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DISTRIBUTED OPTICAL FIBER SENSORS

John P Dakin

Optoelectronics Research Centre
University of Southampton
Southampton SO9 5NH, U.K.

ABSTRACT

This critical review paper covers the field of distributed optical fiber sensors, where measurements may be taken along the length of a continuous section of optical fiber. Such a feature greatly increases the information that can be obtained from a single instrument and hence the cost per sensing point can be more acceptable.

The review will not attempt to cover all methods, but will give a selection of some of the more interesting theoretical concepts, describe the current status of research and indicate where optical sensing methods are being applied in commercial instruments.

1. INTRODUCTION

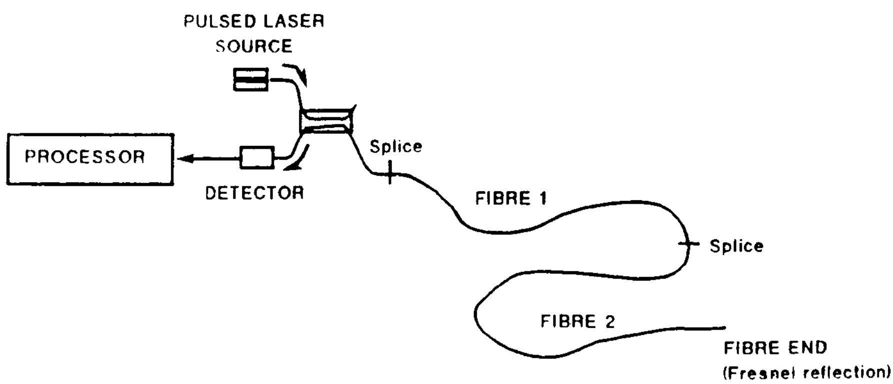
The highest state of the art in optical sensing is achieved with optical fiber distributed sensors. Such sensors permit the measurement of a desired parameter as a function of length along the fiber. This is clearly of particular advantage for applications such as "smart" skins, as a sensor can measure the variation of, for example, temperature over significant areas of the outer layer of vehicles.

There are three main criteria which must be satisfied to achieve a distributed sensor. Firstly, it is necessary to construct (or select) a fiber which will modify the propagation of light in a way which can be relied upon to be dependent on the parameter to be measured. Secondly, one must be able to detect the changes in transmission (or light scattering) arising from the parameter to be measured. Thirdly, it is necessary to locate the region of the fiber where the change in propagation occurs, in order to achieve the desired spatial distribution. The paper will commence with a discussion of the basic methods which can be employed. These methods will then be expanded upon in later sections, and a number of examples of promising and practical sensors will be described. The range of applications is very large, but, as mentioned above, there is currently a strong interest in sensors for smart structures. Potential applications in this area will therefore be given some emphasis, although a broader presentation of the technology will be given.

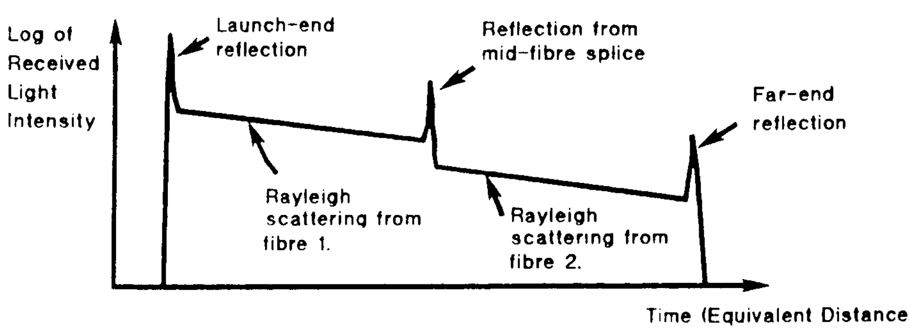
2. BASIC CONCEPTS OF DISTRIBUTED SENSORS

A distributed sensor consists of a continuous length of fiber, usually with no taps or branches along its length. It is therefore necessary to determine the location of any measurand-induced change in transmission or scattering properties by taking advantage of the propagation delays of light travelling in the fiber. Such propagation delays allow differences in the time of arrival of light, travelling in different modes of propagation, to be related to distances along the fiber.

The greatest differences in propagation delay occur when signals are travelling in opposite directions in the fiber. The simplest example of this is the optical time domain reflectometer (OTDR), where a pulsed signal is transmitted into one end of the fiber, and returning back-scattered signals are recovered from the same fiber end, (figure 1).



(a) BASIC OPTICAL ARRANGEMENT OF OPTICAL TIME DOMAIN REFLECTOMETER (OTDR)



(b) INTENSITY VERSUS TIME, OTDR RETURN.

Figure 1 Concept of the basic optical time domain reflectometer

The concept is a guided-wave optical variant of the radar-location principle, where distance, z, is related to the two-way propagation delay, 2t, by the simple formula:-

$$z = t.V_g \qquad (1)$$

where V_g is the group velocity of light in the fiber. Rather than rely on weak backscattered light, it is possible to use counter propagating light, and arrange for a non-linear optical interaction to occur when the beams cross. Thus a continuous "probe" beam can be modulated by a "pump" pulse travelling in the opposite direction (see figure 2).

Changes in the probe intensity with time can again be related to changes with position along the fiber. A third method of location involves signals which travel only in the forward direction.

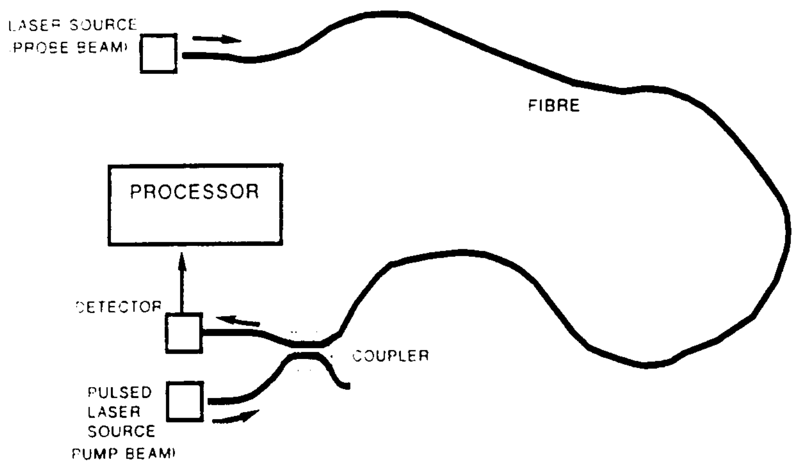


Figure 2 Schematic of distributed sensor concept with counter-propagating pump and probe beam

In order to determine distance in this case, one must use a fiber which will support at least two forward-travelling modes of propagation. These modes must travel at different velocity. The influence to be monitored must cause some conversion of light energy between these modes, such that, for the remainder of the fiber length, the mode-converted light travels in a different mode to the remainder of the original light, (see figure 3). It is necessary to detect the small changes in propagation delay which arise from the intermodal difference in propagation velocity over this latter section. These changes are so small that it is generally necessary to use some form of interferometric approach in order to detect them.

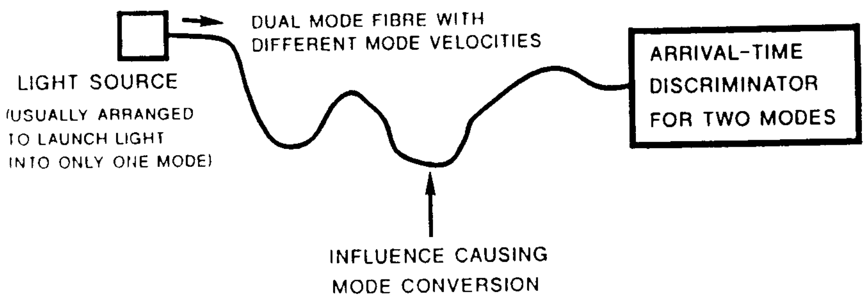


Figure 3 Basic concept of distributed sensing using foward-travelling waves only

Having outlined the basic methods, each will now be described in more detail and variants of each of the basic concepts will be discussed.

3. BACKSCATTERING METHODS, INCLUDING OTDR

3.1 General concept

The OTDR, first reported in reference 1, has been established as a standard item of fiber optic test gear for many years. Its main application is for fault finding and attenuation monitoring in optical networks. As described above, the OTDR relies on backscattering (or back reflection) of light which has been launched into a fiber from an amplitude-modulated (usually-pulsed) source. The light is Rayleigh scattered from refractive index fluctuations in the core of the fiber, or may be reflected from discontinuities,such as connectors, splices, fiber breaks etc. The Rayleigh scattering component, which is detected returning from the arrangement shown in figure 1, is given by the following equation (reference 2) :-

$$P(z) = \tfrac{1}{2} S(z).\ \alpha_s(z).\ V_g.\ \exp\{-\int_o^{z'}[\alpha_f(z') + \alpha_b(z')]\,dz'\} \qquad (2)$$

where P(z) is the detected backscattered power, as a function of the distance, z, of the scattering point along the fiber, S(z) is the captured fraction of scattered light coupled into backward-travelling modes in the fiber, α_s (z) is the scattering coefficient of the fiber, V_g is the group velocity of light in the fiber, and α_f and α_b are the total attenuation coefficients of the fiber in the forward and backward directions, respectively. (Usually α_f and α_b will have the same value; i.e:- $\alpha_f = \alpha_b = \alpha$). As stated in the introduction, the distance, z, is related to the two-way time of flight, 2t, by the relation:-

$$z = t.V_g$$

When the attenuation coefficients and the capture factor are constant, the expression for the detected backscattered power, P, has an exponential time dependence of the form:-

$$P(t) = A_1 . \exp(-B_1.t) \qquad (3)$$

where A_1 and B_1 are constant. This is, of course, the situation for a uniform fiber.

The OTDR can sense changes in the total attenuation coefficient, α, if the scattering coefficient, α_s, and the capture fraction, S, are constant. Under these conditions:-

$$P(z) = A_2 \cdot \exp[-\int_o^z \alpha(z').dz'] \qquad (4)$$

where A_2 is a constant. The rate of change (differential with respect to time) of the detected signal is proportional to the attenuation coefficient. Alternatively, it can sense changes in scattering coefficient α_s if α and S are constant:-

$$P(z) = A_3 . \alpha_s(z).\exp(-B_3 z) \qquad (5)$$

where A_3 and B_3 are constants. (Clearly α will normally change with changes in α_s, but if the value of the integral $\int_o^z \alpha(z').dz'$ is small, the error will be small).

Many parameters can cause (or be arranged to cause) variations in the attenuation or scattering coefficient of a fiber. These will be discussed in the following section.

