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Role of Flexible Macro Fibre Composite (MFC) Actuator on Bragg Wavelength Tuning in Microstructure Polymer Optical Fibre Long Period Grating for Strain Sensing Applications*

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ABSTRACT

The microstructure polymer optical fibre (mPOF) inscribed long period grating (LPG) offers a wide field of application in strain sensors arena within the materials elastic limit. Flexible innovative macro fibre composite (MFC) actuator generates electromechanical force under DC driving voltage. We propose a novel method for Bragg wavelength blue shifting through stretch tuning of mPOF LPG in axial direction under applied DC voltage on attached MFC with LPG. The grating period of mPOF LPG changes refractive index and causes blue shift of Bragg grating fibre wavelength. The shifting governs on the values of generated electromechanically strain transfer from flexible MFC to mPOF LPG and they have potential applications in strain sensor.

Keywords: Microstructure Polymer Optical Fibre (mPOF); Long Period Grating (LPG); Macro Fibre Composite (MFC); Actuator; Strain Sensing; Blue Shifting

1. Introduction

Much attention has been paid by several researchers to inscribed microstructure optical fibre (mPOF) long period grating (LPG) to develop a new class of optical fibres that have significant potential to get wide variety of waveguide properties. In general, multiple microscopic air-holes lattice runs down longitudinally along the length of the optical fibre with different microstructure pattern. A novel waveguides property can be achieved by designing various air hole structures, size, shape and distribution of the holes, which may not be readily achieved in conventional optical fibres [1-4].

The advantages of using microstructures optical fibre are more profound than they are in conventional optical glass fibres. It may fabricate easily in single modes fibres and also useful in visible window with low loss. It is applicable for sensing application depending on dispersion properties of the fibre. Optical loss is a traditional constraint for long length uses in polymer optical fibre (POF). Both POF and mPOF are different from dominant loss mechanism. Intrinsic losses of acrylic materials in both POF cases are for molecular absorption and scattering from in-homogeneities due to local variation in molecular weight which causes density change. The losses of mPOF depending on fibre design, are higher than convention POF. The lowest possible loss of mPOF is 0.192 dB/m compare to 0.15 dB/m for POF of same intrinsic acrylic PMMA materials [5].

Silica based LPG on optical fibre has been explored mostly, but LPG in polymer fibre has not so much potential in past due to difficulties in fabrication of single mode polymer optical fibres. Argos *et al.* [4] have fabricated successfully single mode mPOF LPG and ventured a new company Arkema Ltd. to supply it [6]. It has been established that resonant wavelength decreases with the increasing of LPG grating period. There was extremely optimal mode loss that provided side lobe free, 100% power transfer from core to the cladding mode for a uniform LPG [7].

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The LPG sensitivity can be manifest itself in two ways: spectral shift of attenuation band and a change in the strength of attenuation band. The resonant wavelength of the mechanically induced LPG can be easily tuned as the pressure is reversible. The external perturbation by mechanical force into the polymer optical fibre LPG can be induced through electromechanical force generated by employed flexible PZT-polymer composite actuator namely macro fibre composite (MFC) actuator by applying direct DC voltage.

The young modulus for PMMA polymers materials (3.2 GPa) is significantly lower than silica (72 GPa) glass materials and the elastic limit of PMMA is also an order of magnitude higher than of silica. It is useful for strain sensing application at below elastic limit. The strain sensing can be monitored by shifting of center Bragg wavelength during external perturbation applied on LPG mPOF. The linear response is −11.8 nm per % of strain in mPOF LPG. The high elastic limit of PMMA material and low loss is unique combination in the visible range in single mode mPOF for strain sensing applications [8].

Macrofibre composite actuator (MFC) is an innovative actuator that offers high performance in terms of flexibility as a cost competitive device. It was made with rectangular PZT-piezo fibres which are sandwiched between layers of adhesive, electrodes, and polyimide film, and both sides are covered with polyimide film. The PZT materials can be considered as mass of minute crystallites and acts as actuator under driving DC voltage.

Crystal lattices of electric dipole in PZT molecules are caused electric charge distribution in the axis directions in the chemical bond. Monolithic PZT has restrictions regarding brittleness and a high mass density and limited deformation causes vulnerable to accidental breakage during handling. These restrictions are overcome using rectangular shape of macrofiber fingers cut from PZT thin wafer of 178 μm in height and 356 μm in length and pasted with high shear structural epoxy adhesive, it looks like discrete piezostack actuators. Two sets of copper electrode pattern printed on a polyimide film were sandwiched through structural epoxy adhesive [9]. Polarization of piezocrystal produces electromechanical strain energy density that can be controlled using different spacing of electrode printed on polyimide film to make electric field distribution in the plane of PZT-polyimide composite. The developed composite actuator produces nearly twice the strain and four times the strain energy density during polarization in plane. This configuration of PZT microfiber shows more flexibility, higher performances and durability, compared to a traditional monolithic PZT actuator [10].

The established empirical relation for mode coupling occurs in LPG at the resonant wavelength in the following equation: $\lambda = (n_{01} - n_{cl})\,\Lambda$, where, Λ is grating period and n_{01} and n_{cl} are the effective index of the fundamental core mode and individual cladding mode of the fibre, respectively.

