Fiber-Optic Sensing: A Historical Perspective

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Invited Paper

***Abstract*—Sensing via fiber optics has occupied R&D groups for over 40 years, and some important transitions into the commercial sector have been achieved. We look at the fundamental concepts involved in the various sensing approaches, and the differentiators which have led to commercial impact. We also look to the future of fiber-optic sensors.**

***Index Terms*—Distributed sensors, fiber-optic sensors, gyroscopes, hydrophones, sensor applications, sensor components, sensor markets.**

I. Introduction

It is now over 40 years since the thought that optical fibers could be a useful approach to sensing and measurement first emerged. The Fotonic sensor patented in the mid 1960s (U.S. 03327584 granted June 27, 1967) was based on bifurcated fiber bundles with half the bundle used to illuminate a surface and the reflection from this surface received by the other half of the bundle. After suitable calibration, the received signal can give a very precise indication of the relative position of the end and the reflecting surface. The Fotonic sensor continues to be available offering "unmatched performance in noncontact vibration measurement."

A decade later, the first single mode optical fibers appeared and with this the thought that these fibers could be built into interferometers which promised immense engineering benefits compared to their free space precursors bolted on optical tables. Of course, the principal stimulus for the optical fiber technology was something else, namely communications. On the one hand, fiber sensors rely on communication technology to provide a basic component set and also to facilitate specialist technologies through which slightly different versions of optical fibers can be fabricated purely for the sensing community. Fiber amplifiers, semiconductor sources and detectors, fiber components such as couplers, splitters, wavelength multiplexors, and a host of other photonic devices, not to mention handling and test procedures, could not have been realized without the communication stimulus. However, sensing is a curious industry: It is highly fragmented with dozens and dozens of small market sectors each with their own unique requirements. It is also extremely conservative, reluctant to adopt a new technology and even reluctant to measure at all other than when necessary.

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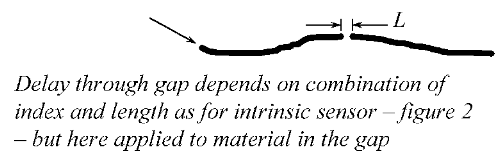

Fig. 1. Extrinsic sensor schematic, illustrated here to measure the optical delay over the gap, but the basic format can be modified to measure any measurand which will affect the optical parameters of the material in the gap.

In this paper, we shall initially briefly explore the basic principles for fiber sensors. We will then continue to look at some examples with particular emphasis on the application context. The commercial and applications environment is highly idiosyncratic, so we shall also spend some time examining the interaction between this environment and the research and development process. We shall attempt to look into the future—where might the technology go?

Our story is far from complete, so we have also provided extensive bibliographic notes organized under topic subheadings to enable the reader to dig further into the subject.

II. Basic Principles

There are numerous realizations of fiber-optic sensors but all sit within two broad categories. For some sensors, the fiber simply guides the light to a sensing region where the optical signal emerges into another medium within which it is modulated. The light is then collected by the same or a different fiber after it has been modulated by the parameter of interest and returned to a remote location for processing. The Fotonic concept is one example of this family known as *extrinsic* sensors (Fig. 1). In contrast, *intrinsic* sensors keep the light within the fiber at all times so that the external parameter of interest modulates the light as it propagates along the fiber. This has the obvious benefit that the numerous interfaces between the fiber and the modulation zone are removed. It also has the obvious restriction that only interactions which influence the light propagating within the fiber can be monitored (Fig. 2). These interactions can include optical delay or optical birefringence (differential delay), optical loss, and the spectral properties thereof. Both types have made some inroads into the commercial application with extrinsic sensors being predominantly targeted at chemical and biomedical measurements and intrinsic sensors focused primarily on physical measurements.

The early work in fiber sensing concentrated on measuring the physical world at a particular point. However, the realization slowly emerged that if it is possible to influence the transmission properties of an optical fiber through external parameter fields then it may also be possible to measure this parameter field as a

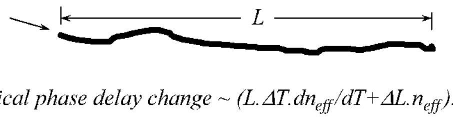

Fig. 2. Intrinsic sensor—also illustrated to measure the length of the fiber through optical delay—comprising both physical length and thermal components. The intrinsic format may also be adapted to measure other parameters.

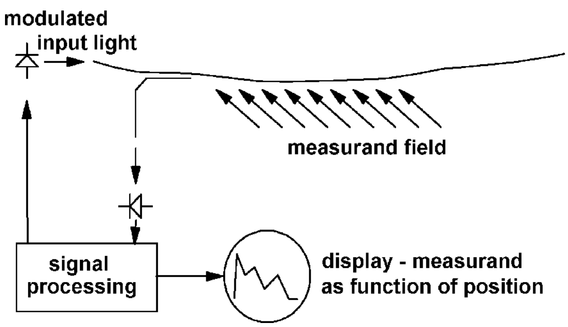

Fig. 3. Distributed sensing—a technique unique to fiber-optic sensors.

function of position along the fiber. These so-called *distributed* measurements (Fig. 3) have emerged as an extremely important differentiator of fiber sensor technology. Indeed, the technical ability to make distributed measurements over distances up to several tens of kilometers is unique to fiber optics. Effective gauge lengths of the order of one meter are common, and there are some which go to even shorter discrimination lengths. This unique capability opened an entirely novel range of application possibilities just a few of which we shall explore later.

Communication technology has realized low-loss fibers and fiber amplifiers which are capable of transmitting modulated optical signals over very long distances with the added benefit of immunity to electrical pick up and the use of an entirely nonmetallic and, therefore, largely corrosion free transmission medium. Distributed measurements also obviously exploit this but our point sensors can be built into networks (Fig. 4) through which our measureand may be sampled at point sensors over very wide areas of ten or more kilometers in dimension. These systems obviate the need for remote electrical power supplies, eliminate consideration of ground loops, pick up and other troublesome electrical sources of interference and offer a host of other advantages which are immediately beneficial in for example hazardous environments or regions of significant electromagnetic interference.

III. Principal Contributor Technologies

There are many, and here we shall briefly look at the approaches to fiber sensing which we feel have made the largest contributions to the development of the subject. All the systems which we shall describe here have emerged into one or more commercial applications.

A. Dual Path Interferometers

Dual path fiber interferometers were the first intrinsic sensor configuration to receive serious research and development attention. The optical fiber directional coupler replaced the beam splitter to realize a convenient and rugged sensing interferometer system. The principal dual path configurations are shown in Fig. 5.

Dual path interferometers effectively measure changes in differential delay between a reference and a signal arm in the interferometer. The sensitivity to changes in this delay can be remarkably high, within the case of gyroscope (see below) better than 10^{-7} radians being relatively straightforward to detect in a 1-Hz bandwidth with optical powers around or even less than 1 mW. This remarkable sensitivity stems from the inherently balanced nature of the interferometer. Even with less "perfect" configurations such as the Mach Zehnder or Michelson, sensitivities in the region of 1 microradian can be relatively easily achieved with careful engineering.

Relating these phase changes to variations in the environment around the fiber is a relatively straightforward process. The detailed numbers vary somewhat with fiber type and wavelength of operation but typically phase changes of around 100 radians per meter per °C temperature change, 10 microradians per meter per $\mu\varepsilon$ of longitudinal strain and 10 microradians per meter per bar of pressure change are obtained. Clearly, the sensitivity increases as the interaction length increases so that very small changes in environmental parameters are relatively straightforward to detect.

1) All Fiber Mach–Zehnder Interferometer: The all fiber Mach Zehnder was the subject of a very great deal of early research in fiber sensors, particularly in the context of its use in hydrophones. The reference coil is protected from the acoustic field while a signal coil responds to acoustic pressure variations. The basic configuration offers many benefits compared to more traditional devices frequently based on piezo ceramics for which buoyancy, frequency response, and electromagnetic interference often pose application problems. When configured as multipoint arrays (Fig. 6), fiber hydrophones offer flexible electronic beam forming and passive deployment capabilities, potentially remote from the mother ship.

There have been many research issues which have been addressed along the way to realizing these systems. Arguably, the most fundamental is that of assuring the interferometer is effectively biased in the quadrature position (Fig. 7) and, likewise, that the signal and reference arms are closely balanced in length for the minimization of laser phase to intensity noise conversion effects. Designing the acoustic interface between the light propagating in the fiber and the acoustic field is an art form in its own right. Acoustically designed coatings and/or mandrels, optimized to transfer acoustic pressure fields into strain perturbations along the fiber, are very important in fiber hydrophones and seismometers. Additionally, the shape of the fiber coil and the former upon which it is assembled can have a profound effect on the directional properties of the individual element and, therefore, on the performance of an electronically steered array.

