MULTIPLEXED AND DISTRIBUTED OPTICAL FIBRE SENSORS

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1. INTRODUCTION

The viability and economy of optical fibre sensors is greatly improved by multiplexing, the method by which many individual passive heads can be interrogated by a common opto-electronics terminal. For space applications, multiplexing offers the added attraction of greatly reduced weight, as the fibre cable network and passive sensor units will generally be much lighter than their electrical counterparts and there is no need for heavy electromagnetic screening materials. The ultimate form of multiplexing, and the maximum weightsaving is achieved when the sensor consists of a single length of fibre cable and where the terminal unit can monitor and resolve the variation of a physical parameter, as a continuous function along the length of the fibre. Such a sensor is called a distributed sensing system.

A fuller description of multiplexing and distributed fibre sensing methods has been given in a general textbook[1] on optical fibre sensors. In addition, a collection of more specific published papers is available in a recent text[2]. This paper will therefore simply outline the basic concepts, then concentrate on a number of methods which show promise for space applications. Finally, it will point the way in which new systems may provide attractive possibilities for future space systems. The lecture presentation will include many other case studies not covered in this short written text. The operating principles of many of these are, however, described in more detail in the references.

In the following discussions, we shall initially assume that the optical sensor is a simple amplitude modulation device, incorporated in a fibre path, although most sensors tend to be a little more complex in practice.

2. SUMMARY OF BASIC CONCEPTS OF MULTIPLEXED SENSORS

The simplest means of multiplexing of sensors is to drive a network of many such passive sensing elements from a common source and to use a separate detector for each [see fig 1 (a)]. Alternatively, separate sources (usually with appropriate modulation to ease separation of signals) may be used to drive each sensor and the output leads can then be combined on a single detector. The post detector processor then separates out the individual sensor responses by decoding of their modulation characteristics.

The next step in complexity of multiplexing is to use an optical switch, to enable an active terminal to address each sensor in an appropriate time sequence. This is appropriate if one has a suitably-fast switch, or if the system can tolerate occasional updating of the knowledge of the state of each sensor [fig 1 (b)].

The multiplexing gain is generally greatest when a common fibre lead (or two separate leads, one for each direction) is used to carry signals to and from arrays of sensors. However, there is then a need to increase the

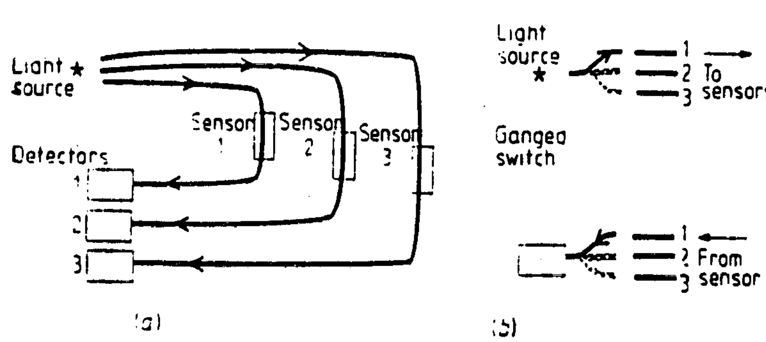

Figure 1. Spatial multiplexing using separate fibre paths:- (a) shows a basic arrangement, and (b) a switched arrangement.

Proc. Internat. Symp. 'Advanced materials for lightweight structures', ESTEC, Noordwijk, The Netherlands, 25-27 March 1992 (ESA SP-336, October 1992)

sophistication of processing, in order to derive the response of individual sensors, free of crosstalk from undesired channels. This problem is analogous to the one met in the optical communications field, so it is therefore no coincidence that similar solutions have been used to provide for sensor multiplexing. The main approaches are time-division multiplexing, optical-frequency division multiplexing (usually called wavelength division multiplexing, or WDM, in order to distinguish it from electrical frequency division multiplexing), frequency division multiplexing of sub-carrier signals (i.e. modulation envelopes imposed on the optical signal) and optical coherence multiplexing.

