Polymer Optical Fibre Sensing

Author:
Peng, Gang-Ding; Chu, Pak

Publication details:
Optical Information Processing Technology
pp. 303-311
0819447188 (ISBN)

Event details:
SPIE'2002
China

Publication Date:
2002

Publisher DOI:
http://dx.doi.org/10.1117/12.483228

Polymer Optical Fibre Sensing

Gang-Ding Peng [1] and Pak Lim Chu [2]

[1] Photonics and Optical Communications Group
School of Electrical Engineering and Telecommunications
University of New South Wales
Sydney, Australia
Email: G.Peng@unsw.edu.au

[2] Optoelectronic Research Centre
City University of Hong Kong,
Tat Chee Avenue, Kowloon, Hong Kong

Abstract

Development of single-mode polymer optical fibres, polymer materials and polymer fibre Bragg gratings has provided new opportunities for optical communication and other related applications. In this paper we report on recent progress and development of polymer optical fibres and devices that would have a significant impact on fibre sensing applications. We also present some of our preliminary experimental work on polymer optical fibre sensing.

1. Introduction

Optical fibre sensing is of great potential for many applications such as industrial process, civil structure monitoring, environmental surveillance, seismic and geophysical study, undersea oil exploration, medical and biological testing etc [1]. Many types of fibre sensors have been developed, including fibre gyroscopes, hydrophones, strain sensor, etc. However, so far the majority of research and development work has been concentrated on silica optical fibre based sensor systems.

Work on polymer optical fibre sensing has been active for many years. However, these polymer fibre sensors are all based on conventional multimode polymer fibres [2]. Therefore these polymer fibre sensors are overwhelmingly intensity types of fibre sensors for simple and low-cost applications. The intensity-type fibre sensor systems are usually compromised in performance and thus their applications are usually limited.

Here our attention is focussed on sensor applications single-mode polymer fibre. We discuss the recent development of single-mode polymer optical fibres, polymer materials and polymer fibre Bragg gratings, as well as related new opportunities for optical fibre sensor applications.

Polymer optical fibre could be significantly advantageous over its better-known counterpart - silica fibre for sensing applications . A main advantage is its low Young's modulus. The Young's modulus of polymer fibre materials is typically many times less than that of silica glass. For strain related optical sensor such as fibre hydrophone and pressure sensor, polymer optical fibres are intrinsically many times more sensitive than silica glass fibres [3]. For the same reason, polymer optical fibre could be advantageous for sensing in liquids and less rigid solid state materials.

2. Polymer optical fibres

Polymer optical fibre (POF) was first developed in the early 1970s, about the same time as silica fibre. In the middle of 1970s, Schleinitz at duPont in the US demonstrated that poly(methyl methacrylate) (PMMA)- based POF could have attenuation as low as 300dB/km [4]. Mitsubishi then developed a continuous casting process in manufacturing POF based on high purity acrylics. This has since led to the development of various POFs at Mitsubishi Rayon in Japan. However, POF has long been overshadowed by the amazing and rapid development of low loss silica fibres. Most of conventional polymer optical fibres are multimode and PMMA (poly methyl methacrylate)-based. These fibres have optical transmission windows in the visible wavelengths. Nevertheless the loss of the PMMA-based fibres is not particularly low, at a level about 100 dB per kilometre. It is significantly higher than that of silica-based optical fibres. This is a factor that limits the applications of polymer fibre sensor in long haul systems.

Polymer optical fibre technology has made remarkable progress in recent years. This development has been greatly boosted by an emerging and important market of high-speed (broadband) local area networks. In these networks polymer optical fibre is deemed to be very competitive to the conventional silica optical fibre, and is more advantageous for its excellent flexibility, low cost and, ease of handling and connection [5]. Great breakthrough has been made in improving the optical property of polymer fibre materials in early 1990s. Researchers in Asahi Glass Co. and Keio University in Japan developed excellent fluorinated polymer materials for making very low loss polymer fibres. The fluorinated polymer has excellent chemical, thermal, electrical and surface properties, very much similar to those of conventional fluoropolymers -- teflon. New polymer optical fibres based on these perfluorinated materials have been made with very low loss. It is reported that fluorinated polymer optical fibre achieved a loss as low as 16dB/km [6].

