OPTICAL FIBRE SENSORS AND MEASUREMENT SYSTEMS

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Abstract: Developments in the field of fibre optics and lasers in recent years have had a very major impact upon the creation of fibre optic-based sensor systems, used for a variety of measurement and instrumentation applications. This paper will review some of the most relevant of these recent developments and discuss the prospects for and new horizons in fibre optic sensors into the future.
Keywords: fibre optics, lasers, sensor systems

1 INTRODUCTION

The 1960s saw the development of the laser and of low-loss optical fibre – two key elements in the later development of optical fibre sensor systems for industrial applications. The first real sensor systems appeared in the 1970s, although the optical fibre endoscope, employing a previous generation of lossy fibres and the use of fibre optics in radiation detection, pre-date this period. Initially fibre optic devices were constructed to meet very simple and relatively unsophisticated sensor needs, such as simple displacement or pressure sensors and card readers for computers, for example. A range of advantages has been cited for the use of optical fibre over conventional sensors for a variety of physical and chemical measurements [1]. These include the non-electrical operation of the device, the small size and weight of optical fibres and the immunity to radio frequency and electromagnetic interference (RF and EMI) as well as potential high accuracy and remote operation. However, the invariable higher price of the sensor and the need for retraining of technical staff to use optical, rather than electrical methods are less often mentioned, and the supposed easy interfacing with optical communications systems is not facilitated by the analogue nature of the output of most optical sensors. Using the same *components* as optical communications systems does not necessarily make for ready coupling of such systems together.

Optical fibre sensor-based instruments are, however, reaching a real maturity to compete in niche markets and offer performance that justifies both the system price and the allows new types of measurements to be made in many cases. The unjustified enthusiasm of the early 1980s to use optical fibres to solve seemly almost every measurement problem (driven inevitably more by the need to ensure funding for fibre optic sensor projects) has given way to a wide range of applications in engineering and science which exploit, to the full, some of the most interesting optical science and associated technology [2]. These are discussed in this paper.

2 CLASSIFICATION OF OPTICAL FIBRE SENSORS

Optical fibre sensors may be classified in a variety of different ways, depending upon the physical mechanisms used in the transduction process, the range of measurands involved or the spatial nature of the sensor process. This process is discussed in some detail by Ning and Grattan [3] but herein a simplified division into **point**, **quasi-distributed** and **(fully-) distributed sensors** is used. Additionally, multiplexing of optical fibre sensors offers major advantages and simplification of sensor systems – and a wide range of multiplexing arrangements may be used. Most important amongst these are wavelength-division multiplexing (WDM), frequency- (FDM) or time-division multiplexing (TDM) and spatial-division multiplexing (SDM) which are particularly compatible with Bragg grating-based sensor systems which have had an important impact upon the field in recent years [2], [4].

3 DEVELOPMENT FIELDS IN MODERN OPTICAL FIBRE SENSORS

With the maturity of the technology from simple intensity-based devices [5] which modulate the amount of light detected as a function of the measurand (and additionally often subject the sensor to error due to such problems as fibre bending losses), a number of key optical technologies are forming the basis of important sensor devices. The most important of these are highlighted below.

Interferometric sensors have a long history, arising from the development of fibre forms of conventional bulk-optical interferometers. Their high sensitivity and relative ease of use has opened up new applications, for example in the measurement of strain and temperature with low-finesse Fabry-Perot cavities formed in-fibre giving good spatial location and relative ease of fabrication In general, interferometric sensors can provide the maximum in sensitivity when the technique is used in a way that is appropriate for the measurement of certain particular physical parameters, although often cross-sensitivity problems arise. Apart from simple displacement sensors, early research was focussed on exploiting the sensitivity of fibres to weak acoustic fields, particularly in the development of hydrophones for naval applications, and the work has expanded over the years since the 1970s into investigating the most appropriate technologies and then developing a range of important advances into the creation of new systems. Recent research has become more generic, addressing areas such as multiplexing of fibre sensors of this type, minimizing the impact of the noise sources present, and the use of interferometric demodulation and the field has expanded with developments in low coherence interferometry, which was the subject of much directed research effort in the late 1980s and early 1990s (see OFS Conference series papers [6]).

