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RECENT ADVANCES ON SPECIALITY POLYMER OPTICAL FIBRES FOR BRAGG GRATING SENSORS

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Abstract: This article covers recent state of the art on polymer optical fibres fabrication and characterisation from different polymer materials and a combination of them for Bragg grating based sensing applications.

Keywords: polymer optical fibre; fibre fabrication and characterisation; optical fibre sensor; low-cost; multi-parameter device.

1. Introduction

There are various types of optical grade polymers with unique features for polymer optical fibre (POF) fabrication. The unique intrinsic features of each polymer materials make them suitable to develop different types of polymer optical fibre Bragg grating (POFBG) sensors. Therefore, by exploring new optical grade polymer materials for the development of high performance FBG sensors for different applications is the primarily motivation. This article discuss the necessary and integral processes towards the development of high performance POFBG sensors based on POFs activities at DTU Fotonik. These includes fibre preforms preparation, fibres fabrication, characterisation and connectorisation. In realisation of high performance POFBG sensors both step index and microstructured types of POFs were fabricated with various optical grade polymer materials. As POFs fabricated from different polymer materials have different absorption to a UV laser, grating inscription parameters in each fibre types is optimised in order to obtain high quality gratings. The polymer materials we investigated for POFs fabrications are poly (metal methacrylate) (PMMA), cyclic olefin copolymer (Topas, trade name), cyclic olefin polymer (Zeonex, trade name) and Polycarbonate (PC). The Topas and Zeonex grades used were Topas 5013S-04, and Zeonex 480R and E48R, respectively. Table 1 details their mechanical, thermal and optical properties.

Table 1: Optical, thermal, and mechanical properties of PMMA[1], *Topas 5013S-04*[2], *Zeonex 480R*[3], *Zeonex E48R*[4] *and PC*[5] *polymers.*

Properties	PMMA	Topas 5013S-04	Zeonex 480R	Zeonex E48R	PC
Refractive index	1.49	1.53	1.525	1.531	1.586
Light transmittance, 3mm, 400-1000 nm, (%)	94	91	92	92	90
Glass transition temperature (T_g)(°C)	106	134	138	139	145
Melt flow rate (g/10min)	-	44	21	25	41.65
Water absorption (saturation value) (%)	2.1	0.01	< 0.01	< 0.01	0.3
Tensile Modulus (GPa)	3.2	3.2	2.2	2.5	2.4

As presented in Table 1 PMMA, Topas, Zeonex and PC have different thermal, mechanical and optical properties that make them suitable for variety of sensing applications. For instance, PC has the highest glass transition temperature (T_g) which makes it suitable for high temperature measurement among others[6,7]. PMMA has the highest water absorption capacity, which is suitable for high sensitive humidity sensor development [8]. Topas and Zeonex present very low moisture affinity that is suitable for humidity insensitive strain and temperature measurement [9–11]. In addition, as they have very close refractive index, enables for single mode step index fibre production [12].

2. Speciality POFs Fabrication and Characterisation

We fabricated POFs from polymer materials PMMA, PC, Topas 5013S-04, Zeonex 480R and E48R, and a combination of them, which are both step index and microstrctured fibre in type. The fibre preforms for all polymers except PMMA are home casted whereas for PMMA a commercial rod from Nordisk Plast A/S [13], which is extruded, is used. We cast our fibre preforms from commercial available plastic granulates into an in-house made aluminium mold to produce an optical quality solid rod. The casting conditions were optimised for each polymer types in order to enhance the preforms transparency and minimise their tendency towards yellowing. Fibre preforms for microstructured fibres productions were prepared by drilling method. First, the polymer rods were machined to have a dimension of 60 mm in diameter and 100 mm in length. Then three rings of hexagonal pattern holes were drilled with hole and pitch size of 3 mm and 5 mm, respectively. But for the step index preform preparation only a single hole was drilled at the center of the host preform and a guest polymer was injection molded in the drilled hole. In this case, the guest and host polymers act as a core and cladding of the final fibre, respectively. With this method single mode(SM) step index polymer optical fibre (SIPOF) is fabricated from Topas 5013S-04 (core) and Zeonex 480R (cladding)[12]. The other method of step index preform fabrication is rod-in-tube method, where a rod, which is the core material, is inserted into a tube, which is a cladding material. Using this method SM SIPOF is fabricated from Zeonex E48R (core) and Zeonex 480R(cladding) [11].

