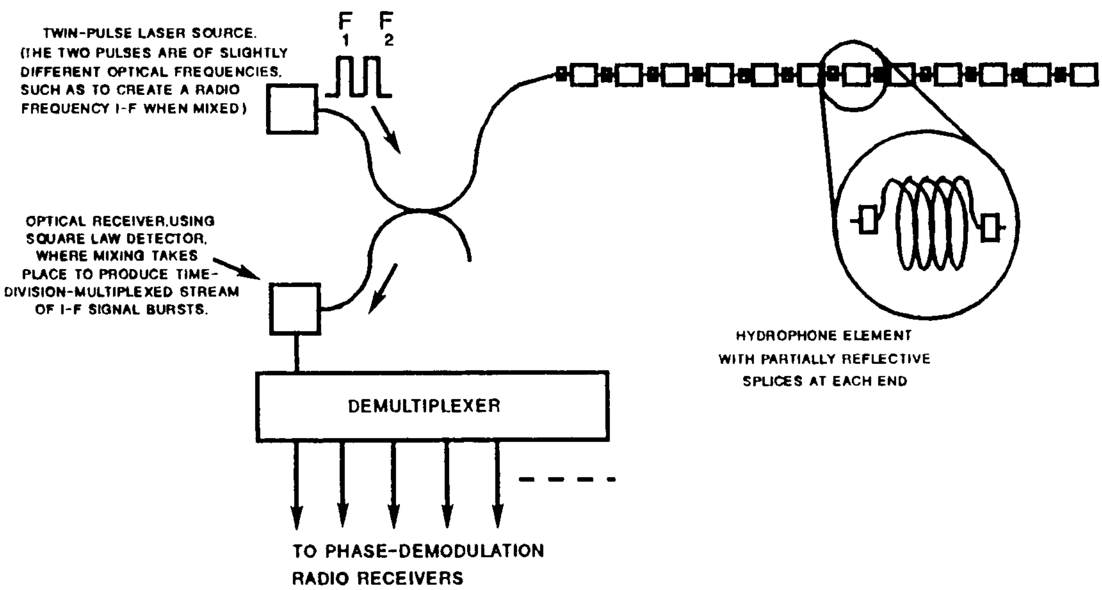


Figure 4 Schematic of Plessey multiplexed hydrophone concept, using differential delay heterodyning.

The use of optical amplifiers is not restricted to intensity-based sensors, as they may also be used to advantage in various forms of interferometric sensor arrays. Figure 4 shows a passive hydrophone array, as described in more detail in references 12 and 13. The system relies on interferometry between returning optical pulses from each of the reflective discontinuities. Acoustic signals are detected by monitoring phase changes between the returning optical signals as they mix on the optical detector. The signal can become heavily attenuated after passage through large sensor arrays. Pre-boosting of the launched signal can potentially help significantly, as can optical preamplification of the weak return signals (see Figure 5). However, additional amplifiers could also be placed along the detector chain, provided care is taken to avoid too many multiple reflections, or, in the extreme, laser oscillation due to excessive optical feedback. The possibility of these problems arising could be reduced by synchronised gain-switching of the optical amplifier. This would allow it to have high gain, to amplify the outgoing interrogation pulses and remain at high gain for the period when pulses are still returning from the later sections of the array.