The He-Ne gas laser has been popular as a source in such sensor systems over the years due to its price, its stable wavelength and what has, in general been the adequate level of power it provides for many sensor situations. The development of effective, room temperature semiconductor lasers in the early 1980s opened up new opportunities and a wide range of solid state devices have been used in recent years in many sensors. Additionally, the fibre laser could prove to be a very important tool in modern interferometric systems – the output is easy to couple to fibre optic sensor systems and devices are compact and have low voltage operation due to the use of semiconductor laser pumping.

Low-coherence interferometry has been applied to the measurement of a range of parameters e.g. temperature, pressure and strain, as well as displacement and is often termed (usually incorrectly) "white light interferometry" (in part due to the similarity of concept to an interferometer with the classical use of a broadband source across the visible spectrum). This is shown schematically in Figure 1. The light from the low coherence source (e.g. a light emitting diode LED or thermal source) is coupled into the interferometer, together with any backscattered light from stray or end-face reflections. The second beam shown schematically in the figure is coupled to a "reference arm" which has a variable path length (reflecting the nature of the measurand) due to the presence of a mirror influenced by the transduction mechanism. The two beams mix at the detector and due to the short coherence length, ℓ_c, of the source (10µm – 100µm for a typical LED) interference only occurs for optical beams which have travelled the same distance to within a length $\sim \ell_c$. Moving the mirror in the sensing process allows the interference signal to be seen over a range of path lengths. A number of different refinements to the basic technique have been explored throughout the years and various interferometer configurations used. Various techniques have been developed to monitor closely the position of the centre of the fringe pattern generated, on which accurate measurement of the sensor parameter involved depends, in electronically scanned devices.

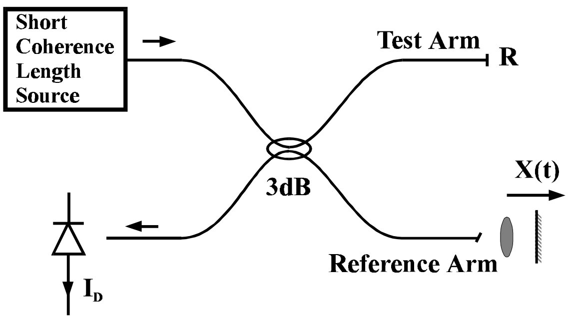

Figure 1. Low coherence interferometry

Fibre-based Sagnac interferometers have been developed, exploiting the Sagnac effect and applied principally, but not exclusively, to Fibre Optic Gyroscope (FOG) development. This topic has been the subject of considerable research and development and is not developed in detail here. Commercial examples of these devices have proved sufficiently successful to be installed in aerospace control systems in missiles and aircraft, and in automotive applications in luxury cars, coupled with GPS systems, for navigation.

The introduction of interferometers into a fibre optic network or loop offers the possibility of creating a series of sensors well suited to a quasi-distributed measurement. The in-line Fabry Perot (F-P) interferometer, operating as a fibre-optic analog of the classical bulk optical device is one way to do this. This is shown schematically in Figure 2(a), together with the extrinsic F-P device, shown in Figure 2(b), used widely for strain monitoring and arising from work at Virginia Institute of Technology. The cavity is formed by the air gap between two uncoated fibre faces and the fibres used may be held using glue or epoxy resin. Figure 2(c) shows an in-fibre elation from the work of Sirkis et al [7] where the two fibres are fusion spliced to a section of hollow core fibre, a micro-tube, of the same outside diameter creating a mechanically stable sensor. Sensors of these types have been created for use in monitoring concrete and composites, especially for strain and temperature analysis.

