Thermal response of Bragg gratings in PMMA microstructured optical fibers

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Abstract: We report on the thermal characteristics of Bragg gratings fabricated in polymer optical fibers. We have observed a permanent shift in the grating wavelength at room temperature which occurs when the grating has been heated above a threshold temperature. This threshold temperature is dependent on the thermal history of the grating, and we attribute the effect to a shrinking of the fiber. This effect can be avoided by annealing the fiber before grating inscription, resulting in a linear response with temperature and an increased linear operating temperature range of the grating.

OCIS codes: (050.2770) gratings; (160.5470) Polymers; (060.2340) Fiber optics components.

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1. Introduction

In the last few years, fiber Bragg gratings (FBGs) in polymer optical fiber (POF) based on polymethylmethacrylate (PMMA) have been reported in both step index [1],[2] and microstructured fibers [3]. Gratings made in these single mode fibers are of particular interest

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as they have the potential to offer low cost sensing solutions. The chemical composition and comparative ease of fabrication compared to silica fiber offers the possibility of chemical modification. In addition, polymers are clinically acceptable which, along with the flexible, non brittle nature of the fibers, makes these gratings an important candidate for in-vivo sensing applications. Gratings in step index POF with a core doped with ethyl and benzyl methacrylate have already been demonstrated as tunable filters [1, 4] where the temperature response of the gratings would also have to be very well understood before making a commercial product. The temperature sensitivity of the gratings in these step index POFs has been studied previously [5,6] revealing a negative temperature coefficient of between -146pm/°C and -360pm/°C; significantly larger in magnitude than that observed for FBGs in silica fibers, which is around 10pm/°C. This increased sensitivity means that the thermal properties of gratings in POF are of particular interest. In this paper we report on a preliminary investigation into the temperature response of gratings in POF at higher temperatures, revealing a different behavior than previously reported [5,6]. We also show how the working temperature range of the sensors can be extended using an annealing process. The gratings in this study were fabricated in pure PMMA single mode microstructure POF (SMmPOF).

2. Experimental method

The gratings were fabricated in pure PMMA SMmPOF with flat sides, shown in Fig. 1. The flat sided fibre was intended to help with alignment during grating fabrication, but no improvement was noted over cylindrical fiber. The fiber was fabricated as described in ref. 7 with the omission of the sleeving step; the sides of the preform being milled off after the holes had been drilled. The fiber has an outside diameter of 150µm (round edges) and 115µm (flat edges) and a core diameter of 14.6µm; the core being surrounded by 60 air holes with diameters (d) of 2.6 µm and a separation (Λ) of 8.6 µm [7] giving d/Λ=0.3.

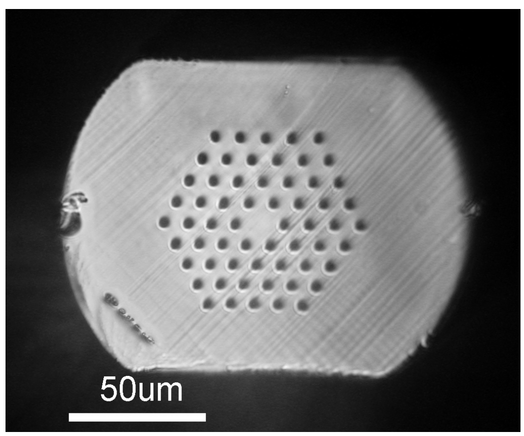

Fig. 1. Microscope image of cross section of the SMmPOF

The gratings were inscribed using a 30mW cw HeCd laser operating at 325nm. The fiber was supported along its entire length by a v-groove during inscription to ensure that the fiber did not sag. A static beam with a width of 1.8mm was focused vertically downwards using a 10cm cylindrical lens to expose the fiber through a phasemask of uniform period 1057.2nm, the grating length being defined by the beam width. The laser irradiance at the fiber was $2MWm^{-2}$ and the exposure time was 50 minutes. The resulting grating wavelengths were around 1562nm.

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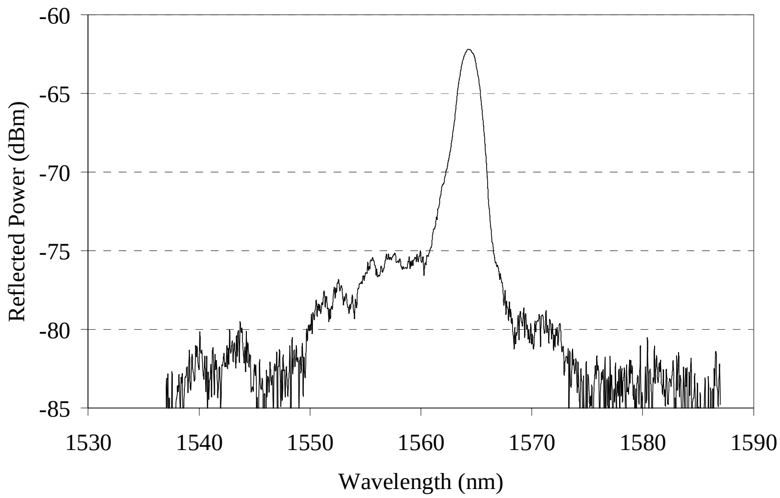

Fig. 2. Reflection spectrum of a grating fabricated in SMmPOF FWHM = 2.2nm.