The strength of the mode coupling at the resonant wavelength to the cladding mode oscillates as $\sin kd$, where k is the coupling coefficient and d is the length of the grating. The coupling coefficient k is proportional to the amount of index variation induced into LPG by the mechanical pressure. It is observed that the blue shift originated from the high dispersion of the cladding mode of the mPOF LPG compared with the cladding mode of a conventional fiber, LPG in mPOF is much more guiding and dispersive in nature due to the presence air holes, which might explain the endless single-mode operation. The important application of single-mode mPOF LPG gratings in strain sensing, monitors engineering and medical applications [11].

The aim of this paper is to study the effect of innovative flexible macrofibre composite (MFC) actuator generated electromechanical force under DC driving voltage experienced on attached mPOF LPG perturbed grating period causes resonant Bragg wavelength shifting towards decreasing of blue shifting. The potential use of this flexible MFC actuator attached in mPOF LPG module is in strain sensor application.

2. Experiments

Microstructure polymer optical fibre (mPOF) long period grating (LPG), FM-340 was purchased from Kiriama Pty. Ltd, Australia. The features of microstructure polymer LPG as received was given in **Table 1**.

2.1. MPOF Design

Single mode mPOF have been inscribed with long period grating (LPG) and possible application is limited for minimum losses before and after grating, respectively as shown in **Figures 1(c)** and **(d)**. The strain of mPOF up to 15% for high elastic limit of PMMA and guide light through the use of a pattern of tiny holes that run the full

Table 1. Specifications of microstructure polymer optical fibre (mPOF) long period grating (LPG) FM-340 fabricated by Kiriama, Pvt. Ltd.

Fibre Diameter (μm)	260
Core Diameter (μm)	15
Core/Cladding Material	Polymethylmethacrylate (PMMA)
Grating Strength (dB)	11
Fibre Length (m)	1
Grating Length (cm)	2.5
Grating Wavelength (nm)	687 and 686

length of the fibre, one hole is missing in the center region acts as the core as shown in **Figures 1(a)** and **(b)**, the holes pattern changes the optical properties of the fibre as well materials properties including Young modulus, greater elastic limit make them desirable sensing application regarding strain and bending. Microstructure was observed in optical microscope using software analysis in Olympus UC-30, Japan.

Figures 1(a) and **(b)** have shown the reflection spectrum characteristics of LPG (**Figure 1(c)**) and FBG II (**Figure 1(d)**). The single mode mPOF made of PMMA fibre designs has hexagonal arrangements of air holes. The distance between two holes are 5.5 µm, diameter of one hole is 3.9 µm, diameter of fibre is 340 µm, and average hexagonal core diameter is 60.28 µm. There was different fabrication steps are explored to fabricate microstructure polymer optical fibre (mPOF). The potential applications of microstructure polymer fibres are for specific applications for use in sensing, medicine, and engineering and communication arena. The fabrication consist two main steps. First fabricated a large 8 cm dia perform with desired design holes arrangement and stretched to 6 mm dia cane. They can is sleeved to increase the outer diameter to 12 mm to make secondary perform from which optical fibre was drawn.

Macrofiber composite (MFC) actuator was purchased from Smart Materials Inc., Germany. MFC actuators consist of three primary components: 1) a sheet of aligned rectangular piezoceramic fibers, 2) a pair of thin polyimide films etched with a conductive electrode pattern and 3 a structural dielectric epoxy adhesive matrix.

Macro fiber composite (MFC) actuator strives to improve current state of the art for a best structural actuation, flexible and replacement of monolithic piezo ceramic predecessors which is shown in **Figure 2**. The electric PZT dipole crystals in MFC are randomly oriented throughout the materials domains and no overall polarization or piezoelectric effect was observed. The

