HUMIDITY SENSING BASED ON MICROSTRUCTURED POF LONG PERIOD GRATINGS

J. Witt [(1)], M. Breithaupt [(1)], J. Erdmann [(1)], K. Krebber [(1)]

1: Federal Institute for Materials Research and Testing, Unter den Eichen 87, D-12205 Berlin, Germany

Corresponding author: jens.witt@bam.de

Abstract: We investigated the capabilities of long period gratings (LPG) in single-mode microstructured polymer optical fibre (mPOF) for humidity sensing. For that mPOF LPGs were exposed to different humidity levels at a constant temperature of 30°C in a climate chamber. During the long term tests, which took up several weeks, the humidity was changed in several steps while mPOF LPG wavelength and fibre attenuation were measured. We also measured the water uptake of mPOF in environment with different relative humidity.

Key words: Microstructured polymer optical fibre (mPOF), long period grating (LPG), humidity sensor.

1. Introduction

Polymer optical fibre (POF) has a higher flexibility including a smaller Young's modulus and a greater elastic limit than silica fibre [1], [2]. This flexibility makes POF very attractive for any sensing application where high strain values have to be measured. Besides its good suitability for strain measurements POF interacts with water. Polymethyl methacrylate (PMMA) can absorb up to 2 wt% of water depending on the relative humidity of the surrounding medium [3], [4]. The relation between water content of the fibre and relative humidity is slightly non-linear [5]. Absorbed water changes the mechanical and optical properties of PMMA. It causes swelling of the fibre [6], [7] and a change of the refractive index due to an altered mean polarizability of the fibre material [8], [9]. In literature investigations about the influence of humidity to fibre Bragg gratings (FBG) in single-mode POF [10] and LPGs in mPOF [11]-[14] can be found.

1.1. Microstructured POF

For our investigations microstructured POF (mPOF) was used. The mPOF consists of a pattern of small air holes drilled into the cladding area of the fibre. These holes continue through the whole length of the fibre as air channels [15].The first mPOF was reported in 2001 by the Optical Fibre Technology Centre at the University of Sydney [16]. The mPOF is fabricated by drilling holes into a poly methyl methacrylate (PMMA) preform with a CNC-Mill and then extruding it to the desired diameter [17], [18]. Light guidance is made possible with a mechanism called index guiding. Due to the air holes the microstructure creates a cladding with an effective refractive index n_{Cladding} which is smaller than the refractive index of the solid core region n_{Core}. Therefore the light is confined to the core and light guiding is made possible. Depending on the structure which is used for the mPOF the optical properties like the number of guided modes or the numerical aperture of the fibre are changing. One advantage of this type of fibre is that is made just from pure PMMA and no dopants are necessary.

1.2. Long period gratings in mPOF

Into the fibre a long period grating (LPG) has been written. A LPG is a periodically varying structure along the fibre which couples light from forward propagating core modes to forward propagating cladding modes. Due to absorption and scattering the light of the cladding modes gets lost and loss features occurs in the transmission spectrum. The coupling wavelength λ_{LPG} of the loss features is given by the phase-matching condition described by the coupling equation [19]

$$m\,\lambda_{\mathrm{LPG}} = \Delta n_{\mathrm{eff}}(\lambda)\,P \tag{1}$$

where

$$\Delta n_{\mathrm{eff}}(\lambda) = n_{\mathrm{Core}}(\lambda) - n^{i}_{\mathrm{Cladding}}(\lambda), \tag{2}$$

m is the order of coupling, P is the period of the grating, n_{Core} is the refractive index of the core and n_{Cladding} is the effective refractive index of the i-th cladding mode.

The period of a LPG is usually in the order of 0.1 mm to 1.0 mm and thus much larger than the wavelength of the guided light. Therefore manufacturing of such grating is easier than making a fibre Bragg grating (FBG). The

technique for fabrication of the LPGs is based on permanent mechanical imprinting. A grooved rod acts as a stamp and is applied with a defined weight to the fibre [20], [21].