Time division multiplexing is generally achieved by using different lengths of fibre to connect to each sensor and using a time-varying modulation signal to drive the source (e.g. pulse or coded digital signal). Then the different propagation-time delays permit simple separation of signals (fig 2). As can be seen, the system can operate in either transmissive or reflective mode. The use of pseudo-random coding, rather than a simple pulse, allows greater average power to be transmitted from the source for a given peak output power limit, yet still permits unique separation of signals, provided a suitable (orthogonal) code is used for the source modulation waveform.

The most common instrument used with optical fibre technology is the optical-time-domain reflectometer (OTDR), which is a radar-type optical system (or to be more exact, a LIDAR system). In this system, a pulsed (or pseudo-randomly-modulated) light source is launched into the fibre, and the back-scattered signal is monitored as a function of time (see fig 3). As the time is proportional to the distance travelled by the light, to and from the scattering point, the location of reflective points

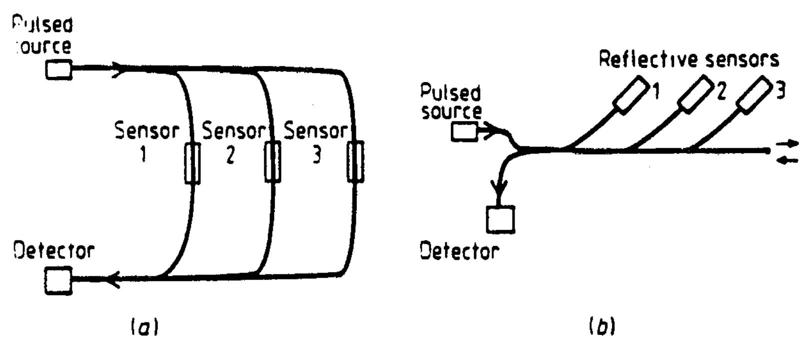

Figure 2. Time division multiplexing of sensor:- (a) shows a transmissive arrangement, and (b) a reflective arrangement.

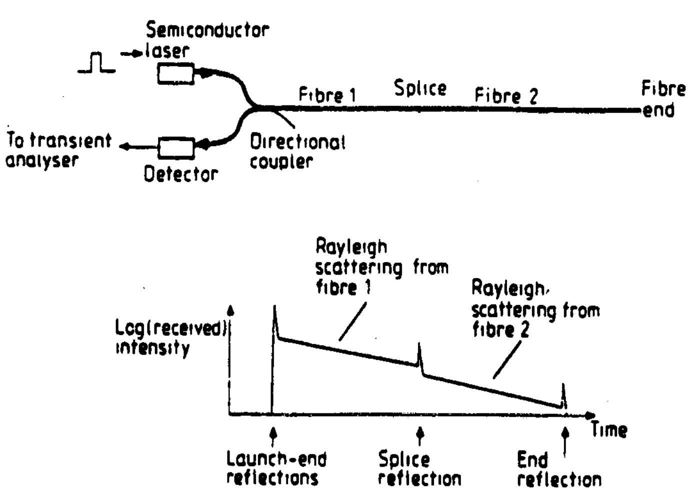

Figure 3. Basic concept of OTDR:- (a) optical arrangement and (b) OTDR returns.

can be determined. Variations in the level of scattering, or in the level of reflection or attenuation in the fibre, can all be monitored by the OTDR.

is broken as a result of severe deformation of a material component. This can be a sensor for detection of impact damage, for example by micrometeorites or space debris,

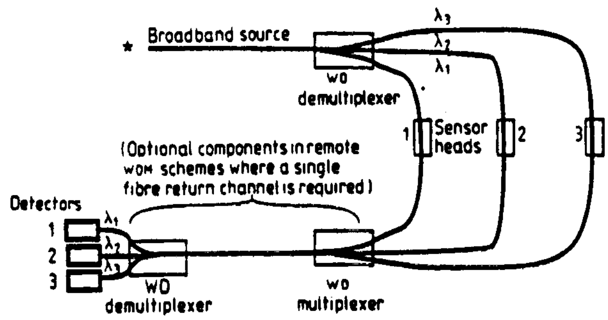

Figure 4. Schematic diagram of a wavelength division multiplexed arrangement for interrogation of the state of three amplitude-modulation sensor heads.

