Fibre Bragg grating sensors in polymer optical fibres

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Abstract

This review paper summarises the current state of research into polymer optical fibre grating sensors. The properties of polymers are explored to identify situations where polymers offer potential advantages over more conventional silica fibre sensing technology. Photosensitivity is discussed and the sensitivities of polymer fibre gratings to strain, temperature and water are described. Finally, applications are reported which utilise the unique properties of polymer fibres.

1 Introduction

Optical fibre Bragg gratings (FBGs) take the form of a periodic (or quasi-periodic) modulation of the refractive index along the core of an optical fibre, which is usually single mode. The structure is normally produced by exploiting the intrinsic sensitivity of the core material to ultraviolet (UV) light and exposing the fibre to a periodic intensity pattern produced by interfering two beams of UV light. The FBG preferentially reflects light with a wavelength, λ_B, determined by the Bragg condition [1]

$$\lambda_B = 2n\Lambda, \tag{1}$$

where n is the effective index of the guided mode and Λ the spatial period of the modulation. For sensing applications, these devices are of interest because any strain or temperature applied to the fibre changes both the period and index of the grating leading to a shift in the reflected wavelength which can be determined by a spectroscopic measurement of some kind.

Over the last 25 years, the technology has become increasingly mature and is being commercially exploited in various fields that are each in some way able to exploit the technology's key features:

- Low fibre loss - enabling remote operation
- Immunity to electromagnetic interference - permitting use in electrically noisy environments
- Small size - allowing the sensors to be embedded in structures
- Multiplexing capability – with some schemes several hundred sensors can be addressed in a single fibre

The vast majority of the research on this technology – and all the commercial activity – has so far involved grating sensors inscribed in silica optical fibres. These developments are well described in books [1, 2] and review articles[3-6].

More recently, there has been growing interest in the development of the technology in polymer optical fibres (POFs). The motivation here lies with the rather different material properties of polymers compared to silica, which may provide advantages in certain applications. This paper seeks to contrast the behaviour of sensors in the two fibre types and summarise the current state of research into grating sensors in polymer optical fibres as well as the applications that have been suggested for them. Throughout this paper, when mentioning POF, we will by default be discussing

fibres fabricated mainly from poly(methyl methacrylate), with other material being specifically highlighted. We should also note that whilst the focus of this paper is polymer optical fibre Bragg gratings (POFBGs), there have been reports of studies involving long period gratings[7, 8].

There are some review articles relevant to POFBG technology. Zubia and Arue [9] and Ziemann et al. [10] provide background information on the properties and manufacture of POF, while POF based sensors were reviewed by Peters in 2011 [11]. The latter article includes a description of some of the early development of POF based gratings.

2 POF vs silica

In this section we explore the different material properties of POF and silica fibre in order to identify situations in which POF may offer some advantage.

2.1 Failure strain

Pristine silica fibre typically has a failure strain of between 5 and 10 % [12]. It is important to note though that it is challenging to obtain such values with grating sensors; great care must be taken to ensure there is no mechanical damage to the fibre surface during the inscription process [13], providing motivation for the production of FBGs on the draw tower during fibre manufacture [14]. Furthermore, repetitive loading can significantly decrease the failure strain. In the case of POF, failure strains of over 100% have been obtained [15], though this is critically dependent on the fibre production process. Annealing (holding the fibre at elevated temperate around 80 degrees for several hours) can be used to improve the tensile properties of the fibre [16]. The yield strain – the limit of quasi-elastic behaviour – is usually around 6% [17].

2.2 Elastic modulus

The Young's modulus for silica is 73 GPa[18], while for PMMA values of around 3.3 GPa are typical [19]. It is important to note though that polymers are viscoelastic materials and the challenges this provides are discussed later. The very different values for the modulus renders a POF based sensor much more sensitive to axial force than a silica fibre of equal diameter. Perhaps more importantly, the difference is significant when FBGs are used to monitor structures that are themselves rather compliant; in this case a relatively stiff silica fibre attached to the structure can locally reinforce it and therefore report a much lower strain than would exist if the fibre were absent[20]. The lower Young's modulus of POF significantly reduces this effect.

2.3 Water sensitivity

PMMA displays an affinity for water, absorbing 2% at 23°C [19]. The absorbed water raises the refractive index of the fibre and causes swelling, both leading to an increase in the Bragg wavelength of any inscribed grating [21]. This property can be used to sense the amount of water in air [21], salt solution [22], and even fuel [23]. Of course, a sensitivity to water can be a serious disadvantage for some applications, e.g. for strain sensing. Fortunately there are polymers that are suitable for fibre manufacture that do not display significant water sensitivity [24].

2.4 Chemical composition

Polymers, being organic materials, can be modified using the vast range of tools from organic chemistry and if necessary this can be done at the preform stage before drawing, which occurs at a much lower temperature (~200°C) than for silica fibre. This is not an approach that has been much exploited as yet, but offers plenty of scope for providing optical amplification[25], enhancing non-linearities[26] and functionalising the POF to selectively respond to different chemical or biochemical species[27].

2.5 Fibre breakage

A final potential advantage relates to the use of POF sensors for in-vivo medical sensing: in the advent of a fibre breakage, a polymer fibre will not produce a dangerous sharp.

2.6 Challenges for POF based sensors

Grating sensors based on POF have a number of issues which must be addressed if advantage is going to be taken of the positive features just described. The first concerns the fibre loss, which we typically measure in our laboratory to be around 1dB/cm at 1550nm for single mode PMMA based POF. The loss falls off though as we move down in wavelength towards the visible region, reaching 0.2dB/m at 650 nm with large core fibre [28]. Single mode fibre currently tends to have a higher loss of a few dB/m at this wavelength [29], probably due to the influence of scattering at the core cladding boundary, which increases in importance as the core size is reduced. A route to improved performance is the use of perfluorinated fibre, which can provide losses down to 10 dB/km in the 1500 nm region[30] and in which the first gratings were recently reported.

