

Research Activities Arising From the University of Kent

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Abstract: In this paper I describe research activities in the field of optical fiber sensing undertaken by me after leaving the Applied Optics Group at the University of Kent. The main topics covered are long period gratings, neural network based signal processing, plasmonic sensors, and polymer fiber gratings. I also give a summary of my two periods of research at the University of Kent, covering 1985–1988 and 1991–2001.

Keywords: Optical fiber sensor, long period grating, neural network, plasmon, polymer, POF

1. Activities at Kent

My time in the Applied Optics Group at the University of Kent spanned three decades, running from my arrival as a graduate student in 1985 through to 2001, interrupted by a 2½ year postdoctoral period at the University of Oxford. This whole period saw significant developments in the field of optical fiber sensing, fuelled in many ways by the relentless development of components and devices for the telecommunications industry.

In the mid to late 1980s, there was an emphasis on taking advantage of the combination of the high sensitivity provided by interferometers, with the practicality of an all fiber system, which overcame the problems of component alignment associated with traditional interferometers and allowed them to move off the optical bench. My doctoral research, supported by GC Avionics, was largely centered around solving problems associated with the use of interferometric sensors for quasi-static (or slowly varying) measurands. The operation of such systems can be compromised by drifts in the reference arm of the interferometer or in the laser source

wavelength, both of which produce shifts in the interferometer phase that is indistinguishable from those introduced by the measurand in the signal arm of the interferometer. I investigated methods of stabilizing diode laser sources and showed that they could be readily locked to a stabilized reference interferometer or a gas cell [1]. Another limitation of interferometric systems when they are applied to quasi-static measurands is the repetitive nature of the interferometric transfer function which limits the unambiguous range of the sensor. I developed techniques for extending the range [2] using two sources [3] and frequency modulated continuous wave techniques [4].

My period of time as an academic at Kent (1991–2001) coincided with the rise in interest in fiber Bragg grating sensors (FBGs). We were instrumental in developing interrogation and multiplexing techniques for such devices [5–9], and exploring their applications. Medical sensing was a significant area of activity, and we studied the use of gratings for ultrasound detection [10], thermodilution flow measurements [11] and undertook the first *in-vivo* sensing experiments with FBGs [12].

Another major area of activity concerned distributed fiber sensing, mainly utilising Brillouin scattering but also taking advantage of Rayleigh scattering [13]. In the case of Brillouin scattering, we developed the use of the Brillouin loss based mechanism [14, 15], studied the statistics of measurement errors [16], used a mode locked fiber laser to remove the need for two independent optical sources [17], developed a fast, single ended system [18] and investigated the transient response to pulses shorter than the Brillouin lifetime [19].

The discrimination between the effects of temperature and strain in FBG and interferometric sensing systems is a difficult problem for which we developed solutions [20, 21]. Finally, in the mid 1990s we started a programme of research into optical coherence tomography (OCT) [22, 23] that has gone from strength to strength.

Subsequent sections describe my research in the Photonics Research Group at Aston University in the UK during the period 2001–2010.

2. Long period gratings

Long period gratings (LPGs) have periods typically of 100s of microns, approximately two orders of magnitude greater than that of fiber Bragg gratings [24]. They act to couple light out of the core to forward travelling cladding modes, from which the light is usually lost. Unlike FBGs, LPGs cannot be viewed in reflection but reveal themselves by a series of attenuation bands in the transmission spectrum of the fiber, each band corresponding to the coupling of light to a specific cladding mode. Compared to typical FBGs, LPGs also tend to produce rather wider spectral features. These features tend to make the interrogation and multiplexing of LPGs less straightforward than that of FBGs, which perhaps explains the commercial emphasis on exploitation of FBG sensor systems.

LPGs do however have some significant advantages over FBGs. One concerns the scale of the index modulation: due to their much larger

period, LPGs can be easily photoinscribed point-by-point or directly using an amplitude mask and can also be made by mechanically deforming the fiber or locally melting the fiber using an electric arc [25].

