Received: 25 March 2017 | Revised: 29 April 2017 | Accepted: 5 May 2017
DOI: 10.37917/ijeee.13.1.7 | Vol. 13| Issue 1 | June 2017
Open Access
Iraqi Journal for Electrical and Electronic Engineering
Original Article

Effect of Temperature Variations on Strain Response of Polymer Bragg Grating Optical Fibers

Hisham K. Hisham
Electrical Engineering Department,
Faculty of Engineering,
Basra University,
Basra, Iraq
E-mail: husham_kadhum@yahoo.com

Abstract
This paper presents a numerical analysis for the effect of temperature variations on the strain response of polymer optical fiber (POF) Bragg gratings. Results show that the dependence of the Bragg wavelength (λ_B) upon strain and temperature variations for the POF Bragg gratings is lies within the range of 0.462 – 0.470 fm $\mu\varepsilon^{-1}$ °C^{-1} compare with 0.14 – 0.15 fm $\mu\varepsilon^{-1}$ °C^{-1} for the SOFs Bragg gratings. Also, results show that the strain response for the POF Bragg gratings changed on average by 1.034 ± 0.02fm $\mu\varepsilon^{-1}$°C^{-1} and on average by 0.36 ± 0.03fm $\mu\varepsilon^{-1}$°C^{-1} for the silica optical fiber (SOF) Bragg gratings. The obtained results are very important for strain sensor applications especially in the environments where the temperature change.

Index Terms– **Polymer optical fiber (POF); fiber Bragg grating (FBG); Strain sensitivity; temperature variations.**

1. INTRODUCTION

Over the recent years, fiber optics technology has seen rapid increase in the field of optical sensors as well as be used widely in the scientific research and in various engineering applications [1, 2]. Optical fiber sensors, especially fiber Bragg gratings (FBGs), show a unique features likes immunity to electromagnetic (EM) interference, low power fluctuations, small size, highly precision, its ability for multi-sensing along single fiber and so on [3]. Thus, FBGs have become the most important and widespread and are being used increasingly by engineers, as a result of their ability to perform measurements under very tough environment conditions, such as highly mechanical vibrations, temperature and pressure variations, where other conventional sensors cannot be operated [4].

Due to their unique features, fiber optic strain sensors are of great importance for many applications. Where, it combines the ability for high sensitivity and high dynamic range. They are of particular important especially for industrial applications with harsh environments such as highly temperature and pressure [5]. Add to that, they are not affected by EM fields and their potentials for monitoring at various locations in the installations [6].

Fused silica, the material used in the manufacture most of the silica optical fibers (SOFs), characterized by an ideal mechanical properties thus making it suitable for many strain sensing applications. However, fused silica have an upper strain limit of ~3-5% and in general their reliability are not exceed 1% strain and under a special procedures. Therefore, conventional silica fibers based strain gauges cannot be used in several applications [7].

The unique merits of polymer optical fibers (POFs) such as a negative and large thermo-optic effect, thereby, high refractive index tuning by heating can be obtained and good flexibility makes them much more suitable in high strain applications than their SOFs, especially that FBGs have been written into POFs [3].

Many researchers have been reported on the strain sensitivity of a FBG sensor. However, in all these reported, the strain sensitivity of the Bragg wavelength is generally assumed to be independent of temperature [8, 9]. However, it is known that the material parameters that determine the strain sensitivity, the effective strain optic coefficients and

Poisson's ratio, are themselves temperature dependent [10-12]. Therefore, the results have been obtained do not reflect the true reality of the performance of these sensors. In this paper, we present for the first time to our knowledge, the effect of temperature variations on the strain sensitivity of the POFs and compare the results with that for SOFs.