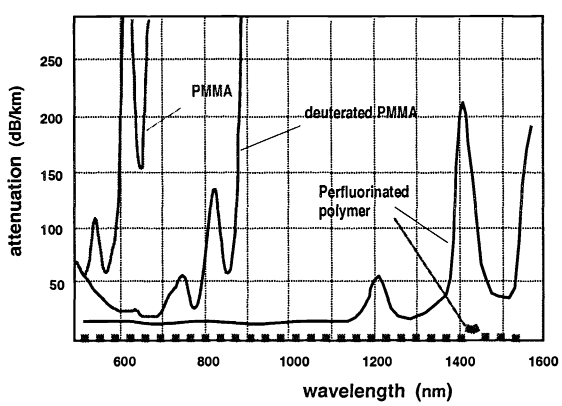

Fig.1 Typical attenuation spectra of polymer optical fibres based on different materials: PMMA, deuterated PMMA and perfluorinated polymer.

Fig.1 compares the attenuations of three types of polymer optical fibres. It is worthnoting that, in addition to its excellent optical property characterised by its high optical transparency, the perfluorinated material has a very broad transmission window, wide open from the 650nm right up to 1300nm. Theoretically it is even predicted that the loss could be as low as 0.3dB/km [7].

3. POF Bragg and fibre sensing

Fibre Bragg Grating (FBG) has been one of very useful fibre-optic components for optical communications as well as optical fibre sensing. FBG has excellent wavelength selectivity in its spectral characteristics. It has been demonstrated as important sensing elements or optical fibre reflectors for measuring temperature, pressure and strain, hydro-sound and industrial process.

Due to the importance of fibre grating for a great spectrum of applications, the fabrication of fibre gratings have been one of the main research topics in recent years. Nevertheless the work has been dominantly concentrated on the silica optical fibre gratings.

Recent work on photosensitivity of POF and successful fabrication of Bragg gratings in single-mode POF clearly provide new opportunities. Photosensitivities of PMMA-based polymer fibres [8] and fluorinated polymer fibres [9] have been investigated and observed. Continued work have lead to Bragg gratings being fabricated in various polymer optical fibres [10,11]. Similar writing techniques to those for silica fibre Bragg grating have been used for fabrication of polymer FBG. A scheme, which includes an interferometer proposed by Meltz et al [12] in combination with a phase mask made from surface relief grating proposed by [13], has produced good grating with high transmission rejection of 28dB [11].

It is believed that there are four mechanisms that can lead to the creation of gratings in polymer by means of light. They are: (1) Ablation --- this involves the melting and burning of the polymer surface, (2) Chain Scission --- this involves the breaking of polymer chains thus decreasing the chain density which in turns reduces the refractive index, (3) Cross-linking --- this involves inducing free radicals and then giving rise to the combination of polymer chains. This has the effect of increasing the density of the chains thus increasing the refractive index of the polymer, and finally (4) Photopolymerization --- The incident light generates free radicals thus causing the polymerization of unreacted monomer within the polymer. As a result, the polymer density increases and the refractive index increases accordingly. The first two mechanisms, ablation and chain scission, are responsible for the creation of surface gratings in the polymer. The last two mechanisms, cross-linking and photopolymerization, are considered to be essential to create polymer bulk gratings and polymer fibre gratings.

Now both polymer optical fibres and polymer optical fibre Bragg grating have been developed to a stage useful for fibre sensor applications. The use of FBG as sensing elements is based on simple and well-known relations. The reflection wavelength of a fibre Bragg grating, λ_B, can be expressed in a simple general form from Equation

$$\lambda_B = 2\Lambda n_{eff}$$

Here the grating period Λ is determined by the period of the interference pattern (fringe) of writing light beam. From this expression, we can see that the Bragg wavelength of a grating can be changed, if a particular mechanism is used to introduce changes in the grating period, Λ, and /or the effective index n_{eff}. Two well-known mechanisms can easily introduce a shift of Bragg wavelength. The first is the mechanical mechanism which involves applying a longitudinal stress to a fibre Bragg grating so that the grating period is stretched. The second is the thermal mechanism in which the grating is heated up to introduce a change in the grating period. In the first mechanism, the resulted wavelength shift is mainly due to two factors: a change in Λ due to stress-induced strain and a change in n_{eff} through the photo-elastic effect.