3.2 Distributed Sensors Based on Monitoring Attenuation Variations with the OTDR

3.2.1 Microbend Sensors for Mechanical Sensing

Any distortion of an optical fiber from its ideal cylindrical shape gives rise to an increase in attenuation. Gradual bends, having a radius above a few cms, generally result in a much smaller loss than very small and sharp bends. Highly localised bends, or kinks, of this type are known as microbends, and cause significant losses in both monomode and multimode fiber. Generally, in monomode fiber, the loss due to a given bend is fairly amenable to theoretical analysis (reference 3). For this type of fiber, it is only necessary to determine the loss of energy from the fundamental mode. Thus, monomode fibers are potentially capable of quantitative determination of the extent of bending of a fiber simply from a measurement of attenuation, provided that the shape of the bend deformation is known.

Multimode fibers, on the other hand, are less predictable in their behaviour. A particular problem is that the attenuation due to a given bend is a complex function of the manner in which power is distributed between the multiplicity of waveguide modes at the entrance to the bend. This mode excitation is a function not just of the launching conditions, but also of the entire topology of the fiber (including any other microbend sensors!) prior to the measurement region. Thus, multimode microbend sensors will generally have some potential value for use as simple qualitative sensors, but are less likely to make practical quantitative types.

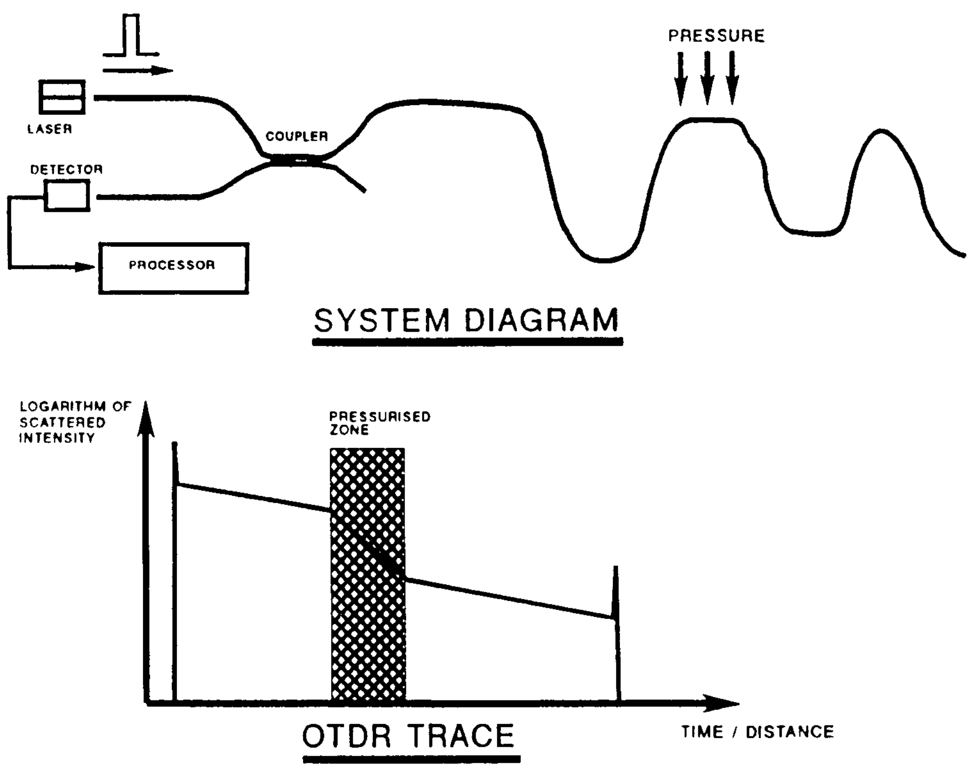


Figure 4 Concept of distributed sensing using a pressure-sensitive cable

In order to construct a microbend sensing system, it is necessary to arrange for the parameter to be measured to cause microbending of a cable which is monitored with an OTDR system (figure 4). A convenient form of sensing cable is one of a type originally designed by Harmer, which is now a commercial product (Herga Ltd., reference 4; see also figure 5). This cable contains an inner communications fiber, with a polymer fiber wound spirally round it. These fibers are then sheathed within a close-fitting outer tube. When compressed, the outer tube squashes against the spiral polymer fiber, which in turn deforms the inner optical fiber to give it a periodic, alternating, lateral displacement. Multimode fibers suffer particularly high microbending loss if the spatial period of the distortion matches the pitch of the 'zig-zag' path taken by the highest order modes in the straight fiber.

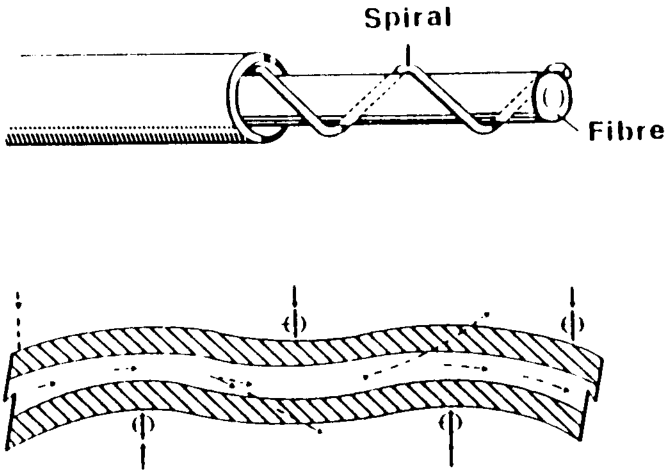


Figure 5 Principle of the microbend-sensing fiber cable (Hergalite)

The spiral-wound fiber cable forms a distributed sensing element which is capable of many qualitative sensing tasks. For example, it can sense the pressure of a footstep and can hence form a security barrier for safety reasons (for example, to switch off a dangerous machine or other manufacturing process if a person approaches: figure 6) or to protect against unauthorised intruders (figure 7).

There are many sensing systems of this type, where it is sufficient for a simple transmission monitor to merely detect the total line-averaged effects of disturbance along a single section. However, the cable is capable of location of disturbance along a continuous length if it is coupled to an OTDR system.

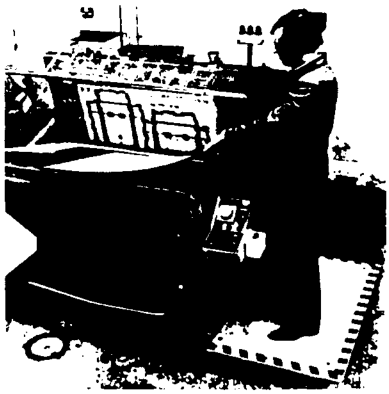


Figure 6 A pressure-sensing mat for machine guarding (Herga Electric Ltd., U.K.)

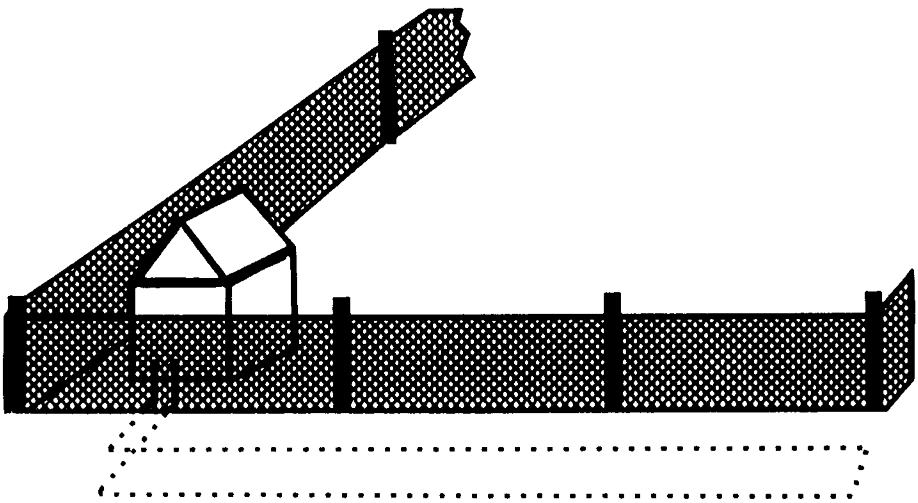


Figure 7 Schematic of application of fibre-optic intruder detector system buried in ground

In addition to detection of footpressure, the microbend sensor has been considered as a sensor for the monitoring of civil engineering structures (reference 5). Clearly, if it can be made in a reliable form, it has considerable potential for use as a strain sensor for "Smart Structures". If the strain in a structure can be reliably converted to a periodic ripple in a fiber, then the structure can be qualitatively monitored. However, if multimode fiber is used in the sensor, then the performance is likely to be rather variable, because the response will be dependent on the mode conversion occurring in earlier sections. In addition, the polymer elements which transfer the strain to the inner fiber can creep at room temperature and will flow more readily at high temperatures. Much work remains to be done, therefore, to develop versions suitable for high temperatures, such as may arise in aerospace applications.

3.2.2 Radiation Sensing

The attenuation of an optical fiber increases when exposed to ionising radiation. In order to cause attenuation, the radiation must be able to penetrate to the core region of the fiber, and must have sufficient energy to cause structural change in the glass core. Three types of radiation affect attenuation:- neutrons, γ rays and X-rays. (The latter, being also photons, are essentially the same as γ rays in nature, but they differ in the way in which they are generated and are usually of lower energy). Gaebler and Braunig (reference 6) were the first workers to recognise the potential of an optical fiber for distributed radiation sensing and to demonstrate the method experimentally using an OTDR. The basic concept of distributed radiation sensing is shown in figure 8. The irradiated section of fiber has a higher loss, and hence the gradient of the OTDR trace changes for positions corresponding to this region.