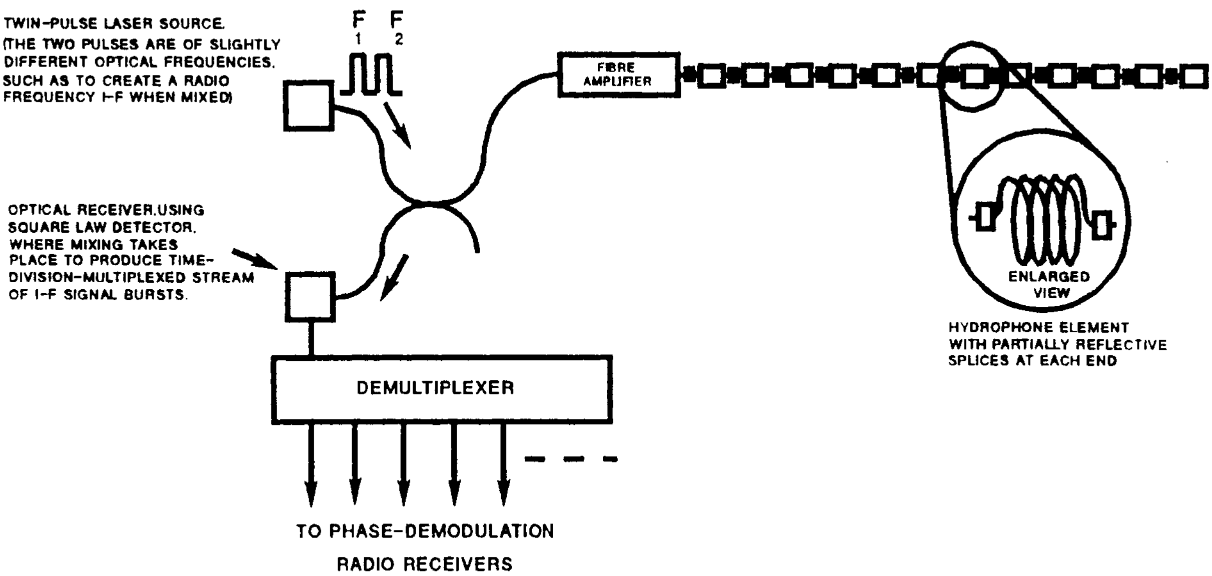


Figure 5 Modified fibre hydrophone array concept, using optical amplifier module. (Note: Other amplifiers could be inserted in long arrays).

3.1. Distributed temperature sensing based on stimulated Brillouin scattering (SBS)

Brillouin scattering is the name given to the process of inelastic scattering of photons by acoustic phonons, resulting in the creation of two new frequencies, one down-shifted and one up-shifted (the so-called Stokes and anti-Stokes signals, respectively). The frequency shift is the same in both cases, is dependent on the scattering angle and corresponds to the addition or subtraction of the phonon energy from that of the original photon. Because a single mode optical fibre is essentially a one-dimensional structure, scattered light can be recaptured into a guided mode for only two scattering angles, 0° (forward) or 180° (backward).

The Stokes shift for Brillouin scattering is zero in the forward direction and reaches a maximum value in the backward direction[14], given by:-

$$\nu_B = \frac{2V_a n}{\lambda_L} \tag{6}$$

where V_a, n and λ_L are respectively the acoustic velocity, refractive index and pump wavelength.

The lifetime of the individual phonons follows a negative exponential probability distribution and so the Stokes and Anti-Stokes components are not single frequencies, but rather are Lorentzians centred on the frequency $\nu_L \pm \nu_B$. The width of the Lorentzian (i.e. Stokes linewidth)[15], is given by

$$\Delta\nu_B = \frac{16\pi^2\eta_s}{\rho_0\lambda_L^2} \tag{7}$$

where η_s and ρ_o are the material viscosity and density respectively.

The phonon lifetime τ_B is related to the frequency spread by:-

$$\tau_B = \frac{1}{\pi \times \Delta\nu_B} \tag{8}$$

For silica at λ_L = 1.5 microns, the Stokes shift ν_B is of the order of 12 GHz while the linewidth is of the order of 20 MHz, corresponding to a phonon lifetime of 16ns. Taking the longitudinal velocity of sound in fused silica to be ~6 Kms^{-1} we find that the e^{-1} decay distance of the soundwave is ~100 microns, ie, about 10 core diameters.

The process of Brillouin scattering in fibre is complicated by the fact that the participating electromagnetic modes are not plane waves and the variation of the transverse fields must be taken into account[16]. Furthermore, the optical fibre is not acoustically homogeneous, as the dopants used to modify the optical properties also affect the acoustic properties, resulting in a widening of the Stokes linewidth.