The gratings were monitored in reflection during inscription using a silica fiber 50:50 coupler, broadband light source (BBS) and optical spectrum analyzer (OSA). The silica monitoring arrangement was butt-coupled to the POF using an FC/APC connector and a very small amount of refractive index gel, in order to reduce Fresnel reflections yet minimize the amount of gel drawn into the holes of the fiber by capillary action. The ends of the SMmPOF were prepared using the hot cleave method [8]. Short lengths of fiber (<10cm) were used due to the high attenuation of PMMA which increases from ~50dB/m at 1530nm to ~100dB/m at 1590nm. The reflection spectrum of a grating fabricated in SMmPOF is shown in Fig. 2. Perhaps due to the high loss at this operating wavelength, we were not able to monitor the gratings in transmission. The grating strength was estimated by taking into account the loss of the fiber and comparing the level of the reflected grating peak to the Fresnel reflection from the far end of the fiber. The grating strength was found to be between ~2-4.5dB, yielding a refractive index modulation of between $2x10^{-4}$ and $3x10^{-4}$.

The temperature response of the gratings was studied by heating the grating section of the polymer fiber. The heating rig is shown in Fig. 3 and was positioned between 2 Melles Griot v-groove blocks, which were used to support the polymer fiber. The grating was positioned between the v-grooves, ensuring that there was no contact between the metal and the grating. The width of the gap between the v-grooves for the heating rig was 5mm. The temperature of the region around the polymer grating was monitored using a temperature calibrated silica fiber Bragg grating of the same length as the POF grating. Care was taken that neither grating was strained during the tests, ensuring that any wavelength shift observed was due to temperature alone.

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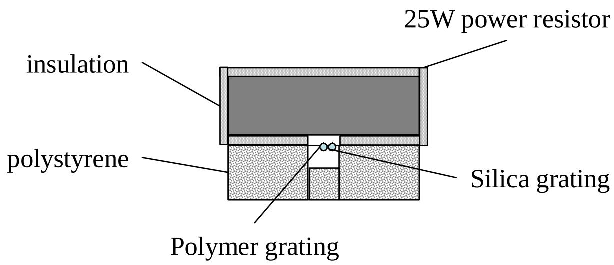

Fig. 3. Heating rig which is positioned between two v-grooves

The same monitoring set up was used as during the grating inscription. Ten minutes was allowed for the temperature to stabilize at each new setting before readings were taken. The first grating was cycled 3 times, returning to room temperature after each cycle. The first cycle took the temperature to 77°C, the second to 86°C, and the third to 92°C. The variation in the Bragg wavelength of the grating with temperature for each cycle is shown in Fig. 4. The results show a significant shift in the wavelength of the grating at room temperature once the grating is taken above the region of near linear response. This quasi-linear region extends to higher temperatures with each cycle (approximately equal to the maximum temperature of the previous heating cycle). Though we have referred to a quasi-linear response and fitted a straight line to this region, showing the approximate temperature sensitivities of each cycle, the response in the low temperature region for each cycle is in fact nonlinear with the greatest sensitivity at low temperatures. The deviation from the linear response is shown in the inset of Fig. 4 and there is a suggestion that the wavelength vs. temperature response at lower temperatures becomes slightly more linear after each heating cycle. In the case of the first heating cycle, the wavelength begins to rapidly decrease with temperature between 60 and 65°C. The hysteresis observed in the Bragg wavelength at 23°C between the first and second cycles is -8.4nm. The wavelength of the grating in the second heating cycle does not begin to rapidly decrease with temperature until 76°C, close to the maximum temperature of the first cycle. The hysteresis observed at 23°C between the second and third cycles is -10.1nm. The wavelength response of the grating with temperature in the 3rd cycle followed the same trend displayed in the second cycle, with the response remaining linear, with a sensitivity of -77pm/°C, until the maximum temperature of the second cycle was reached.