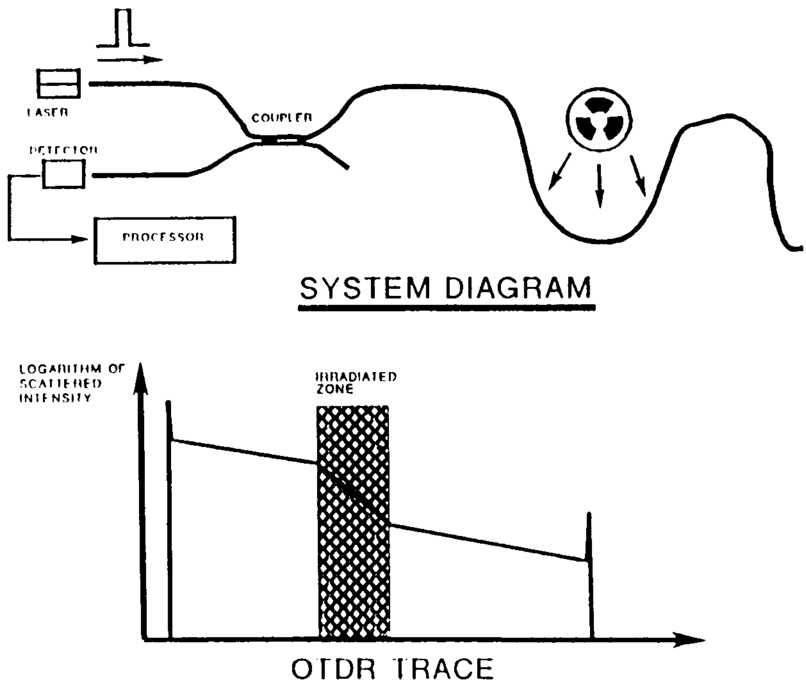


Figure 8 Concept of the distributed radiation dosimeter (W. Gaebler and D. Braunig 1983)

The distributed radiation sensor has particular attractions for detecting the presence of a single localised area of irradiation, as the line-integrated loss is reasonably low and the probe signal is not unduly attenuated. The sensor reported in reference (6) was probably less well suited for quantitative radiation dosimetry, as the sensitivity of normal germania-doped silica fiber is poor, and the response can exhibit a strong dose-rate dependence. The measurement can suffer significant error due to room temperature annealing which will slowly reduce the induced loss.

3.2.3 Temperature Sensing

The first distributed temperature sensor, by Hartog and Payne, was based on a liquid-filled fibre (reference 7, figure 9). This fiber is simply a silica glass tube filled with a higher refractive index, low-absorption, liquid, which acts as the light-guiding core of the waveguide. The scattering loss coefficient, α_s, of the liquid depends on the density fluctuations caused by thermodynamic molecular motion, and therefore shows a strong temperature dependence.

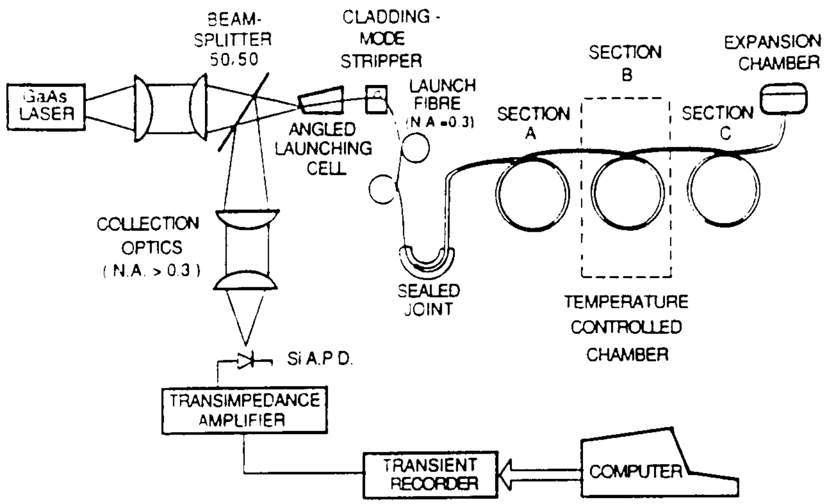


Figure 9 Rayleigh-scattering temperature profiler using liquid-filled fibre (reference 7)

The thermal variations are not significant in glass fibers, as the scattering is caused by "frozen-in" density fluctuations, formed as the glass was cooled from the melt. The scattering variations in the liquid-filled fiber are directly observable from an OTDR trace, (figure 10), due to the dependence of the return signal on the scattering loss coefficient, α_s, in section 3.1. This sensor successfully demonstrated the ability to measure temperature distribution, for the first time, but the use of a liquid-filled fiber renders it impractical for a wide variety of applications. We shall therefore consider a means of using a solid glass fiber with an OTDR system. (Other methods using glass fiber will be discussed in later sections).

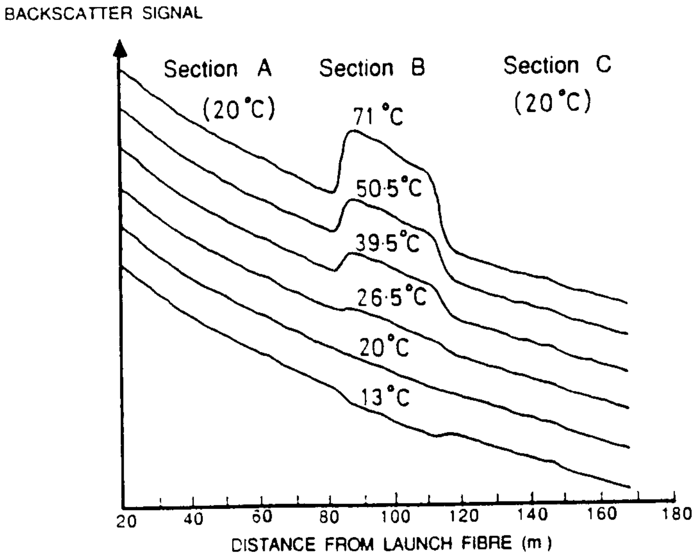


Figure 10 Results of distributed temperature sensing using OTDR in liquid-filled fibre

Optical fibers doped with rare-earth ions, such as Nd^{3+} and Ho^{3+}, show strong absorption peaks in the visible and near infrared regions of the spectrum. Many of these absorbing transitions occur between electronic levels having a temperature-dependent occupancy, and therefore several absorption peaks have a significant thermal dependence (ie the coefficient α is temperature dependent). The OTDR can probe the absorption as a function of length, and hence determine the variation of temperature along the fiber (reference 8). As already mentioned, a disadvantage of using variations in an absorbing fiber to sense a parameter is that both the probe and return back scatter signals are rapidly attenuated by this same absorption. The method is nonetheless attractive for systems requiring only a few measurement elements along the length of the fiber. It is also an excellent method when a fiber is used which has a low attenuation in normal use, yet which increases if sections become either too hot or too cold. This is clearly useful for methods requiring the detection and location of hot-spots or cold-spots, particularly if these are likely to occur only over a short length of the fiber.

The absorption loss along the length of a holmium-doped fiber, as measured at 665 nm, is shown in figure 11 (reference 9). This fiber was cooled to -196°C in liquid nitrogen for much of its length, but the central region was allowed to increase in temperature in stages, being eventually heated to +40°C and +90°C. The attenuation profile shows the potential value of such a sensor for detecting loss of cryogenic coolant. It could, for example, also be used to detect the effects of solar heating on an otherwise-cold spacecraft surface. Many other combinations of rare earth dopants, host fiber and interrogation wavelengths are possible, and there may therefore prove to be suitable candidates for sensors for the detection of a wide range of over- and under-heating and cooling conditions.

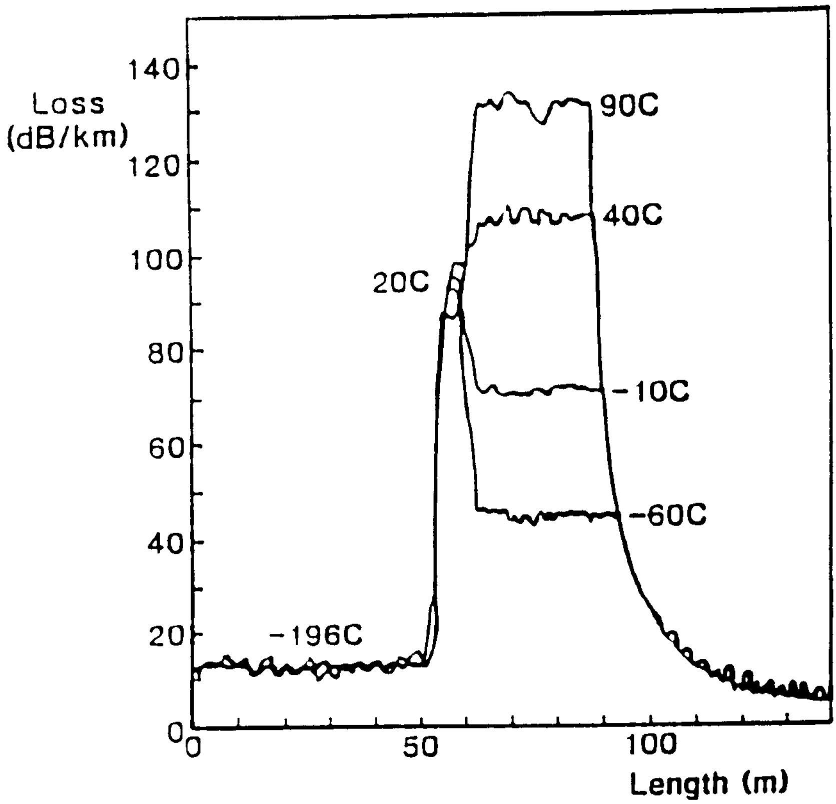


Figure 11 Attenuation versus length in an Ho^{3+}-doped fiber, when a central section is exposed to varying temperature (outer sections are held at -196°C). Loss was measured with an OTDR at 665nm (reference 9)

In addition to fibers using special dopants, there is one type of commonly available fiber which has a significant temperature coefficient of attenuation. This is the polymer-clad-silica (PCS) fiber using a silicone cladding. This fiber has a low attenuation around room temperature and above, but suffers severe attenuation when cooled to below -50°C or so. This effect has been exploited as a practical sensor for detecting leakage in cryogenic liquids which has been launched as a commercial product, (reference 10). The attenuation occurs due to increase in the refractive index of the cooled cladding, which leads to eventual loss of guidance when it approaches the index of the silica core.