When a mPOF is exposed to humidity several things happen. Water absorption causes the mPOF to swell. Therefore the grating period P and the geometry of the microstructure and thus the effective refractive index of the cladding n_{Cladding} are changed. Also the water changes the refractive index of the PMMA material itself and thus the refractive index of core n_{Core} and cladding n_{Cladding}. Hence a shift of the coupling wavelength λ_{LPG} occurs when the water content of the mPOF LPG is changed.

2. Experimental setup

For the experiments we used an Ocean Optics USB4000 CCD spectrometer with a measurement range from 527 nm to 1191 nm and a wavelength resolution of 210 pm. As white light source we used a Yokogawa AQ4305. All experiments were done in a temperature and humidity controlled Vötsch HC4033 climatic chamber. In the chambers the mPOF was fixed on a glass plate paying attention that no stress is applied to the fibre. Temperature and humidity was measured with an Ahlborn 2890-9 measuring device using an Ahlborn FHA646-E1C combined temperature and humidity sensor. For weight measurements a Sartorius CP225D analytical balance with a reproducibility and linearity of 0.02 mg was used.

We used mPOF LPGs from Kiriama. The mPOF shows single-mode behaviour and is made from pure PMMA. The fibre has an outer diameter of approx. 340 µm and a core diameter of 5.5 µm. The sample length is 2 m with the LPG located in the middle. The length of the LPG is 15 cm with a period of 1 mm.

We evaluated all loss features of the mPOF LPGs in the region between 540 nm and 850 nm. Above 860 nm the fibre attenuation is too high for any measurement except for a window between 925 nm and 975 nm. The loss features had full spectral width at half maximum (FWHM) of 8 nm to 10 nm and an amplitudes between 5 dB and 6 dB. We fitted a Gaussian curve to the loss features to determine their location.

2.1. Sample preparation

For better handling the mPOF was elongated on both sides with FC/PC silica fibre pigtails. We used a 50 micron core standard multimode step-index fibre. Therefore the end-faces of the mPOF had to be prepared.

Cutting a mPOF often results in cracks of the microstructure. In Fig. 1 (left) the mPOF end-face after cutting with a cold razor blade is shown. After testing different cutting methods we found that polishing the fibre works well. We used 1000 µm to 0.3 µm abrasive paper. Fig. 1 (right) shows a mPOF end-face after polishing. The air holes are closed with material abrasion which reflects the light of the microscope. This causes the air holes to look brighter than the solid structure. After polishing the end-face is smooth and shows just very slight scratches.

After preparation of the end-faces the mPOF and the silica fibre were aligned and brought into physical contact using a V groove with a length of 3 cm and a sub-micrometre translation stage. For alignment the fibres were connected to a light source and a power meter so we could measure the light transmission. No index matching fluid was used. Both fibres were glued to the V groove to fix the butt coupling. After adding the glue the fibres were realigned to ensure maximal transmission. After 1 hour curing time the fibre connection was mechanically stabilized using a steel sleeve. The cavity between sleeve and V groove is then filled with epoxy glue.