II. TEMPERATURE DEPENDANCE OF FBGs STRAIN RESPONSE

Using FBGs as a fiber sensor is based on the idea that their properties vary depending to environmental changes. The amplitude of the fiber index modulation, the gratings period, the optic thermal-strain effects, the design wavelength are shifts leads to change the Bragg condition [3]. This results in, the reflected and the transmitted lights are changed. By measuring the change in the spectrum, the value of temperature, strain, and other parameters are obtained [13]. The change in Bragg wavelength ($\Delta\lambda$) is described by the formula [3, 14]

$$\Delta\lambda = 2\left(\Lambda\frac{\partial n_{eff}}{\partial L_g} + n_{eff}\frac{\partial\Lambda}{\partial L_g}\right)\Delta L_g + 2\left(\Lambda\frac{\partial n_{eff}}{\partial T} + n_{eff}\frac{\partial\Lambda}{\partial T}\right)\Delta T + 2\left(\Lambda\frac{\partial n_{eff}}{\partial\lambda} + n_{eff}\frac{\partial\Lambda}{\partial\lambda}\right)\Delta\lambda \quad (1)$$

In Eq. (1), n_{eff}, Λ, L_g and T are represents the fiber refractive index, grating period, grating length and temperature variations, respectively. By neglecting the variation in refractive index due to a change in incident wavelength ($(\partial n_{eff}/\partial\lambda)$) [14], Eq. (1) can be reduced to

$$\Delta\lambda = 2\left(\Lambda\frac{\partial n_{eff}}{\partial L_g} + n_{eff}\frac{\partial\Lambda}{\partial L_g}\right)\Delta L_g + 2\left(\Lambda\frac{\partial n_{eff}}{\partial T} + n_{eff}\frac{\partial\Lambda}{\partial T}\right)\Delta T \quad (2)$$

Where ΔL_g and ΔT are the change in grating length due to applied strain and the change in ambient temperature, respectively.

The differential shift in center wavelength of a FBG due to the change in the applied strain can be written as [14]

$$\Delta\lambda_B = 2\left(\Lambda\frac{\partial n_{eff}}{\partial L_g} + n_{eff}\frac{\partial\Lambda}{\partial L_g}\right)\Delta L_g \quad (3)$$

By assuming $(\Delta L_g / L_g) = \varepsilon_z$ and substituting it in Eq. (3), we get

$$\Delta\lambda_B = 2\Lambda\frac{\partial n_{eff}}{\partial L_g}\Delta L_g + 2n_{eff}\frac{\partial\Lambda}{\partial L_g}\varepsilon_z L_g \quad (4)$$

Using the facts that $\frac{\partial n_{eff}}{\partial L_g}\Delta L_g = \Delta n_{eff}$ and $\Delta\left(\frac{1}{n_{eff}^2}\right) = -\frac{2\Delta n_{eff}}{n_{eff}^3}$, Eq. (4) rewrite as

$$\Delta\lambda_B = 2\Lambda\left[-\frac{n_{eff}^3}{2}.\Delta\left(\frac{1}{n_{eff}^2}\right)\right] + 2n_{eff}\frac{\partial\Lambda}{\partial L_g}\varepsilon_z L_g \quad (5)$$

The strain-optic effect in an optical fiber results in a change in the effective refractive index is given by [14]

$$\Delta\left(\frac{1}{n_{eff}^2}\right)_i = \sum_{j=1}^{3} p_{ij}.S_j \quad (6)$$

In Eq. (6), p_{ij} is the strain-optic tensor and S_j is the strain vector. The strain vector S_j for a longitudinal strain along the fiber grating axis (z-axis) is given by [14]

$$S_j = \begin{bmatrix} -v\varepsilon_z \\ -v\varepsilon_z \\ \varepsilon_z \end{bmatrix} \quad (7)$$

Where v is Poisson's ratio, and ε_z represents strain in the z-direction. For a typical germanium-silicate optical fiber, p_{ij} has only two numerical values, p_{11} and p_{12} [14]. Thus, Eq. (6) modified to

$$\Delta\left(\frac{1}{n_{eff}^2}\right)_i = \left[p_{12} - v\left(p_{11} + p_{12}\right)\right]\varepsilon_z \qquad (8)$$

Since $\left(\partial\Lambda/\partial L_g\right) = \left(\Lambda/L_g\right)$, then Eq. (5) rewrite as

$$\Delta\lambda_B = 2n_{eff}\Lambda\varepsilon_z\left\{1 - \frac{n_{eff}^2}{2}\left[p_{12} - v\left(p_{11} + p_{12}\right)\right]\right\} \qquad (9)$$