In the case of mechanical sensing, the strain is related the stress σ

$$\varepsilon = \frac{\Delta L}{L} = \frac{\sigma}{E}$$

where E is the Young's modulus of the polymer. Hence the stress-induced Bragg wavelength shift, $\Delta\ \lambda_B$, can be easily expressed as

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - P_e)\varepsilon = \frac{1 - P_e}{E}\sigma$$

where P_e is the effective photo-elastic coefficient and ε longitudinal strain. Thus the Young's modulus E has a significant influence on the sensitivity of the Bragg wavelength. Large modulus materials such as silica have less stress sensitivity thus require larger stress to produce the same strain in comparison to low modulus materials such as PMMA. It is noted that the Young's modulus of PMMA is much less than that of silica glass. Hence, under a certain stress, polymer fibre with much lower Young's modulus could achieve much higher strain and thus much higher sensitivity. This is the reason that, as mentioned above, the low Young's modulus of polymer fibre could be a significant advantage for strain-related sensing applications.

Moreover, rigid materials such as silica glass usually have low breakdown strain. For silica glass fibre, the breakdown strain is about 1%. This sets a limit to the maximum achievable range. For polymers such as PMMA because of its great flexibility in material synthesis, however, 10% or more breakdown strain could be readily achieved. The great elasticity and large breakdown strain are important for sensing applications with very large dynamic range. In fact, it is possible to tailor the Young's modulus and elasticity of a polymer fibre with readily available synthesis techniques. Hence it is possible to select appropriate materials with desirable Young's modulus or elasticity from a wide range of optical polymer materials. This is an important feature that makes polymer optical fibres or polymer fibre Bragg gratings better candidates for sensing applications in various liquid and elastic material environment --duly covering a full range of strain-related sensor applications.

In the case of temperature sensing which is usually required together with stress or strain sensing, a change in the fibre temperature ΔT also leads to the shift of Bragg wavelength. The relation can be expressed by

$$\frac{\Delta\lambda_B}{\lambda_B} = (\alpha + \beta)\Delta T$$

where α is the thermal expansion coefficient and β is the relative thermo-optic coefficient of the fibre material. It is clear that polymer fibre will have both larger thermal expansion coefficient and larger thermo-optic coefficient than silica fibre.

We summarises the relevant characteristics of typical silica and polymer fibre parameters for sensing in Table 1:

Table 1 Comparison of relevant parameters of silica and polymer optical fibres

Properties	Silica fibre	Polymer fibre
Attenuation [dB/km]	0.2 ~ 3	10 ~ 100
Young's modulus [Gpa]	~ 100	~ 3
Breakdown strain [%]	1~2	5 ~ 10
Thermo-optic coefficient [10^{-5}/°C]	~1	~ -10
Thermal expansion coefficient [10^{-5}/°C]	~0.05	5

From the table we could easily see that POF is advantageous over silica fibre as far as relevant properties for sensing are concerned, and that POF could provide opportunities for sensor applications with high stress response, high pressure response or large dynamic range.

4. Sensing experiment with POF Bragg grating

In our recent experiment, we used single-mode polymer FBGs in sensing related tests [14]. The reflection and transmission spectra of a polymer FBG used in the experiment are shown in Fig.2.