Wavelength-division multiplexing of sensors [fig 4] can be achieved using a broadband source (or combination of several sources of different wavelengths) and splitting its (their) power into several narrow spectral bands, using a network of wavelength-selective couplers. Thus, each sensor is interrogated by light in a particular wavelength band, such light being guided via a specific route determined by its wavelength and the chosen configuration of the wavelength-selective couplers.

or may be a device to monitor excessive strain in structural members. The latter may, for example, arise during the high prevailing acceleration and high levels of vibration during launching.

Proximity of a fibre to an impact site is likely to result in fibre fracture and total loss of light. Also, a fibre attached to a structure subject to excessive strain or microfracture can, in turn, become fractured, particularly

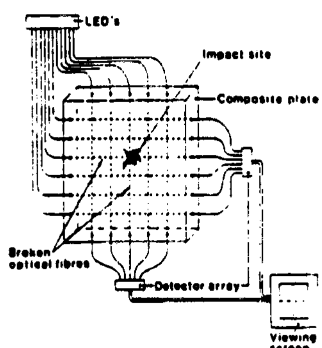

Figure 5. Schematic diagram of an optical fibre system showing the location of impact damage in a composite structure. (Drawing reproduced, with thanks, from Ref 1, chapter by A J A Bruinsma and T M J Jongeling)

There are several other methods of multiplexing other than those discussed above (see refs 1 & 2). However, in common with communications, the most common and practical means of full multiplexing (i.e. common downlead and return lead for each sensor) is the time division multiplexing method. It is now perhaps appropriate to consider a few possible architectures for sensors for future spacecraft.

3. POSSIBLE APPLICATIONS AND ARCHITECTURES FOR MULTIPLEXED ARRAYS OF INTRINSIC FIBRE OPTIC SENSORS IN SPACECRAFT

3.1 Damage Detection

The simplest form of fibre sensor for space applications is a mechanical damage sensor, where the optical fibre if it is deliberately weakened to improve its sensitivity. (One way of causing such weakening is controlled roughening or etching of its surface). A fibre can detect a fracture anywhere over a large surface area if it is suitably laid on, or embedded into the material to effectively cover the entire section of interest. If the fibre-laying topology were accurately known (for example, if it is laid in a precise spiral), it would, in principle at least, to locate a break using optical time domain reflectometry. However, it would, in practice, be likely to be difficult to locate the breaks sufficiently accurately. A somewhat simpler method, however, is to lay sets of fibres in a "grid-reference" system, enabling simple location, in Cartesian co-ordinates, from the particular incidence of broken fibres in both the "x" and "y" directions (see fig 5).

It is not essential for the surface to be fully ruptured in order to detect the damage. For many materials, such as composites, significant internal damage and strain can occur with very little external sign, so an embedded fibre could still be broken. Alternatively, for deformable surfaces, such as metal skins, the inelastic deformation due to a non-penetrating impact can still cause sufficient localise strain to cause high fibre losses, in a surface-bonded fibre, even if insufficient to cause breakage. Such detection of non-visible damage can be extremely important, as the materials may have been critically weakened in a way which would otherwise not be easily detectable by normal observation.

Apart from direct mechanical damage due to meteorites, or simple overstressing, there are many more subtle means by which damage can occur in a space environment. For many of these, a combination of several factors can lead to failure of materials. Examples of individual factors are the following:-

(i) Photon-induced damage due to the exposure to the full electromagnetic spectrum of the sun.
(ii) Exposure to highly-aggressive atomic oxygen (low altitude geo-synchronous operation).
(iii) Extreme level of thermal cycling.
(iv) Corrosion and biological attack during pre-launch storage.