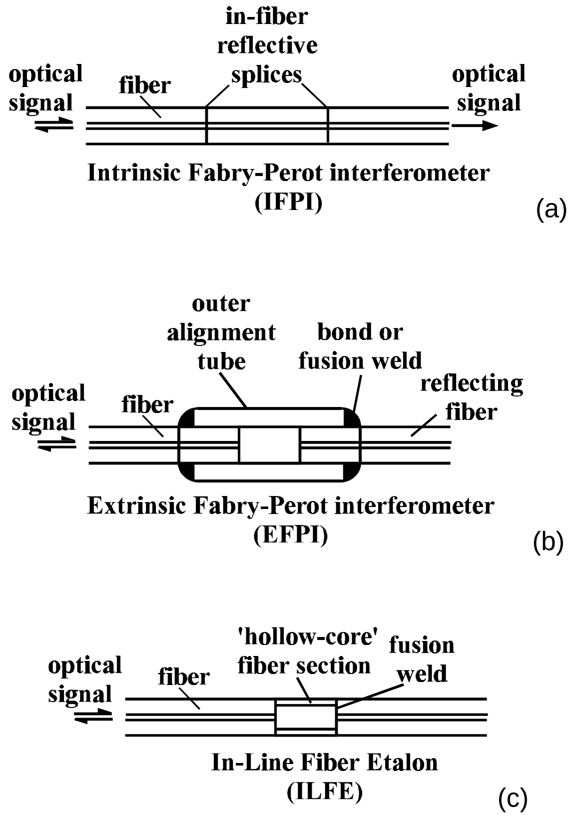

Figure 2. Interferometric fibre Fabry-Perot implementations: (a) intrinsic fibre Fabry-Perot, (b) extrinsic fibre Fabry-Perot, and (c) in-line fibre etalon

Both **quasi-** and **fully-distributed** sensor schemes have applications in the measurement of strain distributions in aircraft wings, pressure in boilers, temperature excursions in high-voltage transformers and state-of-health monitoring of bridges and civil engineering structures. The most popular approach has been to use backscatter methods, employing convenient laser sources and using optical time domain reflectometry (OTDR) as this allows for a useful spatial resolution (typically a few metres) and has the advantages of high sensitivity and operation from one end of the probe fibre. Their disadvantage is that of a low-level signal due to the low non-linear coefficients of the silica, which constitutes the fibre and thus this gives quite a long system response time, resulting from the necessity to integrate over many pulses. Forward-scatter techniques usually employ counter-propagating pulse-wave interactions, and generally are of lower sensitivity and (normally) need access to both ends of the fibre to recover the interrogation light pulse, but they often provide sufficiently powerful signals to operate in a "single-shot" mode. This tends to give a response time not greater than that of the "go-and-return" light passage along the fibre.

The principle of operation of this measurement scheme uses a region of localized high loss due to the perturbation of the fibre by the measurand field (stress, temperature, external refractive index, etc) causing a change in the detected backscatter signal versus time delay.

The most successful distributed fibre optic sensor developed to date is the Raman-distributed temperature sensor system, pioneered in the mid-1980s and developed into a commercial instrument by several companies. In the standard Distributed anti-Stokes Raman Thermometer (DART) [8], an intense laser pulse is launched into the sensing fibre, yielding spontaneous Raman scattering, and as a result of which anti-Stokes and Stokes photons are generated along the fibre. A fraction of these scattered photons is captured in the guided modes of the fibre and then propagated back towards the launching end where they are detected by a fast photodetector. Standard DART sensors are capable of operation over fibre lengths of up to 10km, with ~1°C temperature and 1m spatial resolution.

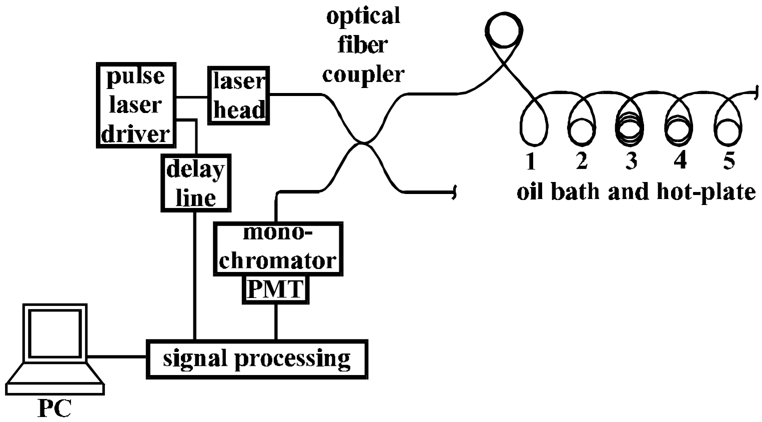

Figure 3. Experimental setup for high spatial resolution distributed optical fibre sensor

Improvements to a Raman-scattering based temperature system in terms of several special applications have been reported in the literature for high temperature sensing, temperature sensing in the nuclear environment and a low cost distributed sensing system, for example [8].

