Front. Optoelectron. China 2010, 3(1): 99–102
DOI 10.1007/s12200-009-0082-0

RESEARCH ARTICLE

Impact of polymer material properties on microstructured optical fibres

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Abstract Polymer optical fibres (POFs) have historically been regarded as a poor relation to their silica counterparts because of their higher attenuation, but they also have a number of advantages, particularly when coupled with a range of properties that can be produced using microstructures. In terms of their mechanical properties, they are lighter, remain flexible at large core sizes and can be stretched well beyond 30% without breakage. They are also biocompatible, they do not produce dangerous shards, and their low processing temperatures allow functionalized organic materials to be incorporated without decomposition. Other advantages for specific applications include better transmission properties (in the THz region) and the possibility of refractive indices that are close to that of water.

Keywords microstructured optical fibres (MOFs), microstructured polymer optical fibres, photonic crystal fibres (mPOFs), strain sensing, THz waveguides

1 Introduction

The field of microstructured polymer optical fibres (mPOFs) is now sufficiently developed that it is possible to begin to assess the areas where it is most likely to have a technological, and perhaps ultimately a commercial, impact. These may be applications in which the use of polymer allows us to do something better than is possible with other materials, or applications that would simply not be possible at all otherwise.

Generic advantages of polymers are the wide range of processing options for making performs (including casting, drilling, stacking extrusion) which allow us to produce a very large range of structures quite easily and the possibility of incorporating other materials into the polymer [1,2]. The lower processing temperatures of polymers (about 250°C rather than 2000°C for silica) make it possible to incorporate organic dopants, which degrade beyond 400°C. This opens up a design space substantially larger than any previously explored. Dopants that have already been used include chiral species for circularly birefringence, organic dyes and quantum dots for lasing and amplification.

In this paper, we explore three applications in which more specific polymer properties are brought to bear, and show how these are likely to have technological impact. Three such applications are explored in this article: mechanical strain testing using Bragg gratings in single-mode mPOF, biosensing, and waveguides for THz radiation.

2 Strain testing

One of the simplest examples where the use of polymer makes a new application possible is strain testing. The advantage brought by using polymer is simply that they can withstand much larger strains, compared to glasses. By far the most commonly used polymer for making optical fibres is polymethylmethacrylate (PMMA). PMMA has an elastic limit of 10% compared to 1% in silica and can withstand strains more than 30% without breakage. The Young's modulus of PMMA is in the range 2.5–3.3 GPa compared to 72 GPa for silica, a difference of more than an order of magnitude [1].

Polymer optical fibres (POFs) have begun to find applications in mechanical testing where a large dynamic range is required, such as for breathing or structural health monitoring [3–6] and the measurement of very high strains to measure subsidence or for earthquake monitoring [7]. However, these sensors have been hampered by the difficulty in obtaining single-mode fibres, which make it impossible to use the simplest interrogation method—fibre gratings. Interferometric studies have been made of

Received August 1, 2009; accepted October 15, 2009

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PMMA-based single-mode POF [8], up to strains of 15.8%, but the attenuation of these fibres was extremely high. By allowing the easy fabrication of single-mode POF with relatively low loss (about 1 dB/m), the microstructured approach has made it straightforward to produce Bragg and long-period gratings (LPGs) that operate in the visible. These have already been used to test fibres at strains above 15%. Strain results using an LPG in an mPOF can be seen in Fig. 1, in which the strain removed rapidly after application. There is a small deviation from linearity at higher strains[1].

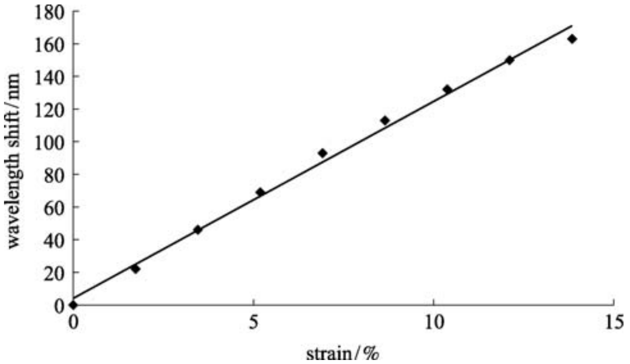

Fig. 1 Strain results using an LPG in an mPOF

Preliminary studies [9] show that the use of polymer fibre increases the range of repeatable strain measurements by several times and the yield limit by an order of magnitude, compared to a silica-based sensor. The visco-elastic properties of the polymer mean that there are time-dependent effects relating to strain rate and magnitude. These effects are small when the sensor is intermittently strained up to 2%, and are relatively small at strains of up to 4%–5%. Further testing is ongoing to characterize these effects at very high strains. The stress relaxation has a small effect on the change in the wavelength of the loss features used in the measurement of strain.