Many of these factors cannot easily be tested on Earth and many are more serious for modern composite materials, which can offer significant strength/weight ratio improvements compared to traditional metallic materials. It is clear that combination of the above factors can combine with mechanical strain to cause localised damage that may be detected with fibre sensors.

A sensing network of fibres such as described above, can, of course, be addressed using a separate light source and detector for each fibre. However, a multiplexing system could address the sensors when connected in the x-y array shown. The distance resolution requirements of the OTDR (and hence the speed and cost of the opto-electronics) can be greatly alleviated if a fibre delay coil

is placed between each of the sensing fibres in the array.

3.2 Dynamic Strain Monitoring

There has recently been strong research interest in developing multiplexed fibre optic sensors for monitoring mechanical strain in sections of an optical fibre network. Here the desired objective is to monitor strain levels below the critical damage level. Applications include the determination of dynamic strain levels in key mechanical structures and also for monitoring higher frequency vibration levels. There is currently strong interest in structures which are not only equipped with strain monitors, but also in ones also containing miniature mechanical actuators. These may then compensate for undesirable strain via electronically-controlled mechanical feedback. A variety of mechanical actuators (eg hydraulic, pneumatic, electro-mechanical motors, piezo-electric transducer and more exotic methods, such as shape-memory metals) can be used to apply this mechanical feedback, in response to control signals from derived fibre sensors.

The problem of vibrational measurement is rather easier than that of the measurement of slowly-varying or static strain. This is because a measurement of fast-changing vibrational strain can be more easily performed by interferometric means and there is no need to determine the absolute fringe-order, as would be the case for a static measurement. In addition, the fast changes in the optical length of the fibre which result from vibration can easily be separated from slow changes which usually arise from temperature fluctuation.

The first experimentally demonstrated array of sensors for vibrational strain monitoring was for underwater acoustic sensing (ie sonar) in a marine environment (reference 3). Since that early paper there has been considerable development, again primarily for sonar applications, and the US navy have recently sea-tested a fibre hydrophone array (Introduction to proceedings of OFS '92, Monterey). Few modifications of the basic technology are necessary in order to sense structural strain, except for configuring the fibre sensor in a manner suitable for bonding to structural components. It will be necessary to redesign such a system, in order to adapt it for use with short fibre sections, but of course it will be possible to reduce the sensitivity requirements, as the extreme sensitivity typically necessary for hydrophones will no longer be required. However, significant re-engineering will be necessary to produce space-worthy systems.

3.3 Static Strain Measurement

For static strain monitoring over a short gauge length, the most promising method so far involves the measurement of the peak reflective wavelength of in-fibre diffraction gratings (reference 4). To produce these gratings, spatially-periodic refractive index variations are written into the core of the sensing fibre with ultra-violet-laser light. When strained, the spatial period of the grating is changed and the peak (Bragg-condition) wavelength of the reflected light from the grating increases proportionally. A typical scale factor of 5.4×10^{-5}% per microstrain is observed. In general, however, a temperature measurement will also be necessary to compensate for thermally-induced changes in the refractive index of the fibre core material.

An attractive feature of in-fibre grating sensors is that they are essentially transparent (i.e. lossless) at optical wavelengths well away from the Bragg wavelength (i.e. away from the wavelength where they have strong reflection). Thus, it is possible to incorporate a large number of sensors in a single length of fibre, each having a different spatial period, and hence having a different wavelength of peak reflection (see fig 6). These can be interrogated by illuminating with a broadband source and examining the reflected light spectrum, in order to determine the peak wavelength