Polymers are visco-elastic materials and this behaviour certainly complicates their use in strain sensors. Firstly, the yield strength and tensile strength have both been shown to increase with increasing strain rate [16]. Secondly, polymers display creep (where under the influence of a constant force the length gradually increases) and stress relaxation (a gradual reduction in the stress or tension when a sample is subjected to a constant strain). When POFBGs are used as strain sensors, this can lead to hysteresis in the sensor response to increasing and decreasing strain as shown in Figure 1. When the strain was reduced the readings diverged significantly at low strain values and in fact in this region the fibre was seen to be hanging loose between its two suspension points, implying there was no longer any tension. Following this experiment it took about 48 hours for the sensor to relax back to close to its original Bragg wavelength.

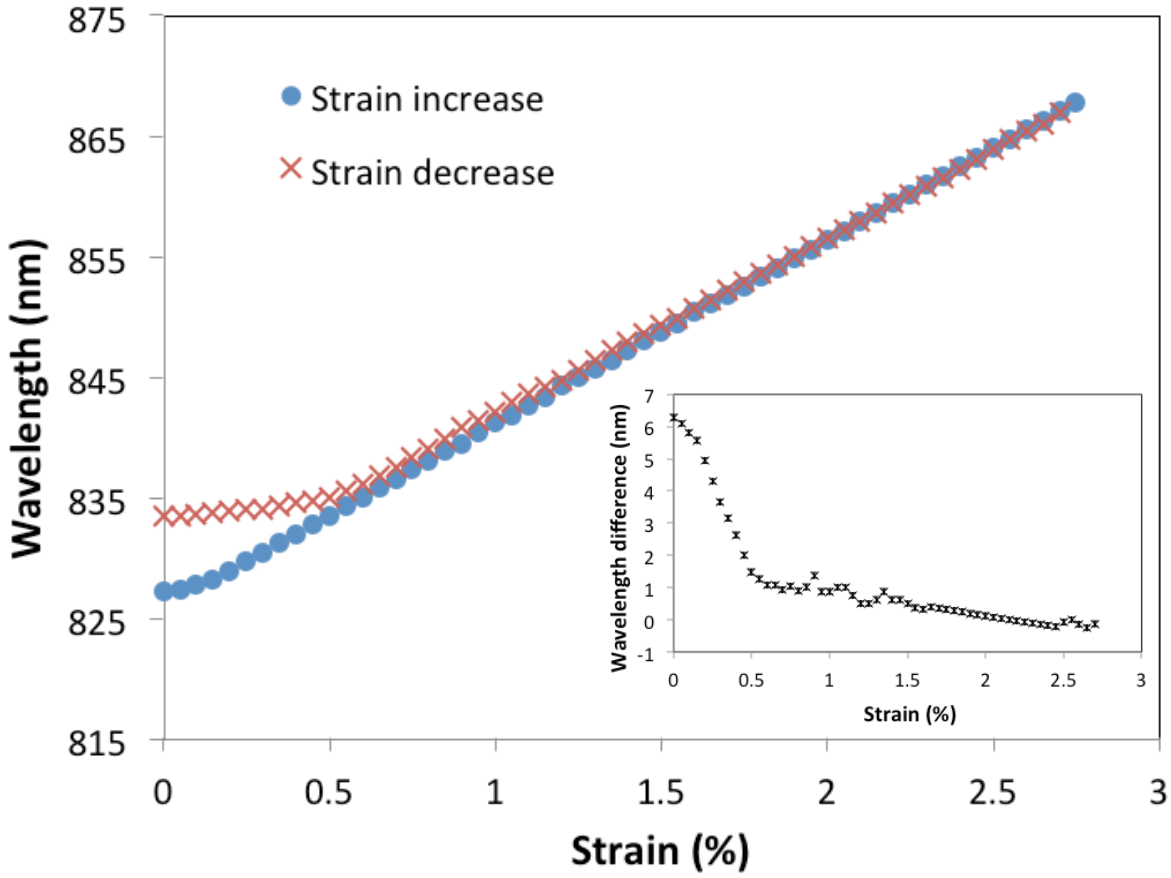

Figure 1 Bragg wavelength versus strain for a POFBG sensor in PMMA fibre. The sensor was strained by suspending it between two posts, one of which was mounted on a translation stage. The sensor was held at each strain point for 30 seconds[31]. Inset shows the wavelength difference between readings taken increasing and decreasing the strain.

This kind of behaviour is clearly undesirable in a strain sensor. Fortunately, in many applications the sensor is likely to be directly bonded to the substrate being monitored, or even embedded in the substrate. In this case, the substrate effectively forces the sensing fibre back to its original geometry. This is illustrated in Figure 2 where a similar experiment to that in Figure 1 was carried out but with the grating region of the fibre glued directly to a plastic beam that was then bent to induce the strain. The hysteresis has almost completely disappeared and what remains (as well as the small nonlinearity in the response that is visible) may be due to the visco-elastic properties of the plastic beam used, rather than the sensing fibre.