A second advantage of LPGs is that they are generally sensitive to bending of the fiber and to the surrounding refractive index — parameters not directly accessible using an FBG. The final advantage concerns the fact that the sensitivity of a particular attenuation band to a specific measurand is strongly dependent on the differential properties of the core and cladding and also on the fiber geometry. Different attenuation bands can exhibit very different sensitivity to the same measurand, while any particular attenuation band may be sensitive to some measurands but not others. This property can be contrasted with the behaviour of FBGs where different fibers exhibit quite similar temperature sensitivity or strain sensitivity.

This final feature means that, at least in principle, it may be possible to design fibers to provide good sensitivity to a desired measurand whilst displaying minimal cross-sensitivity to other parameters. This goal has yet to be achieved, however we have been able to take advantage of a range of existing fiber designs, which exhibit useful sensing properties.

The first example concerns fiber with a W-shaped refractive index profile, known as suppressed-cladding fiber (type HAF-CMS supplied by INO Inc.). The strain sensitivity and temperature sensitivity of the first 30 cladding modes were measured [26] and are shown in Fig. 1. It may be seen that the sensitivity to the two parameters varies by cladding mode order in distinctly different ways, in both magnitude and sign. In particular, it may be seen that the 13th and 14th modes have similar temperature sensitivity but strain sensitivity of opposite sign. When measurements of the wavelength shifts of these two cladding modes are made in order to recover both temperature and strain information, the problem of calculating the

measurands is therefore well conditioned.

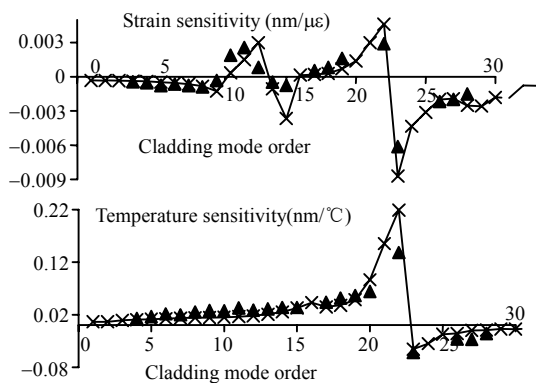


Fig. 1 Strain (top) and temperature (bottom) sensitivity of different cladding mode resonances for an LPG recorded in fiber with a W-shaped index profile (triangle: experiment; cross: theory).

Another example concerns progressive three layered fiber, which has an inner cladding of diameter 45 microns with an index between that of the core and outer cladding. In such fiber, the lowest 15 cladding modes are essentially confined to the inner cladding and are therefore insensitive to external refractive index [27] (Fig. 2). This has been exploited to prevent any shift in wavelength occurring when a bend sensor utilising this fiber was embedded in silicone rubber as a component in a respiratory monitoring system [28]. Furthermore, one of the attenuation bands of this grating had very low sensitivity to bending ($5.1 \times 10^{-2} \text{ nm} \cdot \text{m}$) as well as no index sensitivity [29].

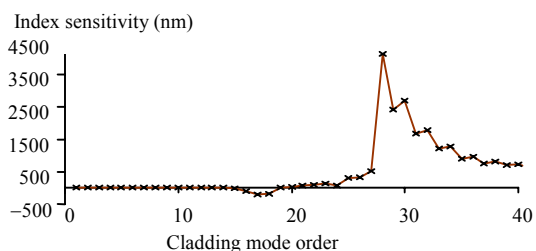


Fig. 2 Sensitivity to refractive index for the first 40 cladding mode resonances of a progressive three layered optical fiber.

The use of photonic crystal fiber (PCF) expands the range of options for LPG sensors. This fiber does not usually possess the photosensitivity to ultraviolet light typically exploited for grating inscription, however gratings produced by the

periodic exposure of the fiber to the electric arc from a splicing machine have been shown to possess very small temperature sensitivity [30] whilst exhibiting useful sensitivity to other measurands [31].

The ability of short pulse (fs) laser systems to modify the structure of glass with sub-micron resolution permits additional functionality. Long period gratings are sensitive to fiber curvature, which distorts the cladding mode field profile. The fiber symmetry indicates that any curvature induced wavelength shift must be independent of the direction of bending, however there are applications where a precise knowledge of the direction and magnitude of bend is important: examples include mapping the spatial profile of a hydrophone array towed behind a ship or determining the position of an endoscope within the body. With these kinds of applications in mind, we have shown that it is possible to break fiber symmetry using a fs laser.