The use of high strains complicates response of the sensor due to the visco-elastic properties, requiring careful calibration; this technology is the only one that feasibly allows the development of fibre strain sensors that can operate at strains of up to 30%–45%. These are very high strain sensors that are currently being developed.

3 Biosensing

One area that is likely to be of increasing importance is biosensing. Biosensing covers a huge range of possibilities from environmental sensing (e.g., water quality) to health monitoring. To this vast field, optical fibres bring an important capability: the possibility of having miniature sensors that can operate remotely or *in vivo*. There are a variety of ways that this kind of sensing can be done. The ranges of structures and fabrication techniques available in microstructured fibres, but particularly in mPOF, have enormously extended the range of possibilities. It is relatively easy to fill the holes with solution, including in the core where the overlap of the fluid and the optical field can be made close to 100%. For surface-sensitive effects, the potential is even greater, as the surface area/volume ratio is exceptionally high, and the evanescent field can be optimized through the fibre design. It is also possible to make robust side-hole fibres (as shown in Fig. 2 [10]) that make all rapid contact of the fluid with the core possible and allow the core surface to be manipulated.

Exposing the core of the fibre in this way has made it possible, for example, to sputter a high-quality metallic film on the core interface. We have exploited this in order to develop a surface plasmon resonance (SPR) sensor. SPR is a technique whose principal virtue is its exceptional surface sensitivity. While this is powerful in terms of analysis, it also makes it unusually demanding in terms of the quality of the deposited metal surface. Sputtering is one of the few suitable techniques that reliably give suitable films, but clearly, it cannot feasibly be used for coating along the length of enclosed holes.

This is not the only challenge in making a fibre SPR sensor. Coupling between the plasmon and the optical field requires that the wave vectors are matched. Where this coupling occurs, energy is coupled from the optical mode into the plasmon, and a transmission dip is observed in the optical signal.

The effective index of the plasmon is dominated by the index of the material to be sensed, normally dominated by water for biological samples. This results in an effective index that is typically much lower than that of the fundamental optical mode, which is dominated by the material of the fibre (i.e., glass or polymer).

Approaches that have been explored to address this problem include air holes in the fibre core to lower its average refractive index or the use of low index coatings. The use of polymers, however, enables a much simpler solution. Transparent fluorinated polymers are available with refractive indices that are close to water, such as cyclic transparent optical polymer (CYTOP), which has a refractive index of 1.34[2] This enables efficient coupling between the optical field and the surface plasmon for a sensor used in aqueous solutions (for other polymer examples, see Ref. [11]). No optical glass has a refractive index that is comparably low.

The usual fibre-SPR configurations include the use of fibre tapers and D fibres to allow coupling to the evanescent field. Microstructured optical fibres offer

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1) Large M C J, Blacket D, Bunge C A. Microstructured polymer optical fibres compared to conventional POF: novel properties and applications. 2009

2) A highly innovated fluoropolymer. http://www.agc.co.jp/english/chemicals/shinsei/cytop/cytop.htm

wider possibilities because their much larger parameter space of design allows optimization of evanescent field and mode tailoring while maintaining a physically robust system. Theoretical studies of SPR in microstructured fibres are conducted, as these give more control of the optical properties and better mechanical integrity [12,13]. However, the problem of coating the holes is challenging not simply because of the previously noted problem about the quality of the films. Loss is always an issue in these sensors because of the inclusion of metals, so the desirable coated lengths are of the order 1 cm.

We have recently demonstrated the first mPOF SPR sensor [14]. The sensor is based on the side-hole approach shown in Fig. 2. This allowed us to coat a small exposed section of the core with a high-quality gold surface. By doing this in a polymer fibre, we created a sensor that is not physically fragile and will not produce harmful shards. Another important advantage is that the fabrication process can easily be scaled up for mass production.