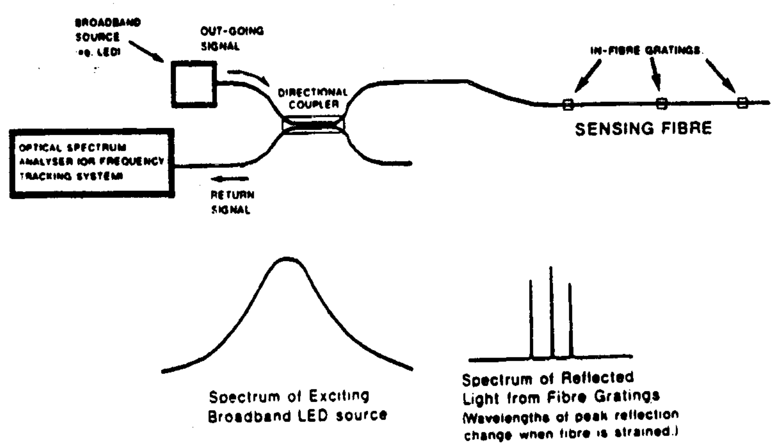

Figure 6. Schematic of a fibre network for sensing of strain by analysis of the spectrum reflected from in-fibre gratings.

corresponding to each sensor. An alternative means of multiplexing such an array of grating sensors is to sweep the wavelength of a tunable laser source and to monitor the intensity of the reflected signal from each sensor element in turn, as the laser wavelength corresponds to the peak reflection of the grating in question.

3.4 Pressure Measurement

The measurement of pressure is essentially the same problem as that of measuring strain in the fibre. It is only sufficient to ensure that the pressure causes an optical path length change in the fibre. For static measurement of very high pressures (many tens of bar) the grating sensors described above should be suitable.

However, as with the strain sensor, temperature measurement or compensation is generally necessary to prevent errors. In the case of lower pressures, it becomes increasingly difficult to determine the much smaller wavelength shifts and to distinguish such small changes from any possible thermally-induced ones. In order, therefore, to make viable intrinsic fibre pressure sensors using gratings sensors it will probably be necessary to arrange suitable mechanical amplifiers to convert the pressure changes and produce more significant displacement/strain effects in the fibre sensor elements. There is, of course, considerable scope here to borrow technology from that used in traditional moving-pointer instruments, such as mechanical barometers, Bourdon gauges, etc., although no engineered versions have yet been described.

3.5 Temperature Measurement

Multiplexed intrinsic temperature measurements can also be performed using grating sensors. In this case, it is necessary to ensure the grating is protected from the effects of strain, and therefore the grating elements must be encapsulated in such a way that external mechanical forces on the fibre are minimised in the regions containing the gratings. Typical scale factors for the temperature sensitivity of gratings are 0.0007% per °C. (Typically 0.006nm/°C at 850nm)

4. Extrinsic Multiplexed Sensors

The possibilities for multiplexing extrinsic fibre sensors are far more diverse, as there are many forms of external optical sensor for physical and chemical sensing, most of which can, in principle, be multiplexed over optical fibre networks (ref 1). There are also many forms of passive fibre network and means of multiplexing (e.g. time-division, wavelength division) (ref 1, chapter 14). Thus the combinations of all possible systems and configurations is far too numerous to list in full here. However, it may be appropriate to describe two simple, yet interesting, possibilities for spacecraft, both based on the collection of light by the sensing fibre.

One possible application is for monitoring the combustion process in rocket motors, by measuring the optical emission. A network of sensors, multiplexed via a commutating fibre switch, if necessary, could check the presence and quality of ignition in such motors, provided the fibre end in the sensor head is suitably protected to withstand the direct heat of the exhaust or suitably located to avoid direct heating. A rather similar application would be to detect solar radiation levels incident from different directions, as determined by the location of optical fibre receiving heads, each multiplexed into a common detector system. The spectrum received at the detectors will, of course, be restricted by the transmission of the fibre.