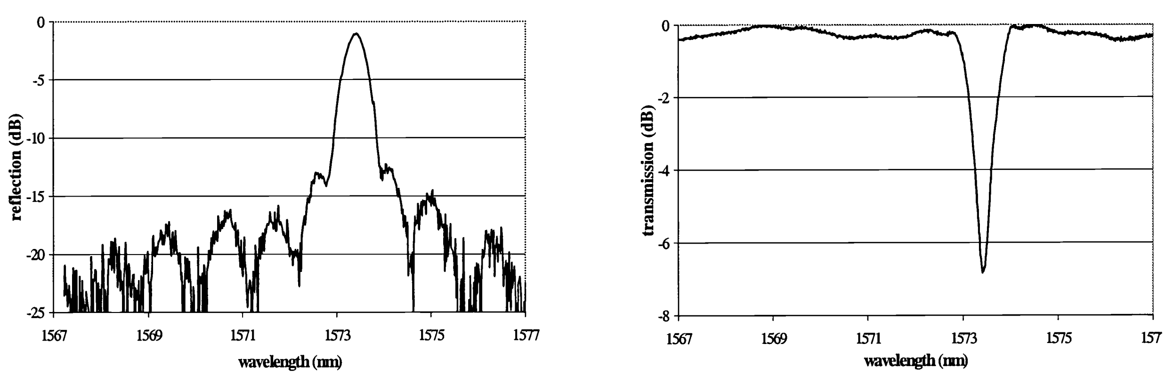

Fig.2 Transmission spectrum of a POF Bragg grating with high transmission rejection and narrow line width.

The POF grating has power reflection about 80% with the bandwidth less than 0.5 nm. The strain response of the polymer FBG is shown in Fig. 3. it is tested in loading mode -- when it is stretched and in unloading mode -- when it is released, respectively. It is clearly shown that the linear relation of Bragg wavelength shift with the applied strain has been observed. Although the loading curve matches well with the unloading one, the long term reversibility of polymer FBG under strain is yet to be tested. In this experiment, the strain of the FBG reaches 3% and the strain response of polymer FBG is found to be 2.7 pm/με. In general, polymer FBG should be able to achieve a large strain with good reversibility. In our experiment on another polymer POF, we tested strain close to 5% (as shown in Fig.5 in the following).

Fig.4 shows the shift of Bragg wavelength as a function of temperature of the polymer FBG. A Peltier cell was used as a heat source whose temperature is controlled by electric current. This cell sat on top of an aluminium block with the POF grating and temperature sensor inserted between the block and the cell. The POF grating was connected to a piece of silica fibre to enable light to be launched into the grating and the transmitted light from the grating was directed to the Optical Spectrum Analyzer (OSA). The accuracy of the temperature measurement was 0.1°C but it took about 10 minutes for the system to reach the desired temperature. When the temperature reached the desired value, the transmission spectrum of the grating was measured using the OSA. An ASE source was used as the light source. The test is carried out when the grating was heated up (heating) from room temperature to about 65 °C. It is also tested when the grating was cooled down (cooling). The wavelength shift to temperature is quite linear. The coincidence of heating and cooling curves indicates the absence of hysteresis. From the temperature response curve, we observed that the Bragg wavelength of polymer FBG is decreased (shifted toward blue wavelengths) with the increase of temperature. It is well-known that the Bragg wavelength of silica FBG is increased (shifted toward red wavelengths) with the increase of temperature. Hence polymer FBG has completely different temperature response from that of silica FBG. The expression for the temperature response of POF gratings in Fig. 3 is determined to be $\lambda_B = 1577(1-9.64\times10^{-5}T)$. The temperature sensitivity of polymer FBG is found to be 152 pm/°C. It is about 10 times higher than that of silica FBG (approximately 14 pm/°C) [15]. .

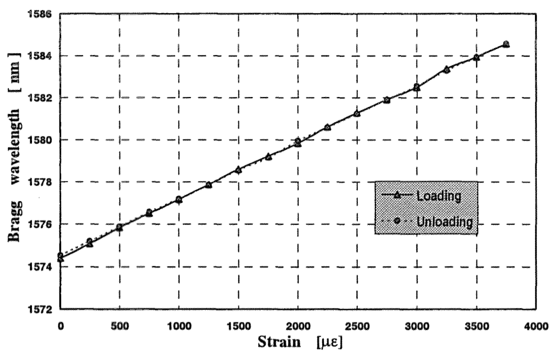

Fig.3 Strain response of a polymer FBG.