3.2.4 Chemical Sensing Using Absorbing Coatings

Distributed chemical sensors can be constructed by coating an optical fiber with indicator chemicals. As mentioned, a pure silica fiber can be coated with polymers of lower refractive index, such as silicone resins. These resins can be impregnated with the indicator, before coating the fiber, and before polymerisation. The guided modes in such a fiber have a small, yet significant,evanescent field penetration into the lower index polymer cladding, and hence the loss is dependent on the absorption of the dye. A schematic of the arrangement for distributed sensing is shown in figure 12. The chemical to be sensed can diffuse into the cladding, modify the absorption of the dye, and hence change the attenuation of the fiber. The first experimental results for

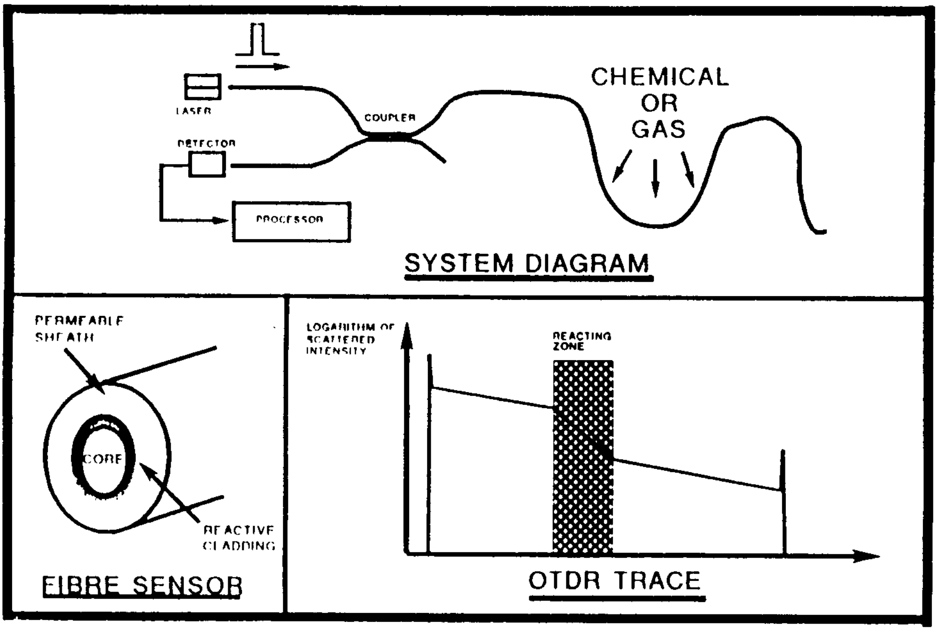


Figure 12 Concept of the distributed chemical sensor

such a sensor were obtained by performing a simple transmission measurement on a single section of fiber. Results for ammonia detection, using the change in colour of a pH indicator, were reported (reference 11). It is quite possible that, by the time this review goes to print, there may be reports of distributed chemical sensors capable of resolving the location of the interactions.

The evanescent-field chemical sensor has a number of potential problems which need to be solved before reliable operation can be achieved. The main problems arise from the variations in evanescent field coupling due either to changes in the temperature of, or adsorption of chemicals (including water) in, the cladding material. In addition, any small bends or fluctuations in the diameter of the fiber, will modify the evanescent field coupling. Finally, there is a need for care to ensure a sufficiently rapid diffusion time to ensure a fast enough response, and also to choose materials which will display a reasonably reversible behaviour, yet avoid any problems of the indicator becoming leached out.

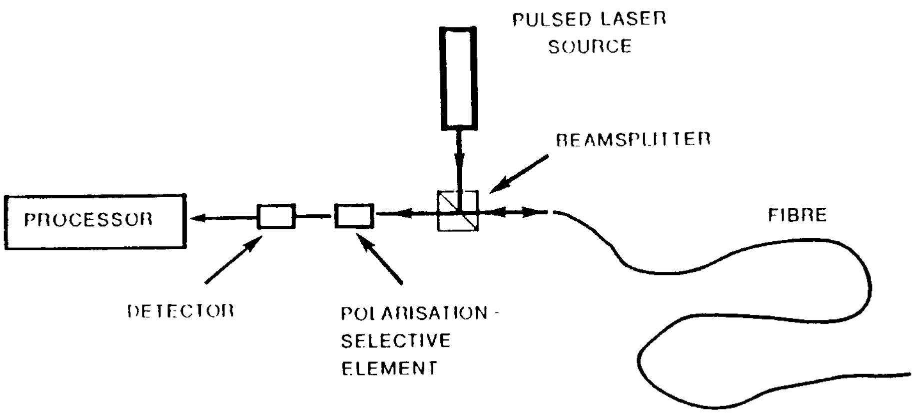


Figure 13 Basic optical arrangment of polarisation optical time domain reflectometer (POTDR) (reference 13)

Even if sophisticated distributed chemical sensors cannot be perfected, they may find application in a much simpler form in smart structures. It has already been shown possible to detect oil leaks, using the increase in cladding refractive index when it becomes contaminated with the oil, (reference 12). This causes severe loss in the fiber, and could therefore form a means of detecting leaks of fuel, lubricant or hydraulic oil. For "smart skins" applications, this will be useful to detect leaks onto structures from containment vessels or transport piping.

3.3 Polarisation Sensing (Polarisation Optical Time Domain Reflectometry or POTDR)

The POTDR method (reference 13; figure 13) is similar to OTDR, except that a pulse of polarised light is launched and the detector is arranged to be polarisation sensitive by placing a polariser before it. The method relies on the fact that Rayleigh and Rayleigh-Gans scattering in silica glass is polarised in the same direction as the incident light. Thus, any changes in the polarisation of the detected light result from changes during propagation over the two-way path to and from the scattering point. Changes in polarisation of light from different points along the fiber resulting differences in the detected signals at the appropriate delay times.

The POTDR method was first suggested by Rogers (reference 13), who pointed out its potential for distributed measurements of magnetic field (via Faraday rotation), electric field (via the Kerr quadratic electro-optic effect), lateral pressure (via the elasto-optic effect) and temperature (via the temperature dependence of the elasto-optic effect). The first experimental measurements were reported by Hartog et al. (reference 14), who used the technique for distributed measurement of the intrinsic birefringence of a monomode fiber. Kim and Choi (reference 15) measured the birefringence induced by the bending of a wound fiber. Ross (reference 16) carried out the first measurement of a variable external field using the Faraday rotation of polarisation caused by the magnetic field environment of the fiber. A comprehensive theoretical treatment of the POTDR method has been presented in the specialist paper of Rogers (reference 17).

The POTDR technique appears to be attractive for the measurement of a large number of parameters. However, as with many potentially useful sensing methods, its main drawback is the variety of parameters to which it can respond. Spurious sensitivity to strain and vibration are particularly troublesome. In addition, POTDR requires the use of monomode fibers, which can, when used with narrow linewidth laser sources, give rise to particular problems from coherent addition of light returning from multiple Rayleigh backscattering centres (reference 18). Significant recent research is being directed towards solving the vibration problems as the current monitor has strong commercial potential. More recent POTDR work has been carried out on birefringent fiber. The beat-length variations of such fiber are temperature dependent. Temperature distribution can be determined by monitoring the frequency of fluctuations of the detected signal when light is launched into both modes and the returning signal is passed through a polariser, (reference 19). In order to reduce the frequency of the fluctuations to a convenient range, a relatively low birefringent fiber is necessary.

3.4 Enhancement of the OTDR Using Active Fiber Components

We shall now consider how the performance of the basic OTDR can be enhanced, using a variety of recently developed active fiber components.

3.4.1 Enhancement of the OTDR using a Fiber Amplifier

An optical fiber amplifier can be inserted within the optical circuit of the OTDR, as shown in figure 14. The position of the amplifier is such that both the outgoing pulse from the laser source, and the weak backscattered signal from the fiber, are amplified in the same device. This is capable of

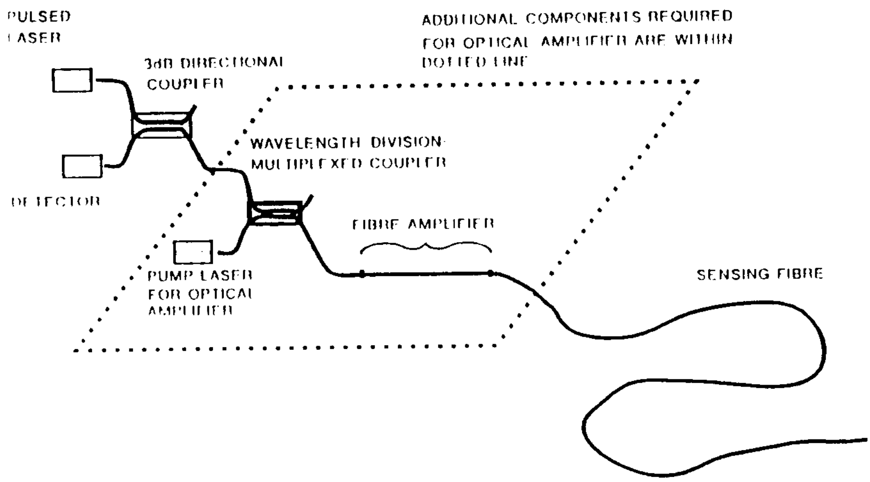


Figure 14 Enhanced OTDR system using an optical amplfier (reference 9)

having a dramatic effect on the performance of the system. At the time of writing, such systems have not yet found significant use in sensing systems. However, their potential is considerable, (reference 9), justifying their inclusion as an important part of this review.

The outgoing laser pulse power could, in principle, be amplified at least 1000 times in a typical erbium fiber amplifier. (This has typically >30dB gain at 1500 nm, and recent laboratory results have shown up to 50dB). In a low-duty-cycle pulsed mode of operation, the small signal gain can be approached. Thus, for example, a semiconductor laser source of 20 mW power can be boosted to launch 10 Watts into the fiber, even after 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. The peak output power for low-duty-cycle short pulses can be very high, as a result of the high energy storage possible in the device. In practice, the maximum power output is more likely to be limited by other considerations, such as the onset of stimulated Raman scattering, (particularly if monomode fibers are measured), and additional constraints such as limitation of eye hazard.

The effect on the returning backscattered signal is also highly significant. Firstly, the amplifier provides gain before the lossy 3 dB directional coupler, and hence can provide an immediate 3 dB optical power improvement in the detectable signal level. However, for high bandwidth signals, the performance of the detector, in combination with an optical fiber preamplifier, has generally a far superior detection limit than with the detector alone. This advantage becomes particularly marked if the detector is equipped with a narrow band filter, included to remove any amplified spontaneous emission (ASE) which falls outside the pass band necessary to amplify the fast-changing optical signal (reference 20). The ASE suppressing filter must have a broad enough bandwidth to include any spurious frequency fluctuations in the source laser (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 required detection bandwidth is high. In high bandwidth receivers,the thermal noise of conventional detection systems tends to rise rapidly, particularly above 200 MHz bandwidth. In addition, 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 fiber amplifier, for a received signal bandwidth of 1 GHz, is given in the paper by Laming et al, reference 21. At 1 GHz, an improvement of 7 dB in receiver sensitivity is possible. In an 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 necessary to achieve ultra-high resolution measurements (a few cms), the potential improvement factor is much greater.

If one multiplies all the potential improvement factors available with an amplifier of moderate (30dB) gain, there is a possible improvement factor of up to 10,000 times (40dB), permitting a fiber sensor to operate with an additional 20 dB one way loss. However, care must be taken to avoid problems of spontaneous oscillation due to optical feedback (caused, for example, by reflections from the source laser and detector, or from coherent Rayleigh backscatter in the sensing fiber). The maximum possible improvement may therefore be less than this in practice. In addition, care will have to 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, to compensate for gain changes that occur). Provided the launched pulse does not seriously deplete the excited-state population in the amplifier (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 will be much less than that of the launched laser signal.