As an example, 400-micron-period LPGs were inscribed into endlessly single mode PCF from Crystal Fiber A/S using 450 nJ, 150 fs pulses from a laser emitting around 800 nm. Some LPGs were inscribed with the laser focused as closely as possible to the fiber center while for some of them, the laser focal point was moved to one side.

For the symmetrically inscribed LPGs, all the visible attenuation bands exhibited a symmetrical response to bending, as shown in Fig. 3(a). In the case of the asymmetrically inscribed LPGs, some, though not all, bands displayed a clear directional response (Fig. 3(b)). Directional bend sensing was also obtained by using a fs laser waveguide inscribed to one side of the core to break the symmetry of an ultra-violet (UV) light inscribed LPG in step index single mode fiber [32].

Long period gratings can also be used as building blocks for constructing more complex devices. For example, we constructed a sensitive refractometer by inscribing two similar LPGs separated by 20 cm [33]. By carefully arranging for the chosen attenuation band to be of a strength of just 3 dB, a Mach-Zehnder interferometer was

formed where the core mode formed one arm of the interferometer with the other being formed by the chosen cladding mode between the two couplers. The device possessed a resolution of 1.1×10^{-5} at index 1.33. A simpler device consisting of an LPG recorded on a fiber taper possessed a resolution of 10^{-4} [34], similar to that of the conventional Abbe refractometer.

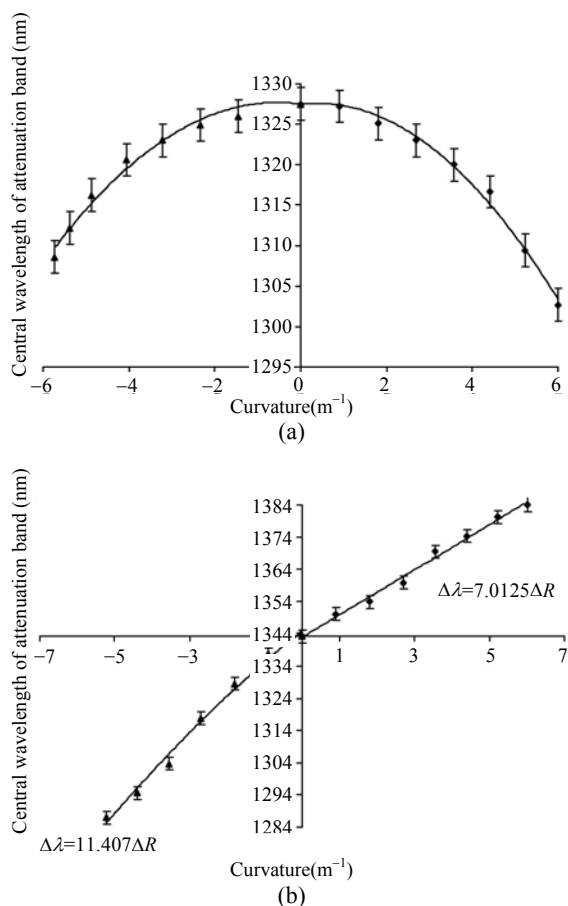


Fig. 3 (a) Response to curvature of a typical attenuation band from a symmetrically inscribed LPG in PCF and (b) response of an attenuation band in an asymmetrically inscribed LPG of the same period.

3. Neural network based signal processing

Large arrays of sensors can generate huge quantities of multi-dimensional data which can pose challenges for data transmission, processing, and storage. In many situations the data themselves are not of direct interest to the end user who may be looking for rather simple information, e.g. does this

aircraft landing gear require maintenance; did that last earthquake compromise the strength of this building; is my endoscope about to puncture the patient's chest cavity. Neural networks offer one approach to making decisions using complex data with the additional advantage that it is not necessary to know *a priori* the mathematical relationship between the input and output data.

We have investigated the use of neural processing with Bragg grating sensor networks [35]. In one demonstration experiment, a 25-cm-length thin cantilever was instrumented with four fiber Bragg gratings and clamped horizontally so that small weights could be placed along its length (Fig. 4).