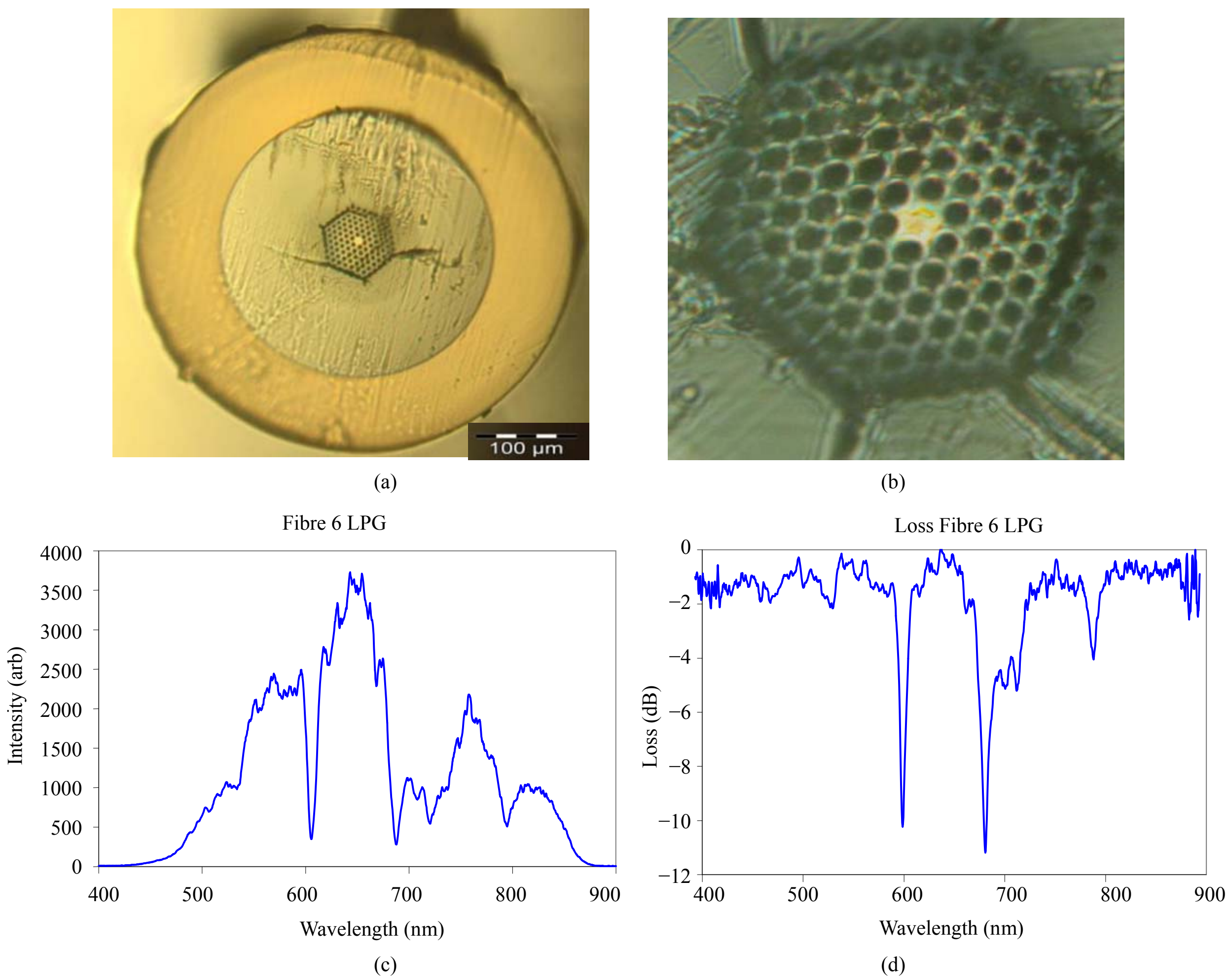

Figure 1. Optical microscope image of the cleaved end PCF: (a) 260 micron dia cross section view of microstructure fibre; (b) Core view of hexagonal air holes; (c) Optical loss of microstructure LPG before writing grating and (d) after writing grating.

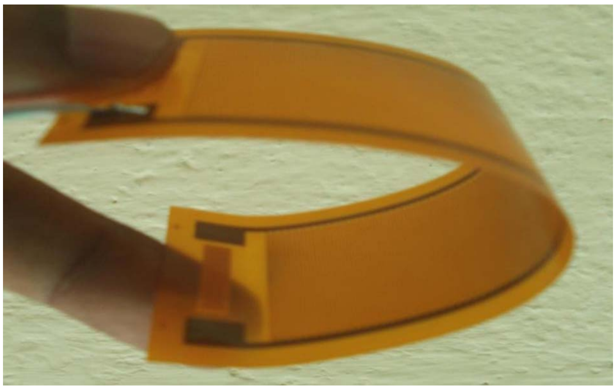

Figure 2. 2D picture of soft macrofiber composite (MFC) actuator shows flexibility and durability.

poling of the materials, the neighboring dipoles are aligns with each other to form regions of local alignment known as Weiss domains. Henceforth, all the dipoles are aligned during application of voltage and producing a net dipole moment into the Weiss domain and show a net polarization as dipoles per unit volume increases. The dipolar orientations aligned in a Weiss domain grow during voltage application changes the polarization and dipoles are oriented towards opposite electric field. The material stretches in the direction of the applied field. The dipoles are locked in that alignment after power is removed, giving the ceramic PZT crystals remnant polarization and a permanent deformation. The shifting of Bragg wavelength with the application of DC driving at particular voltage is proportional to the changes of dipoles orientation towards poling direction at that time. The changes of wavelength is fast at initial time of voltage application as dipoles are forced to orient in the opposite direction and produces Weiss domain into the preferred direction into the crystallites.

The developed composite generated twice the strain and four times strain energy density during polarization in the plane. To mitigate all these limitation regarding monolithic PZT actuators, macrofibre composite actuator is best solve for high performance soft flexible actuator.

The PZT dipole molecules are oriented into the Weiss domain in the poling axis line direction. Applications of DC voltage on macro fiber composite where electric dipoles are oriented in the lateral direction and produces electromechanical force due to alignment of electric dipoles towards the poling axis line of PZT [12].

The changes are more for bigger sizes of composite sample 85-28P1 compare to small size of 28-07P1. The big dimension of composite has more electric PZT crystal dipoles which will have more movement under particular voltage for same time period. The numbers of PZT crystal dipole domains are more for big size of samples rather than small size of composite. The Bragg wavelength changes are more for larger sizes of sample rather than small one at a fixed voltage due to more PZT crystal dipoles involvements. It is observed that changes are rapid at initial time period of DC driving voltage and total changes are very small. The displacement was measured using LVDT sensor device in test rig consists two clamps at two ends.