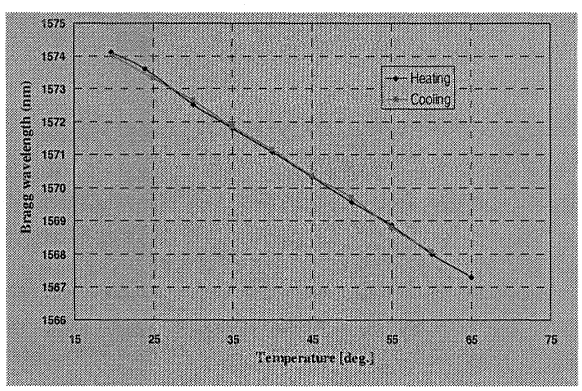

Fig.4 Temperature response of polymer FBG.

One important topic in fibre sensing applications is the simultaneous measurement of strain and temperature. The popular scheme is to use two silica FBGs (say FBG1 and FBG2) with different Bragg wavelengths (e.g. λ_1 and λ_2) to form a sensing head. The shifts of Bragg wavelengths (e.g. $\Delta\lambda_1$ and $\Delta\lambda_2$) of combined strain and temperature factors is given by

$$\begin{bmatrix}\Delta\lambda_1\\ \Delta\lambda_2\end{bmatrix} = \begin{bmatrix}K_{1T} & K_{1\varepsilon}\\ K_{2T} & K_{2\varepsilon}\end{bmatrix}\begin{bmatrix}\Delta T\\ \Delta\varepsilon\end{bmatrix}$$

where K_{1T} and K_{2T} are the temperature sensitivities of the FBG1 and FBG2, respectively, whilst $K_{1\varepsilon}$ and $K_{2\varepsilon}$ are the corresponding strain sensitivities. The measurands T and ε can be determined by calculating the inverse transfer matrix of the above equation,

$$\begin{bmatrix} \Delta T \\ \Delta \varepsilon \end{bmatrix} = \begin{bmatrix} K_{1T}' & K_{1\varepsilon}' \\ K_{2T}' & K_{2\varepsilon}' \end{bmatrix} \begin{bmatrix} \Delta\lambda_1 \\ \Delta\lambda_2 \end{bmatrix}$$

However, because of the similarity in strain and temperature sensitivities of the two silica fibre gratings, the inversion operation of the transfer matrix could be quite problematic and usually subject to significant errors.

From the data described in Table 1, the strain and temperature sensitivities of POF gratings are quite different from those of silica fibre gratings. Hence it is desirable to combine one silica fibre grating and one POF grating into a usual two-FBG sensor head to measure temperature and strain simultaneously. Since in this case K_{1T} and K_{2T} as well as $K_{1\varepsilon}$ and $K_{2\varepsilon}$ are quite different from each other, the problem in the transfer matrix operation could be easily solved. Based on our experimental results, the values for K_{1T} and $K_{1\varepsilon}$ are 152 pm/°C and 2.7 pm/με, respectively for the polymer FBG. Using K_{2T} and $K_{2\varepsilon}$ values for silica FBG referred in [16]. The temperature and strain can be easily worked out once the wavelength shifts are determined:

$$\begin{bmatrix} \Delta T \\ \Delta \varepsilon \end{bmatrix} = \begin{bmatrix} 0.0495 & 0.7229 \\ -0.0057 & 0.0127 \end{bmatrix} \begin{bmatrix} \Delta\lambda_1 \\ \Delta\lambda_2 \end{bmatrix}$$

Because of the much higher sensitivities of polymer FBG, the overall system sensitivities will be much higher.

Larger strain in polymer FBG has also been tested and the Bragg wavelength shift versus strain is depicted in Fig.5. Here a Bragg wavelength shift of more than 70nm in a single-mode polymer fibre grating has been achieved with a tensile strain nearly 5%. The result shows that the capability of polymer FBG for strain sensing with a very large dynamic range (up to 50000με) – it is more than 10 times greater than that achieved in a silica optical fibre grating and it could be sufficient to cover most of structure health monitoring applications.