For the first test the recovered Bragg wavelengths from the monitoring FBGs were used as inputs to a multilayer perceptron containing 15 hidden nodes, which was then trained to provide the position of the force, irrespective of whether there were 1, 2, or 3 weights placed together on the cantilever to cause that force. When subjected to a substantial testing regime, the system was able to deduce the position of weights to better than 2 cm more than half the time.

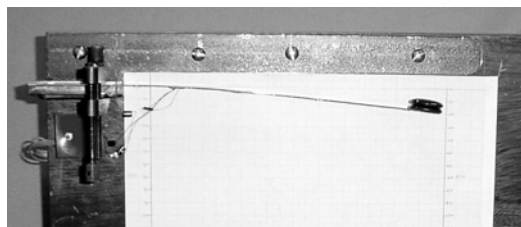


Fig. 4 Cantilever supporting small weights and instrumented with 4 FBGs.

For the second test the network, now with 10 hidden nodes, was trained to provide the number of weights on the beam, irrespective of position. Under tests the network was correct over 85% of the time.

In a second experiment, a thin rectangular steel plate, supported round the edge and measuring 34 cm by 24 cm was instrumented with 9 FBG sensors capable of detecting the strain induced by weights placed on the plate. The flexibility of neural processing approach was illustrated by firstly

training the network to recover the position of an object placed on the plate, which it did with a rootmean square error of just 11 mm, and secondly by training the system to distinguish between four weights with differently shaped cross-sections but the same cross-sectional area and mass (Fig. 5). This it did with a success rate of more than 85%.

More recently the instrumented plate concept has been extended to recover in real time the position of two objects on the surface, and a much stiffer plate has been constructed which can provide information on the weight distribution of a person standing on the plate [36].

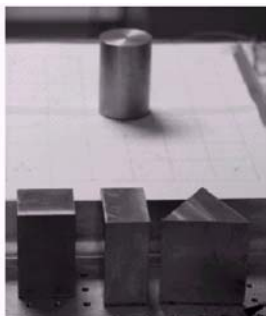


Fig. 5 Shapes of equal weight and cross-sectional area in front of the sensing plate instrumented with FBGs processed using a neural network.

4. Plasmonic fiber sensors

Surface plasmon resonance (SPR) refers to the coupling of light incident on a metallic film to collective oscillations of free electrons at the surface of the film. It is traditionally observed by directing a laser beam through a glass prism on one surface of which has been deposited a thin film of, for example, gold. The beam reflected from the metal surface has a sharp minimum in power at a particular angle when power is resonantly transferred to surface plasmons at the metal surface. The electric field associated with the plasmons extends beyond the far surface of the metal film, typically by a few hundred nanometers and this causes the resonance condition to be strongly dependent on the refractive index of that narrow region. SPR based sensors are used to monitor biochemical reactions occurring in the sensing volume [37].

We have been investigating all-fiber geometries for SPR based sensors which can bring several advantages:

1)The waveguide geometry removes the need for accurate alignment associated with bulk optic SPR devices.

2)By varying the incident polarisation we have shown that the resonance wavelength can be tuned over roughly an octave from the visible to the near infra-red spectral regions, which in turn alters the extension of the plasmon's electric field above the surface coating.

3)The resonance wavelength shows very good sensitivity to the refractive index of the medium above the surface coating, notably in the aqueous index regime and below.

4)Different coating combinations can be used to provide photosensitivity, enhance measurand sensitivity and permit immobilisation of appropriate biochemical species.

The first configuration we investigated is shown in Fig. 6. The device is constructed in three stages. Firstly, a tilted fiber Bragg grating is written in a single mode fiber using a uniform phase mask. Secondly, the fiber is lapped down to $10\mu\text{m}$ from the core-cladding interface (the fiber is carefully positioned so that the grating vector, the fiber axis, and the normal to the lapped surface all lie in a plane). Thirdly, the flat of the lapped fiber is then coated with silver (thickness: 35nm) using a sputtering machine and mask.