2) All Fiber Michelson Interferometers: The all-fiber Michelson interferometer is clearly a simpler configuration than the Mach Zehnder. However, it must by definition be used in a reflective mode and so is far more vulnerable to reflection induced instabilities in the source and spurious interference phenomena from stray reflectors within the interferometer path.

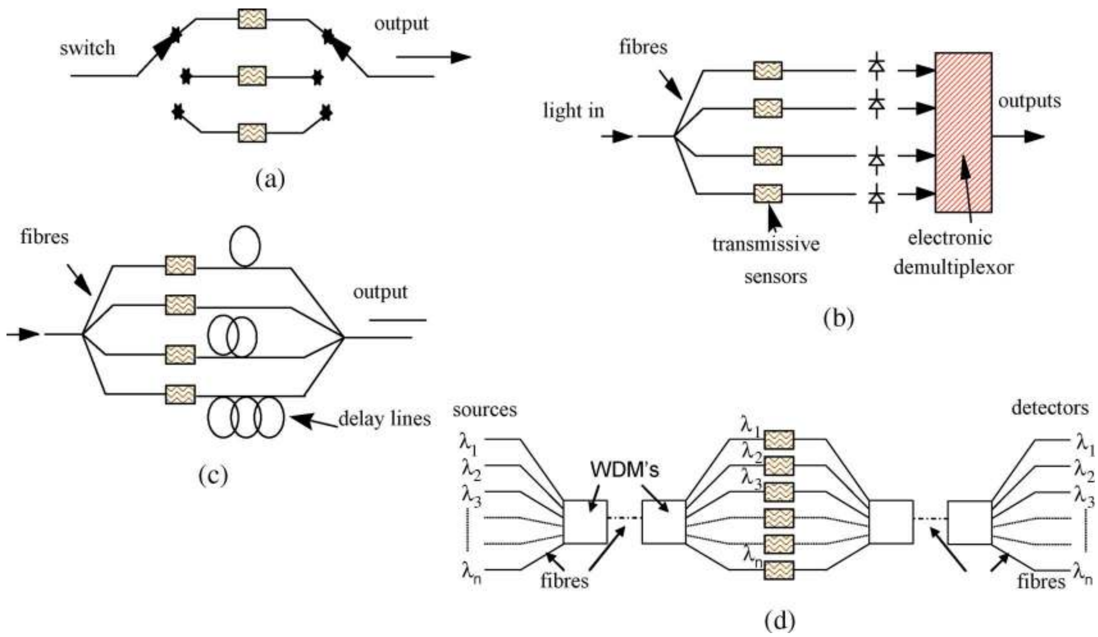

Fig. 4. Examples of fiber-optic passive point sensor networks. (a) Switched multiplex system with single channel optoelectronics; (b) transmissive star system with electronic demultiplexer; (c) fully time multiplexed system; (d) wavelength multiplex system with single point sensor pec channel—can also incorporate arrays in each channel.

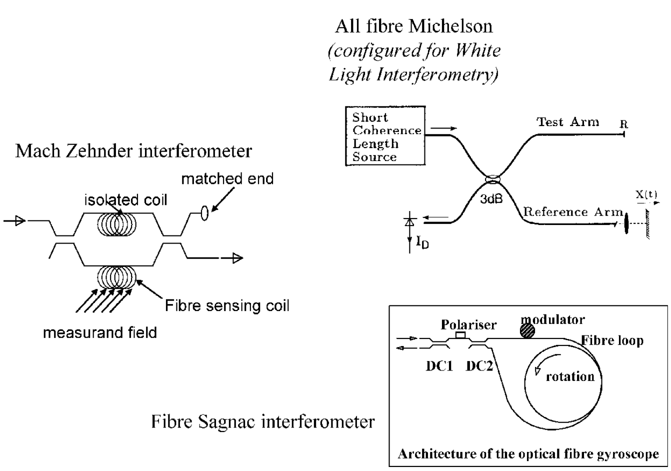

Fig. 5. Dual path interferometer configurations realized in optical fiber.

Of course, if the source is incoherent, then none of these issues cause significant problems and the double Michelson "white light" interferometer shown in Fig. 5 is an example of such a configuration. In this system, the reference is mechanically adjusted to match the signal arm to within a tolerance determined by the source coherence. The repeatability of this matching process can in practice be of the order of one micron so a precise remote measurement system becomes feasible linking the measurement point and the detection system through a single mode fiber carrying the time delay signals from the remote Michelson interferometer. This basic system has found extensive application as a civil engineering extensometer used to monitor the relative movements of two points in a structure as indicated in Fig. 8. The applications have been many from verifying rebuild and construction processes to measuring movements in historical monuments (Fig. 9). There is now extensive experience in the installation and application of these sensors going back well over a decade and establishing confidence in the long term micrometer accuracy and repeatability of the measurement process.

White light all-fiber Michelson interferometers are also at the heart of optical coherence tomography, a techology which is beginning to make significant contributions to medical imaging for example in the eye, in the region just under the skin and in intravenous examinations.

3) Interferometric Multiplexing: Many of the applications for interferometric fiber sensors have focused on the use of arrays of such devices, and this has led to the development of a variety of multiplexing approaches. This is particularly true for interferometric acoustic sensor (hydrophone) arrays.

Multiplexing approaches based on time, frequency, and wavelength-based techniques have been developed and implemented. In many cases, these approaches are analogues of the multiplexing techniques developed for optical fiber communications systems, and consequently can take advantage of many of the fiber-based modulators, frequency shifters, and wavelength combiners and splitters developed for communication in order to implement the sensor system.

Some of the most extensive multiplexing formats have exploited the power of hybrid approaches—e.g., combining time and wavelength division multiplexing. Fig. 10 illustrates a time- and wavelength-division multiplexed array that has been demonstrated as an effective entirely passive interrogation system for over 120 sensors.

4) Sagnac Interferometer: The Sagnac interferometer—the fiber-optic gyroscope—is arguably the most successful to date of fiber sensor technologies. The principle of the Sagnac interferometer has been established for almost a century though its

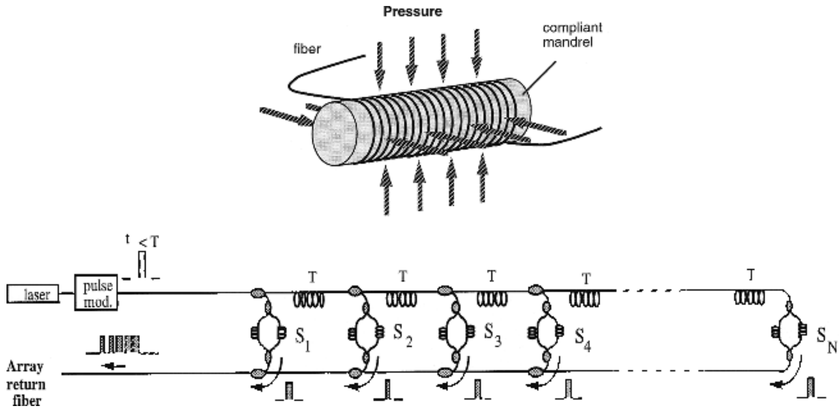

Fig. 6. Hydrophone schematic above and an array based on Mach–Zehnder interferometer sensors.

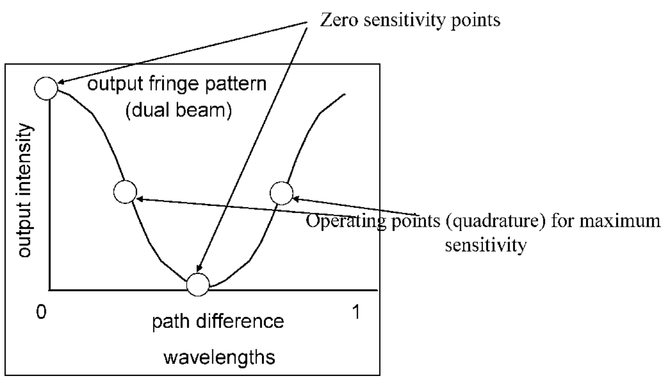

Fig. 7. Quadrature bias on the fringe pattern in dual beam interferometers.

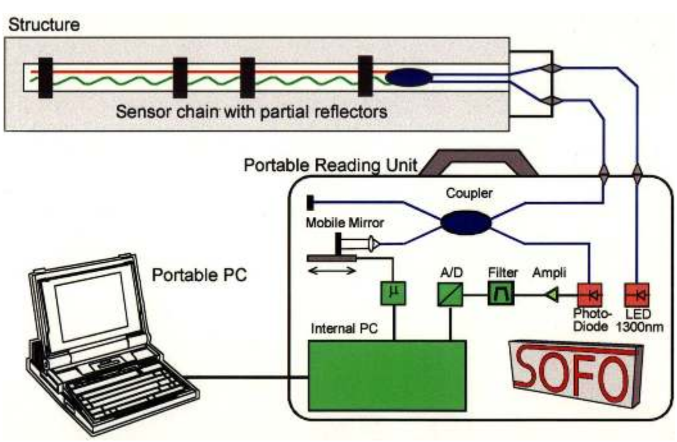

Fig. 8. SOFO (Smartec SA—Switzerland) white light interferometer displacement sensor—conceptual diagram.