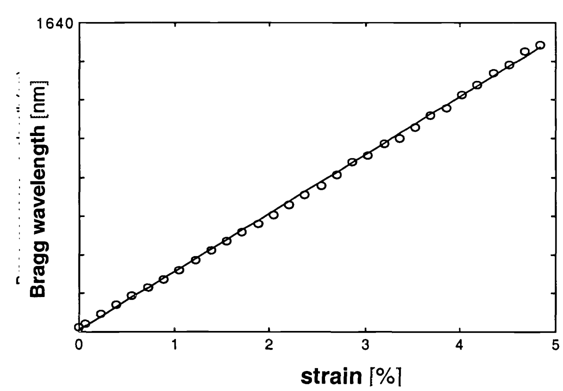

Fig.5 Bragg wavelength shift of a POF grating with large strain.

The preliminary experimental observations only confirm the great potential of POF, especially polymer FBG, for fibre sensing from the fundamental aspects. There are many relevant issues, including experimental implementation and practical application are yet to be further investigated.

To continue this research work, we have just developed a strain sensing system using two FBGs with similar spectral characteristics [17]. Its schematic diagram is shown in Fig.6. In this system, one FBG is used as strain sensing element and the other for direct strain-to-signal power conversion. This is a very simple and practical scheme that expensive equipment such as optical spectrum analyzer or wavelength meter is avoided. Initial experimental results on two silica FBGs have shown that that a good linearity and a large dynamic range can be achieved in this system. We will use this system as a test-bed for our experiments of fibre sensing using polymer FBG.

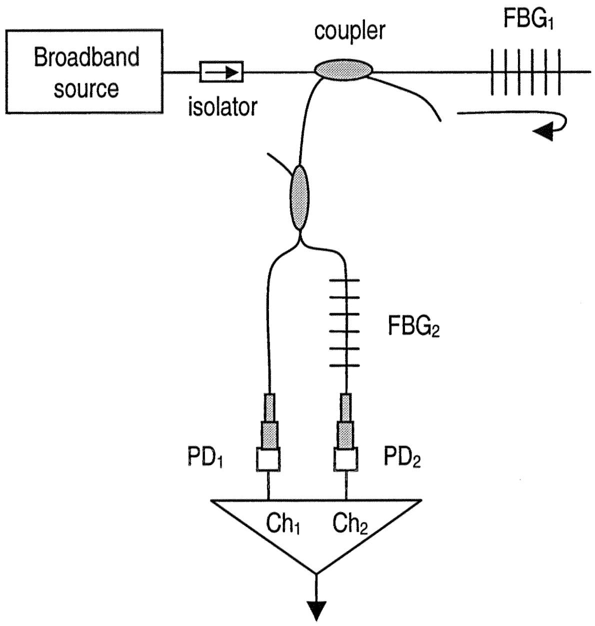

Fig.6 Scheme of strain sensing system using two FBGs.

5. Conclusion

For interferometric or Bragg grating-based fibre sensors such as acoustic sensors, hydrophones and strain sensors, their performance is closely related to the mechanical, thermal and elasto-optical properties of fibre materials. In pressure or stress-related applications, the system sensitivity is mainly determined by its mechanical property parameter –Young's modulus and it is intrinsically low when silica-based optical fibres. The main reason for the poor stress / pressure response of silica glass fibres is clearly linked to its relatively high Young's modulus (~100GPa). On the other hand, polymer optical fibre (POF) is highly flexible and elastic compared with silica fibre and, as far as flexibility and elasticity are concerned, POFs (typically ~ 3GPa) have quite complementary properties to their silica counterparts.

It is believed that POF such as health monitoring of civil engineering structure, could be a significant advantage for sensor applications.

We have started and done preliminary sensing experiments on polymer fibre Bragg gratings. The experimental results have demonstrated the fundamental aspects and properties of POF and polymer FBG for strain sensing applications, especially where strain and temperature are to be measured simultaneously.