The displacement was governed with the following equation; $\delta = \alpha N d_{33} V$, where α is a constant of correcting coefficient from the weak field d_{33} value to strong field strain constant, and is about 1.5 for multilayer actuators. d_{33} is piezoelectric strain constant and V is the applied voltage. N is (2n-1), where n is the number of electrode lines on one layer [13].

It was reported that the central Bragg lasing peak wavelength tuning was 1.25 nm using MFC sizes 2807P1, 1.82 nm for 4010P1, 2.15 nm for 8507P1 and 3.47 nm for 8528P1. The lasing line width is around 0.04 nm at 20 dB which corresponds less than 0.006 nm at 3 dB. The output power does not change with application of voltage as well as for different time duration [14].

2.2. Experiment Set-Up

In this proposed experimental model, we have explored two separates POF LPG with Bragg wavelengths at 687 and 686, which are depicted in **Table 1** with loss ~11 dB each. These LPG were placed in separate experiments. LPG was mounted on different size of MFC's actuators. The actuator dimensions are 28 mm × 07 mm, 40 mm × 10 mm, and 85 mm × 28 mm, respectively. They were mounted with special adhesive DP-460 supplied by 3 M, USA which has high shear and good elastic in nature.

In this setup, the POF LPG was mounting on MFC actuator and blue shifting of Bragg wavelength is achieved through electromechanical stress generated into MFC attached with LPG under driving DC voltage as shown in **Figure 3**.

In each set of experiment, LPG is mounted on different sizes of macro composite (MFC) actuator with zero shear high elastic dielectric glue under certain strain condition. The driving of DC voltage on MFC generates electromechanical force and stretches mPOF LPG in axial direction due to d_{33} effect of MFC actuator. This changes the pitch length in LPG and modulates refractive index which in turn shifts the center Bragg wavelength of LPG. The amount of axial strain generates under DC driving voltage into piezo actuator MFC transfer to the LPG and changes the grating pitch lengths which are directly proportional with blue shifting of Bragg wavelength.

The strain testing of MFC was done using LVDT sensor using test rig consists of two clamps at two ends. The real displacement was measured by the active length/ clamp distance. The total displacement is not possible to measure by maximum active length. It may be calculate

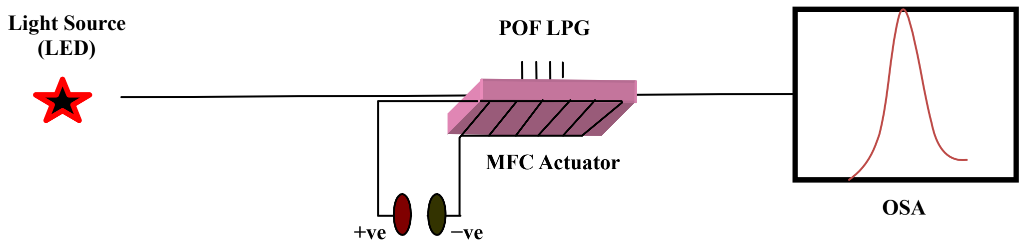

Figure 3. Schematic representation of experimental set up using PZT-polyimide macrofibre composite (MFC) actuator for pitch modulator of LPG mounted on for strain sensor.

through following equation. Max displacement = real strength × max. active length.

3. Results and Discussion

3.1. Theory of LPG

The fabrication of LPG was done by inscribing periodic refractive index variation by photo induced into polymer optical fibre (POF). The transmission mode spectrum consists of distinct resonant loss bands that are coupled with fundamental core modes. At phase matching condition, it will give resonant transmission wavelength at λ_{res}.

$$\lambda_{res} = \left(n_{core}^{eff} - n_{m,clad}^{eff}\right) \cdot \Lambda \quad (1)$$

Where n_{core}^{eff} and $n_{m,clad}^{eff}$ are the effective index of fundamental core mode and m^{th} cladding mode, respectively and Λ, is the period of LPG [15].

3.2. Strain Sensitivity

The resonant wavelength (λ_{res}) of the POF LPG will shift under axial strain due to index modulation period (Λ) of the LPG increases. The effective index of core and clad modes will decreases due to photo elastic effect of the fibre material [16],

$$\frac{d\lambda_{res}}{d\varepsilon} = \lambda_{res} \cdot \Upsilon \cdot \left(1 + \Gamma_{strain}\right) \quad (2)$$

where, ϒ is waveguide dispersion factor, it plays an important role on the applied strain and temperature sensitivity on the POF LPG. The strain sensitivity ($\frac{d\lambda_{res}}{d\varepsilon}$), of an LPG in the POF depends on the following four parameters, the elasto-optic coefficients of the core and clad materials, waveguide dispersion factor (ϒ), the index modulation (Λ), and mode order (m).

The waveguide dispersion factor,

$$\left(\Upsilon\right) = \frac{\frac{d\lambda_{res}}{d\Lambda}}{\left(ncore - nm, clad\right)} \quad (3)$$

The dispersion curve of single mode hexagonal microstructure design air holes in mPOF LPG has shown in **Figure 4**. These values were obtained for the mPOF LPG fibre with Λ = 5.5 µm, diameter of one hole is 3.9 µm, diameter of fibre is 340 µm, and average hexagonal core diameter is 60.28 µm. The design has done for low loss confinement by inserting optimum air holes surrounded to the core of the fibre.