A two steps heat and draw technique is used to draw the fibres. First 5-6 mm canes were drawn from the fibre preforms and then the cane was sleeved with a sleeving tube made from the same material the preform is made. The diameter of the sleeving tube is determined based on the final fibre dimension need to be drawn. The secondary preform (a cane sleeved with a tube) was then drawn to a fibre. In the case of Zeonex-PMMA fibre fabrication a microstructured Zeonex cane was first sleeved by a Zeonex tube followed by a PMMA tube, which resulted in a fibre with Zeonex core and cladding and PMMA over cladding[14]. The optimum fibres drawing temperature and the corresponding drawing stress implemented to the fabricated fibres are summarised in Table 2.

Table 2: POFs drawing temperature and stress.

Fibres	**Average drawing temperature (°C)**	**Average drawing stress (MPa)**
PMMA mPOF	~178	~9.8
PC mPOF	~185	~11
Zeonex 480R mPOF	~180	~10
Zeonex 480R-PMMA mPOFs	~182	~10
Topas 5013S-04-Zeonex 480R SM SIPOF	~180	~8
Zeonex E48R-Zeonex 480R SM SIPOF	~180	~8

An important and an integral step in POFs fabrication processes is annealing. Every time before drawing the primarily preforms to canes and the secondary preforms to fibres both the primarily and the secondary preforms were annealed in a conventional oven 20 °C below the T_g of the polymer material at least for 48 hours. This step was particularly essential when the preform was made from moisture absorbing polymers such as PMMA and PC. In such a case, if the preforms were not annealed and stored in an oven at their annealing temperature before drawing, bubbles appear during cane and fibre drawing as shown in the Fig.1 and thus increasing the final fibre losses significantly. Sometimes there could be too much bubbles that the preform even was not drawable at all. However, this problem is not significant for fibre preforms made of Topas and Zeonex as they have a very low affinity to moisture.

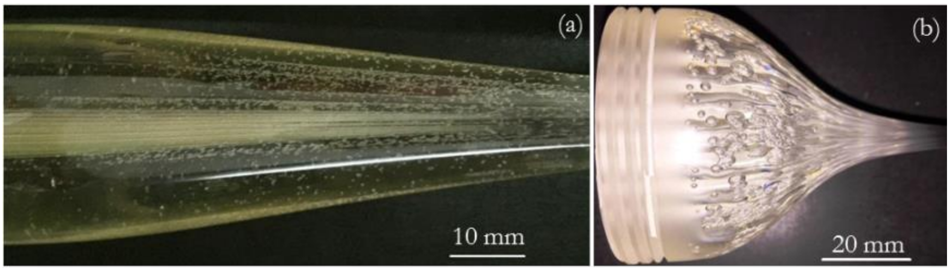

Fig. 1: Bubbles arose in (a) PMMA secondary preform (b) PC primary preform when drawn with no pre-annealing.

Once the fibres are fabricated they were cleaved with homemade POFs cleaver[15] and inspected with optical microscope (Axioskop 40, Zeiss). The hole to pitch ratio of the fabricated mPOFs was 0.4 which ensures that the fibres are endlessly single mode (ESM) [16]. The fibres cleaving temperature and dimensions are presented in Table 3. The fibres facet optical microscope images are shown in Fig.2 (a). The transmission losses of the fabricated fibres were measured with a cut back method. Several cuts have been made during the measurements in order to minimise any uncertainties arising from power fluctuations, cleave quality and coupling instabilities. The measured transmission losses of the fibres are plotted in Fig. 2(b). As presented in Table 1, PMMA has the highest transmittance compared to other polymers we used for fibre fabrication, this is manifested in the fibre loss, which makes PMMA mPOFs to have the lowest loss compared to the other fibres. This could be due to PMMA preform was made from a commercially extruded rod and it provides high purity compared to the mechanical casting methods we used in house to cast our preforms. The Topas-Zeonex fibre presented the highest loss particularly at lower wavelength.

Table 3: The fibres cleaving temperature and dimensions as measured with the optical microscope.

Fibres	Blade and fibre temperature (° C)	Fibre core (µm)	Fibre diameter (µm)	Hole to pitch ratio
PMMA mPOF	73	~8.5	~150	~0.4
PC mPOF	80	~10	~125	~0.4
Zeonex 480R mPOF	76	~8.8	~150	~0.4
Topas 5013S-04-Zeonex 480R SM SIPOF	76	~4.8	~150	V=2.38 @850 nm
Zeonex E48R-Zeonex 480R SM SIPOF	76	~4.8	~125	V=2.395 @850 nm
Zeonex 480R -PMMA mPOFs	75	~8	~150	~0.42