Several systems based on Brillouin scattering in optical fibres have been demonstrated, since the Brillouin frequency shift in an optical fibre depends linearly on the fibre strain. Unfortunately, as the Brillouin shift also depends on the fibre temperature, this approach has suffered from temperature cross-sensitivity problems. The spontaneous Brillouin scattering efficiency is approximately 20 dB weaker than that of Rayleigh scattering, but can be enhanced by using the stimulated scattering process, to form the basis of usable sensor systems, which have recently been reported [6].

In-fibre Bragg gratings are sensor elements which are photo-written into optical fibre using intense ultra-violet beams and have the potential for the measurement of strain and temperature, in particular, through the perturbation of the grating structure. Coupled with the multiplexed schemes discussed earlier, these are powerful devices, with applications reported including monitoring of highways, bridges, aerospace components and in chemical and biological sensors.

The basic principle of operation of a Fibre Bragg Grating (FBG)-based sensor system lies in the monitoring of the shift in wavelength of the returned "Bragg" signal, as a function of the measurand (e.g. strain, temperature). The Bragg wavelength, λ_B, is related to the refractive index of the material, n, and the grating pitch, Λ, by the simple formula

$$\lambda_B = 2n\Lambda \quad (1)$$

Sensor systems involving such gratings usually work by injecting light from a spectrally broadband source into the fibre, with the result that the grating reflects a narrow spectral component at the Bragg wavelength, or in transmission this component is missing from the observed spectrum. Figure 4 shows this simply and schematically.

Bragg grating sensors are well suited to quasi-distributed point measurements of strain or temperature at known positions in an optical fibre network, for example. The operation of the sensor is very simple – the strain response occurs because of both the physical elongation of the sensor (and the corresponding change in the grating pitch), and the change in fibre index due to photoelastic effects. The inherent thermal expansion of the fibre material and the temperature dependence of the refractive index cause the response to the temperature change, to give a change in the wavelength associated with the grating which has thus been perturbed.

The field of optical fibre sensors has been dominated by silica-based devices, but recently lower loss **plastic (or polymer) fibres** have been developed, and a number of innovative measurement applications reported. These have expanded from the early simple intensity-based sensors to fully employing the new range of materials. Automotive applications in particular benefit from the lighter weight and additional flexibility of polymer fibre, as do other roles, include dynamic weighing.

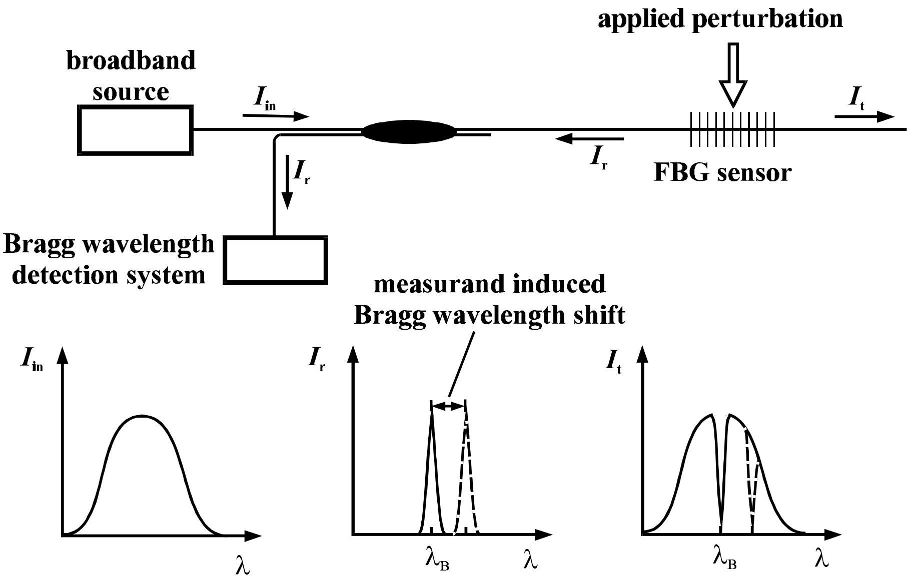

Figure 4. Basic Bragg grating-based sensor system with transmissive or reflective detection options