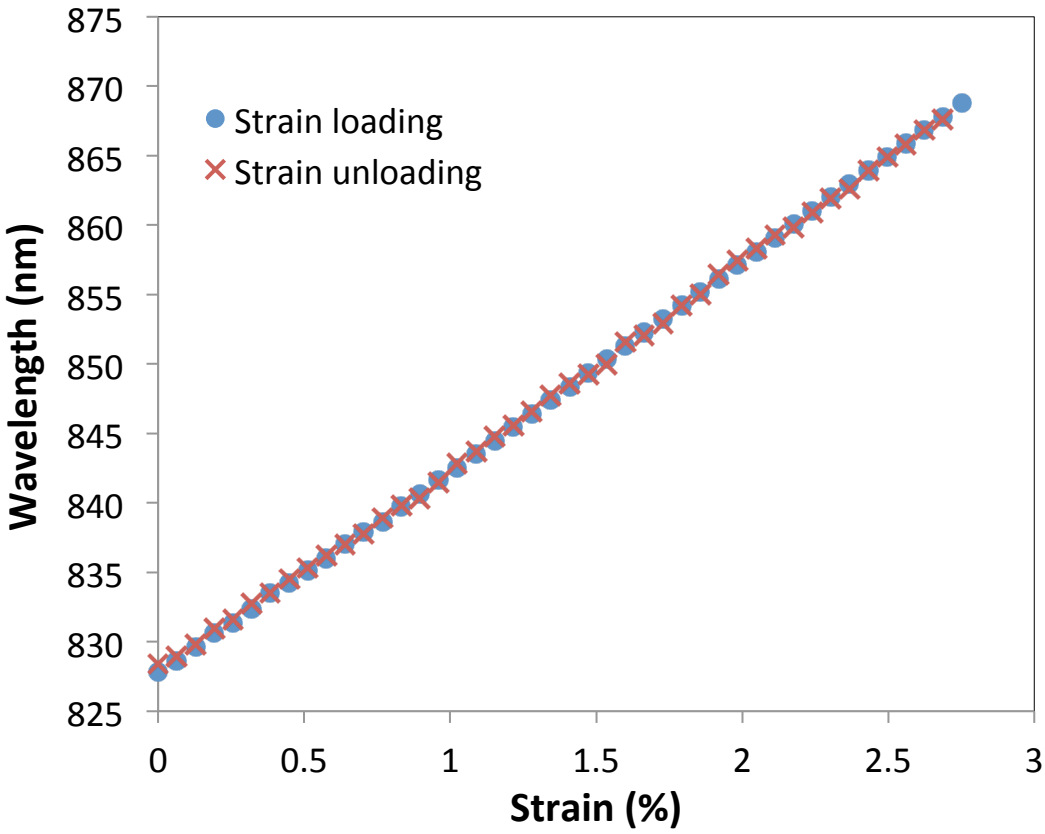

Figure 2 Strain characteristics of POFBG bonded to surface of beam[31].

The performance of POF based strain sensors can be affected in other ways. Annealing the fibre for several days at 95 °C tends to reduce the Young's modulus, the yield point and the tensile strength whilst increasing the failure strain [16]. Annealing the fibre and applying a pretension have also both been shown to reduce the amount of hysteresis exhibited by POF strain sensors[32].

The effects of annealing on the fibre arise as a consequence of the fibre drawing process, in which the tension used to draw the fibre from the oven results in an axial stress being present in the melt zone, which preferentially aligns the long polymer chains along the fibre axis. As a consequence, the drawn fibre is structurally anisotropic, to a degree that depends on the magnitude of the drawing stress. The fibre anisotropy reveals itself in several ways. Firstly, the fibre is birefringent when observed normal to its axis; in one set of experiments, the transverse birefringence of PMMA fibre was observed to increase from $1x10^{-4}$ to $8x10^{-4}$ as the drawing stress increased from 2 MPa to 27 MPa [33]. Secondly, POFBGs display a positive wavelength with pressure that can be explained by the fibre being a transverse isotropic material[34]. Thirdly, thermal expansion along the fibre axis can be smaller than in directions normal to the axis[35]. Annealing the fibre allows the molecules to relax back towards a more isotropic configuration, reducing all these effects. For example, in one experiment with PMMA fibre, annealing at 100 °C for 20 hours reduced the birefringence of fibre drawn under high stress (>20 MPa) by between 55 and 70% [30].

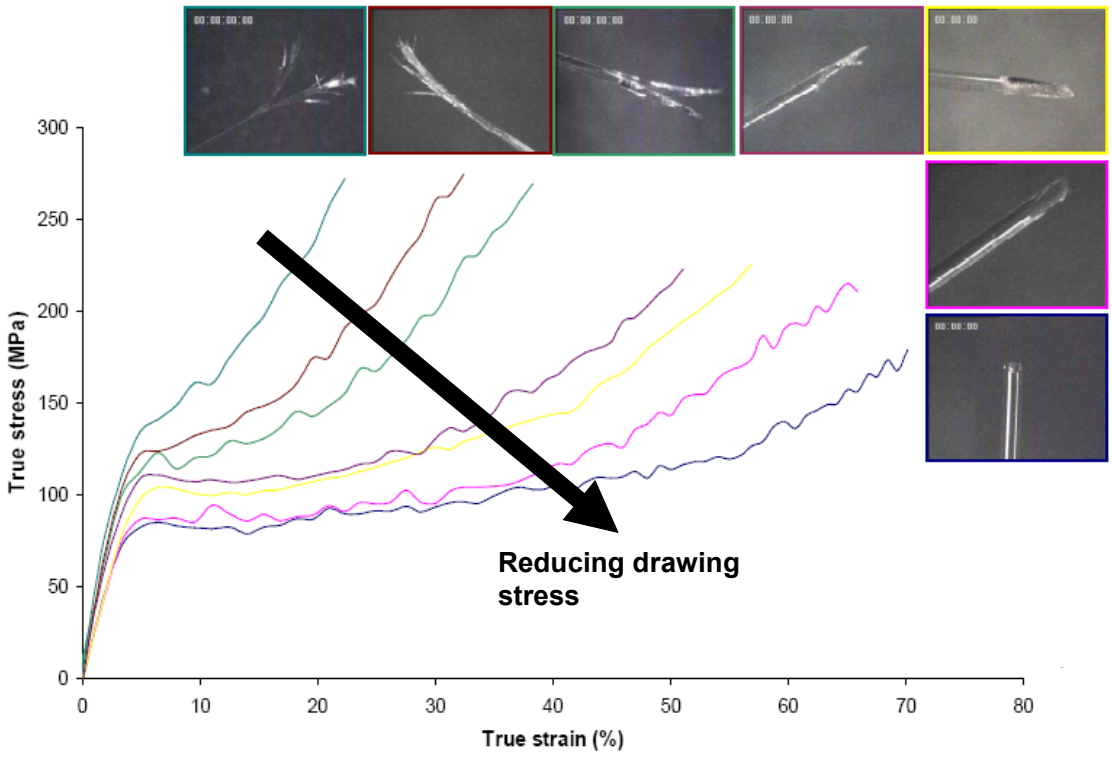

Figure 3 Effect of drawing stress on fibre properties[15].

Controlling the stress in the fibre during the drawing process has a significant effect on the stress-strain behaviour of the fibre, as shown in Figure 3[15]. Here it may be seen that as the drawing stress is reduced (achieved by increasing the oven temperature) the breaking strain increases and the Young's modulus decreases. Another feature is the changing morphology of the fibre end following failure, as shown in the inset photographs. Related to this is the observation in our laboratory that when fibre is drawn under high stress and later cut for connection purposes, the initially smooth fibre end can develop a frayed structure over time, ending up looking like the photographs towards the top left of Figure 3.