Therefore, the differential shift in the Bragg wavelength due to the applied strain given by

$$\frac{\Delta\lambda_B}{\lambda_B} = \left(1 - p_{eff}\right)\varepsilon_z \qquad (10)$$

Where in Eq. (10) p_{eff} is the index-weighted effective strain-optic coefficient given by [13]

$$p_{eff} = \frac{n_{eff}^2}{2}\left[p_{12} - v\left(p_{11} + p_{12}\right)\right] \qquad (11)$$

The dependence of the Bragg wavelength (λ_B) upon strain (ε_z) and temperature variations after taking into account the temperature dependence of the effective strain optic coefficients (p_{ij}) and Poisson's ratio (v) is given by [12]

$$\lambda\left(T, \varepsilon_z\right) = \lambda_B\left\{1 + \varepsilon_z - \frac{n_{eff}^2(T)}{2}\varepsilon_z \mathrm{P}(T) + \left(\xi + \alpha\right)T\right\} \qquad (12)$$

Where,

$$P(T) = p_{12}(T) + \left(p_{11}(T) + p_{12}(T)\right)v(T) \qquad (13)$$

Equation (12) represents the modified Bragg wavelength resulting from longitudinal-applied strain and temperature changes. By using Eq. (12), the temperature dependence strain sensitivity given be

$$\frac{\Delta\lambda(T)}{\Delta\varepsilon_z} = \lambda_B\left\{1 - \frac{n_{eff}^2(T)}{2}P(T)\right\} \qquad (14)$$

According to the Eq. (14), the temperature dependence of the FBG strain sensitivity arises from the temperature sensitivity of the strain optic coefficients and of Poisson's ratio.

III. RESULTS and DISCUSSION

In our simulation, we assumed a single-mode fiber with uniform Bragg gratings. Table I shown the typical values of P_{11}, P_{12} and v for SOFs and PMMA POFs have been used in the analysis.

Table I
Typical values for the strain-optic tensor and Poisson's ratio [8, 9, 14]

SOF			PMMA POF		
P_{11}	P_{12}	v	P_{11}	P_{12}	v
0.113	0.252	0.16	0.3	0.297	0.35

Figure 1 (a) and (b) show the effect of temperature variations on the Bragg wavelength for SOF and POF, respectively. It is clear that the response is linear and there is no hysteresis effect. Due to the negative temperature coefficient [3], POF has a negative slope of the temperature response. This is in contrast to the temperature response of SOF which has a positive slope. It can be seen also that almost 10 nm tuning range can be achieved when the POF is temperature heated up from 25ºC (it is assumed the reference temperature) to 75ºC, which is larger than the few nanometers achieved in SOF. Furthermore, in order to increase the tuning range for SOF, this requires increasing the grating temperature by several hundreds of times than that for POFs.