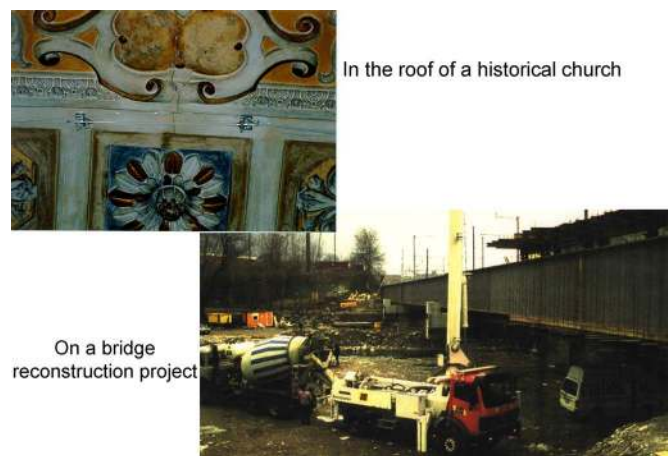

Fig. 9. Some locations on which the SOFO has been used.

fiber implementation first appeared in the mid 1970s. The principle is indicated in Fig. 5. Light is launched in two counter propagating directions around a loop of fiber. If the loop is rotating, the light launched in the direction approaching the directional coupler will arrive at the directional coupler slightly before the light propagating in the opposite direction. These differences in arrival time are directly proportional to the rotation rate and can be conveniently measured as phase differences with great sensitivity and accuracy.

The basic principles of the fiber-optic gyroscope were established by the mid 1980s. Since then, numerous engineering refinements have been implemented, notably in packaging and signal processing to improve performance, for example, over wide temperature ranges, in very high vibration environments and withstanding high-speed thermal shock. The fiber-optic gyroscope has become extremely competitive in the mid-to-high-performance (1 degree per hour and better) gyroscope categories and space qualified systems (Fig. 11) with noise levels of less than 10^{-3} °/h are now commercially available.

Interestingly, the fiber gyroscope relies heavily on specialist optical fibers, predominantly polarization maintaining configurations. These are now produced by a few specialist fiber manufacturers worldwide using a process which—linking into the earlier comments about the optic communications industry—has much in common with that used in standard single mode fibers.

Fiber-optic gyroscopes have become established as essential components in platform stabilizing systems, for example, for large satellite antennas, in missile guidance, in subsea navigation, in aircraft stabilization and navigation, and a host of other applications.

B. Faraday Rotation

Faraday rotation is well known. Light propagating through most transparent solids will see rotation in its plane of polarization dependent upon the value of the magnetic field component

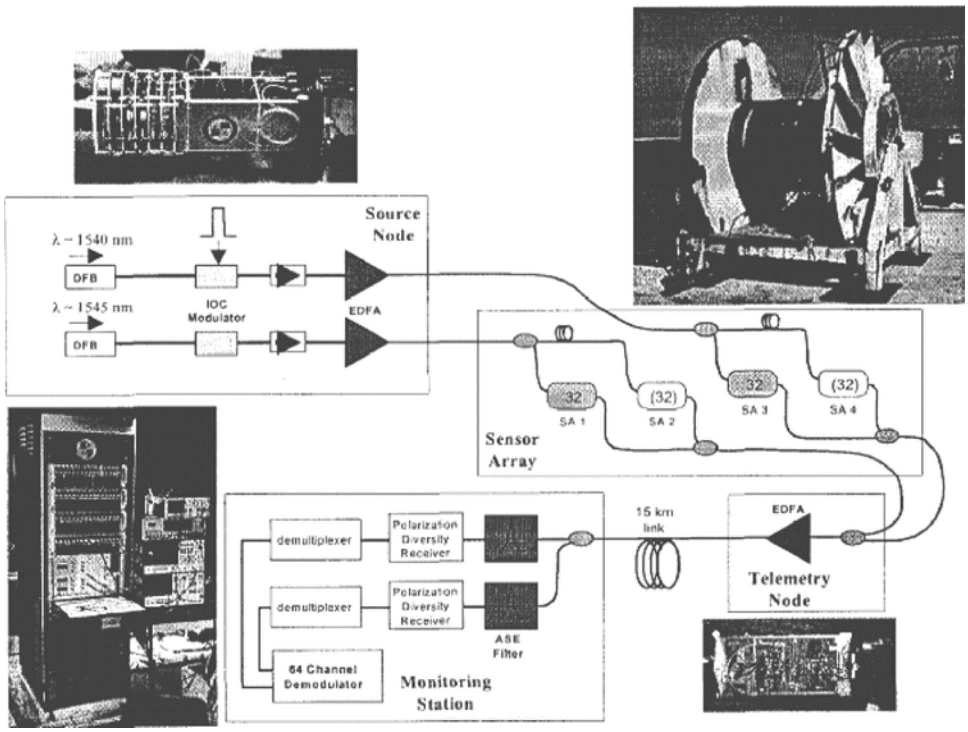

Fig. 10. Optical interferometric array-based on wavelength and time division multiplexing.

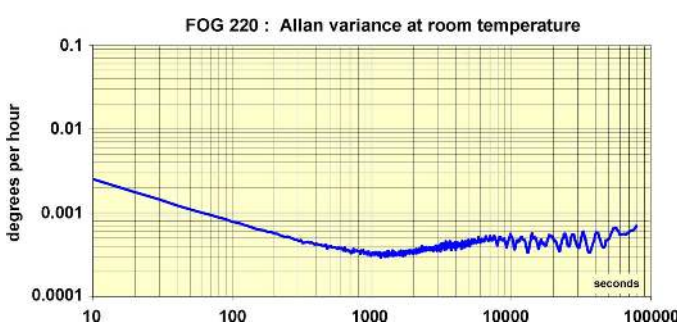

Fig. 11. Space qualified optical fiber gyroscope characteristics with demonstrated 10^{-3} °/h noise level (courtesy of Thierry Giaffe, IxSea).

along the direction of propagation of the light. In single mode optical fibers this forms the basis of a successful current monitoring technology illustrated in Fig. 12. The apparent simplicity of this configuration, as usual, belies the subtlety of implementation. Dealing with spurious birefringence, stabilizing the polarization history of the light to and from the measureand region, coping with temperature fluctuations and vibration fields and packaging for operation in difficult environments are among the major factors to consider. There are several examples of commercial activity in fiber-optic current sensors, most based on polarization rotation. There are also a few examples of the use of Sagnac interferometers configured to detect current induced circular birefringence in the coil. There are also a few separate crystal-based point sensors which have the benefit of being compatible with both voltage (electric field) and current (magnetic field) measurements. Additionally, the use of a separate crystal accesses a much wider range of transducer materials, many with Verdet constants far, far higher than that in silica.

The magnitude of the Faraday rotation depends upon the Verdet constant which is typically in the region of a few micro radians per ampere for silica though this varies somewhat around this value with optical wavelength, temperature and the detailed dopant composition of the material. In other words one meter of optical fiber aligned exactly parallel with a magnetic field of 1 A/m will produce a Faraday rotation along the fiber length of a few micro radians. The typical detection sensitivity of a fiber-optic current sensor is then in the region of a fraction of 1 A/m. This, in turn, is roughly an order of magnitude greater than the Earth's magnetic field. Consequently, for precision measurements, and to allow for headroom for correction for temperature effects, fiber-optic current sensors are typically applied to monitoring electrical power systems carrying currents of the order of 100 A. The principal benefits of fiber-optic systems include complete inherent electrical isolation between the current measuring point and ground and the capability to measure over wide bandwidths, a feature which is especially useful for system fault detection.