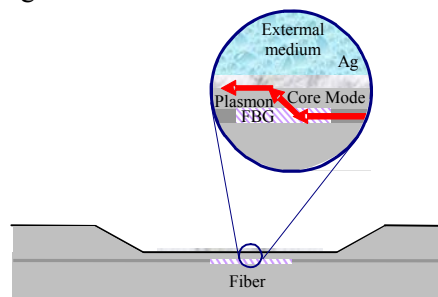


Fig. 6 Configuration for coupling to surface plasmons using a tilted FBG.

Figure 7 shows the variation in the resonant wavelength as a function of refractive index for

gratings with three different tilt angles [38]. An index resolution of approximately 2×10^{-5} was obtained in the aqueous index regime, which is important for biochemical sensing applications.

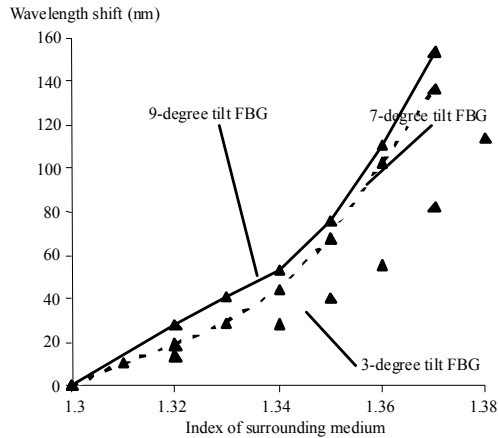


Fig. 7 Wavelength shift as a function of surrounding refractive index for an SPR based fiber device incorporating a tilted FBG.

A second type of plasmonic device which we have investigated [39] is illustrated in Fig. 8. The fabrication process is:

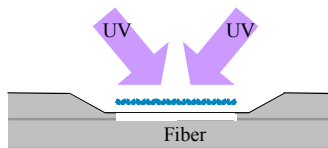


Fig. 8 Configuration for SPR based fiber device involving post-coating exposure to UV.

1) A standard single mode fiber is lapped down to 10 microns from the core.

2) Radio frequency sputtering is used to deposit one or more coatings on the flat of the lapped fiber.

3) The device is exposed to the intensity pattern produced by exposing the fiber to UV light through a phase mask of period 1.018 microns.

The coatings in these devices serve two purposes. Firstly they support the propagation of surface plasmons and secondly they provide UV photosensitivity.

One device, coated successively with germanium (48 nm), silica (48 nm) and gold (32 nm), provided a maximum index sensitivity of 4000 nm/RIU (refractive index unit) in the index region 1.33 to 1.39 (Fig. 9).

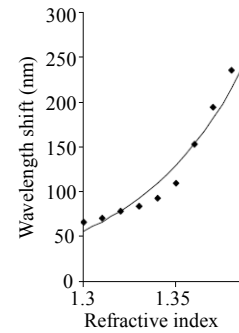


Fig. 9 Refractive index sensitivity of SPR fiber device involving post-coating exposure to UV.

A particular feature of these devices is their sensitivity at very low refractive indices. As an illustration Fig. 10 shows the results of the exposure of a device coated successively with germanium (48 nm), silica (48 nm), and platinum (38 nm) to successive alkane gases. The sensitivity in this index region is 3400 nm/RIU.

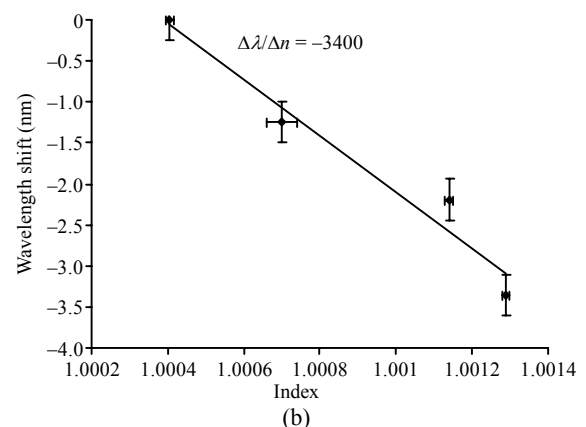
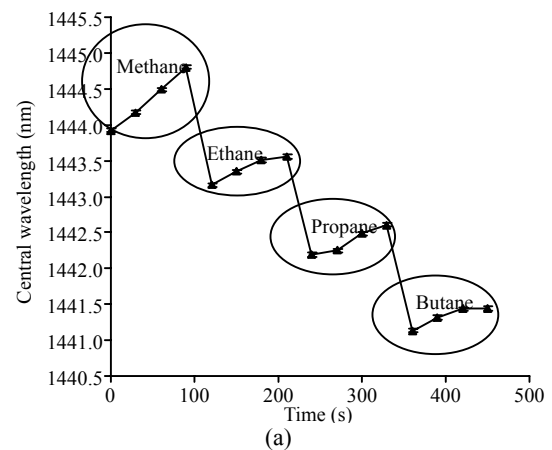