5. Basic Concepts of Distributed Sensing Systems

As mentioned in the introduction, distributed fibre sensors are ones in which a parameter can be measured as a continuous function of length along an optical fibre. Simple types merely provide an indication of the average value of the parameter along the length, but the term is usually reserved for types which are capable of measuring the variations in the parameter along the fibre length. Except for the well-known optical time domain reflectometer for fibre fault finding (ref 5), distributed sensing systems represent a relatively recent state of the art. There are two basic forms of distributed fibre sensor, firstly types based on the OTDR concept, where backscattered light from a modulated (usually pulsed) source is monitored as a function of time and, secondly, types based on forward light propagation.

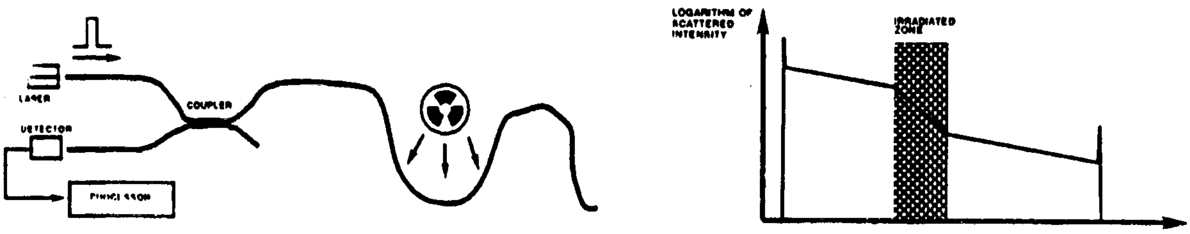

Figure 7. Concept of the distributed radiation dosimeter.

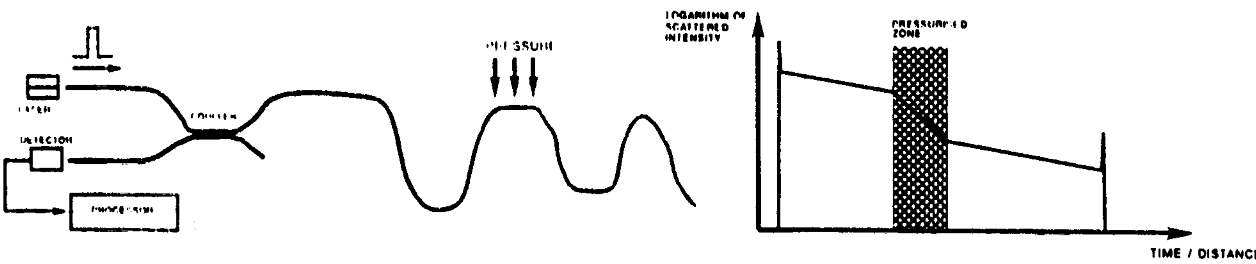

Figure 8. Concept of distributed sensing using a pressure-sensitive cable.

Even the basic OTDR gives considerable scope for distributed sensing and it has the advantage that the instrument is readily available from a number of commercial sources. The OTDR can detect changes in the backscattered light from along the length of a fibre as a function of distance, and can therefore detect parameters which change this. However, the degree of scattering from the core of a glass fibre is relatively independent of temperature and pressure, and hence the instrument is better equipped to monitor parameters which change the attenuation characteristics of the fibre.

The standard form of OTDR return from a continuous fibre is an exponentially-decaying function of scattering versus time, due to a constant attenuation coefficient. If a parameter changes the attenuation, then the effects of this are seen in changes in the slope of the time response. There are three useful effects which can be measured in this way, attenuation caused by either: ionising radiation (see fig 7 and ref 6); microbending of the fibre due to perturbation from its cylindrical form, as a result of uneven lateral pressure (see fig 8 and ref 7); or chemical interaction with a lossy fibre cladding containing indicator dye, (see fig 9 and ref 8). All of these could, in principle, have application in spacecraft. However, there is a particularly attractive fourth option