A final issue that should be mentioned is that POF has a much smaller usable temperature range than silica fibre, though the 110 °C upper limit reported for gratings in TOPAS fibre [36]should be sufficient for many applications.

3 Photosensitivity and inscription

The techniques used for inscription are essentially the same as those used for silica fibre, which are covered in several review papers cited in the introduction. The vast majority of groups use the phase mask approach, which minimises alignment and stability issues. There are two differences that sometimes need to be taken into account. Firstly, the high loss of POF in the 1550 nm region means that fibre lengths are typically restricted to around 5cm and this may require the construction of a special fibre holding jig for the inscription set-up. Secondly, because the compliant nature of POF, if it is to be suspended horizontally between two supports, as is usual in silica fibre inscription set-ups, it is necessary to tension the fibre, leading to an inscription strain of several tens of mε. This means that following inscription the Bragg wavelength will relax to a lower wavelength than that expected

from the phase mask period. To overcome this problem, a vertical recording geometry can be used, with the fibre supported by horizontal v-grooves[37].

At the time of writing, the photosensitivity that permits the inscription of POFBGs is not fully understood, even if we restrict the discussion to PMMA illuminated by continuous wave UV light. Research on this topic dates back to the early 1970s when work was done on bulk PMMA at Bell Labs. Following illumination with 325 nm light from a HeCd laser, Tomlinson et al. discovered an increase in the refractive index of the polymer[38]. Index changes of over 10^{-3} were obtained, accompanied by a density increase of 0.8% and the group eventually attributed this process to the UV photo-polymerisation of unreacted methyl methacrylate monomers within the material[39], the role of the monomers later being confirmed by Marotz[40]. When relating this early work to current research on POFBGs it is important to keep in mind that whereas gratings in PMMA fibres typically form during UV illumination in a few tens of minutes, the index changes produced by the Bell Labs group developed over a period of a few hundred hours *after* illumination[41]. Furthermore, it was found to be necessary to polymerise the PMMA from monomer that had first been oxidised[38].

In 1984 Kopietz et al. studied the formation of gratings in PMMA induced by a mercury lamp[42]. They supported the role of photo-polymerisation in the inscription process, but also incorporated an initial generation of monomers to explain a *decrease* in refractive index that occurred prior to an *increase* of as much as 0.01. A potential mechanism for the initial generation of monomers is provided by work from Mitsuoka et al., who investigated the photo-degradation of PMMA produced by a range of wavelengths around 300nm[43]. They noted that main chain scission could produce monomer and radical groups. Further evidence for what appears to be a competitive process between photo-degradation and photo-polymerisation is provided by recent work by Sáez-Rodríguez et al. who studied grating inscription in PMMA based mPOF[44]. They discovered a strong correlation between the strain applied to the fibre during inscription and the final grating reflectivity. They suggested this was strong evidence for the role of photo-degradation as the application of stress is known to significantly enhance photo-degradation[45].

There are other reports of grating inscription in the literature which complicate this picture, indicating perhaps that – as with silica FBG inscription – there are several possible mechanisms for photosensitivity, depending on the characteristics of the light source used as well as on the precise composition of the PMMA sample (molecular weight distribution, amount of unreacted monomer, degree of branching, presence of initiators etc.). Wochnowski used mass spectrometry to study the ablated products resulting from exposure of PMMA to UV light with wavelengths from 193 nm to 308 nm and SPS and FTIR spectroscopy to investigate the irradiated samples themselves[46]. They were able to detect side-chain scission at shorter wavelengths but surprisingly did not detect any polymer modification at 308 nm. Working with fibres composed of PMMA doped with benzyl methacrylate, the group of G.D. Peng at the University of New South Wales, Australia, reported studies of grating inscription using a pulsed laser at 325 nm. With an average intensity of 60 mW/cm^2 they observed two regimes: an initial linear increase in index modulation with time up to 60 minutes, followed by a much more rapid increase in modulation[47]. The first regime was characterised by complementary reflection and transmission spectra indicative of low loss, index gratings, while in the second regime losses occurred at wavelengths below the Bragg wavelength and damage was visible in the fibre. A blue wavelength shift of the Bragg peak was visible during inscription, suggesting a decrease in index was taking place. In a second paper, Peng's group

observed radically different behaviour at a lower intensity of 45 mW/cm^2[48]. They reported an increase in reflectivity for 28 minutes after which the reflectivity remained roughly constant up to 48 minutes. The reflectivity then decreased until by 88 minutes there was virtually no reflected signal visible. The UV laser was then blocked and the reflectivity increased over about 8 hours, after which it remained constant.

Recording times for POFBGs in PMMA fibre are typically 10s of minutes, though careful adjustment of the inscription set-up can reduce this to less than 10 minutes[49]. Several groups have explored the use of dopants to improve the photosensitivity. As early as 1971 Laming[50] added p-benzoquinone to PMMA leading to photosensitivity at 488nm; the grating was then fixed by exposure to UV, with an index decrease of 1×10^{-3} being obtained. Peng's group at the University of New South Wales, Australia, have experimented with a number of dopants; for example fluorescein was used to provide sensitivity to light at 488 and 524 nm[51]. Yu et al. have utilised trans-4-stilbenemethanol, which exhibits UV-induced photo-isomerisation[52]. The same group reported the inscription of long period gratings (LPGs) with an index modulation as high as 0.02 using a mercury lamp and fibre doped with methyl vinyl ketone and benzyl methacrylate. Trans-4-stilbenemethanol has been used in the production of an mPOF targeted specifically at LPG fabrication; the dopant was added to the external part of the solid cladding of the fibre[53].

A 10% concentration of benzyl dimethyl ketal (BDK), a photo-initiator, was used by Peng et al.[54] to enhance UV induced photo-polymerisation leading to a positive index change of $4.5\text{x}10^{-5}$, though this index change was nearly two orders of magnitude below that obtained with similarly doped PMMA films[55]. BDK was also used to dope the core of a PMMA based mPOF leading to an index change of $3.2\text{x}10^{-4}$ and allowing a 23dB grating to be written in 13 minutes[56].