Figure 4 shows the variation of refractive index at different wavelength (λ) and pitch length (Λ) are 0.8. 0.9, 1.0. 1.1, or 1.2. The refractive index (n) of PMMA is 1.48998 at 632 nm wavelength. The sensitivity was predominant influences by central air-hole diameter (d_c) and the distance between consecutive air holes (Λ) over the dispersion characteristics. It was observed that dispersion factor (λ) is always negative, and this causes blue shifting of the resonant wavelength under axial strain through perturbation with flexible actuator [17].

3.3. MFC Displacement Measurements

Figure 5 showed displacement of different dimensions MFC actuator under DC driving voltage in test rig consists of two clamps using LVDT sensor device. MFC with dimension of 85-28P1 (**Figure 5(c)**) will produce maximum 92.5 micron displacement with clamp distance 65 mm whereas it is more which 120.7 micron for 85 mm clamp distance. This value is much less for actuator dimension of 40-10P1 (**Figure 5(b)**) and 28-07P1 (**Figure 5(a)**), respectively. It was observed that displacement of 40-10P1 MFC with clamp distance 20 mm was 31.6 micron and 63.2 micron for clamp distance 40 mm, respectively. Similarly the maximum displacement was 58.8 micron of 28-07P1 MFC for clamp distance 28 mm whereas it was 27.3 micron for clamp distance 13 mm. There was a hysteresis observed in MFC which is an inherent property of PZT materials [12] as shown in **Figures 5(a)-(c)**.

The MFC is unique design innovative actuator that offers flexible, soft, durable, and increases strain actuator efficiency, directional sensing and damage tolerant. The displacement of the rectangular piezoceramic aligned fibres sandwiched between layer of adhesive, electrode and polyimide film can be measured using following

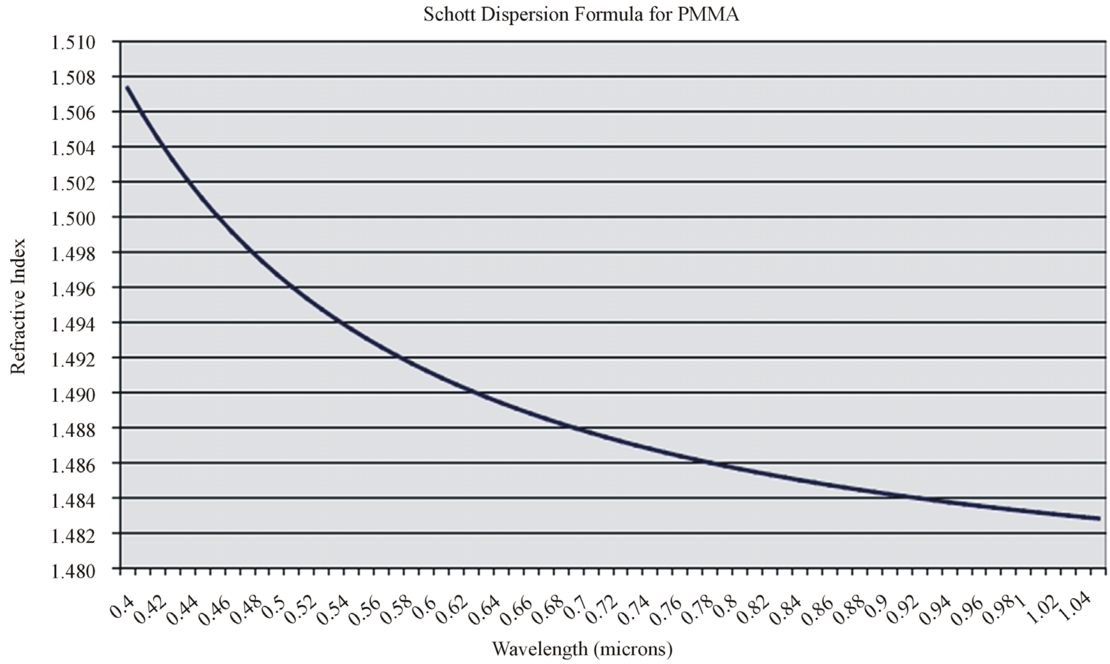

Figure 4. Schott dispersion of acrylic PMMA matrix of mPOF LPG.