3.4.2 Use of High-power Q-switched Fiber Laser Sources

High-peak-power, short-duration, pulsed sources are required in a number of distributed sensors, in order to provide good spatial resolution and signal-to-noise ratios. Q-switched neodymium-doped fiber lasers are attractive sources for this application, by virtue of their ability to produce short duration pulses using relatively low power laser diode pump sources. Neodymium-doped silica fibers can be fabricated to give 0.3-0.5 dB gain (at 1.06 μm for each mW of launched pump power (at 810 nm). Such pump light can easily be obtained from AlGaAs laser diodes. The use of high concentration (> 1000 ppm) Nd^{3+} doped fiber permits short fiber lengths to be used, thus minimising the photon lifetime in the cavity. This is an important requirement for the generation of short-duration Q-switched pulses.

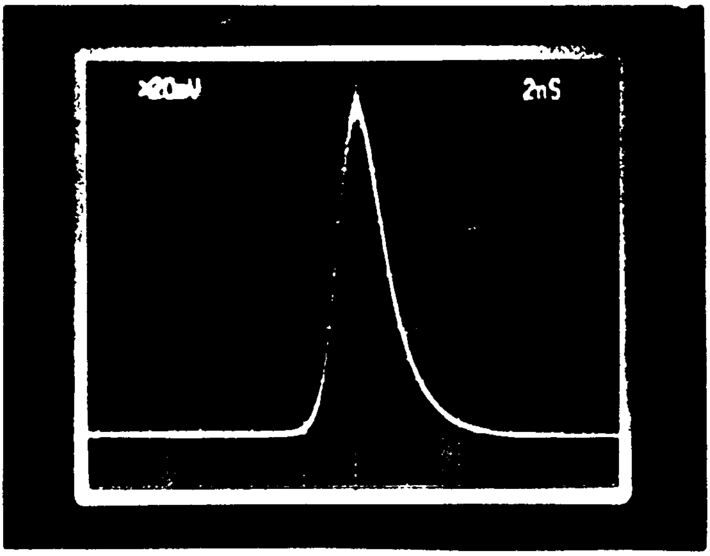


Figure 15 A pulse from a Q-switched Nd^{3+} YAG laser (peak power 600W, duration 5 nsec)

A typical cavity configuration for a 1.06 μm Nd^{3+}-doped fiber laser would include a mirror with a high reflectivity at 1.06 μm, a doped fiber (length < 10cm), an intra-cavity lens, an acousto-optic or electro-optic modulator, and a partially-transmitting output coupling mirror. Pump light at 810 nm from a laser diode is launched through the input-end mirror, which has a high reflectivity at 1.06 μm, but good transmission at 810 nm. Figure 15 shows a typical Q-switched Nd fiber laser output pulse, with a peak power of ~600 W and a pulse duration of 5 ns. Such pulse characteristics would enable a spatial resolution of 0.5 m to be obtained in a distributed sensor system. For these reported results, a 100 mW laser diode, (SDL5411), was used as the pump source. For Nd^{3+} doped fibers, the pulse characteristics remain unchanged up to a repetition rate of 400 Hz, above which the peak power reduces and the pulse duration increases. It should be emphasised that Q-switched fiber laser sources are more than just a research component, having already been incorporated into a commercial distributed temperature sensor (reference 22).

3.5 Distributed temperature sensing using Raman scattering, Brillouin scattering and fluorescence

All the backscattering methods described so far have relied on elastic scattering processes. These are ones where the scattered light is at the same wavelength as the incident light. Rayleigh scattering and Fresnel reflections are both examples of elastic scattering. There are several commonly occurring physical processes which cause a wavelength change in the scattered light. In quantum theory, this implies either a loss or gain in energy by an incident photon, when creating a scattered one. (It is this change of energy that explains the use of the term inelastic, by analogy with energy loss in inelastic mechanical systems). A spectral plot of several inelastic processes is shown in figure 16. The use of these for distributed sensors will be described in the following sub-sections.

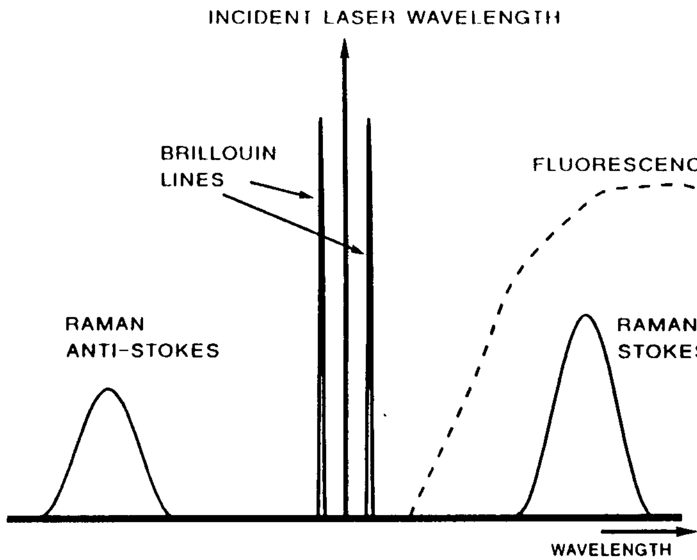


Figure 16 Inelastic scattering phenomena used for sensing

3.5.1 Distributed Temperature Sensing using Spontaneous Raman Scattering

If the spectral variation of backscattering from a germania-doped silica fiber (reference 23) is examined (figure 17), it may be seen that there is a strong central line, primarily due to elastic Rayleigh (or Rayleigh-Gans) scattering. This central line also contains lines due to Brillouin scattering, which are much closer in frequency to the incident frequency, and hence more difficult to resolve. At each side of the central line, however, there are side-lobes due to Raman scattering, which are shifted in frequency to a much greater degree. These Raman lines may be used to detect temperature profiles in conventional (vitreous) communications fiber, using an OTDR system with additional filters to select out the Raman light (reference 24). From standard texts on Raman scattering, the ratio, R, of anti-Stokes (higher frequency band) intensity to Stokes (lower frequency band) intensity at wavelengths λ_{a-s} and λ_s, respectively, (separated at equal frequency shift, $\Delta\nu$, from the central line) is given by the relationship:-

$$R(T) = \left(\frac{\lambda_s}{\lambda_{a-s}}\right)^4 \exp - \left(\frac{h.c.\Delta \nu}{K.T}\right) \qquad (6)$$

where h is Planck's constant, c is the velocity of light in vacuo, k is Boltzmann's constant and T is the absolute temperature.

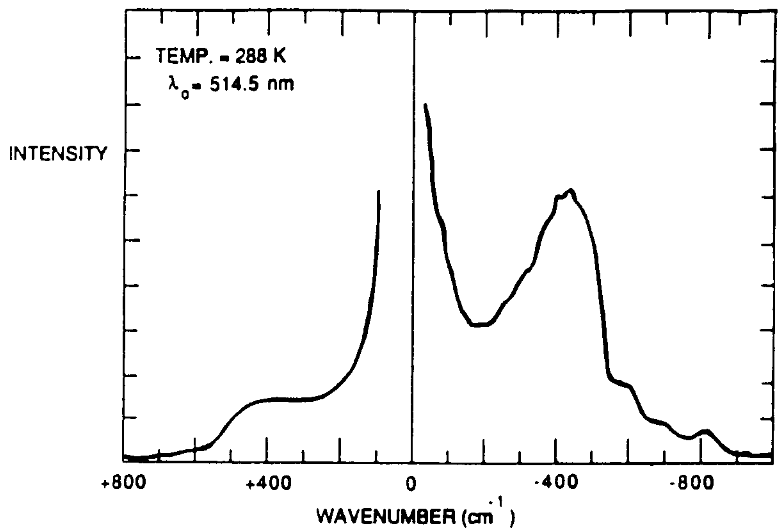


Figure 17 Raman scattering spectrum from a conventional germania-doped silica fibre

Thus, a measurement of the ratio of Stokes and anti-Stokes backscattered light in a fiber should provide an absolute indication of the temperature of the medium, irrespective of the light intensity, the launch conditions, the fiber geometry and even the material composition of the fiber. In practice, however, a small correction has to be made for variations in fiber attenuation between the different Stokes and anti-Stokes wavelengths. The Raman technique appears to have only one significant practical drawback; that of a relatively weak return signal. Usually, the anti-Stokes Raman-scattered signal is between 20 and 30 dB weaker than the Rayleigh signal. In order to avoid an excessive signal averaging time, measurements have been taken using pulsed lasers which are capable of providing a relatively high launched power. In the first experimental demonstration of the method (reference 24), a pulsed argon-ion laser was used in conjunction with Corning, telecommunication grade, 50/125 μm GRIN fiber.

The experimental arrangement is similar to that of the conventional OTDR, except that a wavelength-selective directional coupler is used, which allows the launch laser to be coupled into the fiber, but directs backscattered light at Raman wavelengths onto different detectors to receive Stokes and anti-Stokes bands, respectively.

More recent experimental results (references 25, 26) and first generation commercially developed systems (reference 27) have used a pulsed semiconductor laser and avalanche photodiode detectors, greatly reducing the size and power requirements (see figure 18). Such first generation systems have been capable of measurement of up to several hundred separate resolution elements over a few Kms of fiber. A measurement accuracy of better than $\pm 1°C$ is possible with resolution of a few metres. A typical form of temperature versus distance plot from a Raman DTS is shown in figure 19. A later generation system (reference 22) has an option of using Q-switched fiber laser sources and the range is extended to over 10 Km, with a resolution of around 1 metre.

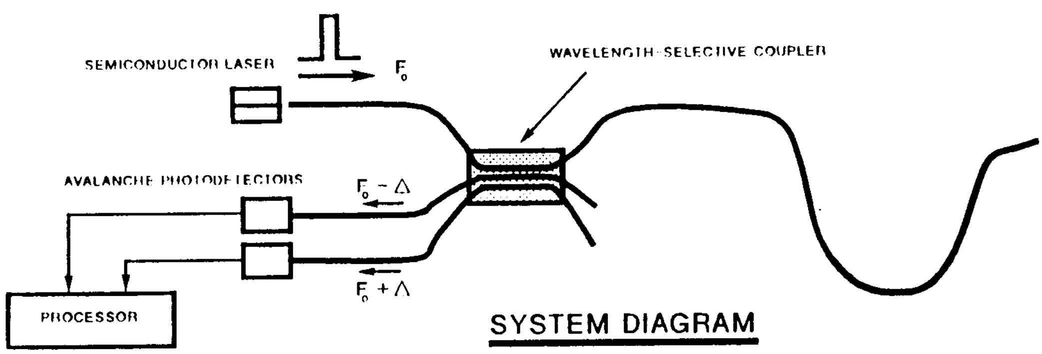


Figure 18 System diagram for Raman distributed temperature sensor, using semiconductor source and detector

The Raman DTS is now well-established as a practical sensor and has a low cross-sensitivity to other parameters such as strain, pressure, variations in type of fiber and cable, etc. It has applications for monitoring electrical machines, cables and transformers, location of fires, and for sensing industrial plant. It is clearly attractive as a temperature sensor for smart skins, being capable of measuring temperature at many thousands of points with a single instrument and fiber cable.