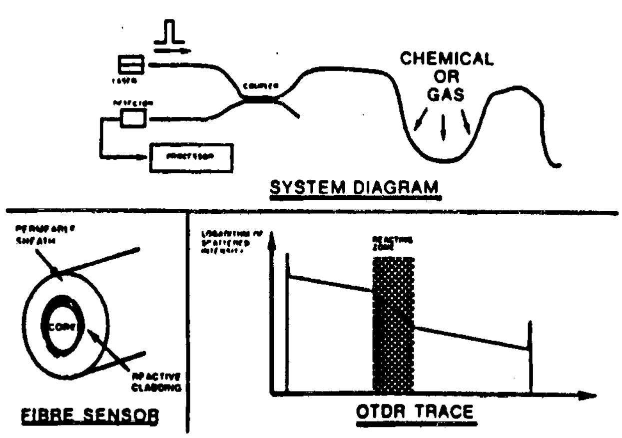

Figure 9. Concept of the distributed chemical sensor.

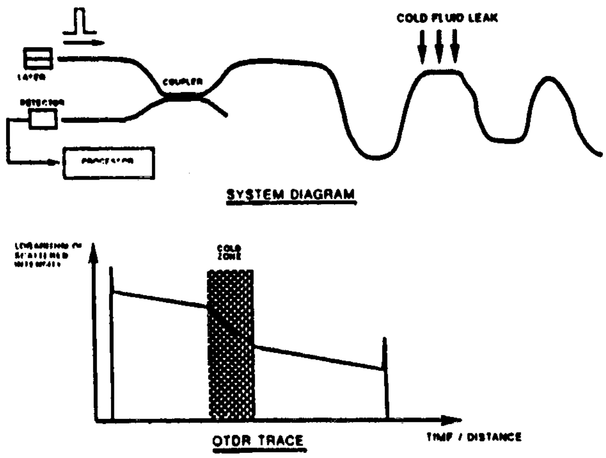

Figure 10. Concept of distributed sensing of cold-spots, using silicone-clad fibre sensor.

(see fig 10 and ref 9) which could have particular attractions in space vehicles. If a plastic clad fibre using a silicone cladding material is cooled, the refractive index of the silicone increases, leading to higher losses as a result of weaker guidance of light. Thus the fibre cable can form a sensor for the detection of cryogenic fluids or for detection of overcooling from other causes. This could be used to detect leakage of liquid cryogenic propellants or loss of heat from spacecraft if thermal insulation fails.

A modification to the standard OTDR is one in which the weak Raman component of the scattered light from the fibre is monitored instead of the more normal Rayleigh component (ref 10). The Raman component is strongly dependent on the temperature of the fibre, and the response can be normalised by comparison of the Stokes and anti-Stokes components. Although the method sounds rather complicated, the optics is relatively straightforward (see fig 10) and a number of commercial types are now available. Currently, these are capable of monitoring temperature to an accuracy of 1°C or less, and resolving several thousand points along the length of a few km of fibre (ref 11). The resolution is typically 1 metre, although the effective resolution can be enhanced by coiling the fibre in a spiral or "flattened spiral" form.

Research on distributed sensors is being continued in several areas. The main objectives are to enhance the resolution of existing types of sensor and to develop new types. One particularly attractive type would be one capable of resolving mechanical strain, in a truly distributed manner, along the length of a fibre. So far, the location of pressure points along a fibre has been measured by a number of methods, but no really successful quantitative sensor for distributed pressure or strain has been reported.

A number of new sensors are based on forward light propagation are these are rather complex to describe in this short paper. It is perhaps appropriate, however, to point out their main potential attraction: the optical power available for detection in transmission mode is many orders of magnitude higher than for those types reliant on backscatter. They therefore have the potential for measurement with a greatly improved signal/noise ratio (or, alternatively, they will require less averaging time to perform a given measurement).

CONCLUSION

A short description overview of the state of the art of multiplexed and distributed sensors has been given. The verbal presentation expands on this paper and presents examples of commercially-successful application of the technology. The evolution of well-engineered sensors of this type is still proceeding and there is scope for many future systems. Perhaps the most sought after type is a reliable strain sensing system, as this will be an excellent tool for structural monitoring in a wide range of applications.

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