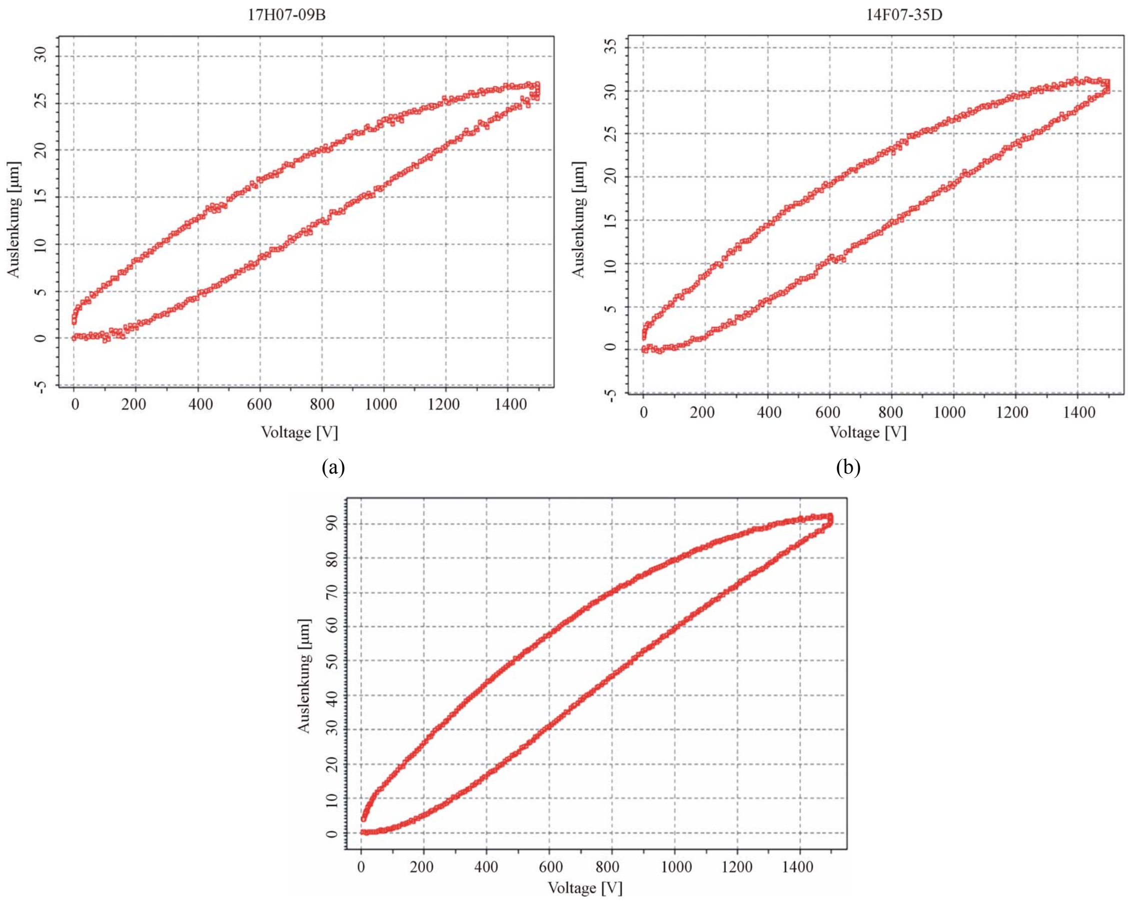

Figure 5. Displacement vs. voltage for different dimension of MFC under driving voltage of 0 V to 1500 V: (a) 28-07P1, (b) 40-10P1 and (c) 85-28P1.

equation [13], displacement, $\delta = \alpha \times Nd_{33} \times V$, where α is constant and is about 1.5 and N is 2n-1, where n is the number of electrode lines on one layer, d_{33} is piezoelectric strain constant and V is the applied voltage.

Big dimension MFC has more piezo electric dipoles crystal which is able to produce large electromechanical force under certain driving applied DC voltage. Similar trend was also observed in Bragg wavelength blue shifting for larger dimension of MFC. MFC of 85-28P1 has more Bragg wavelength shifting compare to small size MFC of 2807P1 as shown in **Figure 6(b)**. It was observed in the **Table 2** that the shifting is 0.672 nm for 2807P1 MFC, 1.058 nm for 4010P1 MFC and 2.255 nm for 8528P1 MFC, respectively. The strain optic co-efficient of plastic optical fibre is about twice that of silica optical fibre, that will produce twice the Bragg wavelength shifting of microstructure LPG silica glass fibre under same strain produces into MFC actuator .The thermo optic coefficient of polymers is negative owing to the predominant effect of the density change with temperature. The experimental operational temperature is in between 80˚C to 120˚C of polymer fibres, they are good enough for structural analysis [18].

Figure 7 shows wavelength shifting with different applied DC voltage on MFC which is attached with mPOF LPG which causes electromechanical force on its changes periodic index (Λ). The Bragg peak position moves lower visible length, peak shape and line width does not vary with applied DC voltage. The above **Figure 7** shows that shifted Bragg wavelength peak width is remain same. This represents that the PZT electric dipoles are oriented into the Weiss domain in axis d_{33} direction. There was no broadening of peak observed and reveals that dipoles are not align into the perpendicular