C. *Fiber Bragg Grating*

The fiber Bragg grating is very simply a periodic structure printed along the propagation axis of an optical fiber. The printing process usually relies upon photochromic mechanisms to induce permanent index changes. By far, the most common versions of the grating are designed to couple a precisely defined wavelength from an input direction into a reflected beam though some (long period gratings) have a slightly different function. These are designed to couple a (usually) somewhat broader range of wavelengths from a propagating mode into a cladding mode travelling in the same direction. We shall only consider reflection-based Bragg gratings here though there

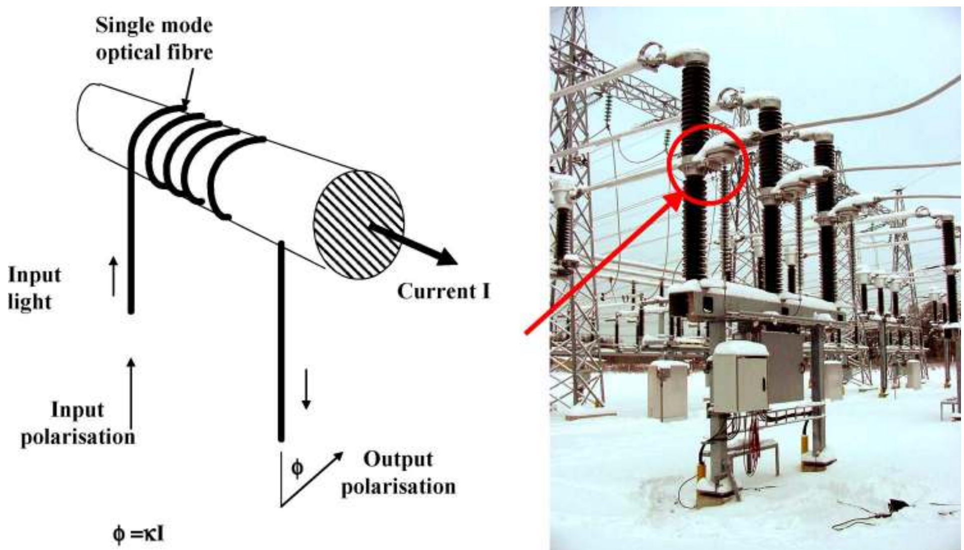

Fig. 12. Basic features of (left) a Faraday rotation optical fiber current monitor and (right) an installation (courtesy of T. Bosselman, Siemens).

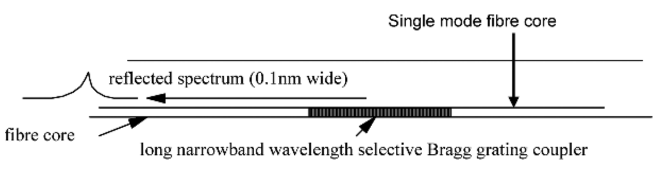

Fig. 13. Fiber Bragg grating—basics.

has been some activity in long period gratings which can be explored elsewhere.

The wavelength which is reflected (Fig. 13) depends on the optical period of the grating which in turn is a function of index and length. Consequently, for a particular fiber, this reflection wavelength is a function of temperature, strain, and, to a lesser extent, pressure. The coefficients involved are those corresponding to changes in optical path length and are typically of the order of 1 ppm/$\mu\varepsilon$ and 10 ppm/°C temperature change. A high-resolution wavelength interrogation and measurement system is consequently necessary. Measuring wavelength changes to around 1 part in 10^6 proves to be a feasible challenge at an economic cost even for very slowly changing measurands. Examining dynamic strains in the regions of kHz and above can be done using fiber Bragg gratings achieving resolutions in the region of 0.1 $\mathrm{n}\varepsilon$. As a mechanical transducer, the fiber Bragg grating is then very competitive with devices available based on other technologies.

Fiber Bragg gratings are most commonly found in strain transducers usually incorporating some form of temperature compensation typically as an uncoupled reference Bragg grating. They can be arranged in large arrays (Fig. 14) with each grating operating at a slightly different wavelength with the differences between these wavelengths determined by the anticipated scan ranges of the various gratings. There have been numerous evaluation systems using Bragg gratings, typically in bridges and composite material panels used in ship or aircraft construction with a few excursions into much more demanding applications such as down-hole monitoring within the oil industry. Typically, the challenges lie in the packaging processes and in ensuring repeatability and long term stability in the wavelength interrogation mechanisms and within the grating itself.

Very large arrays of strain measurement points—to many hundreds—can be facilitated using Bragg gratings enabling unprecedented characterization of an operating structure without the complications of wiring harnesses and local amplifiers typifying electrical strain gauges. Fiber Bragg gratings have been a major stimulus to the concept of the "smart" structure which can in principle be adaptive to its environment and set its own alarm systems. There is though one major challenge—it is relatively straightforward to make the strain measurements but it is far more difficult to work out what to do with the measurement when it has been made. There are also complex criteria determining the optimum location of the sensors within a structure and related to this the threshold levels for corrective action when taken over a full array of measurement points.

Consequently, the fiber Bragg grating has probably generated more papers describing application trials in fiber sensors than any other technology. There have though been relatively few true commercial breakthroughs into operational use. It is the complex mix of technology, economics, and, often, politics, which raises the difficult questions concerning the use and interpretation of the data which the sensor array can collect.

The paradox with many fiber sensor technologies, and especially Bragg grating systems and distributed measurements, is that they facilitate hitherto unrealisable measurement regimes. The acceptance of these new regimes into widespread application requires a complex mix of technological, economic, and socio-political factors to coincide. Technologically the system should do the job required and this is often the simplest criteria. Economically there is frequently no competitor against which to compare so a potential customer must compare an overall system performance with and without the information that the sensor system can yield. In some examples, surprisingly common ones in fact, the purchaser is not responsible for the user budget. This is especially true of major public works

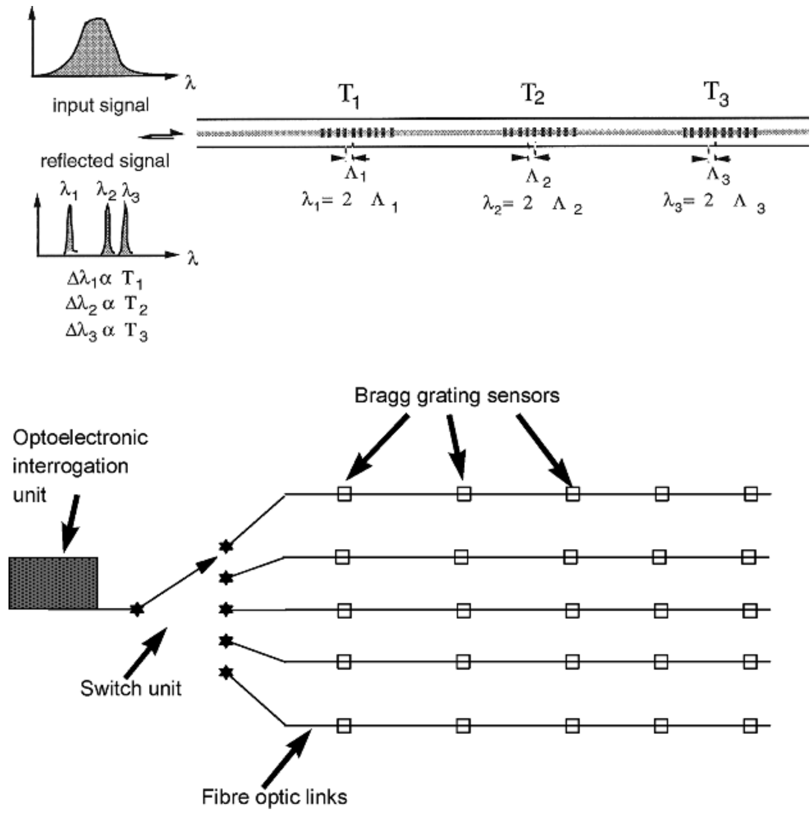

Fig. 14. Fiber Bragg grating arrays for very large passive sensor systems. There can be many tens of gratings on a single fiber.

projects such as bridges where one legislator's bargain is a successor's maintenance headache. There is also the blissful ignorance factor to take into account. There are certainly occasions when it is better not to know about system deterioration and become liable for its correction particularly if achieving that knowledge requires the use of innovative systems. This is but a taste of the very complex mix of factors which dictate the acceptability of new sensor technologies. It is rarely as simple as a naïve technologist would anticipate.

D. Distributed Measurements

Distributed sensing promises to develop into the most buoyant single technology sector for fiber-optic sensors. Indeed, it is likely to completely dominate the medium to long term market volume.

There are essentially two basic approaches. The first utilizes changes in Rayleigh scatter along the length of a fiber. Such changes can be caused either externally through induced microbend loss or through measurand induced changes in cladding loss (Fig. 15). While the former is essentially a mechanical coupling, these mechanical changes are often induced through modifications to the local chemical environment. The latter is almost always introduced through chemically induced modifications to a specially designed cladding material. In both cases, the perturbations to the propagation characteristics of the base fiber produce relatively large losses limiting the range of this class of sensors to perhaps 10 km. However, a chemically sensitive system which is capable of detecting hazardous materials, liquid spills, or other related phenomena in storage tanks, ducts, tunnels, and pipes over these distances is potentially a very useful sensor system. At time of writing a few of this class of distributed sensors have entered prototype evaluation phases in field trials with particular relevance to security and environmental applications.

Examples include leak detection systems based upon thin layers of swellable polymers which respond to the liquid of interest. The consequent swelling process can be relatively simply caused to induce microbend at a specific location. An alternative approach uses the chemically sensitive outer coating as the fiber cladding. Chemically induced changes in the properties of this fiber cladding can cause local loss. At present this is under evaluation as a hazardous/toxic gas sensing system with potential application in buildings and tunnels. This particular sensor has the benefit that by changing the illuminating source directed along the fiber the chemically active cladding can be reactivated in response to typically ultraviolet excitation. Both these systems are described in more detail in the references included in the distributed sensing bibliography.