The use of both plastic and silica fibre containing various dopants has developed to serve the fibre laser and optical amplifier markets, and applications of **doped optical fibres** in sensors include, in particular, temperature measurement and gas or chemical sensing through the change in the fluorescence characteristics of the fibres, often excited with light from convenient solid-state diode lasers and using rare-earth or organic scintillator dopants. The use of luminescent phenomena, concentrating particularly on fluorescence for optical sensing, has been observed with a range of different fibre hosts. This usually involves rare earths which have been doped into silica-based fibres, or alternatively into fluoride glass or more exotic fibre materials, and can equally be applied to the generation of simple fluorescence as to the creation of laser action. However, there is a wide range of other fluorescent materials which have been doped into plastic fibres, offering an alternative medium, particularly for sensing applications, where the loss mechanisms in plastic hosts, usually responsible for quenching laser action, are largely unimportant when the fluorescent output only is used. A major difference between silica and plastic fibre is the extreme flexibility of the latter, which allows it to be bent, often to a greater extent and with a smaller radius, than silica fibre.

Fluorescent techniques in optical sensing using crystalline materials coupled to optical fibres have been applied regularly to the measurement of pressure and temperature, and such work has been discussed in some detail by Grattan and Zhang [9].

Silica-based fibres with an appropriate dopant have the advantage of both lower attenuation and higher durability over plastic fibres for some of these specific sensing applications. The variety of such fibres available has increased dramatically over the years, from the early use of the most successful of the laser solid-state media, neodymium-doped glass, to sensors containing erbium, thulium, praseodymium, holmium and ytterbium, for example. The potential for high-temperature use is particular important and has strongly influenced the development of a range of devices, especially temperature sensors designed for extreme environments.

A detailed investigation of the characteristics of an Nd^{3+} doped fibre, based on alumino-silicate glass and in particular under extreme temperature conditions, has been developed, in which certain specialized characteristics such as the annealing behavior of the fibre has been exploited to achieve a stable and reproducible response to the measurand. The relationship between the fluorescence intensity and the length of the doped fibre has also been the subject of study. The effect of high temperature on sensors based on commercial erbium-doped fibres, at temperatures up to 1100°C, has been discussed and the underpinning science of the luminescent effects in such fibres, for example considering the influence of the upper levels of erbium doped into silica fibres, has been explored by a range of authors. In further work, results on an intensity-based sensor, using the thermal behavior of the relative emissions at 530 nm and 555nm for the measurement has been reported, obtaining calibration data in the temperature region from -200°C to +700°C.

An investigation of the fluorescence characteristics of Er^{3+} - doped fibres in high temperature sensing has been given in work of Grattan and Zhang [9]. The experimental arrangement used in these study is essentially that depicted in Figure 5 for erbium-doped fibre. Their temperature sensitivities increase significantly at temperatures above ~500°C, from ~2.5µs°C^{-1} to ~12µs°C^{-1} over the 0 to 400°C and 700 to 900°C regions, respectively.

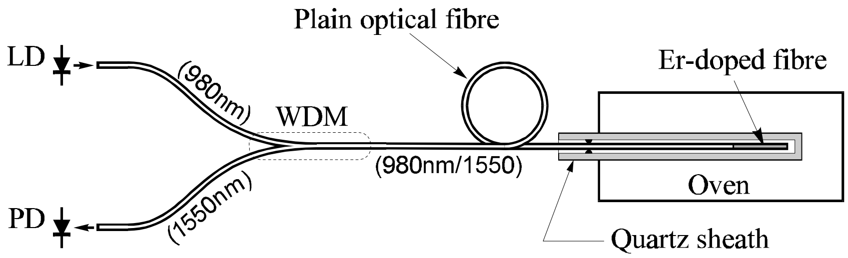

Figure 5. Schematic diagram of the probe arrangement. LD, laser diode; PD, photodiode; WDM, wavelength division multiplexer

The fluorescence lifetime of the Tm-doped fibre has been measured, along with the fluorescence intensity, as a function of temperature from 50°C to 1250°C. The lifetime decreases monotonically from ~63µs at 100°C to ~ 15µs at 1250°C, and this provides a convenient system for high temperature sensor applications. Other fibres including those doped with Sm^{3+}, and Yb-doped fibre has also been used in both temperature and strain sensing as has Yb:Er co-doped fibre been used for the detection of neptunium, for example.

4 SUMMARY

Building upon the above, a number of illustrations of topical applications and performance details have been discussed and the lessons for the future considered. Illustrations from contemporary work by a range of international authors are used to reinforce the message of the success and versatility of fibre optic sensor technology.

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