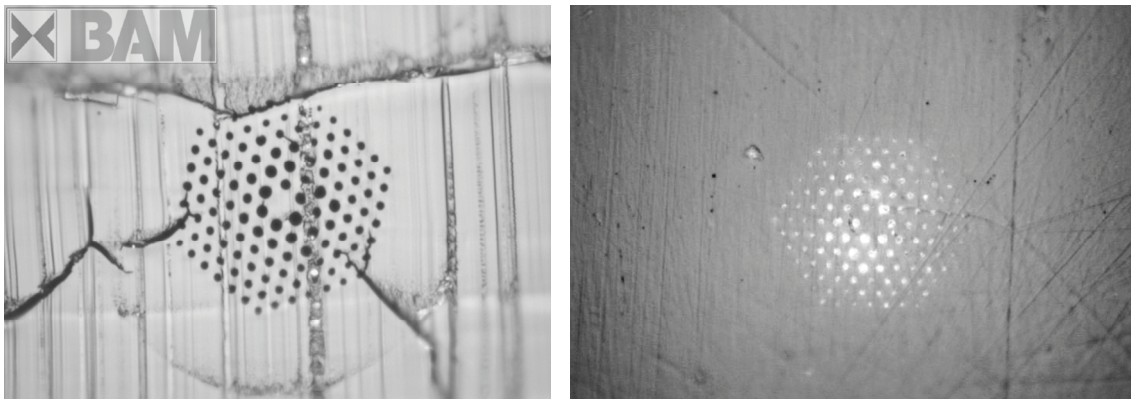

Fig. 1: Left: Cross section of a microstructured polymer optical fibre. The cracks are a result of a rough cut with a cold razor blade. Right: mPOF end-face after polishing. The air holes are closed with material abrasion which reflects the light of the microscope. This causes the air holes to look brighter than the solid structure.

3. Results

3.1. Water absorption

For this experiment a 15 m long mPOF sample with a weight of 1.316 g measured at 24°C and a relative humidity of 50% was used. The fibre was exposed to different levels of relative humidity. After several hours of acclimatization time the fibre weight was measured. The result is shown in Fig. 2. The sorption values are slightly higher than the values given by Thomas for PMMA film [5].

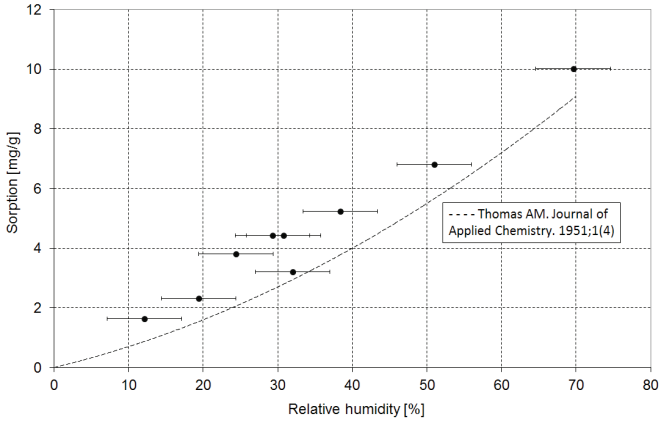

Fig. 2: Water sorption in mPOF for different relative humidity.

3.2. Response of the mPOF LPG to humidity changes

We exposed a mPOF LPG to certain humidity values in a climatic chamber. Starting at 20% the relative humidity was increased in steps of 10% every 10 hours up to a value of 90%. After holding this value for ten hours the relative humidity was decreased again in 10% steps every 10 hours back to a value of 20%. During this procedure the temperature was held constant at T = 30 °C. The measured shift of the LPG wavelength can be seen in Fig. 3. The steady state shows an increased LPG wavelength λ_{LPG} for increasing relative humidity and a decreased λ_{LPG} for decreasing relative humidity. On a shorter time scale λ_{LPG} initially runs in the opposite direction. These results show the opposite behaviour compared to a UV inscribed long period gratings in mPOF [11], where λ_{LPG} decreased for increasing humidity.