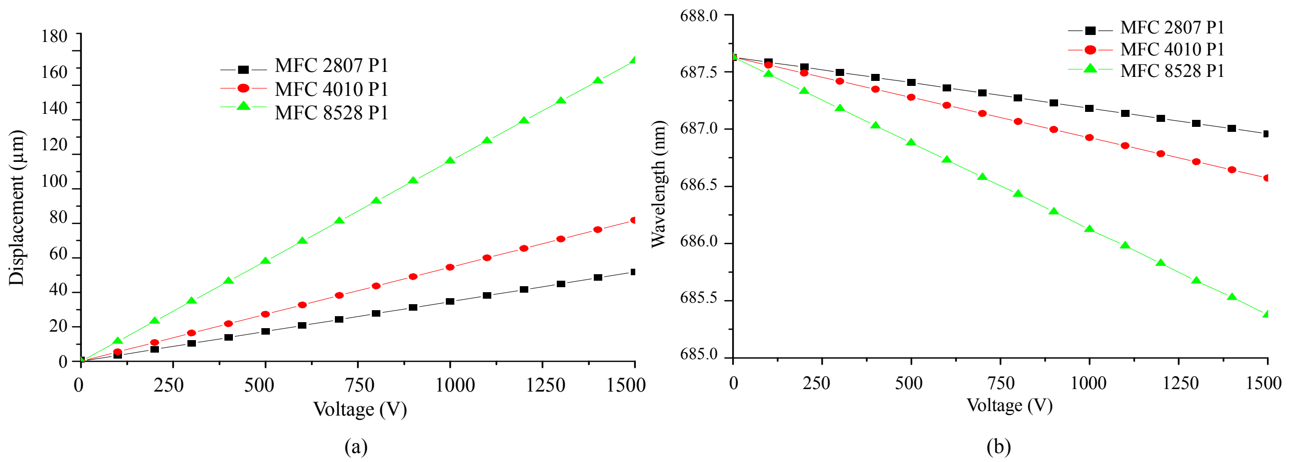

Figure 6 (a) Voltage (V) vs. displacement (μm) and, (b) Voltage (V) vs. wavelength (nm) shift for different dimension of MFC: (▪) 2807P1, (●) 4010P1 and (▲) 8528P1.

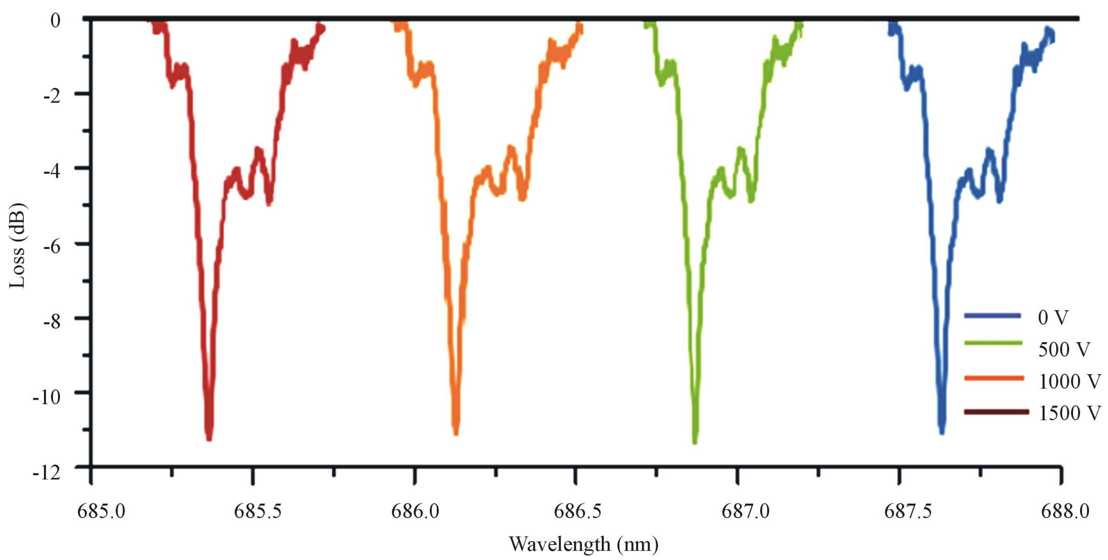

Figure 7. Bragg wavelength shift at different voltages: (a) 0 V, (b) 500 V, (c) 1000 V, and (d) 1500 V.

Table 2. Strain %, changes periodic index (Λ) and wavelength shift (Δλ) under applied DC voltage on mPOF LPG attached MFC.

Dimension of MFC (P1)	Applied DC Voltage, (V)	Strain %	Resonance Wavelength (nm) λ_{res}^{min} at 0 V	Wavelength Changes (nm), λ_{res}^{max}	Wavelength shift, Δλ (nm)
28-07	1500	0.067	687.3	686.958	−0.672
40-10	1500	0.096	687.3	686.572	−1.058
85-28	1500	0.205	687.3	685.958	−2.255

direction of d_{33} effect. Similarly it was shown in **Figure 7** that peak power remains same for different voltage to tune Bragg wavelength intensity. It represent that peak intensity variation was not observed during application of voltage on macro fiber composite where electric dipoles are orient in the lateral direction and produces electro-mechanical force due to alignment of electric dipoles [12-14]. The Bragg peak changes are more for big dimension of MFC sample rather than small one at particular voltages.

4. Conclusion

This aim of this work is to make strain sensor device using mPOF LPG mounted on flexible innovative MFC actuators. The microstructure polymer optical fibre (mPOF) LPG makes single mode operations in visible wavelength window, low insertion loss, small backward reflection, and low cost and large diameter possible high potential for strain sensing applications. The blue shifting of Bragg wavelength is effectively more for using either big size of MFC or at applied higher DC voltage. They were 0.672 nm and 2.255 nm for 28-07P1 and 85-28P1 MFC under applied 1.5 KV, respectively, keeping line peak shape and line width unchanged with applied DC voltage. The sensitivity of LPG can be tailored by controlling microstructure design through controlling dispersion factor with mode matching of core and clad. This proposes model on mPOF LPG that has strong potential for sensor tuning device. It is simple, low-cost, flexible and efficient for future Bragg wavelength tuning in sensor device applications.