The discussion above is limited to UV grating inscription in PMMA based fibre where most of the research on photosensitivity - and its improvement - has taken place. PMMA is not the only polymer that is suitable for fibre manufacture, nor the only one that exhibits UV photosensitivity. A very significant polymer currently being studied is TOPAS, a cyclic olefin copolymer[57][57][57][56][55][54]. This material has good optical properties, is suitable for fibre drawing and exhibits sensitivity to UV light at 325 nm[24]. Importantly, unlike the case with PMMA based fibres, POFBGs inscribed in TOPAS fibre are not significantly affected by the presence of water in the environment surrounding the fibre[58]. A recent development that is of great potential benefit is the production of POFBGs in perfluorinated fibre[59], in which the losses are significantly less than in PMMA. There do not appear to be any studies of the photosensitivity mechanism in TOPAS or perfluorinated PMMA fibre. Finally, it should be noted that "normal" photosensitivity is not required when inscription is carried out using high power, ultra-short (femtosecond) pulse lasers[60]. Inscription by such short pulse lasers may ultimately provide a path to low cost grating fabrication during the fibre drawing[14].

4 Measurand sensitivity

Silica FBGs are directly sensitive to strain induced by an axial stress, pressure induced by isotropic stress, temperature and axial magnetic field (though we will from now on ignore the last, as the effect is quite small[61]). POFBGS are sensitive to the same range of parameters and in addition,

some polymers can respond to the presence of water. This is true of PMMA, which forms the basis of most POF.

4.1 Strain

There is some variation in the reported strain sensitivity of POFBGs. For example, for gratings in the 1550 nm region, values in the literature range from 1.15 pm/με[62] up to 1.5 pm/με[63], though most measurements seem to be in the range 1.3-1.4 pm/με[32]. In comparison, the strain sensitivity of silica fibre FBGs in this region is about 1.2 pm/με[64]. With POF it is straightforward to obtain large strain tuning ranges; for example, 73nm was achieved as early as the year 2000[63].

The much lower Young's modulus of POF compared to silica fibre means that POFBGs are much more sensitive to stress in the fibre and by using a POF etched down to 30 microns Rajan et al. achieved a force sensitivity of 643 nm/N[65], with the added bonus that the inscription time of the grating was significantly smaller than for pristine fibre[66] (Hu et al. have noted that even a slight amount of etching can have a significant effect on fibre inscription time[67]). Finally we note that single mode POFs fabricated in research labs often have somewhat variable fibre parameters, with the diameter fluctuating along the fibre length and the core sometimes being off centre. This latter feature has been used to advantage as it renders the fibre intrinsically sensitive to bending, which induces a strain in the off-centre core[62].

Straining the fibre during the inscription process can be used to record gratings at different wavelengths using a single phase mask; in one study a useful strain range of 0.9% was obtained allowing gratings to be produced over a 12nm range[68].

4.2 Temperature

Whilst the literature shows broad agreement over the strain sensitivities of POFBGs, there is a much greater range of reported values when it comes to temperature. In part this is because in the early days of the technology, many measurements were made in the open laboratory environment where the humidity was not controlled leading to cross sensitivity issues. In such experiments, sensitivities as high as -360 pm/°C have been reported [69].

Over a sufficiently small temperature range to ensure a linear response – and in the absence of cross-sensitivity issues – the shift in the Bragg wavelength of an FBG is given by [56]

$$\Delta\lambda_B = \lambda_B(\alpha + \xi)\Delta T \qquad (2)$$

where $\Delta\lambda_B$ is the Bragg wavelength shift, ΔT is the temperature change, λ_B is the Bragg wavelength, α is the thermal expansion coefficient and ξ is the thermo-optic coefficient. In the case of silica fibre, both coefficients are positive, ensuring a positive wavelength shift with temperature. For polymers, ξ is negative so that the sign of the wavelength shift depends on whether refractive index change dominates over thermal expansion. Normally this is the case; in fact there is only one report of a (small) positive thermal sensitivity for a POFBG [70]. The sensitivity depends on the humidity environment of the fibre, with Harbach [21] reporting values ranging from –10±0.5 pm/°C under dry conditions to –36±2 pm/°C in water for a grating of nominal wavelength 1545 nm. The precise value is also fibre dependent, for example Zhang et al. [71] have reported a sensitivity of 55pm/°C at a constant 50% relative humidity, also for a grating in the 1550 nm region. Gratings fabricated in

TOPAS based fibre, which is water insensitive show a similar thermal sensitivity, with -37 pm/°C being reported for a grating recorded at 1568 nm[24].

Annealing of the fibre, either pre- or post-inscription, has a significant effect on the thermal sensitivity. In one experiment a grating inscribed in pristine fibre exhibited a reversible temperature response from room temperature only up about 55 °C [72]. Beyond this temperature there was a rapid and permanent reduction in the Bragg wavelength associated with a reduction in the fibre length. By annealing the fibre, a repeatable working range up to over 80 °C was obtained, though by this stage the room temperature Bragg wavelength had reduced by almost 20 nm from that before annealing. This annealing process has been used to tune the Bragg wavelength, enabling a wavelength multiplexed sensing system with three gratings to be fabricated using just one constant period phase mask [73].