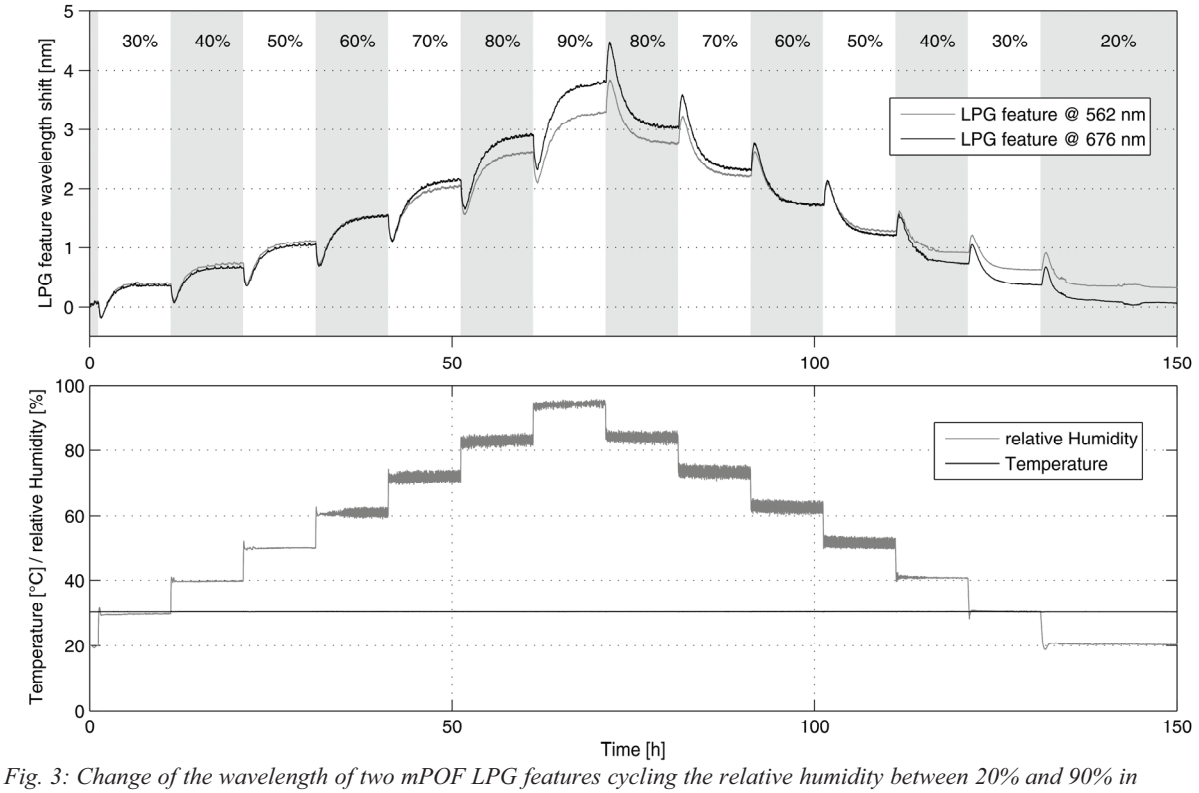

Fig. 3: Change of the wavelength of two mPOF LPG features cycling the relative humidity between 20% and 90% in 10% steps at a constant temperature of 30 °C.