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REFERENCES

[1] M. C. J. Large, L. Poladian, G. W. Barton and M. A. van Eijkelenborg, "Microstructured Polymer Optical Fibres," Springer, Berlin, 2007.

[2] T. A. Birks, J. C. Knight and P. J. St. Russell, "Endlessly Single-Mode Photonic Crystal Fiber," *Optics Letters*, Vol. 22, No. 13, 1997, pp. 961-963. doi:10.1364/OL.22.000961

[3] B. J. Eggleton, P. S. Westbrook, R. S. Windeler, S. Spalter and T. A. Strasser, "Grating Resonances in Air-Silica Microstructured Optical Fibers," *Optics Letters*, Vol. 24, No. 21, 1999, pp. 1460-1462. doi:10.1364/OL.24.001460

[4] A. Argyros, "Microstructured Polymer Optical Fibers," *Journal of Lightwave Technology*, Vol. 27, No. 11, 2009, pp. 1571-1579.

[5] M. P. Hiscocks, M. A. van Eijkelenborg, A. Argyros and M. C. J. Large, "Stable Imprinting of Long-Period Grating in Microstructured Polymer Optical Fibre," *Optics Express*, Vol. 14, No. 11, 2006, pp. 4644-4649. doi:10.1364/OE.14.004644

[6] http://www.kiriama.com/POFLPG

[7] M. A. van Eijkelenborg, W. Padden and J. A. Besley, "Mechanically Induced Long-Period Gratings in Microstructured Polymer Fibre," *Optics Communications*, Vol. 236, No. 1-3, 2004, pp. 75-78.

[8] M. C. J. Large, D. Blacket and C. A. Bunge, "Microstructured Polymer Optical Fibers Compared to Conventional POF: Novel Properties and Applications," *IEEE Sensors Journal*, Vol. 10, No. 7, 2010, pp. 1213-1217. doi:10.1109/JSEN.2010.2041056

[9] http://www.smart-materials.com/Smart-choice.php?from=MFC

[10] Y. Nagata, S. Park and A. Ming, "Structural Sensing and Actuation Utilizing Macro Fiber Composite," *Proceedings of the IEEE International Conference on Robotics and Biomimetics*, Kunming, 17-20 December 2006, pp. 1275-1280.

[11] J. H. Lim, K. S. Lee, J. C. Kim and B. H. Lee, "Tunable Fiber Gratings Fabricated in Photonic Crystal Fiber by use of Mechanical Pressure," *Optics Letters*, Vol. 29, No. 4, 2004, pp. 331-333. doi:10.1364/OL.29.000331

[12] A. K. Dikshit and S. K. Bhadra, "Characterization of PZT Macrofiber-Polyimide Composite through Distributed Bragg Reflector Fiber Cavity Laser," *Sensors and Actuators A*: *Physical*, Vol. 158, No. 1, 2010, pp. 90-98. doi:10.1016/j.sna.2009.12.015

[13] Y. Fuda, T. Yoshida and T. Ohno, "Ceramic Actuator

with Three-Dimensional Electrode Structure," *Proceedings of the Eighth IEEE International Symposium on Applications of Ferroelectrics*, Greenville, 30 August-2 September 1992, pp. 573-576.

[14] A. K. Dikshit, M. Pal, P. Biswas and S. K. Bhadra, "Efficient Lasing Wavelength Tuning in Distributed Bragg Reflector Fiber Laser Using PZT Macrofiber Composite Actuator," *Journal of Lightwave Technology*, Vol. 28, No. 12, 2010, pp. 1783-1788. doi:10.1109/JLT.2010.2048889

[15] C.-L. Zhao, L. Xiao, J. Ju, M. S. Demokan, W. Jin, *et al.*, "Strain and Temperature Characteristics of a Long-Period Grating Written in a Photonic Crystal Fiber and Its Application as a Temperature-Insensitive Strain Sensor," *Journal of Lightwave Technology*, Vol. 26, No. 2, 2008, pp. 220-227. doi:10.1109/JLT.2007.911106

[16] T. W. MacDougall, S. Pilevar, C. W. Haggans and M. A. Jackson, "Generalized Expression for the Growth of Long Period Gratings," *IEEE Photonics Technology Letters*, Vol. 10, No. 10, 1998, pp. 1449-1451. doi:10.1109/68.720290

[17] X. Shu, L. Zhang and I. Bennion, "Sensitivity Characteristics of Long-Period Fiber Gratings," *Journal of Lightwave Technology*, Vol. 20, No. 2, 2002, pp. 255-266. doi:10.1109/50.983240

[18] M. S. López, A. Fender, W. N. MacPherson, J. S. Barton and J. D. C. Jxones, "Strain and Temperature Sensitivity of a Single-mode Polymer Optical Fiber," *Optics Letters*, Vol. 30, No. 23, 2005, pp. 3129-3131. doi:10.1364/OL.30.003129