Fig. 10 (a) Response of SPR fiber device to different alkane gases and (b) wavelength shift as a function of refractive index for this device.

We have exploited the high index sensitivity in the aqueous index regime for biochemical sensing. A germanium/silica/gold device of the type described earlier was utilised on which was immobilised an aptamer (15-mer 5' - SH(CH₂)₆ - GGT TGG TGT GGT TGG - 3') sensitive to alpha thrombin from human plasma [40]. Figure 11 shows the variation in coupling strength to the plasmon as a function of thrombin concentration. The minimum detection level is estimated to be potentially sub-picomolar.

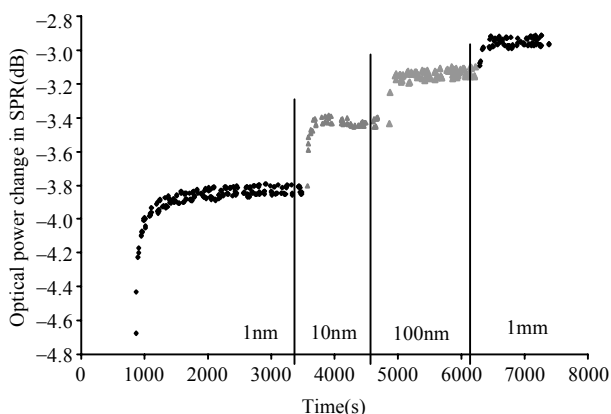


Fig. 11 Response of SPR sensor to different concentrations of thrombin.

5. Polymer optical fiber gratings

A major topic of our research recently has been the development of grating technology in polymer optical fibers (POFs). The use of POF is not without some significant difficulties [41]:

- 1)Fiber losses are much higher than for silica.
- 2)There are very few sources of single mode fiber.
- 3)Fiber connection is rudimentary.
- 4)Preform production and fiber drawing affect the fiber properties.
- 5)Polymers are viscoelastic materials.

Nevertheless, polymeric materials have some potentially useful differences compared to silica that lead us to believe there should be many niche applications where such fibers are preferred. Here we discuss some of those differences, with specific reference to fibers constructed mainly from poly

(methyl methacrylate) (PMMA), the most common constituent of POF.

Firstly, the Young's modulus for POF (3.3 GPa [42]) is much smaller than that of silica (73GPa). A consequence of this is that when grating sensors are needed to monitor strains in structures that are themselves quite compliant, the silica fiber will tend to reinforce the material resulting in a reported strain much lower than the background strain in the material. This was illustrated in a project investigating the use of FBGs for monitoring the strain in historic tapestries [43]. Figure 12 shows an image produced by digital image correlation of surface strain in a piece of textile subjected to a load of 20 N, on which four FBGs were fixed. There were two POF devices and two of silica. One of each of the fiber types was fixed with a rather stiff Araldite adhesive while the other two devices were fixed with the much more compliant conservation adhesive DMC2. It may be seen that the POF fixed with DMC2 shows a significantly lower strain than the other devices. Indeed the strain deduced from the wavelength shift of the FBG was more than a factor of 2 higher for a given load than the next best device, which was the POF grating fixed with Araldite.

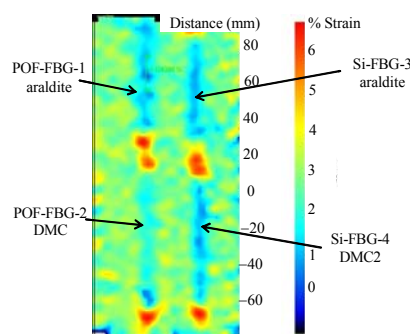


Fig. 12 Surface strain map produced using digital image correlation for a loaded fabric sample to which FBG sensors are fixed.