The other basic class of distributed sensors modifies in effect the spectral content of the light propagating through the fiber in response to an external measurand. The measurand is determined by evaluating the spectral content in an appropriate way. Changes in spectral content require nonlinear interactions and Raman and Brillouin scatter are the most frequently deployed. In Raman scatter, light absorbed by the fiber is reemitted as photons with a different energy distribution where the energy distribution is determined by the Raman spectrum of the material. A particularly useful feature of Raman scatter is that measuring the intensities of the Raman signal at equal energy differences

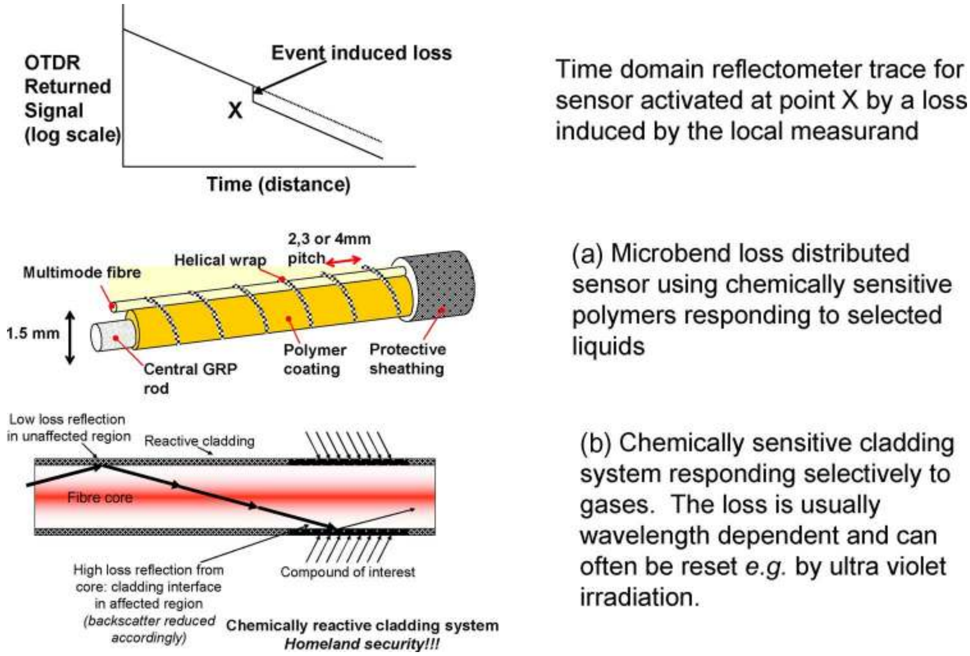

Fig. 15. Loss-based distributed sensors using (a) microbend and (b) cladding loss modulation mechanisms.

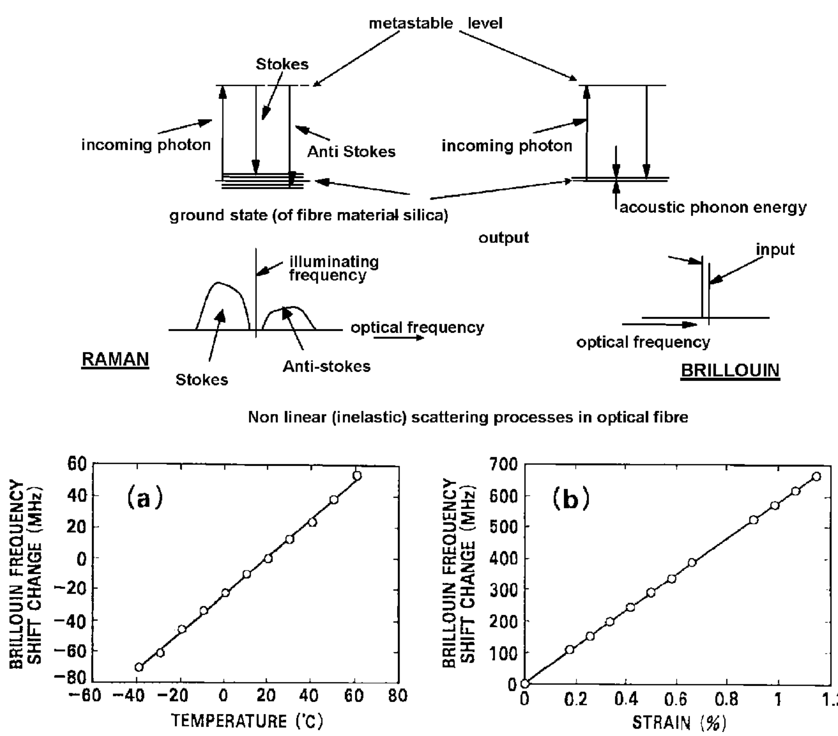

Fig. 16. Basic mechanisms of Raman and stimulated Brillouin scatter and typical stimulated Brillouin frequency shifts (lower).

in the upshifted and downshifted directions produces a ratio which is uniquely related to temperature. This relationship has been used extensively in distributed temperature probes. Brillouin scatter is a related phenomenon but the energy differentials concerned reflect the acoustic phonon spectrum rather than the optical phonon spectrum. Here, stimulated Brillouin scatter is especially interesting. In stimulated Brillouin, backscattered radiation couples exactly to an acoustic wave whose wavelength is exactly half that of the incoming light. The coupled wave is a frequency shifted by the corresponding acoustic frequency and measuring this frequency shift together with knowing the acoustic wavelength (that is the optical wavelength) immediately gives acoustic velocity along the core of the fiber. This, in turn, depends upon the stiffness:density ratio, dominated by stiffness variations. These, in turn, depend on temperature and strain. Stimulated Brillouin scatter can, therefore, be used to detect varying strain fields given sufficient background knowledge of any temperature variations (Fig. 16).

Both Brillouin and Raman scatter have the benefit that they do not involve either measuring or modulating the optical loss from the fiber. Consequently, both mechanisms are viable over extremely long interrogation distances, up to many tens of kilometers. Couple this with the ability to examine spatial increments of the order of one meter (or less with sufficient processing) combined with temperature resolutions of the order of 1°C and strain resolutions measured in the microstrains, we have an immensely power tool.

The simplest is Raman scatter and the so called DTS (distributed temperature sensors) has made significant inroads into fire alarm systems in tunnels, overheat alarms in electrical machinery, for example escalators in underground systems and a wide variety of similar applications. Brillouin scatter systems have also found application in similar temperature measuring requirements though the signal processing can be more complex and, therefore, more costly than the Raman equivalent. Brillouin systems come into their own in strain measurement and have found application in monitoring strain fields on railroad tracks where electromagnetic radiation is a significant issue and in measuring the performance of overhead power lines.

Distributed sensing will expand its acceptance in the coming years as its unique and powerful capabilities become more widely known with applications in environmental monitoring, safety, and security systems, marine and aerospace structures, civil engineering, and many other sectors. All these applications will require slightly different packaging solutions for the sensor elements (which incidentally are nothing more than the optical fiber itself). The basic interrogation units are, however, essentially common for each of the three classes of sensor systems. In all cases, some form of the optical domain reflectometer is all that is required.

While the above techniques have to date dominated the interest in distributed sensing, we should mention that there are most definitely other options. These typically involve distributed interferometry or polarimetry. There has been some success in monitoring coherent Rayleigh backscatter using a highly coherent source and time gated interferometry. This has already begun to find applications in intruder detection and other security contexts. Similarly, distributed polarimetry, looking for example at changes in local birefringence has been explored in the context of a variety of polarization optical time domain reflectometers (POTDR). Applications have included detecting current carrying conductors at long range using the magnetic field induced changes in local circular birefringence (the Faraday effect) and also in intruder alarms and similar systems.

E. Spectroscopy

Spectroscopy—the art and science of relating colour measurements in emission, reflection, or transmission to the chemical composition of a sample—is an amazingly versatile tool. Fiber-optic spectroscopy utilizes the fiber as the source of illumination to, and the same or a different fiber as a means of collection of light from, a remote sample. Since we are using optical fibers the source of light and the electronic system may be many many kilometers from the sample volume and indeed one source of light may be divided among numerous sample points which gives conceptually a huge variety of feasible point sensor network options.

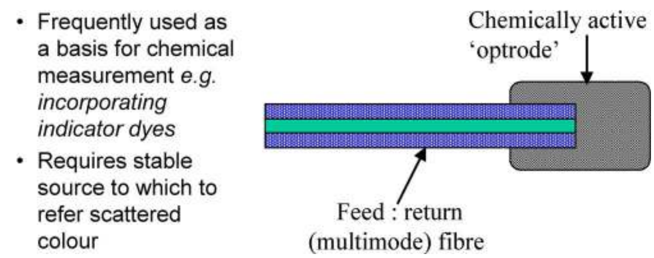

Fig. 17. Optrodes for chemical sensing.