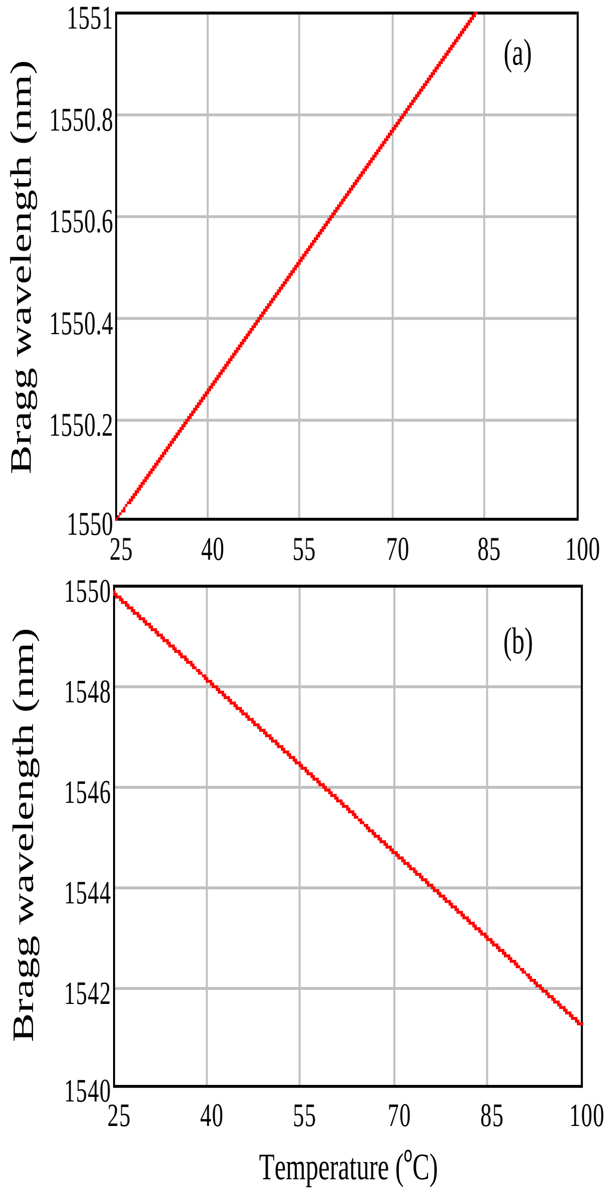

Figure 1 Temperature effect on Bragg wavelength of (a) Silica Optical Fiber (SOF) and (b) Polymer Optical Fiber (POF)

Figure 2(a) and (b) show the effect of strain on the Bragg wavelength of SOFs and POFs, respectively. As shown, the Bragg wavelength shift in POF over a strain range of 10 milli-strain is more than 15 nm. In addition, the strain sensitivity of the POFs is found to be 1.48 pm/με. This is nearly 1.2 times larger than the value for the SOFs, which is 1.2 pm/με at the designed wavelength. This is because the strain sensitivity of POF is more than of SOF [4, 13].

For example, the Young's modulus of POF is more than 30 times smaller and its break-down strain is also much larger than for SOF. Thus, the tunability of POF is higher than that of SOF [3].

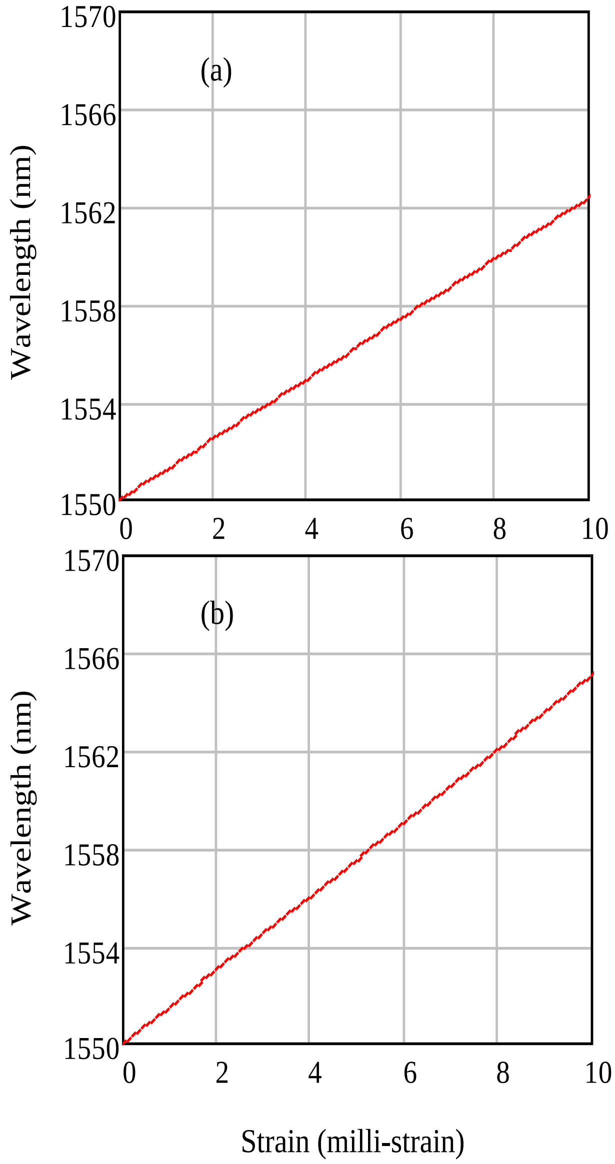

Figure 2 Effect of strain on Bragg wavelength of (a) Silica Optical Fiber (SOF) and (b) Polymer Optical Fiber (POF)