From equation 6 we see that the Stokes shift is proportional to the refractive index, which in turn is dependent on strain and temperature. It is this dependence which is exploited in order to construct a distributed sensor. If the pump is pulsed in order to obtain a sensor with spatial resolution, as the pulse travels down the fibre, noise generated in the illuminated region grows into a coherent signal at a centre frequency depending on the mean refractive index in that section. Unlike the distributed temperature sensor (DTS) based on Raman scattering, a DTS based on stimulated Brillouin scattering produces an output in the form of an instantaneous frequency, which has advantages for signal processing. Previously described sensors of strain[17] and temperature[18,19] based on SBS effectively probed the Stokes lineshape at every point of the fibre, using a separate narrow linewidth signal injected from the distal end. Access to both ends of the sensing fibre was required, and a complete scan of probe frequencies had to be made to obtain the maximum and hence the temperature or strain of a particular section of the fibre. The system proposed here (Figure 6) uses two fibres, one of which is held at constant temperature and serves as a reference.

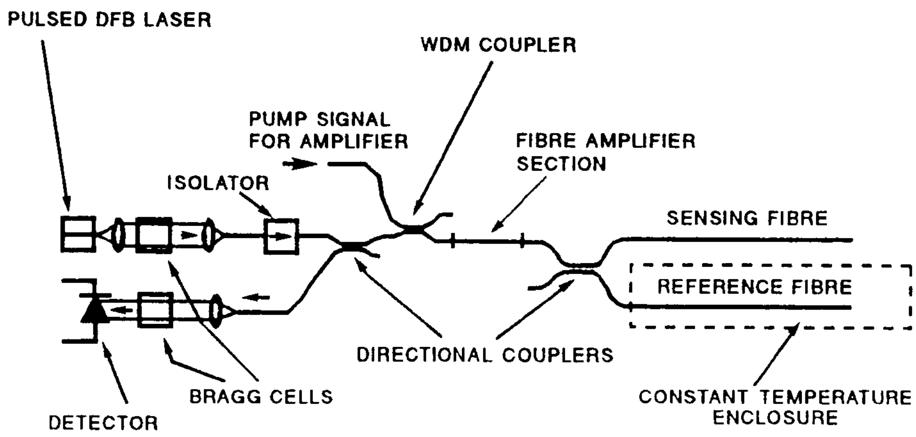


Figure 6 Schematic of distributed sensor using Brillouin scattering.

Pulses from the DFB laser are amplified and subsequently travel down both fibres producing SBS. A second fibre amplifier may be used to boost the returning signal (or, as shown in Figure 6, the same amplifier may in fact be used) and the beat frequency between the signal and reference arm is displayed on an electronic spectrum analyser. A variable delay between the pump pulse and the receiving gate allows the repetitive sampling of a particular portion of the fibre. Temperature sensitivities between 10 MHz/K[18] and 3 MHz/K[19] have been reported, the exact figure depending on fibre dopants and construction.

3.2. Rare-earth-doped sensor fibres with temperature-dependent absorption

One attractive form of distributed sensor is based on the monitoring of attenuation changes in optical fibre using a simple OTDR system. The OTDR return signal can be differentiated with respect to time, and normalised by division by the instantaneous value of the signal, in order to obtain a measure of the attenuation of the fibre[20,21]. If a suitable fibre is used, the method can produce a distributed temperature sensor.

An optical fibre temperature sensor using the properties of rare-earth ions has potentially important characteristics. OTDR monitoring of the environment is possible due to the intrinsically low losses and the long interaction lengths possible in optical fibres and the spectral characteristics of many rare-earth and transition metal ions are highly temperature sensitive[22]. In a distributed temperature sensor of this type, the loss of a fibre at a wavelength on the edge of an absorption band is monitored by interrogating the local fibre absorption by back scatter techniques. A number of temperature sensors based on the spectral characteristics of rare-earth ions have been developed [23,24,25], and in all cases the change in loss due to an increase in population of excited state levels with temperature is monitored.