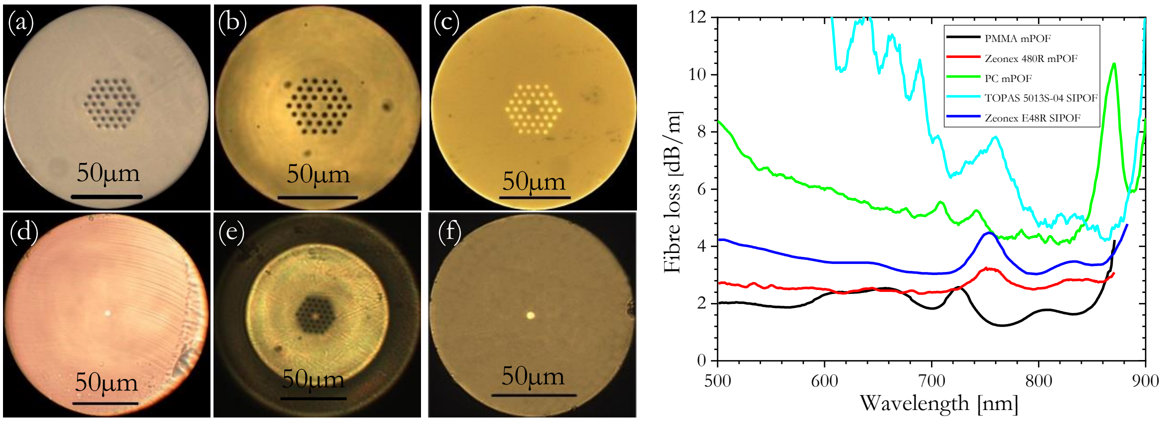

Fig. 3: (a) Optical microscope facet image of (a) PMMA mPOF (b) PC mPOF (c) Zeonex 480R mPOF (d) Topas 5013S-04-Zeonex 480R single mode SIPOF (e) Zeonex 480R-PMMA mPOF (d) Zeonex E48R-Zeonex 480R single mode SIPOF (b)The corresponding measured transmission loss of the fibres

We studied to minimise the loss of our POFs by optimising the casting methods so as to get high purity fibre preforms. Towards this, we have improved the loss of PC mPOF by optimising our mechanical casting and annealing procedure [7]. Similar procedure can be followed to minimise the loss of other POFs and works are in progress. The fibres minimum loss and loss at 850 nm region are summrised in Table 4.

Table 4: Summary of measured minimum and at 850nm transmission loss of the fibres.

Fibres	Minimum loss	Loss at 850 nm
PMMA mPOF	~1.43 dB/m @ 766 nm	~1.97 dB/m
PC mPOF	~4.11 dB/m @ 819 nm	~5.65 dB/m
Zeonex 480R mPOF	~2.38 dB/m @ 672 nm	~2.81 dB/m
Topas 5013S-04-Zeonex 480R SM SIPOF	~4.24 dB/m @ 863 nm	~4.71 dB/m
Zeonex E48R – Zeonex 480R SM SIPOF	~3.03 dB/m @ 798 nm	~3.35 dB/m

3. Fibre Connectorisation

Before the fibres loss measurement and grating fabrication the fibres were first connectorised with standard single mode FC/APC connector. As the connectors bore diameter is 126 µm, the fibres were first etched down to 125 µm from their original diameter. We found that acetone (4.3 µm/min), cyclohexane (8.9 µm/min) and trichloroethylene (3.3 µm/min) are a good etching solvent for PMMA, Topas and Zeonex, respectively [17]. After the fibre was etched, it was inserted into the bore of the connector ferrule and pulled gently from the tip of the ferrule until it gets tight in it. Then polished with fibre micro polishing machine (REVTM, Krelltech). The fibres are polished in three phases: first 3 times with 6 µm diamond film, then 3 times with 1 µm diamond film and finally twice with extra fine diamond film. This technique of POFs connectorisation and polishing enabled to reuse the connectors as gluing was not required unlike it was previously demonstrated by Abang et al [18].

4. Grating Fabrication and Characterisation

FBGs are inscribed in the fabricated fibers in order to investigate their potential for sensing applications. The gratings were fabricated with a phase mask technique. The phase mask (Ibsen Photonics) used has 572.4 nm uniform period and the inscription laser was a 325nm He-Cd UV laser (IK5751I-G, Kimmon), which are suitable for FBG inscription in the 850nm wavelength region. The gratings are used to develop humidity, temperature, strain, thermo-hygrometer, pH and pressure sensors [7,8,11,14,19,20]. These developments resulted in the first POF based sensor company called SHUTE Sensing solutions A/S.

5. Conclusions

We belive that there are several optical grade polymers with a unique feature that are not yet investigated and need to be explored for POFs fabrication. Optimisation in the fibre fabrication is also necessary to reduce the transmission loss of single mode POFs which is essential for remote sensing and sensors network development.

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