4.3 Water

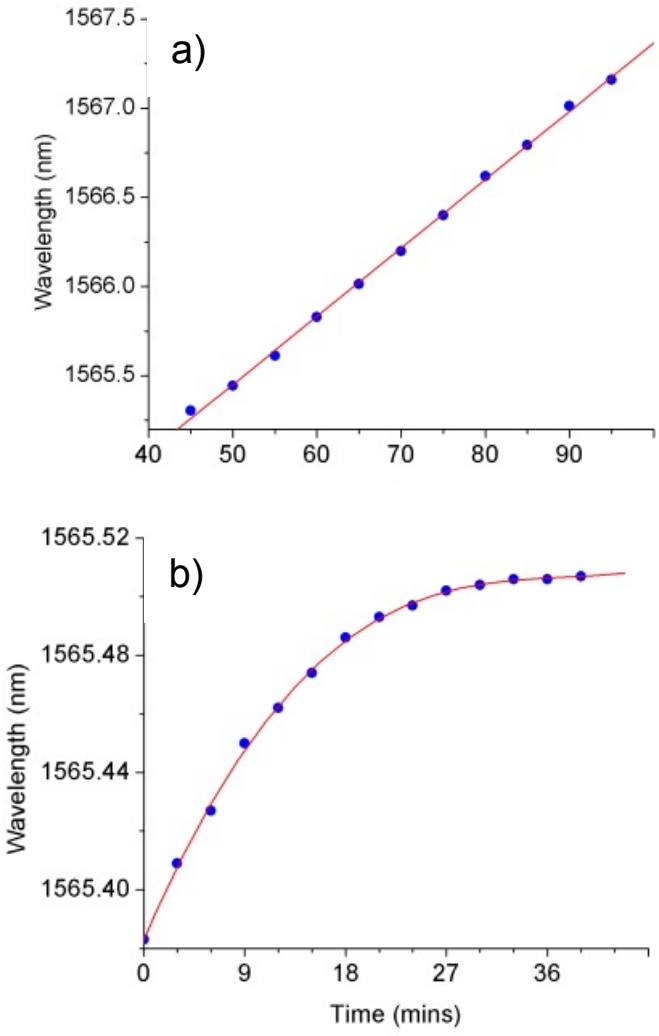

Figure 4 Humidity response at 22 °C of a POFBG recorded in PMMA based fibre. a) Wavelength shift. b) Response time.

As previously mentioned, PMMA has an affinity for water, the absorption of which causes the fibre to swell and the index to rise, both leading to a positive shift in the Bragg wavelength [21]. This renders PMMA based POFBGs sensitive to humidity as shown in Figure 4, but POFBGs are also sensitive to aqueous solution concentration [22] and even water dissolved in aviation fuel [23].

The dependence of the Bragg wavelength on humidity is linked to that on temperature. For the Bragg wavelength shift arising as a result of a change in humidity ΔH and a change in temperature ΔT we can write [74]

$$\Delta\lambda_B = \lambda_B(\eta + \beta)\Delta H + \lambda_B(\xi + \alpha)\Delta T \quad (3)$$

where η is the normalized dependence of refractive index on humidity and β the swelling coefficient related to humidity induced volumetric change (% RH)$^{-1}$ (the other coefficients having been defined in equation 2). Complications arise because η and β are not constants. The former decreases approximately linearly with increasing temperature while the latter is independent of temperature, but only constant in the region 40-100% RH, decreasing below that range. Adding to this complexity is the fact that because the humidity response is partly due to water induced fibre expansion, it is also affected by any strain that is applied to the fibre [74].

As shown in Figure 4, the nominal response time of POFBGs to humidity tends to be a few tens of minutes. This does vary significantly from fibre to fibre, which is probably related to the differing molecular weight distributions of the fibres. Significant improvements to the response time have been achieved by etching down the fibre using acetone. Zhang et al. were able to improve the response time of one fibre from 31 to 12 minutes by reducing the diameter from 190 to 135 microns [75]. The authors noted a correlation between the rate at which the fibre was etched by the acetone and the response time to humidity and suggested that both were enhanced by a less tightly connected molecular structure. More recently Rajan et al. [76] etched a POFBG down to a diameter of just 25 microns, leading to a response time of just a few seconds.

It is important to note that the response of a POFBG to water in the surrounding environment is not directly related to the total *amount* of water present but rather to the water *activity* [77]. The water activity is defined as the fraction of the maximum water content in the surrounding medium, so the water activity is equal to 1 if the surrounding medium is fully saturated with water. If the surrounding medium is air, then the water activity is equal to the relative humidity, with 100% relative humidity corresponding to a few percent of water by mass at room temperature. If the surrounding medium happens to be aviation fuel then a water activity of 1 at room temperature corresponds to a few tens of parts per million. Both situations would lead to similar shifts in Bragg wavelength compared to a completely dry environment and for this reason POFBGs can provide a very sensitive measurement of water content in media that dissolve very little water. For example, with a POFBG operating in the 1550nm region in air, a change in relative humidity of 50% results in a shift in Bragg wavelength of around 2 nm at room temperature [74]. A 50% change in the dissolved water content of aviation fuel produces the same wavelength shift [78].

5 Applications

5.1 Practical concerns

In this section we focus on applications proposed for POFBGs, where the particular properties of polymers offer some advantage over the use of the better-established silica technology, but first we will discuss some of the practicalities involved in POFBG usage. Some things are on the face of it trivial and yet turn out to be important in handling POF. For example, silica fibre is either in one piece and functional or it is broken, whereas it is possible to snag a piece of single mode POF so that it remains unbroken but may have a sharp bend induced in it that prevents light guidance.

At the moment it is almost always necessary to connect POFBGs to a silica fibre lead, either because of the relatively high fibre losses of POF or in order to connect to a single mode coupler or a pigtailed source, which are only available with silica fibre. There is not yet a POF equivalent of the silica fibre splicer; instead it is necessary to either glue the fibres together[79] or connectorise the fibre[29, 80]. As previously noted, single mode POF samples made in research labs sometimes do not have a concentric core, making the glued connection the only option in this case. Finally, it should be noted that POF cannot be cleaved like silica fibre; instead it must be cut and studies have investigated the optimum approach for this, involving control of the fibre and blade temperature[81, 82].

5.2 Tuneable filter

The first application suggested for POFBGs made use of the wide strain tuning range that can easily be achieved with POF. A grating in PMMA based fibre was used as a mirror in a fibre laser system, where a tuning range of more than 35 nm was obtained in the C band with an applied strain of just under 2.5%[83]. The enhanced temperature sensitivity of POFBGs was also later exploited to produce a thermally tuneable filter[84]. A POFBG was coated at room temperature with a Pd/Cu film to permit electrical heating, with a sensitivity of -13pm/mW and a response time of 0.6 seconds being obtained for electrical powers up to 160. It has also been shown that the high absorption of POF in the 1550 nm region can permit optically induced temperature tuning of gratings[85].