The use of dopant ions to monitor temperature changes allows considerable scope for improvements in performance. For example, alternative ions may be employed to allow the use of a more convenient probe source and the dopant concentration may be increased for improved resolution. An example is given of a germanosilicate core fibre doped with 100ppm of Ho^{3+}. A significant change in the spectral loss is obtained by increasing the temperature from 77K (-196°C) to room temperature (20°C), with the absorption peak being shifted to longer wavelengths.

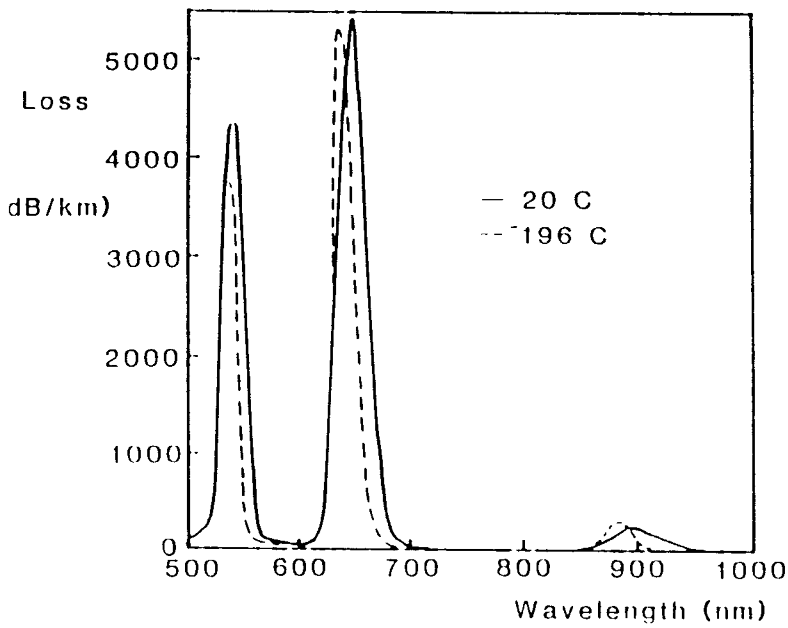


Figure 7 Spectral loss characteristics of Ho^{3+} doped GeO_2-SiO_2 core fibres

It is clear, from Figure 7, that there are large changes in the loss with temperature at wavelengths of 555nm, 670nm and 910nm. By monitoring the absorption at 665nm, a linear change in loss with temperature is obtained, as shown in Figure 8. With reference to the figure, it can be seen that, over the range -60°C to 90°C (the highest value tested), a linear change in loss is obtained, corresponding to 0.79%/°C of the absorption at 20°C, the highest recorded value to date. Below -60°C the unit change of loss decreases as the Ho^{3+} absorption loss approaches the limit of the intrinsic loss (10dB/km at 665nm in this case), so limiting the resolution.

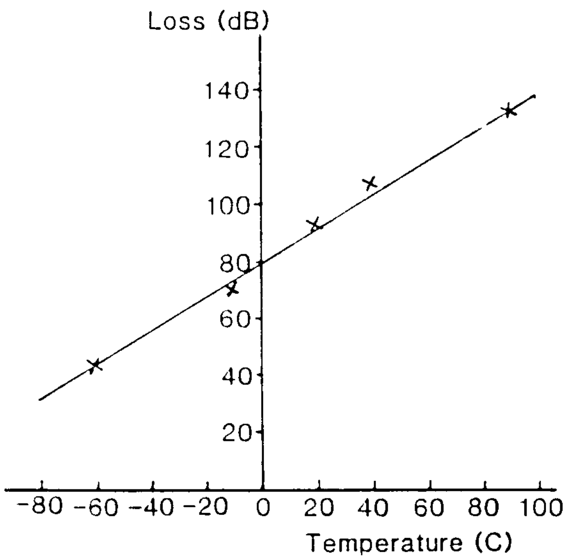


Figure 8 Change in absorption at 665nm of Ho^{3+} doped GeO_2-SiO_2 core fibre with temperature.