There are other operational benefits including the spatial coherence of the optical source fiber, the relatively straightforward mechanical engineering of the source and optical collection geometries and enormous flexibility in the configuration of the sample volume.

Fiber-optic-based spectroscopy has emerged in two dominant formats. The first looks at broadband illumination and is predominantly associated with measurements made on liquids and solids. The second utilizes very narrow band precisely controlled illumination, typically targeted towards measurements on gases within pressures and temperatures at which line broadening is sufficiently low to preclude significant merging of adjacent absorption lines. The first of these—typically targeting solids and liquids—are frequently referred to as optrodes.

1) Optrode Technologies: Optrodes can make direct measurements on samples or, as shown in Fig. 17, use intermediate chemistry. The latter includes pH indicators, dyes which respond to oxygen hazardous gas species, fluorophores which exhibit quenching in the presence of oxygen and a whole host of other colour change chemical phenomena. Much of the art of spectroscopic measurements lies in deriving appropriate intermediate chemistry and the details of this are covered extensively elsewhere. Direct measurements have been relatively unusual though some considerable success has been achieved (Fig. 18) using combined spectroscopic and scattering measurements to characterize a wide range of liquids. Much of the success of this technique stems from the use of appropriate signal processing based upon pattern recognition to match spectral signatures with reference samples or to group samples within a particular batch (Fig. 19).

This approach to the "optical nose" appears to offer much potential for characterization of foodstuffs, oils, other liquid products, and in applications needing precision colour matching. The intermediate chemistry systems have already found numerous niches in water quality monitoring, in some medical applications and sometimes in hazardous gas detection. These are also widely used as biochemical and biomedical probes in for example immunological assays.

In contrast to the direct technique, intermediate chemistry always has to rationalize the long term stability of the intermediate chemical compound with sensitivity to the species of interest, with the effects of contamination from the environment with which it must be in contact and also with the impact of inevitable cross sensitivities to other measureands. Consequently,

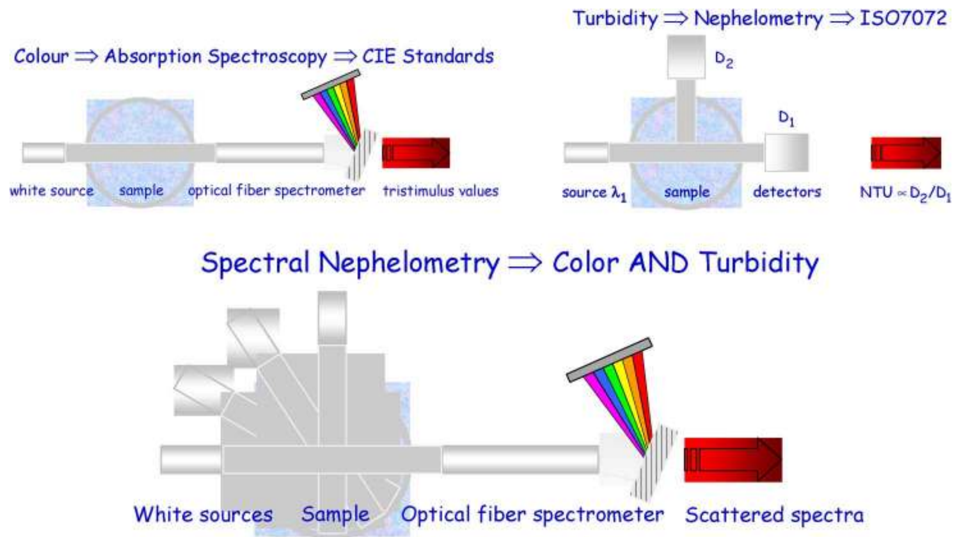

Fig. 18. Combining spectral measurement in direct absorption and scatter to characterize, even slightly, turbid liquids.

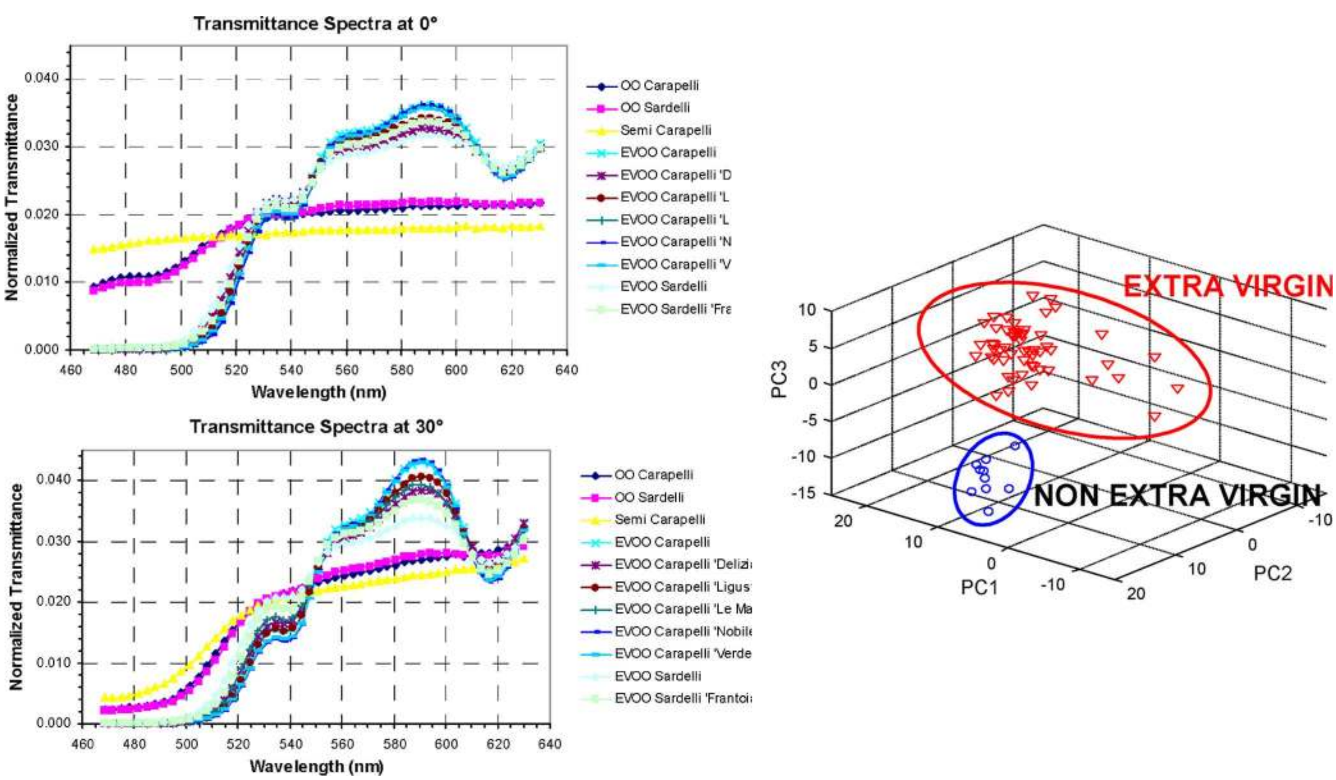

Fig. 19. Processing the data to obtain signatures—here for olive oils. Data from measurements as at left is put through PCA or similar analysis to give the clustering at right (courtesy of A. G. Mignani, IFAC CNR).

in contrast to, for example, interferometers or distributed technologies, optrode techniques are highly fragmented in their implementation and are typified by large numbers of application specific sensors designed for very individualistic measurements.

2) Gas Spectroscopy: Line Spectra: For a wide range of operating conditions, gases have highly individual precisely defined and easily characterized line spectra. The lines are subject to temperature and pressure broadening and so under some conditions can begin to merge together, thereby removing some of the relatively straightforward discrimination potential between species. Furthermore, while temperature and pressure both influence line width it is often the case that the ratio of the strengths of, for example, adjacent lines, is uniquely related to temperature. Hence, in principle, combined line broadening and line strength measurements can give the precise operating temperature and pressure conditions for a gaseous process.