5.3 Compliant structures

As mentioned earlier, when FBGs are used to monitor structures composed of low elastic modulus, POF sensors provide a truer representation of the strain in the material silica sensors, where the effect of the stiff fibre is to locally reinforce the structure. The first of such an application came from a project developing sensors for monitoring historic comparison was carried out on a representative textile sample, where POFBGs and silica glued to the sample using two types of glue: Araldite epoxy resin and DMC2 a compliant

used in the conservation industry [20]. As may be seen in

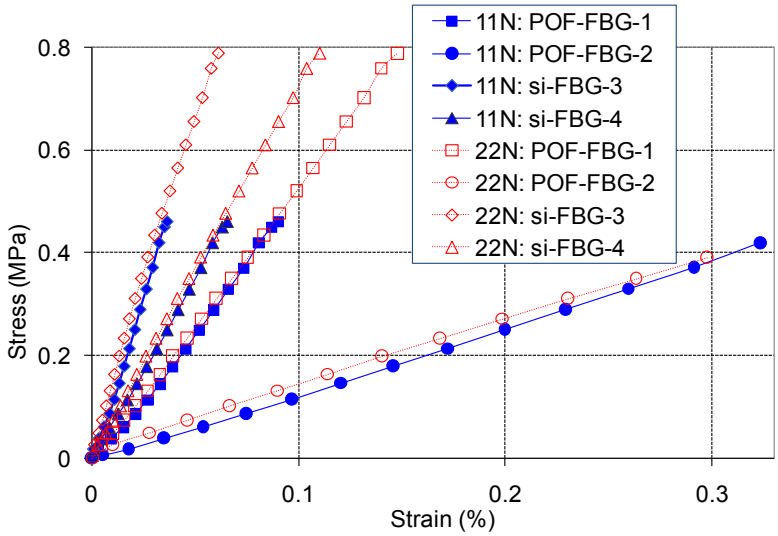

Figure 5, for a given stress, by far the highest strain is recovered by POF-FBG-2, a PMMA based sensor glued using DMC2.

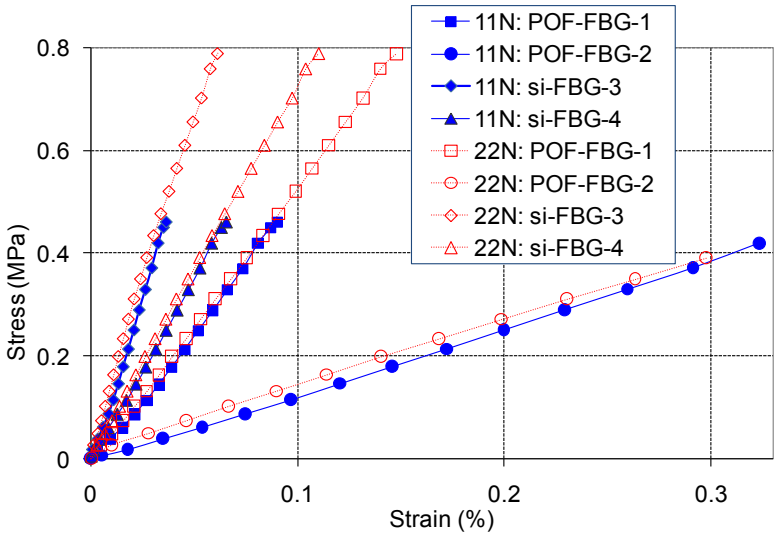

Figure 5 Stress strain curves for silica and POF gratings glued to a textile sample and subject to loads up to 11 N and 22 N [20].

A further graphic example of the ability of POFBGs to monitor compliant structures was brought out in an experiment in which silica and POF Bragg gratings were embedded in thin sheets of poly dimethyl siloxane (PDMS) [86]. With the sheets lying on a flat horizontal surface a small weight was translated along the sheets directly above the fibre, with the response being shown in Figure 6. It may be seen that the POFBG experiences approximately 10 times the wavelength shift of the silica FBG, despite the intrinsic strain sensitivities of the fibre being comparable.

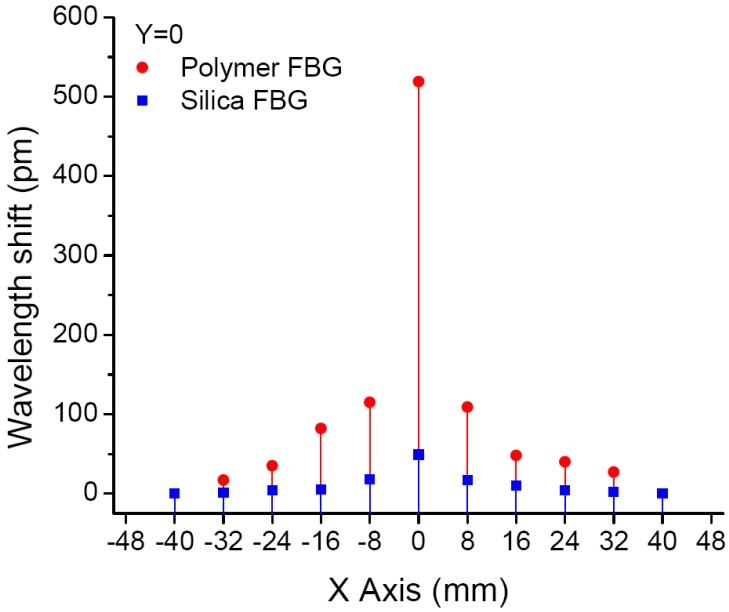

Figure 6 Comparison of the response to a weight translated over FBGs recorded in silica and POF and embedded in a PDMS sheet[86].

It has been shown that POFBGs can survive being embedded into composite materials. In one study, measurements of both the Bragg wavelength and the spectral width of the grating permitted discrimination between the temperature and the thermal expansion of the composite structure[87].

5.4 Dynamic strain sensing

The two previous examples concern the response of POFBGs to quasi-static strain. The low elastic modulus of POF suggests they may have advantages for use in dynamic applications, e.g. as acoustic sensors or accelerometers, however the viscoelastic nature of POF means that some caution must be exercised. Stefani et al studied both PMMA and TOPAS fibres, concluding that for dynamic strains up to 0.28% the Young's modulus was constant up to a frequency of 100 Hz – the limit of the measurement equipment – with very little sign of viscoelasticity [88]. The authors demonstrated an accelerometer with a flat frequency response to over 1 kHz, capable of sensing up to 15g and with a sensitivity 4 times that of an equivalent silica FBG[89].