Figure 3 (a) and (b) show the dependence of the Bragg wavelength (λ_B) upon strain and temperature variations for the SOF and the POF, respectively. Results show that there is a change in the response of the FBG at different temperatures, though the magnitude of this change is such that its effect would only be significant over large temperature or strain ranges. Also, results indicate that the dependence of the Bragg wavelength (λ_B) upon strain and temperature variations for the POF Bragg gratings is lies within the range of 0.14 – 0.15 fm $\mu\varepsilon^{-1}$ $°C^{-1}$ and in the range of 0.462 – 0.470 fm $\mu\varepsilon^{-1}$ $°C^{-1}$ for the SOF and the POF, respectively.

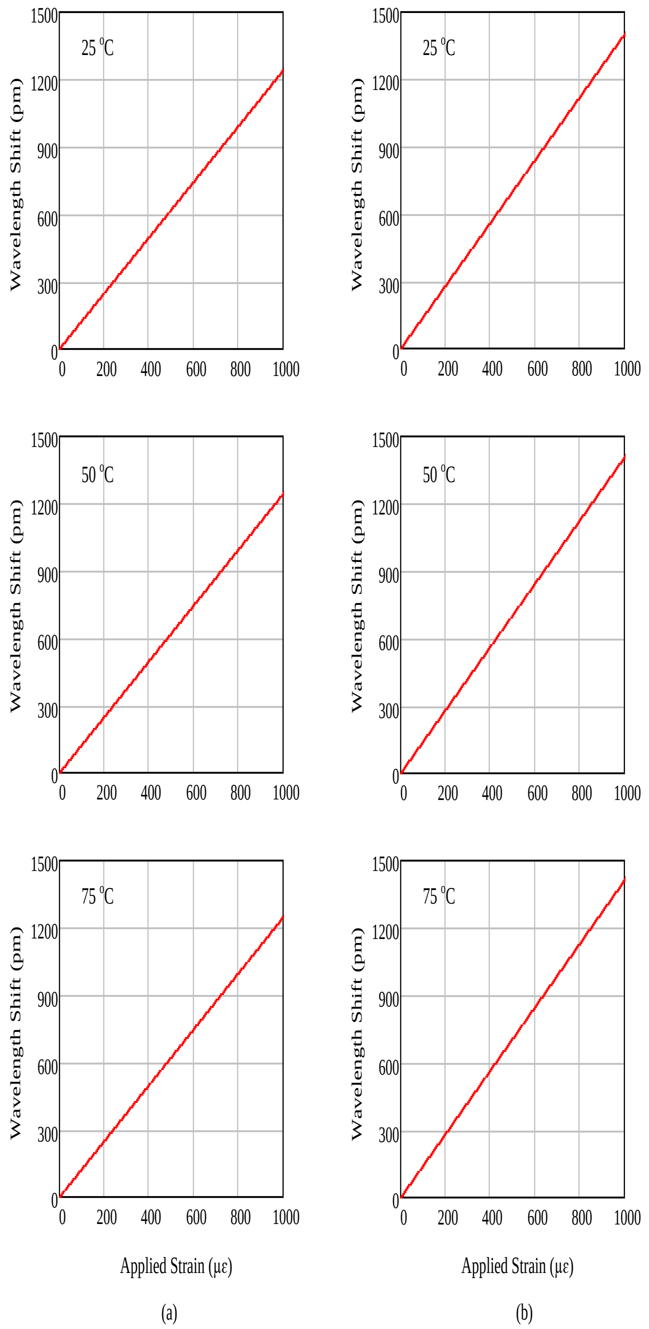

Figure 3 Temperature Effect on Strain Response of (a) Silica Optical Fiber and (b) Polymer Optical Fiber