An OTDR temperature sensor which uses this fibre has been demonstrated. A pulse of defined duration (35ns) is launched into the fibre, with the pulse width limiting the resolution of the system. Some of the launched light is absorbed by the dopant, decreasing the pulse intensity. As discussed in section 2.1, the intensity detected at the front end depends on the initial intensity, E_0, the degree of backscatter, α_s, and the integrated loss, α, over twice the length, z, under consideration. In the temperature sensitive fibre, changes in α, and hence in the form of the above relationship, occur as regions of different temperature are encountered. Hence a plot of the type shown in Figure 9 is obtained for a holmium doped fibre when it is subjected to a range of temperatures. This is compared with the characteristics of a conventional, temperature insensitive, fibre. Hence, knowing the change in loss for unit temperature change (as shown previously in Figure 8), the local temperature can be determined.

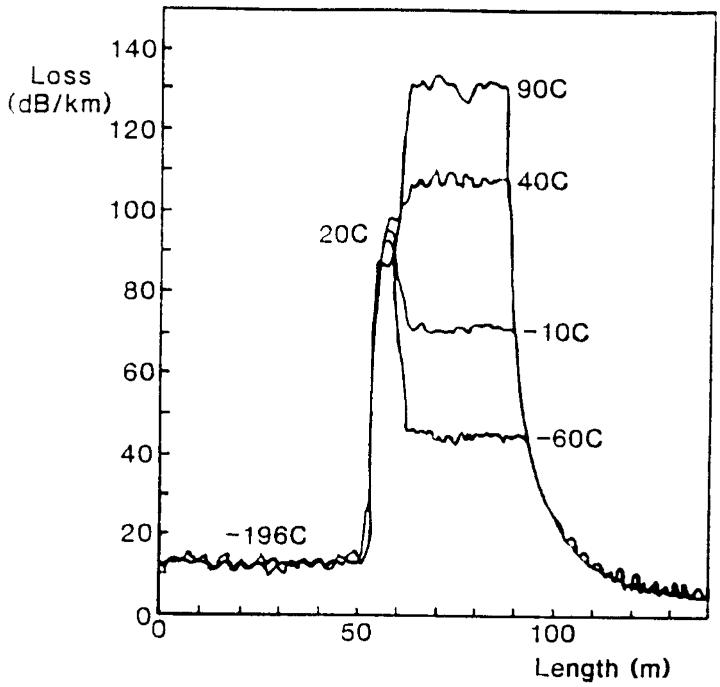


Figure 9 Dependence of intensity of backscatter signal along length of Ho^{3+} doped GeO_2-SiO_2 core fibre subjected to a range of temperatures along the fibre length.

Several examples of spatially resolved absorption plots are presented in Figure 10, overleaf. A resolution of 3.5m was obtained, a value dependant on both the pulse length used (3ns) and on the detector response. The large change in loss with temperature gives a temperature resolution of better than 1°C over the 180m tested, which is sufficient for many applications.