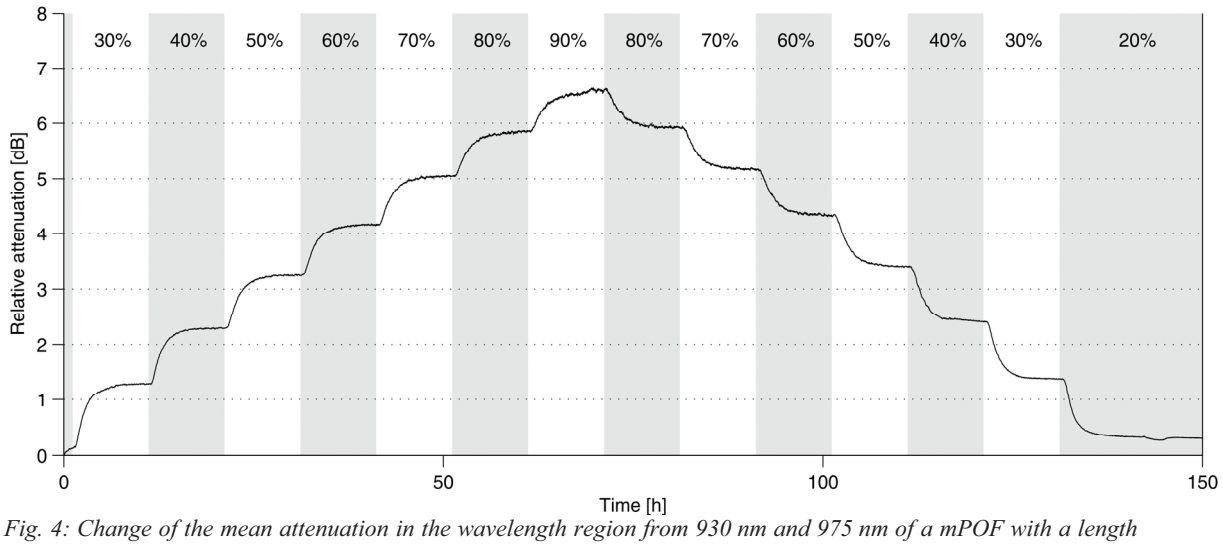

Fig. 4: Change of the mean attenuation in the wavelength region from 930 nm and 975 nm of a mPOF with a length of 2 m for cycling the relative humidity between 20% and 90% in 10% steps at a constant temperature of 30 °C.

We assume that this effect is caused by the humidity which first affects the cladding and later reaches the core. In the first phase water changes the refractive index of the cladding. Also it causes swelling which changes the period of the grating and the geometry of the microstructure and thus the effective refractive index of the cladding. According to [11] the refractive index change should be the dominating effect. In the second phase the water reaches the core which changes its refractive index, cancelling out the effects in the cladding. As the refractive index change for the solid core is stronger than for the cladding (solid materials with air holes), the final wavelength shift has the opposite direction compared to the shift which occurs in the first phase.

The wavelength shift increases non-linear with relative humidity. This corresponds to the results from [5] where a similar dependence between water sorption in PMMA films and relative humidity was shown. We expect that there is in first approximation a linear relation between wavelength shift and water content. The offset between the wavelength shifts of both LPG features is caused by the fitting algorithm. As the LPG spectra of the wavelength feature changed their shape during the experiments from symmetric to asymmetric irregular shapes calculation of the LPG wavelength introduces some error.

Based on the constant levels reached after several hours we calculated the mean sensitivity of the mPOF LPG to relative humidity changes for wavelength features in the range between 550 nm and 850 nm at T = 30 °C. The mean normalized wavelength shift $\Delta\lambda_{\mathrm{LPG}} / \lambda_{\mathrm{LPG}}$ for humidity changes is:

$$\frac{\partial(\Delta\lambda_{\mathrm{LPG}} / \lambda_{\mathrm{LPG}})}{\partial \mathrm{rH}} = (7.8 \pm 1.6) \times 10^{-4} \ / \ 10\%$$

Absorbed water increases the attenuation losses in PMMA POF especially for longer wavelength [22]. Therefore we measured the mean change of attenuation in the region between 930 nm and 975 nm. In Fig. 4 the result is shown. The increase of attenuation is non-linear and stronger for lower humidity. When the relative humidity is changed it takes some time until the attenuation starts increasing. We assume that this delay is caused by time the water needs to reach the core. The mean increase of attenuation at 950 nm is calculated to 45 dB/km / %.

3.3. Time response to humidity changes

After changing the relative humidity it takes several hours for the water to diffuse into the fibre and thus a constant wavelength shift is reached. In Fig. 5 the time evolution of fibre attenuation and LPG wavelength can be seen for the step from 40% to 50% relative humidity. Two minutes after start changing the relative humidity, at this time the humidity in the climate chamber has reached a value of 45%, the LPG wavelength begins to decrease. After 4 minutes the climate chamber reaches the 50% level. Between minute 10 and 20 the fibre attenuation increases slightly and the decrease of the LPG wavelength shift slows down as the water reaches the core. After 30 minutes the increase of the fibre attenuation gets stronger and the LPG wavelength shift changes its direction and starts increasing.