6. Acknowledgment

This research is supported by the Australian Research Council and Australian photonic Cooperative Research Centre. The authors would like to acknowledge contributions to the work from our colleagues: T. Whitbread, H. Y. Liu, H. B. Liu, R. Wang and H. Hewa-Gamage.

7. References

[1] For example: N. Takahashi, K. Tetsumura, K. Imamura and S. Takahashi, "Fiber-Bragg-grating WDM underwater acoustic sensor with directivity", Proc. of SPIE, v.3541,18-16, 1999; also G. D. Peng and P. L. Chu, "Optical fibre hydrophone systems", a book chapter in Fiber Optic Sensors, F. Yu and S Yin (ed.), Marcel Dekker, Inc., New York, Chapter 9, 417-447, 2001

[2] For example: J. Zubia, O. Aresti, J. Arrue and M. lopez-Amo, "Barrier sensor based on plastic optical fiber to determine the wind speed at a wind generator", IEEE J. Selected Topics in Quant Electrn. Vol.6, No.5, 773-779, 2000

[3] G. D. Peng, "Prospects of POF and Grating for Sensing", invited paper, presented at the 15th International Conference of Optical Fiber Sensors, Portland, OR, USA, 6-10 May, 2002

[4] H. M. Schleinitz, Proc. Inter. Wire and Cable Symposium, 352, 1977

[5] G. Giaretta, W. White, M. Wegmueller and R. V. Yelamaty, "11 Gb/sec data transmission through 100 m of perfluorinated graded-index polymer optical fiber", Tech. Digest, OFC'99, 3, 1999

[6] Y. Koike, "Progress in GI-POF: status of high speed plastic optical fiber and its future", Proc. of the International POF Technical Conference, POF'2000, 1-5, 2000

[7] N. Tanio and Y. Koike, "What is the most transparent polymer?", J. of Polymer, v.32, 43-50, 2000

[8] G. D. Peng, Z. Xiong, and P. L. Chu, "Photosensitivity and grating in dye-doped polymer optical fibres" Optical Fibre Technology, vol.5, 242-251, April 1999

[9] H. Y. Liu, G. D. Peng, P. L. Chu, Y Koike and Y. Watanabe, "Photosensitivity in low-loss perfluoropolymer (CYTOP) fiber material", IEE Electronics Letters, vol.37, no.6, 347-348, 2001

[10] Z. Xiong, G. D. Peng, B. Wu and P. L. Chu, "Highly tunable single-mode polymer optical fibre grating", IEEE Photonic Technology Letters, vol.11, no.3, 352-354, March 1999

[11] H. Y. Liu, G. D. Peng and P. L. Chu, "Polymer Fiber Bragg Gratings with 28dB Transmission Rejection", IEEE Photonics Technology Letters, vol.14, 935-937, July 2002

[12] G. Meltz, W. W. Morey and W. H. Glenn, " Formation of Bragg grating by transverse holographic method", Opt. Lett. vol.14, 823-826, 1989

[13] K. O. Hill, B. Malo, F. Bilodeau, D. C. Johnson and J. Albert, "Bragg gratings fabricated in monomode photosensitive optical fiber by UV exposure through a phase mask", Appl. Phys. Lett., v.62, 1035-1037, 1993

[14] H. B. Liu, H. Y. Liu, R. Wang, and G. D. Peng, "Strain and temperature response of polymer fiber Bragg gratings", submitted to ICOCN'2002

[15] O. Andreas and K. Kyriacos, "Fiber Bragg Gratings Fundamentals and Applications in Telecommunications and Sensing," Chapter 3, pp. 98-99.

[16] A. D. Kersey, M. A. Davis, H. J. Patrick, M. Leblanc, K. P. Koo, C. G. Askins, M. A. Putnam, and E. J. Friebele "Fiber Grating Sensors" *IEEE J. Lightwave Technol. Lett.*, 1997, **15**, (8), pp. 1442-1463

[17] R. Wang, H. B. Liu and G. D. Peng, "Simple strain sensing using two fiber Bragg gratings", submitted to Opt. Comm.