Much of what has been achieved using remote spectroscopy in fiber-optic sensor systems has exploited the concepts of tuneable diode laser processing. Here, a typically small frequency deviation is introduced on the output wavelength of a semiconductor diode laser by applying current dither (Fig. 20). Even though this current fluctuation causes equivalent intensity

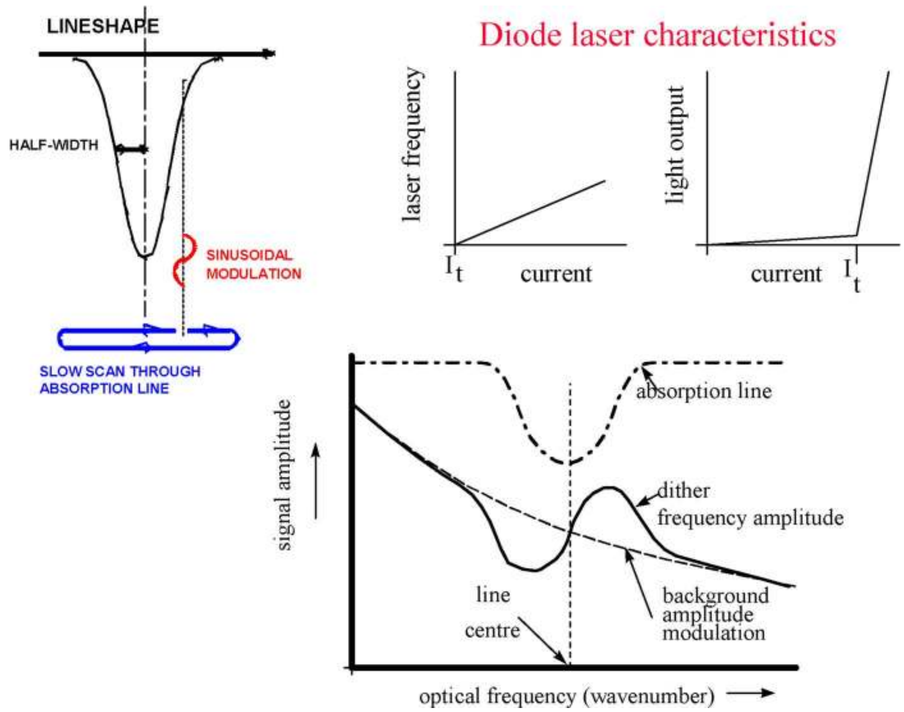

Fig. 20. Principle of tuneable diode laser spectroscopy using a current induced frequency modulation of the laser current.

changes in parallel with the frequency changes with suitable processing, these optical intensity changes can be removed leaving a signal dependent upon the slope of the absorption spectrum. Furthermore, referencing the attenuation of the system back to a zero attenuation point is relatively straightforward. All that is required is to tune the laser into a spectral region with no absorption.

Consequently, the benefits of fiber coupled tuneable diode laser spectroscopy measurement systems are immense. There is the self calibration potential just alluded to, there is the ability to operate large and widely spaced networks often from a single semiconductor laser source, and there is the capacity for multiple sensing points (tens or even hundreds) none of which will require any local electrical power. Fig. 21 shows a typical site map of a system operating on a landfill site with a total area in the region of 15 km^2. Furthermore, selectivity and sensitivity typically lie comfortably within the performance expectations of a very wide range of gas monitoring systems requiring thresholds for detection of the order of one part per million. Applications have included landfill gas monitoring, gas engine control systems and water vapour monitoring in fuel cells.

Fiber-optic-linked gas absorption cells are an excellent example of a technology which in terms of technical performance clearly surpasses that which is available from most if not all competing technologies. Consequently, had it been invented first, it would have totally dominated the market place. However, a range of competing approaches including electrochemical systems and broadband optical absorption measurement systems have already established themselves and their idiosyncrasies have become accepted within the user community. Consequently, in this context, fiber-optic sensing has considerably more "to prove" than those of us in the technology feel is appropriate. Most important, those who actually use the technology, often in safety critical systems, quite appropriately prefer to continue with less technically perfect (in our opinion), but well-known and characterized technologies and procedures. This leads us into…

IV. Commercial Diversion

Some have argued that the market penetration of fiber sensors has been "disappointing." Those who make this argument have, often sub consciously, compared the situation in sensing with that in transmission systems for communications where fiber-optic technologies now totally dominate especially at the high performance level. Sensing is, as we have already intimated, a highly fragmented activity with innumerable technologies contributing. The niches for fibers sensors are becoming evident and the unique benefits of the distributed techniques, which are confidently predicted to account for well over half the total volume (Fig. 22), are slowly becoming appreciated by potential users. The total world market for fiber sensor technologies remains though of the order of one billion dollars per annum. Recognizing the multiple sectors and diverse requirements implies a very large number of relatively small volume markets, often less than \$10 M per annum, and by implication a multiplicity of specialist manufacturers and suppliers.

There are arguably two remaining factors which inhibit future penetration. The first is communication between technologists and practitioners and the need for effective partnership between the two communities. While the successful fiber-optic sensor companies have recognized and embraced this requirement there is still much to do in matching the undoubtedly significant benefits which the fiber-based approach offers into the

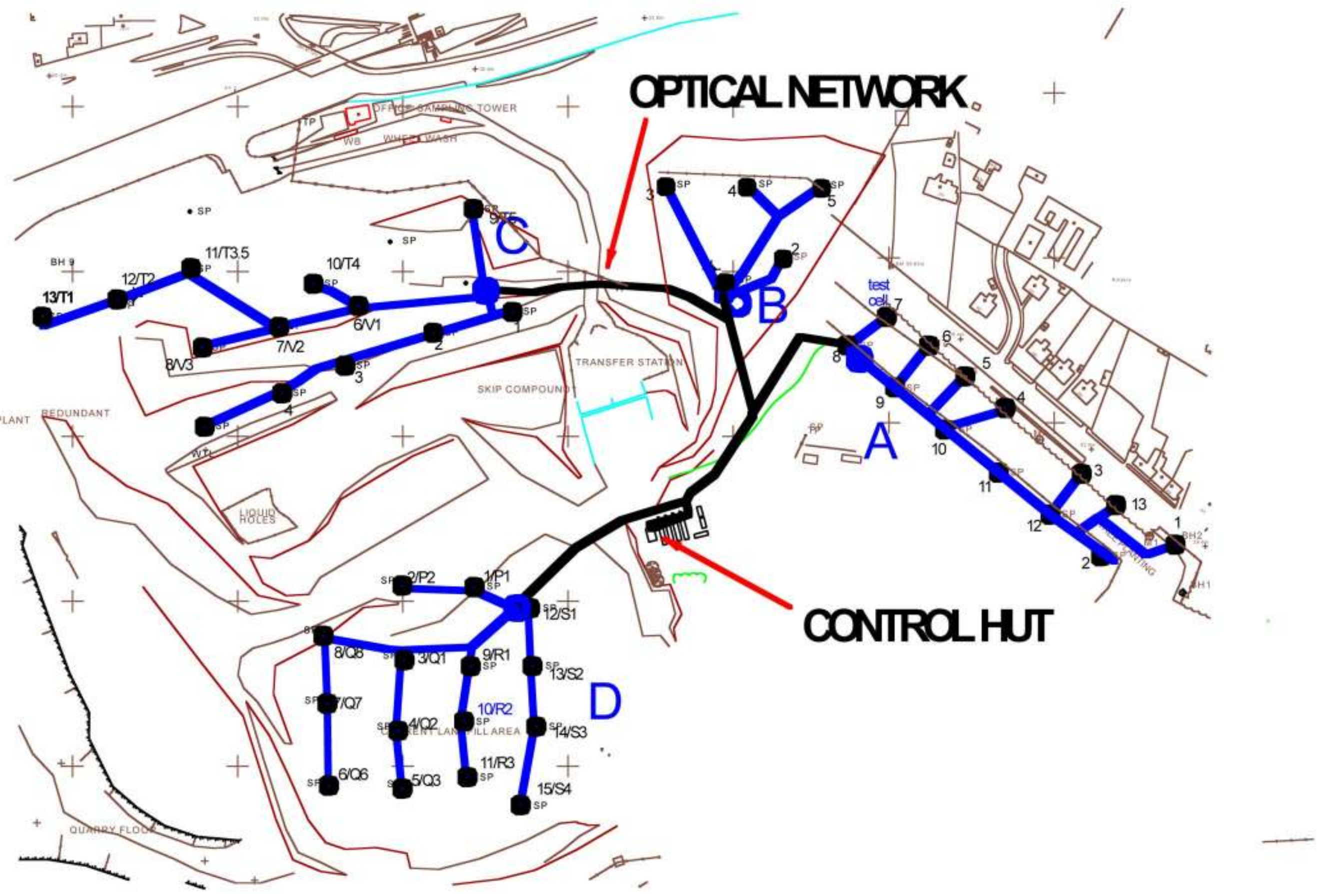

Fig. 21. Partial map of a trial landfill site with installed multiplexed 60-point TDLS methane concentration monitoring system responding from <100 ppm to 100% methane gas concentration by volume.

potential user's vocabulary. The importance of this communication process cannot be over stated—many prospects flounder because of a lack of full understanding in the user direction of what the technology may offer them and in the technologist's direction in the often subtle nuance of the application context. This nuance includes one or more of existing technologies and their level of acceptance, legislative needs, environmental constraints, reliability specifications, long-term service and maintenance demands, procurement processes, safety legislation, physical and software interfaces, local, national, and international usage specifications, and standards. . .