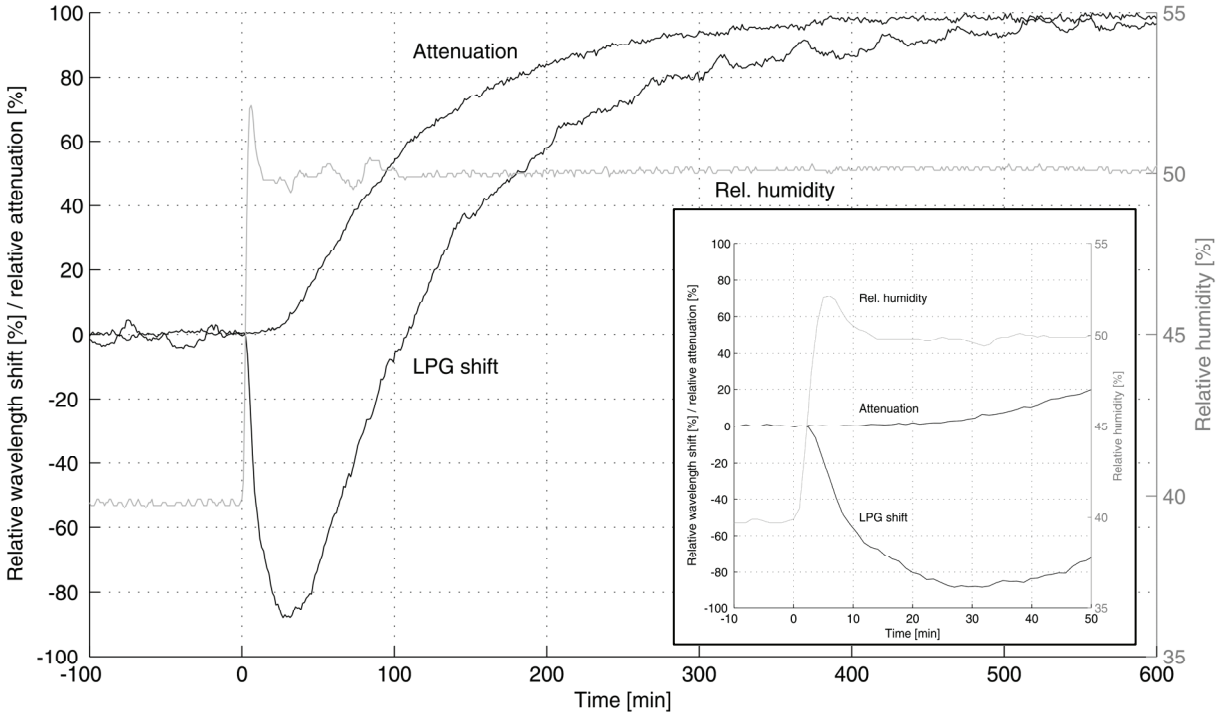

Fig. 5: Time response of fibre attenuation and LPG wavelength for increasing the relative humidity from 40% to 50% at a temperature of 30°C.

4. Conclusions

In the paper we investigated the capabilities of single-mode mPOF with mechanically imprinted LPGs for humidity sensing. We measured the water uptake of mPOF at different relative humidity and we exposed mPOF LPGs to different humidity levels at a constant temperature of 30°C in a climate chamber. We measured the time response of LPG wavelength and fibre attenuation which needed around 10 hours to follow a 10% change in relative humidity. As the water diffusion first affects the cladding and later the core the first LPG wavelength shifts changes its direction when the water reaches the core.

References

[1] W. Daum, J. Krauser, P.E. Zamzow, O. Ziemann, *"POF-Polymer Optical Fibers for Data Communication"*, Springer Verlag, Berlin, 2002.

[2] D. Yang, J. Yu, X. Tao, H. Tam, Materials Science and Engineering A, 364(1-2), 256-259, 2004.

[3] F. Bueche, *"Diffusion of water in polymethyl methacrylate",* Journal of Polymer Science, 14(76), 414-416, 1954.

[4] L.S.A. Smith, V. Shmitz, Polymer, 29, 1871– 1878, 1988.

[5] A.M. Thomas, *"Moisture permeability, diffusion and sorption in organic film-forming materials"*, Journal of Applied Chemistry, 1(4), 141-158, 1951.