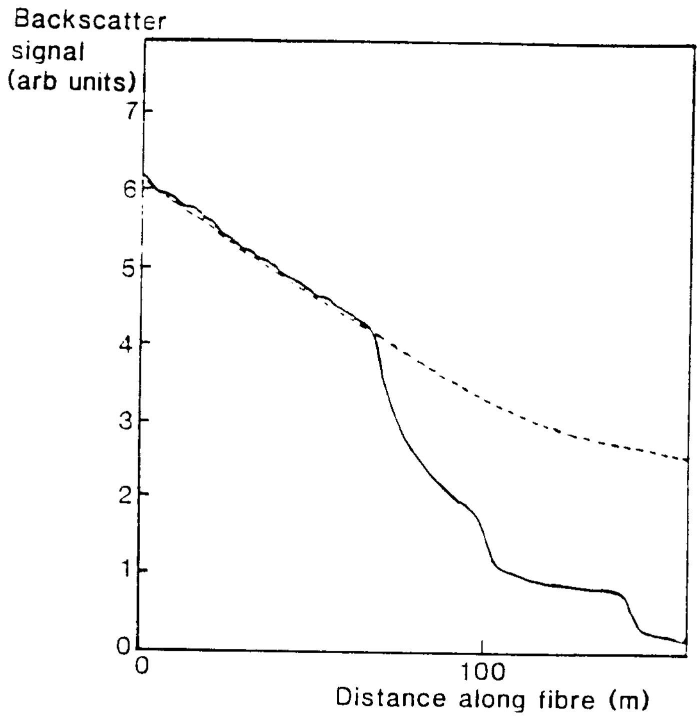


Figure 10 Typical change in loss along length of Ho^{3+} doped GeO_2-SiO_2 core fibre with temperature, as determined from backscatter measurements.

The main disadvantage of such sensors is the high attenuation that inevitably occurs when attenuation changes are used to measure physical parameters along the length of a fibre. In order to determine accurately any changes in attenuation, the level of attenuation in the measured section must be high. This leads to high losses if the number of separate sections to be monitored is significant. Clearly, the use of optical amplifiers can again greatly extend the overall dynamic range of the OTDR, as discussed in section 2.2. The gain of 40dB dynamic range permits an additional 20dB single-way attenuation and hence will permit measurement of several more zones using this method.

4. OPTICAL SOURCES

4.1. Q-switched fibre laser sources

High peak-power, short duration pulsed sources are required in a number of distributed sensors to provide high spatial resolution with good signal to noise ratios. Q-switched neodymium-doped fibre laser sources are attractive in this application by virtue of their ability to produce short duration pulses using relatively low power laser diode pump sources. Neodymium-doped silica fibres can be fabricated to give 0.3-0.5dB gain at 1.06μm for each mW of launched pump power at 810nm. Such pump light can easily be obtained from AlGaAs laser diodes. Using high concentration Nd-doped fibre (>1000ppm) permits short fibre lengths to be used and thus enables the cavity photon lifetime to be minimised. This is an important requirement for the generation of short-duration Q-switched pulses.

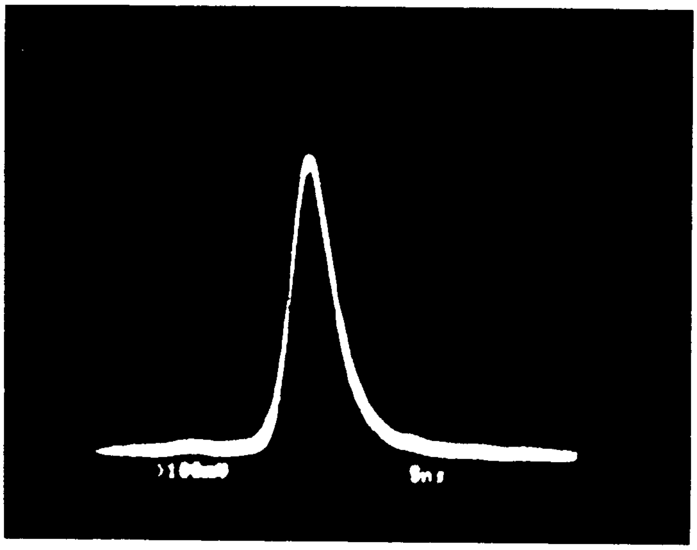


Figure 11 Q-switched Nd-doped fibre laser performance
(Max peak power of pulse shown on oscilloscope, 600W)

A typical cavity configuration for a 1.06μm Nd-doped fibre laser would include a high-reflectivity (HR) mirror, doped fibre (length<10cm), intra-cavity lens, modulator (AO or EO) and a partially transmitting output coupling mirror. Pump light at 810nm from a laser diode would be launched through the HR (1.06μm) mirror. Figure 11 shows a typical Q-switched Nd fibre laser output pulse. The peak power is $\approx$600W and the pulse duration 5ns. Such pulse characteristics would enable 0.5m spatial resolution to be obtained in a distributed sensor system. In this case a 100mW laser diode was used as the pump source (SDL 5411). For Nd-doped fibres the pulse characteristics remain unchanged up to $\approx$400Hz repetition rate, above which the peak power reduces and the pulse duration increases.