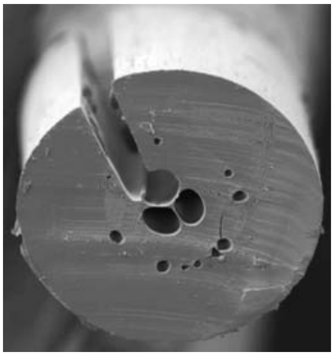

Fig. 2 Side-hole fibre, allowing direct access to the core [10]

The preliminary results of this sensor are encouraging. While there is certainly room for optimization (both of the design and the fabrication), a potential route to enhanced sensitivity has been identified. Over the short lengths of fibre used in our SPR sensor, the fibre was few moded. Two of the modes were close enough in effective index to couple relatively easily (as shown in Fig. 3 [14]). Intermodal beating of this kind is extremely sensitive to changes in the system, making it possible to dramatically improve the sensitivity of the sensor.

4 THz transmission

Polymers have higher attenuation than silica in almost (but not quite) all regions of the electromagnetic spectrum. An important exception is the THz region. This region of the spectrum is of increasing interest given that common packaging materials are transparent in this region, while metals reflect strongly, and many drugs and explosives have distinct spectral signatures. The THz region sits between those of optics and microwaves, and shares some features of both. As in the microwave region, the electric field can be detected rather than simply the intensity, enabling phase to be measured. The wavelengths are sufficiently small that they enable relatively simple imaging, without any health concerns (as in optics).

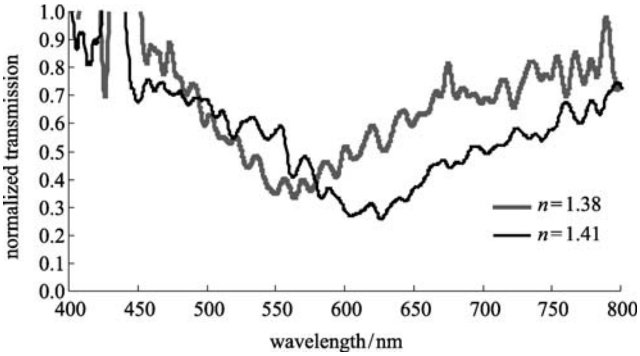

Fig. 3 Normalized transmission data for SPR sensor when exposed to different analytes (extended dip is the normal SPR loss feature; ripples are due to beating between the two lowest order modes) [14]

However, guiding THz radiation is far more problematic than in optics. Thus, despite the variety of important security, forensic and medical applications, THz waveguides have not been developed to a point where they are useful. Indeed, in many ways, THz is an unexplored region of the electromagnetic spectrum, which may yet yield phenomena aside from the applications that are motivating current research.

Fibres offer potential solutions to producing THz waveguides, but there are also important challenges. Firstly, hollow-core or photonic bandgap THz waveguides would need to guide radiation over a large range of frequencies (10–100×, compared to approximately 4× for vis/IR), and the much larger wavelengths (up to 3 mm) would need to be guided in a waveguide that is thin enough to remain flexible. This size constraint is a reason for believing that polymers are a more likely solution since large glass waveguides are inherently less flexible and more brittle.

Preliminary results identified four higher-transparency polymers, with material absorptions of order 100 dB/m. These are CYTOP, polytetrafluoroethylene (Teflon), high-density polyethylene (HDPE) and cycloolefin polymer (Zeonex) [15]. The microstructured THz waveguides fabricated so far are simply scaled-up versions of existing designs, operating at the longer wavelengths of THz radiation with no further considerations taken into account. Several designs with a solid polymer core have been demonstrated [16–18] or proposed [19,20], as well as a hollow-core example [21]. The solid-core waveguides achieved losses in the range of 50–400 dB/m, and the hollow core achieved a loss of 90 dB/m, significantly lower than the > 6000 dB/m material absorption; the propagation lengths were limited to centimetres. These preliminary results represent the huge potential given what has been achieved with MOF/mPOF at optical wavelengths.

This work is in a very early stage of development, but extrapolating from the results of microstructured fibres in the optical regimes suggests that losses of 0.01 dB/m could be possible. This would be a dramatic improvement on the current best case of a THz waveguide (1 dB/m using a rigid metal-coated glass capillary).

Acknowledgements This work was performed in part at the Optofab node of the Australian National Fabrication Facility (ANFF) using Commonwealth and NSW State Government funding. ANFF was established under the National Collaborative Research Infrastructure Strategy to provide nano and microfabrication facilities for Australia's researchers.

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