[6] P. Masai, L. Nicodemo, C. Migliaresi, L. Nicolais, Polym Commun, 25, 331–333, 1984.

[7] S. H. Goods, R.M. Watson, M. Yi, *"Thermal Expansion and Hydration Behavior of PMMA Molding Materials for LIGA Applications"*, Technical report, Sandia National Laboratories SAND2003-8000, 2003.

[8] T. Watanabe, N. Ooba, S. Hayashida, T. Kurihara, S. Imamura, *"Polymeric optical waveguide circuits formed using silicone resin"*, Journal of Lightwave Technology, 16(6), 1049-1055, 1998.

[9] T. Watanabe, N. Ooba, Y. Hida, M. Hikita, *"Influence of humidity on refractive index of polymers for optical waveguide and its temperature dependence"*, Applied Physics Letters, 72(13), 1533, 1998.

[10] N.G. Harbach, *"Fiber Bragg gratings in polymer optical fibers"*, Polymer, 4021, 2008.

[11] D. Saez-Rodriguez, J.L. Cruz, I. Johnson et al., *"Water Diffusion Into UV Inscripted Long Period Grating in Microstructured Polymer Fiber"*, IEEE Sensors Journal, 10(7), 1169-1173, 2010.

[12] J. Witt, M. Steffen, M. Schukar, K. Krebber, *"Investigation of sensing properties of microstructured polymer optical fibres"*, in Photonic Crystal Fibers IV, Proc. SPIE 7714, 2010.

[13] M. Steffen, M. Schukar, J. Witt, K. Krebber, M.C.J. Large, A. Argyros, *"Investigation of mPOF-LPGs for Sensing Applications"*, in Proc. 18th International Conference on Plastic Optical Fibers, Sydney, Australia, 2009.

[14] M. Schukar, K. Krebber, M.C.J. Large, R. Lwin, *"Climatic investigations of microstructured polymer optical fibers"*, in Proc. 18th International Conference on Plastic Optical Fibers, Sydney, Australia, 2009.

[15] M. Large, L. Poladian, G.W. Barton, M.A. van Eijkelenborg, *"Microstructured Polymer Optical Fibres",* Springer, Sydney, 2007.

[16] M.A. van Eijkelenborg, M.C.J. Large, A.Argyros, J. Zagari, S. Manos, N.A. Issa, I.M. Bassett, S. Fleming, R.C. McPhedran et al., *"Microstructured polymer optical fibre"*, Opt. Express 9, 319-327, 2001.

[17] M.A. van Eijkelenborg, A. Argyros, G. Barton, I. Bassett, M. Fellew, G. Henry, N.A. Issa, . M.C.J. Large, S. Manos, W. Padden, L. Poladian, J. Zagari, *"Recent progress in microstructured polymer optical fibre fabrication and characterization"*, Optical Fiber Technology 9, 199-209, 2003.

[18] G. Barton, M.A. van Eijkelenborg, G. Henry, M.C.J. Large, J. Zagari, *"Fabrication of microstructured polymer optical fibres"*, Optical Fiber Technology 10, 325-335, 2004.

[19] B. Vikram, *"Applications of long-period gratings to single and multi-parameter sensing"*, Optics Express No 11, Vol 4, 457-465, 1999.

[20] M.P. Hiscocks, M.A. van Eijkelenborg, A. Argyros, M.C.J. Large, *"Stable imprinting of long-period gratings in microstructured polymer fibre"*, Optics Express 14(11), 4644-9, 2006.

[21] M.C.J. Large, J. Moran, L. Ye, *"The role of viscoelastic properties in strain testing using microstructured polymer optical fibres (mPOF)"*, Measurement Science And Technology 20 034014, 2009.

[22] T. Kaino, *"Absorption Losses of Low Loss Plastic Optical Fibers"*, Japanese Journal of Applied Physics, 24, (Part 1, No. 12), 1661-1665, 1985.