Gallego and Lamela have explored the potential for POF based sensors to detect ultrasound for medical applications, finding a POF based interferometer offered an intrinsic phase sensitivity about 15 times greater than an equivalent silica one[90]. Marques et al. investigated the use of acoustic waves launched onto a fibre to modify the spectral profile of a grating filter inscribed in the fibre.

They found in both simulation and experiment that there was a much higher strain level in the POF compared to an equivalent silica system[91].

5.5 Water

As mentioned earlier, POFBGs recorded in PMMA based fibre respond to the water activity of the surrounding medium, displaying for example a strong dependency on the relative humidity of air. This property makes them sensitive to the concentration of any aqueous solution surrounding the fibre. Essentially an equilibrium is set up, balancing on the one hand the water affinity of the polymer and on the other the osmotic pressure of the surrounding solution, which seeks to draw water from the fibre. The dependence of the Bragg wavelength on the concentration of sugar and salt[22] solutions have both been demonstrated. An example of the latter is shown in Figure 7, where it may be seen firstly that significant changes in Bragg wavelength occur with varying concentration, and secondly that the process is reversible, with any small differences being consistent with the temperature stability of the laboratory.

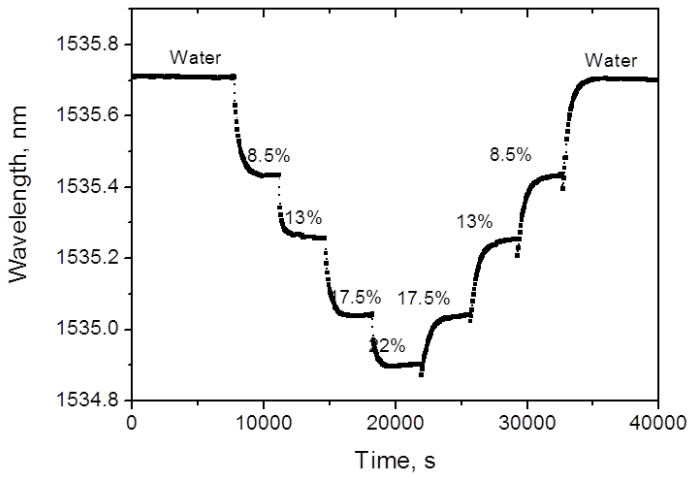

Figure 7 Bragg wavelength versus concentration of saline solution for a POFBG inscribed in PMMA based fibre[22].

The aviation industry places great emphasis on the minimisation of the amount of water in aircraft fuel tanks, since free water acts as an incubator for anaerobic microbial contamination and when frozen can in extreme circumstances block the fuel system. Water exists in a fuel system either dissolved in the fuel or else as free water lying at the bottom of the fuel tank or as an emulsion suspended within the fuel. Water can enter the fuel system in solution but as the temperature falls, the fuel can become saturated with water, after which the water condenses out as free water. The saturated water content is very low in absolute terms, e.g. about 70 ppm at room temperature[92], but as this represents a water activity of 1, it nevertheless results in a significant Bragg wavelength shift. Figure 8 shows the measured dependence of Bragg wavelength shift versus water content for a grating with a nominal wavelength of 1532 nm. It may be seen that the sensor benefits from a linear response.

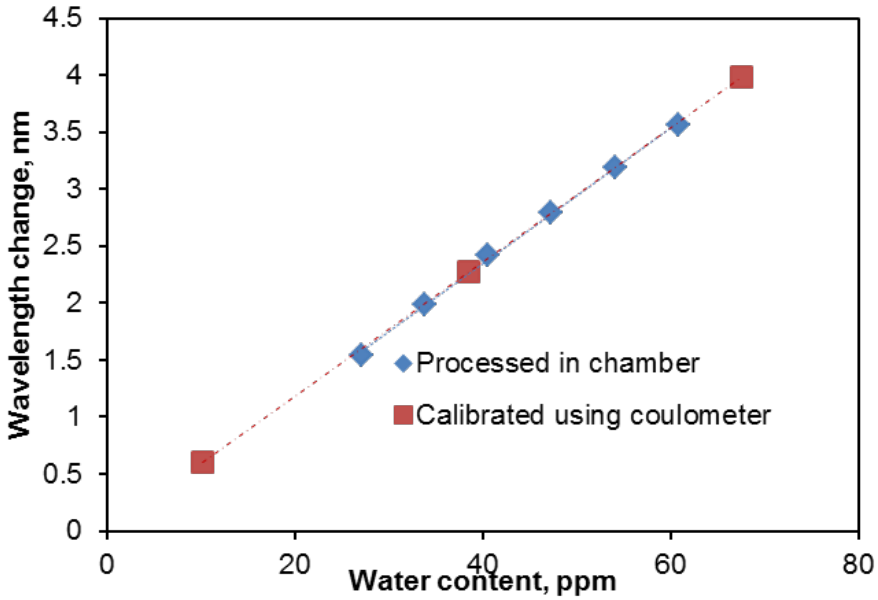

Figure 8 Bragg wavelength shift vs water content in Jet-A1 for a grating with a nominal wavelength of 1532 nm.

The fact that PMMA POFBGs are sensitive to humidity while silica FBGs are not,, coupled with the different signs of their temperature sensitivities has been used to good effect in a combined humidity and temperature sensor, in which a silica FBG and a POFBG were juxtaposed either side of a glued connection between the two fibres. Measuring the wavelength shifts from both gratings allows the temperature and humidity to be recovered in a well-conditioned manner [71].

6 Conclusion

POFBGs are of increasing interest due to the different material properties of their constituent fibre compared to silica. There remain however a number of challenges that are still to be addressed:

- Understanding the mechanisms for photosensitivity and optimising these – perhaps by the inclusion of photosensitising dopants
- Optimising sensor performance and creating sensors with reproducible characteristics by controlling all stages of the sensor production process – polymerisation, fibre drawing, annealing and inscription
- The lack of a ready source of single mode fibres and components along with the absence of a polymer equivalent of the fusion splicer

There are an increasing number of research groups around the world currently tackling these problems.

7 References

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