The second, closely linked to the above, lies in the need for carefully selected international standards. There remain significant differences among the values which for example a fiber Bragg grating decoding system may produce for a given wavelength and this is but one instance of a need for international system standardization. There is also a need for clarity in external communication to users. This is particularly apparent for distributed sensor technologies, where parameters such as effective gauge length, bandwidth, resolution, and resolvable point count require careful definition to prevent hopeless confusion among the user community. There certainly are apocryphal examples where misunderstandings in this particular, very unfamiliar, context have resulted in user confusion and erosion of potential customer confidence.

However, we believe that these factors are gradually becoming increasingly recognized and there are certainly initiatives within the international community designed to redress the balance. Standards groups for example in Europe associated with COST action 299 and in the U.S. linked to organizations such as OIDA are among several who are contributing to this debate.

V. What of the Future?

The optical fibers sensor community has for many years supported its own somewhat idiosyncratic series of research conferences—OFS. The first of these took place in 1983 and the next in Australia (the 19th) is planned for Spring 2008. These conferences have proved to be consistently extremely popular. The inevitable conclusion is that the research continues and that there are potential improvements in the future.

Certainly, much of what is reported in these conferences is either applications analysis and engineering, often to meet very demanding specifications, or is incremental improvements on established technique. There are though new concepts emerging, many exploiting new component technologies originated in other domains. Perhaps the most dominant of these is the exploration of prospects for microstructured fibers in fibers sensing. Certainly, it is possible to tailor mechanical and optical properties somewhat independently in the microstructured systems, though exactly how practical this will eventually

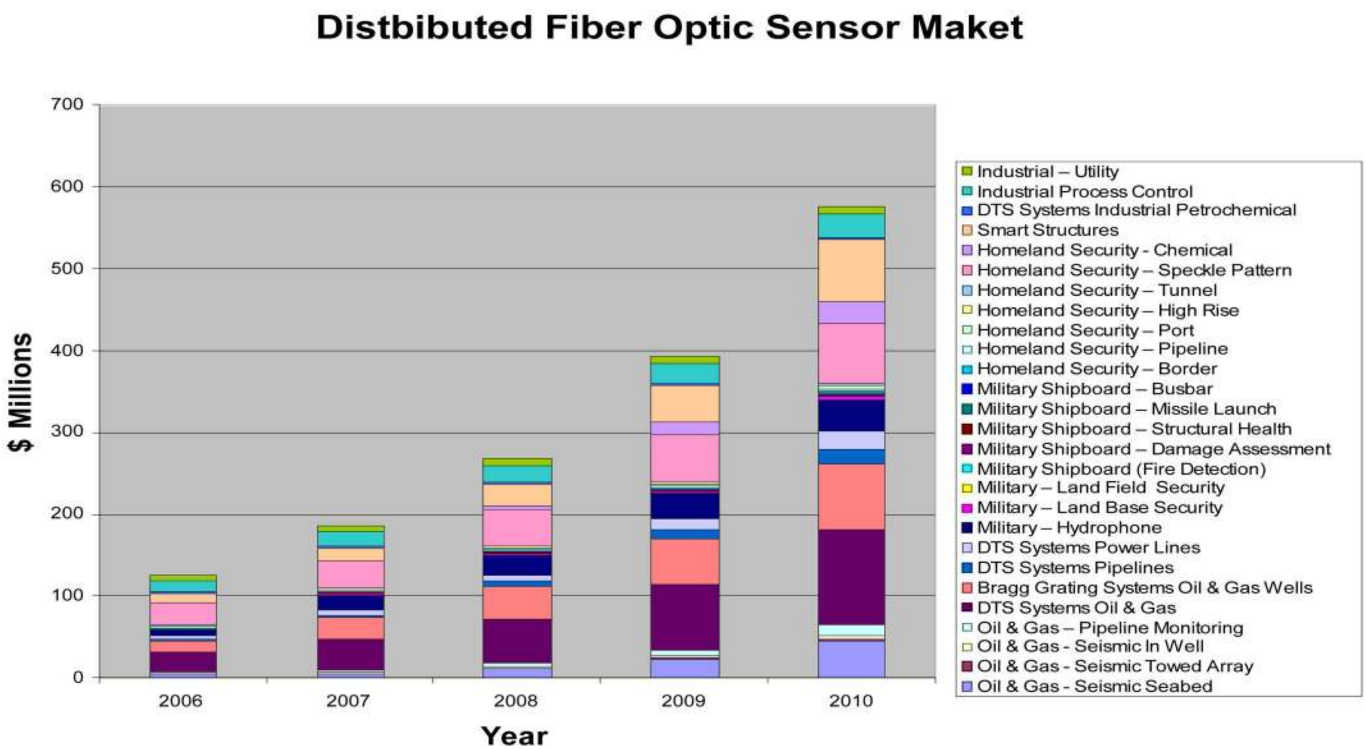

Fig. 22. Distributed fiber-optic sensor market predictions (OIDA 2007).

prove to be remains to be resolved. There are also potential benefits in the enhanced nonlinearities that such fibers can bring and, therefore, reducing optical power thresholds for nonlinear interactions and inelastic scatter processes. These fibers also offer the prospects for multianalyte chemical and biochemical sensing in a single capillary probe with the potential for a micro-miniature optical nose.

The continual improvement in optical fiber amplifier technologies also opens new sensing opportunities. Optical fiber-based LIDAR for remote sensing is an area which has recently emerged as a potential practical system. Amplifiers also open the prospect for huge sensor arrays and already some multiplexed systems using in network amplifiers have been demonstrated.

Perhaps, though, the most important area is one common to all sensor network technologies, namely how to interpret the data. We have already have seen progress thanks to readily available computing power, in for example the processing of the optical nose. There is though much to be learnt in the art of interpreting data and equally in the art of extrapolating reliably from imprecise information. This is a task which we approach with confidence as humans—our own processing systems assemble a multitude of very imprecise inputs into a firm conclusion with remarkable efficiency—but are somehow we are far less assured when attempting to engineer the equivalent.

Working with the user community, educating users in the substantial prospects offered by the technology and absorbing user priorities and vocabularies is also a very important domain. Hopefully this article has presented a view that much of the technology can be confidently engineered though its potential contributions have yet to be fully recognized. This interaction between the user community in its broadest sense and technologists is absolutely critical in realizing the full potential which fiber sensors can offer.

Finally, we must thank all those in the OFS community whose work we have drawn upon in this paper and also generations of friends and colleagues who have made critical contributions to the development of the ideas and systems which we have outlined in this paper. We also apologize to the many whose particular speciality we have had to omit. Sensing is first and foremost a diverse and specialized industry so it is impossible to do justice to all of this fascinating and multifaceted activity in a single paper. The interested reader may gain much from the OFS proceedings which as complete a record of the evolution of the OFS state of the art as any readily available in the literature.

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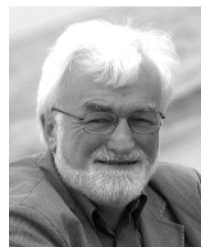

Brian Culshaw (M'83) was born in Lancashire, U.K., on September 24, 1945. He graduated from University College London (UCL), London, U.K., in 1966 in physics and thereafter completed the Ph.D. degree in 1969 in electronic and electrical engineering, specializing in microwave semiconductors.

After a year at Cornell University, Ithaca, NY, he joined Bell Northern Research (now Nortel), Ottawa, ON, Canada, and, while continuing to work on microwave semiconductors, developed an interest in fiber-optic technology. Late in 1973, he returned to UCL and, after two further years as a postdoctorate working on semiconductor device simulation, developed his interest in fiber-optic sensor technologies, their principles, and applications. His research has encompassed fiber gyroscopes, hydrophones, spectroscopic analysis systems, and mechanical interferometric sensors. In 1983, he became a Professor of optoelectronics at Strathclyde University, Glasgow, U.K.

Dr. Culshaw was *de facto* Technical Chair of the First (1983) International Conference on Optical Fiber Sensors (OFS), now a series regarded as the definitive meeting in the community; he chaired the tenth in Glasgow and was Technical Co-Chair of the 17th in Bruges, Belgium, in 2005. He orchestrated, with SPIE, Bellingham, WA, the CD-ROM of the series proceedings which has recently been reissued. He also initiated European meetings in smart structures and the EWOFS workshop series in optical fiber sensor technology. Predominantly with SPIE, he has organized numerous other conferences and workshops in Europe, the U.S., and Asia. He was the 2007 President of the SPIE. In the mid 1980s, he was the founding Editor of the *International Journal of Optoelectronics*, and until mid 2004, he was a Topical Editor for *Applied Optics*. He has edited for over a decade with A. Rogers of Surrey University the Artech House series in Optoelectronics, now over 50 titles. He has administered several major research initiatives, particularly multipartner EU programmes in sensing, measurement, fiber optics, and smart structures. He has reviewed research activities and proposals in the U.K. and elsewhere. He has also acted internationally in Ph.D. and Habilitation examinations.

Alan Kersey, photograph and biography not available at the time of publication.