4.2. Narrow linewidth sources for multiplexed sensors requiring long coherence lengths

Narrow linewidth erbium-doped fibre lasers operating in the 1.55μm region offer considerable potential as sources for multiplexed and distributed fibre sensor systems. Single-frequency sources have attracted much interest, since travelling-wave erbium fibre lasers were demonstrated to be capable of linewidths of the order of tens of kilohertz[26]. Travelling-wave fibre lasers operate in a single longitudinal mode by preventing spatial holeburning from occurring in the gain medium. The long resonator lengths of travelling-wave fibre lasers, typically several metres, mean that very narrow spectral widths are obtainable once single-longitudinal-mode operation is achieved[27].

A variety of resonator configurations have been demonstrated, capable of achieving different spectral properties. The broad gain bandwidth allows tuning ranges of at least 45nm to be achieved with the inclusion of a suitable tunable filter in a ring laser resonator[28]. Alternatively, highly-efficient single frequency operation can be achieved at a well-defined fixed wavelength[29]. These fibre laser resonators are directly compatible with the fibres used as transmission and sensing media.

Narrow linewidth sources will be of great interest for addressing interferometers requiring highly-coherent signals or fibre gratings written into sensing fibres at distributed points of the system. In addition, the very high spectral purity of travelling-wave erbium-doped fibre lasers may be of interest for sensing systems based on non-linear effects within the sensing fibre, such as stimulated Brillouin scattering.

Narrow-bandwidth Bragg gratings can be conveniently written into commercial fibres having germania-doped cores[30] in order to produce distributed and multiplexed sensor networks. The reflectors respond only to a specific-wavelength optical signal. Gratings can be used as temperature or strain sensors, as the wavelength of reflection changes linearly with each of these parameters. Pairs of reflection gratings can be used to define the reflectors of a Fabry-Perot interferometer for enhanced selectivity, and may be addressed using a high-coherence source, such as a single frequency fibre laser. The wavelength selectivity of the gratings makes them suitable for wavelength multiplexing schemes, using either a broadband source or tunable narrow-band source (Figure 12). Travelling-wave fibre lasers will have linewidths narrower than the grating reflection bandwidth, hence enabling small changes in reflection wavelength due to temperature or strain to be detected by frequency tuning.

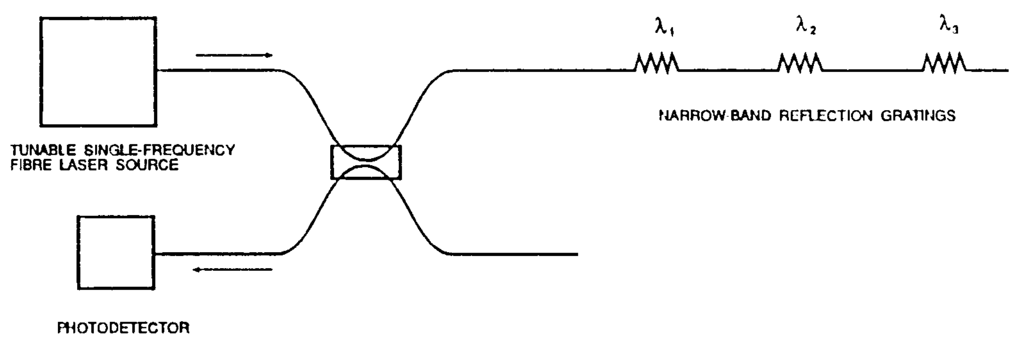


Figure 12 Schematic of multiplexed temperature/strain sensor system employing Bragg reflectors

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