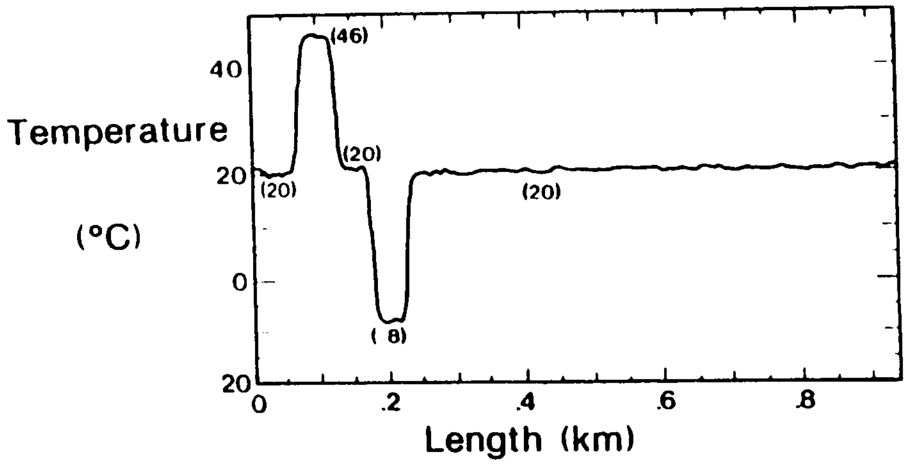


Figure 19 Typical temperature versus distance display for Raman DTS system

3.5.2 Sensing using Brillouin Scattering

In addition to Rayleigh scattering and Raman scattering, glasses also exhibit Brillouin scattering. In a classical model, this latter form of scattering can be considered to be diffraction of light from the refractive index variations arising from acoustic waves. The light can be considered to be Doppler shifted as a result of the movement of the acoustic wave. The Doppler shift is characteristic of the acoustic velocity in the glass, which is a function of both temperature and pressure. In the more accurate quantum model, the light is more correctly considered to be scattered as a result of particle interactions, the incident photons being scattered from acoustic phonons, with an appropriate energy change in the scattered photon. This energy change in the photon represents a frequency change equivalent to the Doppler shift expected from the less-correct classical model. The frequency shift with Brillouin scattering is very small ($\approx$ 12GHz) so, unlike Raman scattering, it is difficult to select out Brillouin lines with conventional optical filters. However, the intensity of Brillouin scattering is at least an order of magnitude higher than that of Raman signals, so it is an attractive possibility for sensing. There have been various research attempts to detect these lines, all by mixing (or heterodyning) optical signals scattered from the fiber with light which is frequency shifted from the original laser source. [ie., the source used to excite the Brillouin scattering] (references 28, 29; figure 20). The frequency-shifted light, required as a reference for the mixer, could be conveniently derived using a Brillouin fiber laser, with the original laser as a pump source. (A Brillouin fiber laser is simply a fiber with reflective end-mirrors, optically pumped at a level sufficient to cause lasing action via the phenomena of stimulated Brillouin scattering). This laser light is shifted, essentially to the same extent as the spontaneous Brillouin scattering in the measurement fiber. As a slightly different frequency is required for heterodyning, it should be tuned to a slightly different frequency, for example, by forming the Brillouin laser in a fiber composed of a different material to the measurement fiber.

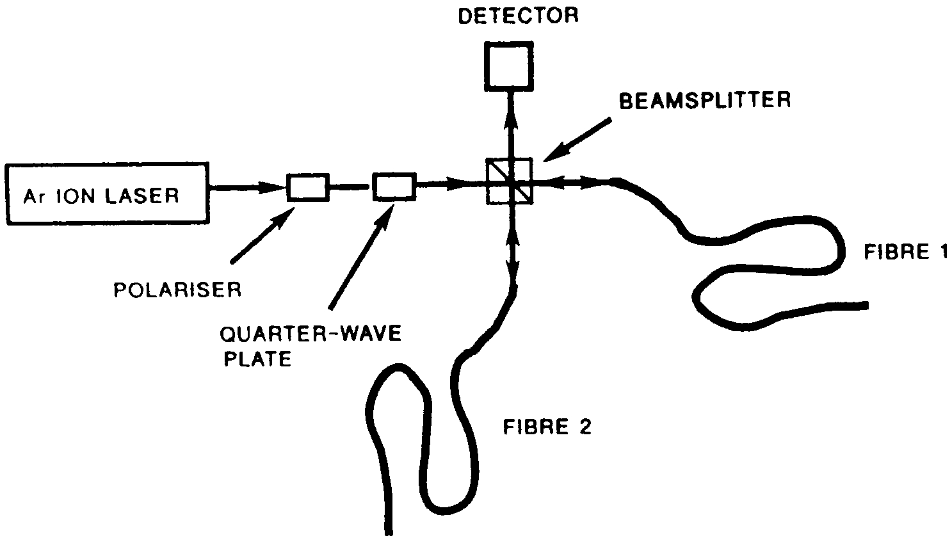


Figure 20 Basic optical arrangement for mixing of stimulated Brillouin scattering signals to create a heterodyne or difference frequency (reference 28)

The potential attraction of Brillouin scattering as a means of sensing is that the response to the measurand, such as a change in temperature or strain in the fiber, is manifest as a change in frequency of the scattered light. (These parameters change the acoustic velocity, and hence the Brillouin "Doppler" shift). By optical heterodyning, the frequency shifts can be down-converted to a more convenient electronic frequency, and are then in a particularly convenient form for accurate logging. Unfortunately, the Brillouin method has yet to be developed into a practical sensor. Apart from the relatively recent conception of the method, a further significant factor is the additional complexity of the optical system when compared either to the conventional OTDR or its Raman version. In addition, the limited distance resolution of the Brillouin system presents a significant drawback. The Brillouin linewidth effectively restricts the distance interval to several tens of metres, and will remain a problem unless satisfactory solutions are found.

3.5.3 Time Domain Fluorescence Monitoring

The re-emission reduce space spectrum of many fluorescent materials exhibits a significant temperature variation. It has been proposed that, in order to construct a sensor, an optical arrangement similar to that used for Raman OTDR could be constructed, using a laser source as before, but with the detector filters now selected to examine regions of the fluorescent decay spectrum of the fiber (reference 30, figure 21). In order to produce a distributed temperature sensor, wavelengths which exhibit the maximum possible temperature variation should be used. The potential attraction of the method,first proposed by Dakin (1984), is that the fluorescent quantum efficiency may be many orders of magnitude higher than that for Raman scattering, and higher doping levels can be used in order to greatly enhance the signals in short distributed sensor systems. However, there remains a problem with the availability of suitable fibers.

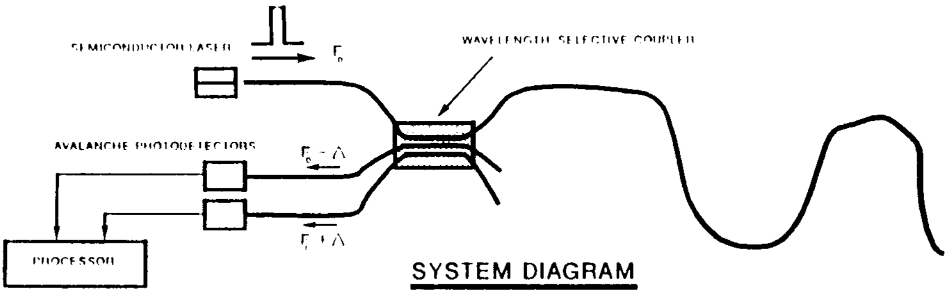


Figure 21 System diagram for distributed sensing using fluorescent OTDR

Silica-based optical fibers, having appropriate doping for high fluorescent efficiency, have been prepared using rare-earth doping (reference 31). Unfortunately, these are likely to have limited distance resolution in a fluorescent OTDR system, due to the long fluorescent lifetimes. Reduction in the lifetimes of the excited states of fluorescent dopants in glasses may generally be achieved by increased coupling to non-radiative processes, but this also reduces the fluorescent efficiency. Polymer fibers are believed, by the present author (reference 32), to offer more promise in short distance systems, as these may be doped with organic dye materials having an excellent combination of high quantum efficiency ($\approx 50\%$ or better) and short fluorescent lifetimes (of the order of only a few nanoseconds). Of course, polymer fibers will only have a limited temperature range, a feature which could be a major problem for many applications.

A theoretical paper (reference 33) has made a comparison of the performance expected from distributed temperature sensors based on the various techniques of temperature-dependent absorption, scattering, Raman scattering and fluorescence. Although fluorescent doping necessarily increases the loss in optical fibers, it was found that this would, for short distance operation, be more than compensated by the much higher light levels expected with fluorescence. If suitable glass fibers can eventually be produced it is likely to be an attractive future method for distributed thermometry.

3.6 Backscattering Systems using other Modulation Methods

The main methods discussed above have used a pulsed source, an approach used in first-generation electronic radar systems. (reference 34). This approach has the disadvantage that a low duty cycle signal is transmitted, leading to limitations in the mean power level. We shall now discuss three means by which the duty cycle of the transmitted signal can be increased. Each of these methods has been applied in sophisticated modern radar systems before finding use in experimental optical sensors.

3.6.1 Methods using a Pseudo-Random Encoded Source Modulation

The first method is that of encoded amplitude modulation of the source, using an orthogonal binary code sequence (reference 35). There are numerous binary codes that can be used for this modulation. The basic requirement is that the code should have a poor correlation with itself (ie. an autocorrelation function close to zero) for all conditions, except for the one where precisely-time-synchronised sequences are compared. Under this latter condition, the autocorrelation function has a maximum value. The effect of using such a code is to increase the duty cycle of the source to 50%, compared to typical values of 0.1% or less for the pulsed system.