Pristine silica fiber has a typical failure strain of 5%–10%, though achieving this in a practical environment is quite difficult and under repeated straining the fiber often fails at less than 1%. PMMA based POF can survive strain in excess of 100%,

though this depends on how the fiber is drawn; lower drawing tension tends to provide a greater failure strain [41]. Of course such strains are well beyond the quasi-elastic region which tends to be in the range of 5%–10%.

PMMA is hydrophilic, with water absorption causing both a swelling of the fiber and an increase in refractive index, both of which lead to an increase in the Bragg wavelength of a grating in the fiber [44]. We have shown that this sensitivity to water can be used to monitor the very small quantities of water that can be present in aviation fuel [45]. Figure 13 shows the effect of inserting a POF grating into successive fuel samples that were: 1) dried using molecular sieves (approximate water content 15 ppm), 2) in equilibrium with the laboratory air (approximate concentration 30ppm–50ppm), and 3) containing liquid water and hence saturated (approximate concentration 150 ppm). It is clearly seen that significant wavelength shifts are obtained between the samples and there is evidence of repeatability.

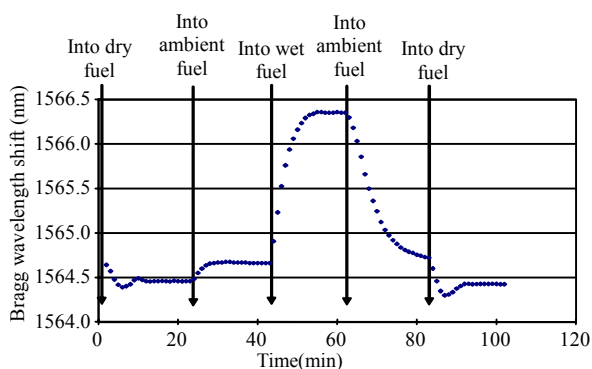


Fig. 13 Bragg wavelength shift for a POF grating sensor inserted into fuel samples containing different amounts of water.

The sensitivity to water can be utilised to make a combined temperature and humidity sensor [46]. A short length of POF containing an FBG was glued to the end of a silica fiber, which also contained an FBG. The wavelength shifts of both FBGs were monitored as a function of temperature (at constant humidity) and humidity (at constant temperature) with the sensor in an environmental chamber, the results being shown in Fig. 14. For POF in the

ranges shown the temperature sensitivity and humidity sensitivity were $-55 \text{ pm}/^\circ\text{C}$ and $35 \text{ pm}/\%$, respectively while the equivalent figures for silica were $14 \text{ pm}/^\circ\text{C}$ and $0.3 \text{ pm}/\%$; the latter figure arising presumably due to the polymer fiber coating rather than the fiber itself. The different signs of the temperature sensitivity and the different magnitudes of the humidity sensitivity lead to a very well conditioned problem (condition number obtained from the 2-norm = 8.8) when the wavelength data are used to deduce the temperature and humidity.

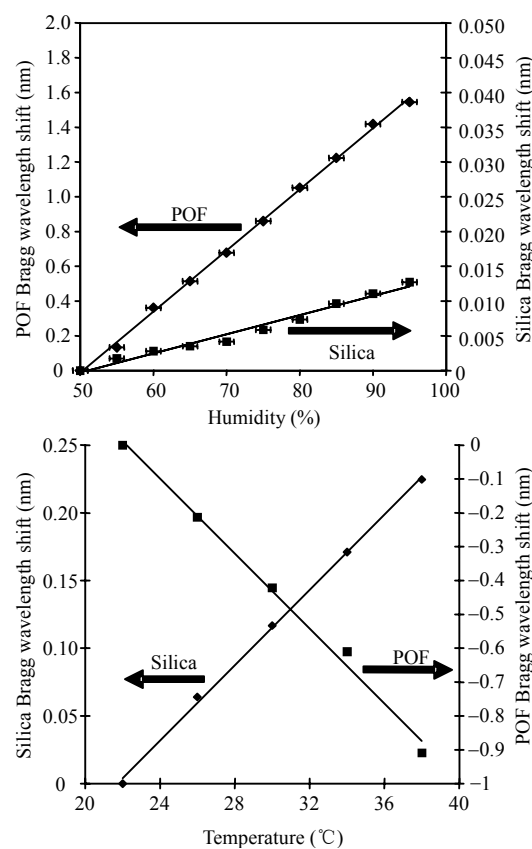


Fig. 14 Humidity (upper) and temperature (lower) responses of dual FBG sensor constructed from POF and silica fiber.