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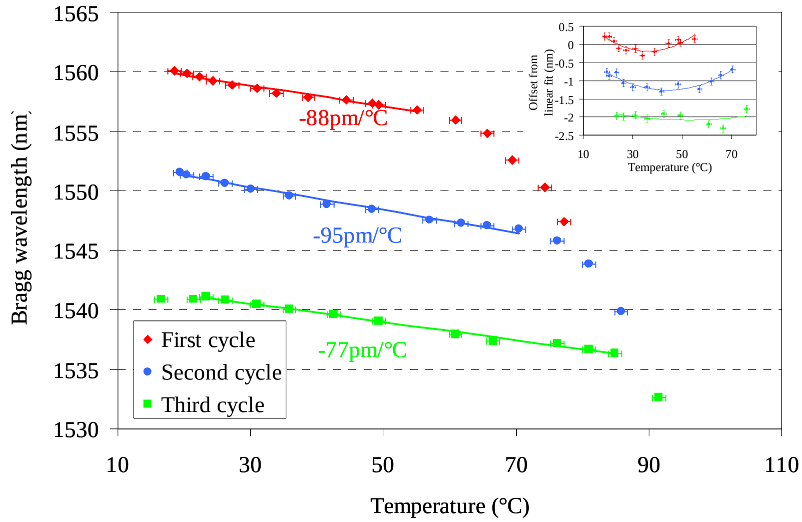

Fig. 4. Bragg wavelength shift with temperature for three consecutive heating cycles. ◆ First cycle, ● second cycle, ■ third cycle. Inset: deviation from linear response for each cycle (data from successive cycles is offset by -1nm for clarity).

Several different gratings fabricated in pure PMMA SmMPOF were studied in order to investigate the repeatability of the results. Each of the gratings had the same exposure time, and was fabricated in fiber which had not been annealed after drawing. The wavelength responses with temperature of three different gratings are shown in Fig. 5. The first grating is that which was cycled 3 times (with results shown in Fig. 4). The second grating was heated to 86°C and the third to 92°C, each in a single cycle. Once these temperatures were reached the grating was barely visible, leading to a reduced precision in the determination of the Bragg wavelength; this effect was a combination of the limited optical source bandwidth and the grating decaying. These data agree well with those from the first cycle of the first grating, heated to 77°C. The wavelength shift with temperature is repeatable, with each of the 3 data sets overlapping. There is also good agreement between the first and third gratings in the elevated temperature region where the wavelength changes very rapidly. This would not necessarily have been expected because the first grating was heated in 3 separate cycles. The vertical lines on the graph represent the region found, in Law's work on the cleaving of mPOF [9], to give the best cleaves using a hot fiber/ hot blade technique. Law found that this region correlated with a tanδ value of ~1-1.3 (where tanδ is the ratio of the Loss Modulus to the Young's Modulus).

The permanent wavelength shift observed at room temperature, and the rapid decrease in wavelength with temperature after a certain temperature during heating, is largely explained by the fiber shrinking. Polymer optical fiber is pulled under tension, resulting in an axial orientation of the polymer chains and residual strain in the fiber. However, at a certain temperature, the chains are thought to relax from the axial orientation causing shrinkage of the fiber. This effect has been reported previously to be a function of the drawing tension [10]. The temperature at which this shrinkage starts is dependent on the thermal history of the grating and could be related to the β relaxation in PMMA when the side chains of the polymer begin to move. This temperature has previously been shown to be influenced by the fiber draw parameters [10] and by UV exposure [11]. The permanent shift in wavelength of -18.5nm after heating to 85°C equates to a decrease in grating length to (98.8±0.5)% of the original value. This can be compared to tests we carried out where fiber was placed in an

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oven at 80°C for 2 hours, which resulted in the fiber length reducing to (98.3±0.5)% of its original value.

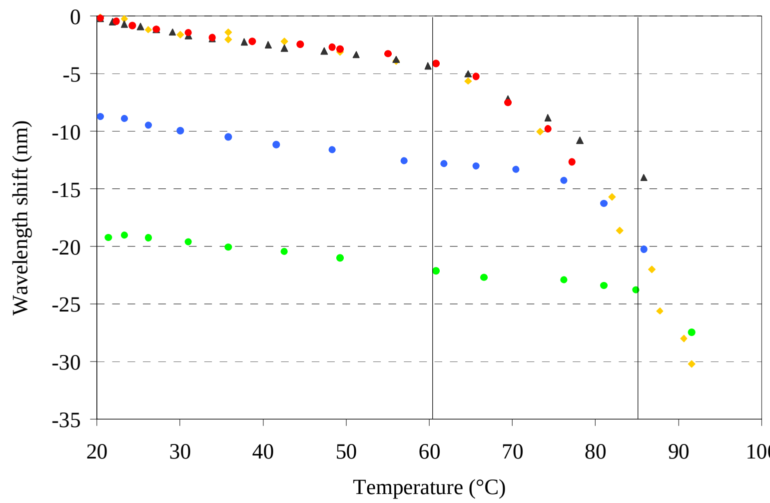

Fig. 5. Bragg wavelength shift with temperature for three different gratings. ●●● - shown in Fig. 4 heated in 3 consecutive cycles, ▲ – grating heated to 86°C, ◆ – grating heated to 92°C,.