In order to decode the backscatter signal with such a code, it is necessary to correlate the returning signal with a sample of the transmitted code sequence. The signature can be recovered by sweeping the relative delay between the reference code and the detected signal. Alternatively, a parallel processor system can obtain correlation signals in a series of multiplier cells, each cell corresponding to a measurement range determined by the delay of the reference signal applied to it.

Provided the averaging systems are of similar type, the coded system gives a signal/noise ratio improvement of the order of $\sqrt{N/2}$, where N is the number of discrete, resolvable, range cells. With finite length codes and imperfect waveforms, care must betaken not to introduce additional artifacts in the correlation signal which fail to correspond to real features in the backscattered signal. It has been found that the use of complimentary code sequences can lead to significant improvements in signal distortion in encoded OTDR systems (reference 36).

It should be emphasised that the encoded signal approach is applicable both to conventional OTDR (reference 35) and to Raman OTDR (reference 37).

3.6.2 Optical Frequency Domain Reflectometry (OFDR)

A second method of increasing the duty cycle is to "chirp" the optical source. This involves applying a periodic frequency modulation to the source, which should be a device, such as a laser, having a reasonably narrow instantaneous bandwidth. The preferred frequency-modulating waveform has a "sawtooth" variation with time, with a fast 'flyback'. This method is essentially similar to the frequency-modulated carrier wave (FMCW) technique used in radar systems. If an OFDR system is operated in backscattering mode, in a continuous monomode fiber, the beat signal produced at the detector increases in frequency, in direct proportion to the distance from which the light is retroscattered (references 38, 39). If the detected beat signal is examined with a conventional electronic spectrum analyser, the power in each frequency interval represents the level of scattered light received from a short section of fiber, situated at a distance corresponding to the frequency offset observed. The minimum theoretical range resolution, ΔR, possible, assuming a perfect linearly-chirped source (and a sufficient signal to noise ratio) is given by Kingsley and Davis (reference 39) as:-

$$\Delta R = 2V_g/\Delta f$$

where V_g is the velocity of light in the fiber, and Δf is the peak-peak frequency deviation of the optical source.

As the frequency-slew rate of current-ramp-driven semiconductor laser diodes may be very high (100 GHz/s is easily achievable), and the frequency resolution of commercial electronic spectrum analysers is a few Hz or less, the technique has a far superior distance resolution capability than OTDR methods. The above equation predicts a typical distance resolution of the order of 1mm, taking into account the reduced velocity of light in the fiber. Kingsley and Davies have suggested using the technique to perform distributed measurements in integrated optical wave-guide circuitry (reference 40).

Unfortunately, a major potential problem with OFDR is caused by uncertainties in the coherence function of the source. This coherence function modulates the received spectrum and therefore distorts any spatial variation of scattering that it is desired to observe. Some recent research directed towards converting this problem into a virtue and actually use the changes in the coherence to determine changes in the scatter function (reference 41).

Although several publications have reported OFDR results for fiber attenuation monitoring, none have so far used the method for distributed sensing of parameters external to the fiber.

3.6.3 Sub-carrier Frequency Domain Reflectometry (SCFDR)

The third method of encoding is to amplitude modulate the source with a chirped electronic signal (reference 42). This is essentially the same as the OFDR method, except that the sub-carrier is modulated rather than the source. This gives considerable more control of the source characteristics, as chirping of an electronic oscillator with a sawtooth modulation function is somewhat easier to achieve in practice. In addition, there is no longer a requirement for the source to have a long coherence length, as, unlike the OFDR method, no optical interference is necessary. Of course, the maximum frequency sweep and frequency-slew rate possible with the electronic sub-carrier method is generally less than that with an optical source, so the range resolution will generally be less. Despite several interesting research papers, the OFDR and SCFDR methods have, unlike the OTDR, not found significant application in commercial instruments.

4. TRANSMISSIVE DISTRIBUTED SENSING SYSTEMS

We shall now consider sensing systems where only transmitted light is monitored. The advantage is that the signal strengths are much greater than those for weak backscattered signals. The disadvantage is that there is a much smaller difference in propagation delay between modes of propagation. As mentioned in the section 1 introduction, it is necessary to have the signals carried in two modes, so that propagation delay differences can be derived, and the location of measurand-induced changes can be computed. We shall now consider various methods which have been reported. All are still at the research stage, none having yet been taken to the stage of commercial instrumentation.

4.1 The Transmissive Frequency-Modulated Carrier Wave (FMCW) Method for Disturbance Location

The optical FMCW method may be used to locate points where mode coupling in a fiber has occurred, provided that the fiber is capable of supporting two modes having significantly different phase velocities. The frequency of the source is chirped, as with the OFDR method, and the chirped signal is fed into one mode of a two-moded fiber. Any external disturbance, capable of cross-coupling energy from the initially-excited single mode, will produce, on a detector situated at the far end of the fiber, a heterodyne or beat signal. This beat signal is at a frequency equal to the difference between the optical frequencies of the signals incident on the detector. Because of the frequency-ramped nature of the source, the difference frequency detected is proportional to the distance from the source, at which mode coupling to the second mode has taken place. This approach, first suggested by Franks et al. (reference 43), is depicted in figure 22. Their particular implementation used a birefringent fiber, with the transmitted signal being launched into only one of the two principal polarization modes. The disturbance to be monitored was a transverse pressure applied to the fiber, which caused coupling of part of the propagating energy into the orthogonal polarisation mode.

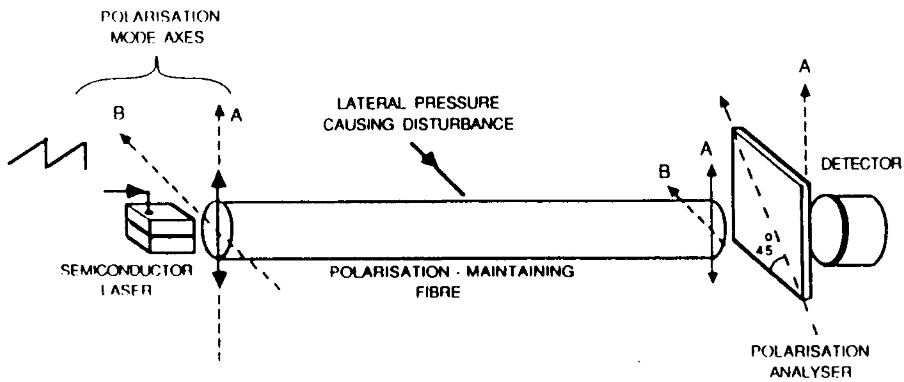


Figure 22 Transmission FMCW distrubance location sensor (reference 43)

A convenient attribute of the technique is that the relatively close velocity matching between the polarization modes, even in so called high birefringence fiber, allows the FMCW technique to be used over lengths far in excess of the coherence length of the source. Two potential difficulties exist with the approach, however. Firstly, mechanical strains of certain critical magnitudes may cause coupling of power from one polarization mode to the other, and then completely back again, resulting in no net energy transfer, and hence no beat signal. Secondly, disturbances causing strain in a direction aligned exactly with either of the polarisation axes of the fiber will cause no mode coupling. Otherwise, except for these somewhat unlikely conditions, the technique appears to a simple and elegant method of locating the position of disturbances on a continuous fiber. Attractive applications include the detection and location of sources of noise or vibration, for example for fracture location in materials or for intruder location (figure 7).

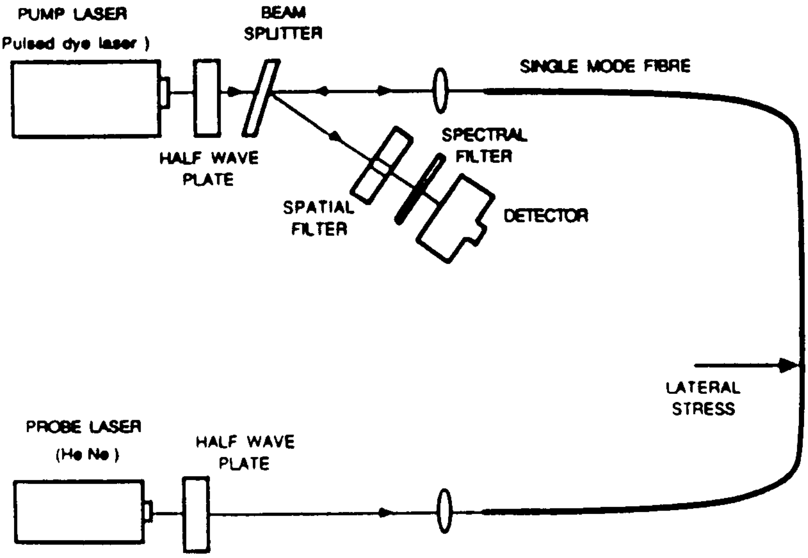


Figure 23 Sensor system with counterpropagating probe and pump-pulse signals, based on Raman amplification (reference 44)

4.2 Distributed Sensing Using an Amplifying Fiber, with Counter propagating Probe and Pump-Pulse signals

If an optical signal from a steady CW source is transmitted through a fiber to a detection system, the power level received will be dependent on the total attenuation in the fiber. If the fiber is capable of amplification, the results can be more interesting. For example, if an intense optical pulse is transmitted in the optical fiber, in the opposite direction to the CW signal, the detected signal will be affected by any nonlinear gain processes which may be created by the effects of the pump.

The first example of such a system was reported by Farries and Rogers (reference 44). This monomode fiber system used a reverse-travelling pulse from a Nd:YAG-pumped dye laser at 617 nm to provide Raman gain in a fiber. The gain was monitored using a continuous 633 nm forward-travelling signal from a helium-neon laser source. The Raman gain is strongly sensitive to the relative polarization of pump and probe signals. The arrangement of figure 23, in a fiber of low intrinsic birefringence, is capable of detection and location of lateral stresses, as these cause polarisation mode conversion, which modifies the Raman gain.