As is the case with silica gratings, following grating inscription in POF, annealing is required to provide repeatable thermal behaviour. The explanation for POF is rather different. When the fiber is drawn there is some alignment of the long polymer molecules, leading to anisotropic optical properties [47]. When the fiber is first heated there is a relaxation of this alignment, which leads to a reduction in the fiber length and a permanent negative wavelength shift for

any FBG recorded in the fiber. This shift can be up to 20 nm for gratings initially recorded in the 1550 nm region [48]. This process can be taken advantage of to record wavelength multiplexed FBGs in POF using a single phase mask with annealing steps carried out between recordings [49].

The research into POF gratings described above was carried out mainly using step index single mode fiber. We were also the first to show that FBGs could also be recorded in single and few-moded pure PMMA microstructured POF (mPOF) [50]. More recently we have been working extensively with a multimode mPOF shown in Fig. 15. Despite the large core size of around 50 microns, which simplifies fiber alignment and offers the possibility of using low cost, broad area sources, the modes that are present have a narrow spread of propagation constants which leads to a usefully narrow reflection peak. Figure 16 shows a reflection from a grating in such fiber recorded with a Bragg wavelength of 827 nm, which displays a spectral width of only 2.45 nm [51].

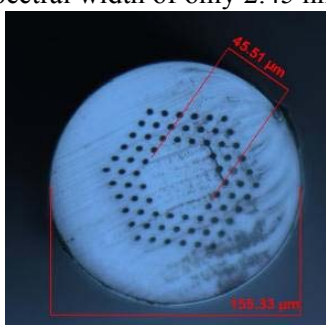


Fig. 15 Image of end-face of multimode mPOF.

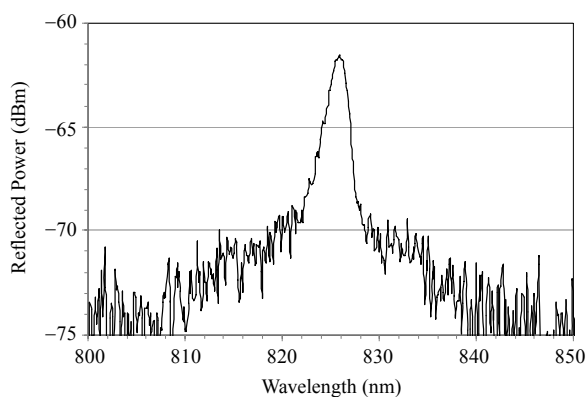


Fig. 16 Reflection spectrum from FBG recorded in multimode mPOF.

6. Other work

The sections above describe the main areas of my research in the period 2001 to 2010, though there are a number of other activities. I have a long interest in grating interrogation and multiplexing systems, developed originally at Kent, and have explored the use of arrayed waveguide gratings for interrogating both FBGs and interferometers [52, 53], used an acousto-optic tuneable filter to provide high bandwidth interrogation of wavelength multiplexed FBGs [54] as well as developing a compact interferometer for grating interrogation using a highly birefringent fiber [55]. The work on LPGs has been applied to respiratory monitoring [56] where a multiplexing topology for the LPGs was interrogated using a variant of derivative spectroscopy [57].

Acknowledgement

The work reported here warrants the acknowledgement of a great many academic colleagues, collaborators, research fellows and graduate students, too numerous to mention by name, though all are hopefully given due credit in the references cited in the text. One name does deserve to be mentioned. I am indebted to Professor David Jackson for my initial opportunity to work at Kent as a PhD student back in 1985 and my subsequent return as a lecturer in 1991. I learnt a great deal from him.

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