In order to test whether fiber could be annealed prior to inscription, a length of the SMmPOF was heated in an oven at 80°C for 7 hours. The fiber length decreased to (98.7±0.5)% of its original value over the 7 hour period and the diameter of the fiber increased to (105.6±0.5)% of its original value, possibly leading the fiber to become few moded. A grating was then written and temperature tested using the methods described previously, and the spectrum is shown in the inset of Fig. 6, revealing a double peak due to the fiber no longer being single mode. Fig. 6 shows the variation of wavelength with temperature for this grating along with a single heating cycle for a grating which was made in non-annealed fiber. The grating made in the annealed fiber shows a linear wavelength shift with temperature which was successfully measured up to 89°C. The measured sensitivity is -52pm/°C, which is lower than observed in the third cycle of heating the grating in non-annealed fiber. This result shows that it is possible to preanneal fiber prior to grating inscription in order to extend the quasi-linear operating temperature range.

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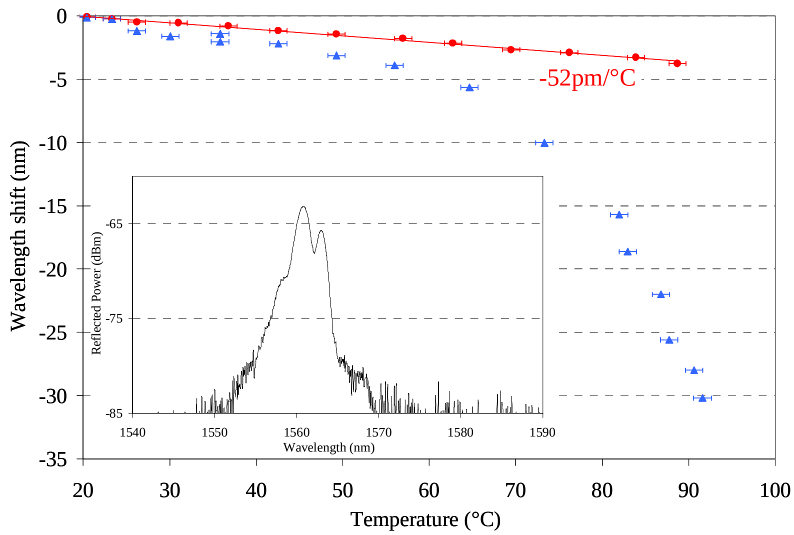

Fig. 6. Bragg wavelength shift with temperature for ● a grating made in fiber preannealed for 7 hours at 80°C, and for ▲ a grating made in the non-preannealed fiber. Inset: grating spectrum showing double peak, possibly due to the few-moded nature of the fiber.

3. Conclusions

We have studied the thermal properties of gratings made in pure PMMA microstructured polymer fiber to higher temperatures than previously reported for FBGs in POF and observed a complex behavior. We have observed that a transition occurs at a temperature determined in part by the thermal history of the fiber and that for temperatures above this transition, permanent shrinkage of the fiber is observed. This shrinkage manifests itself as a permanent blue shift in the grating wavelength. It is important to note that whilst this study has been carried out using mPOF fabricated from pure PMMA, we have also seen clear evidence of this kind of behavior in step index PMMA based POF where the core index has been raised by the addition of ethyl and benzyl methacrylate. Gratings with higher operating temperature ranges than those made in untreated fiber can be achieved by annealing the fiber. Though this can result in the fiber becoming few moded, that could be factored into the design of future fibers to ensure that they were endlessly single mode after shrinking. However, it has been shown previously that annealing mPOFs results in increased loss [12]; another option may be to draw fiber at very low tension. In addition, whilst we have confirmed the negative sign of the temperature coefficient previously observed by Liu et al [5] we report a much lower magnitude of between -52pm/°C and -95pm/°C. This difference in sensitivity of gratings in the two different fiber types could be explained by the different materials used, or different drawing parameters. However, for applications in temperature sensing these sensitivities still compare very favorably with the typical value of 10pm/°C for FBGs in silica fibre. A more extensive study is required in order to confirm the mechanism(s) behind the observed shift in the grating wavelength, and the physical changes in fiber length observed with heating.

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