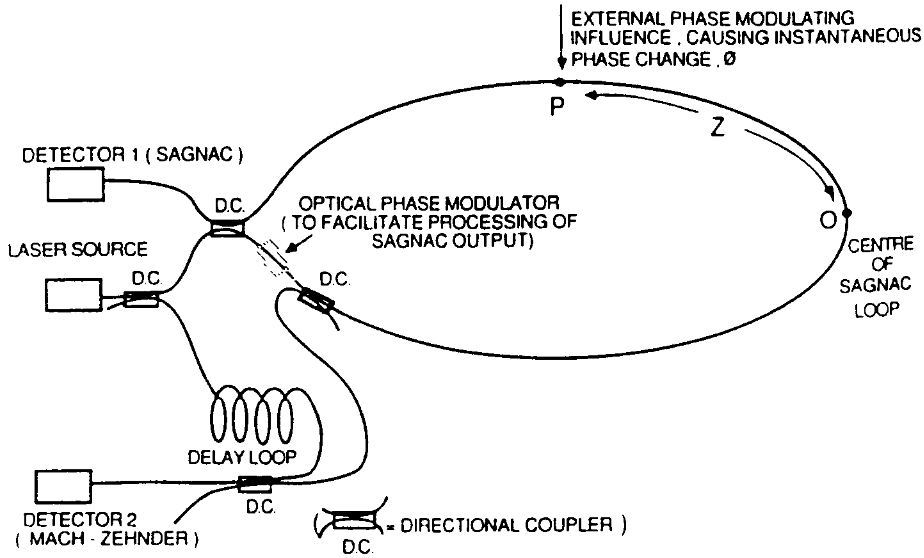


Figure 24 Modified Sagnac interferometer with Mach-Zehnder reference interferometer for disturbance location (reference 46)

The technique has considerable academic interest, as it was the first of a new class of sensors. However, it suffered from a number of practical disadvantages because it uses inconvenient optical sources, and is likely to be critically dependent on the pump power level of the dye laser source and to suffer from undesired polarization drift under the influence of normal environmental conditions on other sections of the fiber.

4.3 Disturbance Location using Sagnac Interferometers

The fiber optic Sagnac interferometer consists, in its simplest (See footnote) form, of a monomode fiber loop and a directional coupler. The arrangement allows the launching of counter-propagating beams into the loop, from a single source, and the detection of the superimposed waves returning to a detector via an exit port of the same coupler (figure 24). Such arrangements have been studied extensively for use in optical fiber gyroscope systems, although additional components are usually inserted to produce a reciprocal configuration.

A major source of phase error in optical gyroscopes (reference 45) may occur if rapid changes in optical path length, due to thermal or mechanical effects on the fibers, are allowed to occur at the position, P, away from the geometrical center, O, of the fiber length used to produce the coil. The reason for the error is that the two counter-propagating beams encounter the varying path length changes at different moments in time, and therefore will suffer different phase changes. The difference in phase change is proportional to the product of two factors; firstly the rate of change, $d\phi$ / dt of the optical signal induced at the point, P, by the external influence and, secondly, the distance, z, between the point, P, and the coil center, O.[†]

Although the effect is a drawback for gyroscopes, the method has been researched as a means of locating disturbance in a fiber (reference 46). In the first instance, in order to prove the concept, thermal changes were chosen as a suitable time-varying influence, although location of mechanical disturbance will probably have more potential applications. In order to calculate the distance, z, from the imbalance in the Sagnac interferometer (which, as has already been described, is proportional to the product of z and $d\phi/dt$), the method requires a knowledge of the rate of change, $d\phi/dt$, induced by the influence. This quantity cannot be readily measured using only the Sagnac loop. However, an additional Mach-Zehnder interferometer may be introduced, by adding an additional fixed-delay fiber link from the source and combining the output of this with a signal extracted from one of the counter-propagating beams in the Sagnac loop (figure 24). The output from the Mach-Zehnder interferometer gives an output proportional to change, ϕ, and differentiation of this phase output (conveniently performed in these measurements by a frequency-counting system, which monitors the number of interference fringes passed through per second at the detector) yields the required rate of change, $d\phi/dt$. Simple division of the Sagnac phase offset by $d\phi/dt$ finally gives the desired distance, Z, of the point of disturbance, P, from the center point, O. Experimental results for location of the thermal disturbance are shown in figure 25.

With a suitable nonreciprocal Sagnac configuration, and accurate interferometric processing, the technique shows promise for accurate location of quite modest disturbance levels. The location capability of such a system has been analysed in reference 47. More recent theoretical proposals have been made by Udd, to improve the configuration of the Sagnac disturbance-sensing system (reference 48). These modifications enable are intended to allow the sensor to be used with broader band sources and reduce the effects of back-reflected light to the source.

[†] For accurate low-drift operation of gyroscopes, reciprocity of counter-propagating beams is necessary. To ensure this, an addition single polarization mode filter is necessary, along with additional coupler to permit its inclusion into the system (reference). The sensor experiments described here would also benefit from such an arrangement, although the preliminary reported results were, for convenience, carried out with the simpler Sagnac loop.

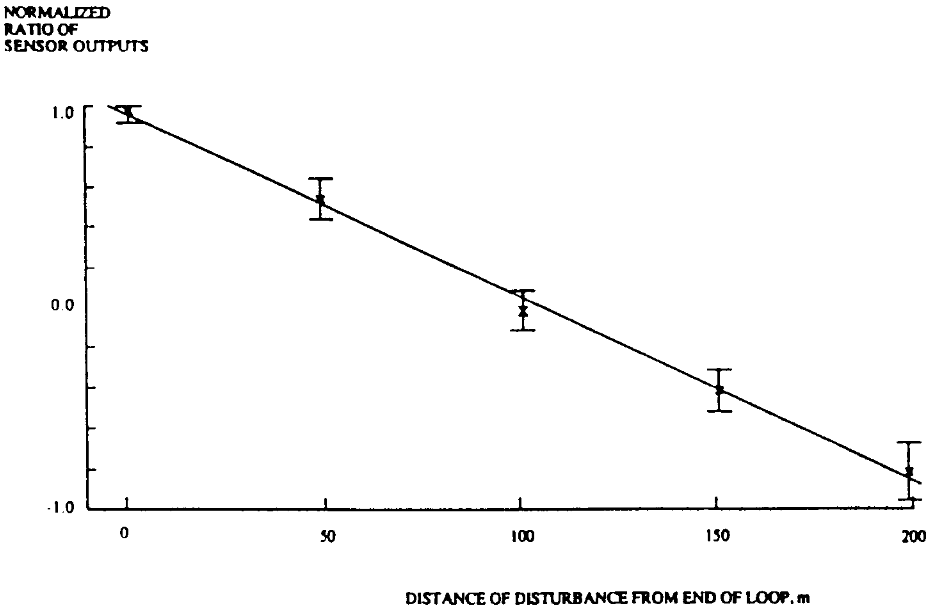


Figure 25 Response of Sagnac location system to thermal disturbances located at different points in the Sagnac loop

4.4 Transmissive Location Systems using White Light Interferometry

A recent method of location of disturbance in a two-moded fiber is based on white light interferometry (reference 49). If a broadband source, such as an LED, is directed along two independent monomode paths and then recombined, interference fringes can only be observed when the paths are almost equal. For path differences much greater than the coherence length of the source, the superposition of multiple, differently-phased, fringes, from each individual frequency component of the broadband source, will lead to a total loss of visible interference. For a typical LED, the coherence length is of the order of only 30 μm, so quite small intervals in optical path length can be resolved.

A two-moded fiber having significantly different mode velocities does not have to be very long in order to generate path differences which are sufficient to prevent visible interference fringes from a broadband light source, when the mode outputs are combined at the end of the fiber. For a high-birefringence fiber with 2 mm beat length, a length greater than 100 mm will suffice to lose coherence. However, if a separate twin-path interferometer is placed at the exit end, and the optical path length differences is matched to that in the fiber, then two equal length interfering paths to the detector can be generated. When the external interferometer brings the system close to equal optical path length conditions, intensity fluctuations can be observed as the path is changed (figure 26; reference 49). If the external interferometer is a free space type, such as a Michelson arrangement, quite small differences in this external path can balance much longer lengths of fiber, as the latter will generally have only a small difference propagation velocity between modes.

To form a disturbance location system, broadband light is launched into only one mode of a high-birefringence fiber. Pressure along the length can couple part of the propagating energy into the other mode. From an observation of the time at which visible fringes are observed, a scanned-path-difference external interferometer can now determine the distance between the in-fiber coupling point and the output end of the fiber.

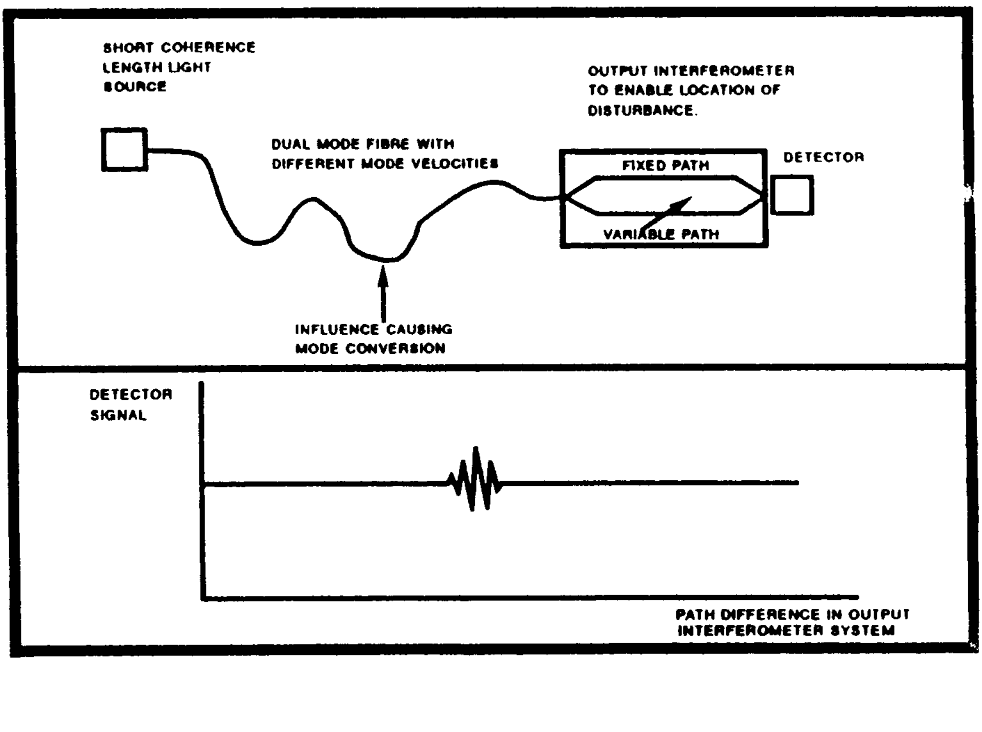


Figure 26 Illustration of white light interferometry for location of disturbance in dual-mode fibres (Kotrotsios and Parriaux 1989)

CONCLUSIONS

The current status of distributed fiber sensors has been reviewed. The field is still one of rapid development, but commercial versions of the distributed temperature sensor, of the type first reported in reference 24, are now becoming available from several industrial sources. It is likely that practical systems will eventually be developed to cover other important application areas, such as the distributed measurement of mechanical strain, chemical concentration, electrical and magnetic fields. There is still a considerable challenge in the technology and many areas where new innovations are required.

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