Figure 4 (a) and (b) show the temperature dependence of the strain response for POF Bragg gratings and SOF Bragg gratings, respectively. As we have mentioned, the temperature dependence of the strain response is arises from the temperature-strain optic coefficient and the Poisson's ratio dependence [13, 14]. Results show good linearity over the range of temperature used. Also, Results show that the strain response for the POF Bragg gratings changed on average by 1.034 ± 0.02fm $\mu\varepsilon^{-1}°C^{-1}$ and on average by 0.36 ± 0.03fm $\mu\varepsilon^{-1}°C^{-1}$ for the SOF Bragg gratings.

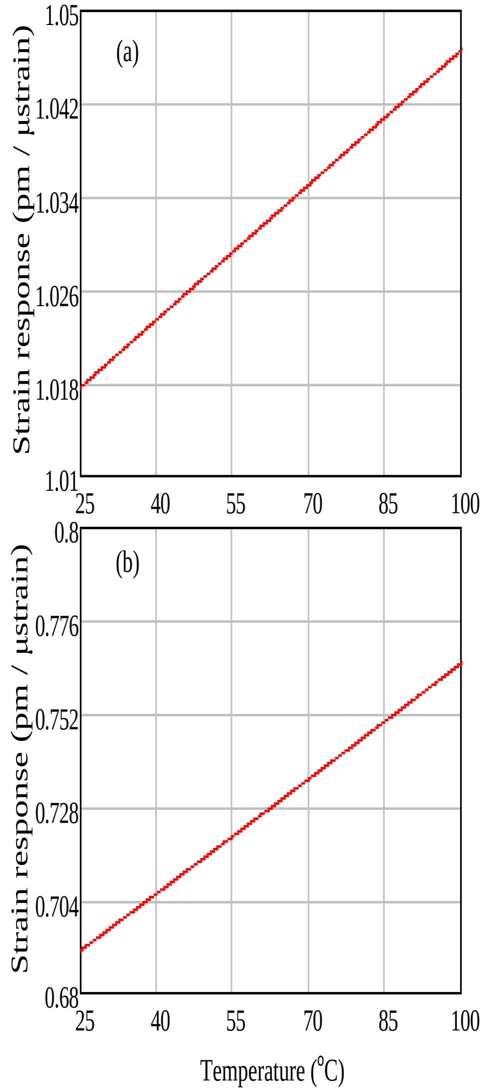

Figure 4 Effect of temperature variations on strain response for (a) silica optical fiber (SOF) and (b) polymer optical fiber (POF)

V. CONCLUSION

The effect of temperature variations on the strain response of polymer optical fiber (POF) Bragg gratings has been investigated for the first time successfully. It was found that the dependence of the Bragg wavelength (λ_B) upon strain and temperature variations for the POF Bragg gratings is lies within the range of 0.462 – 0.470 fm $\mu\varepsilon^{-1}$ °C^{-1} compare with 0.14 – 0.15 fm $\mu\varepsilon^{-1}$ °C^{-1} for the SOFs Bragg gratings. Also, results show that the strain response for the POF Bragg gratings changed on average by 1.034 ± 0.02fm $\mu\varepsilon^{-1}$°C^{-1} and on average by 0.36 ± 0.03fm $\mu\varepsilon^{-1}$°C^{-1} for the SOF Bragg gratings. The obtained results provide a good idea for the temperature strain sensor applications.

REFERENCES

[1]Hisham K. Hisham, "Design Methodology for Reducing RIN Level in DFB Lasers", Iraq J. Electrical and Electronic Engineering, Vol. 12, pp. 207-213, 2016.

[2]Hisham K. Hisham, "Turn_On Time Reduction in VCSELs by optimizing laser parameters", Iraq J. Electrical and Electronic Engineering, Vol. 12, 2016.

[3]Hisham K. Hisham," Numerical Analysis of Thermal Dependence of the Spectral Response of Polymer Optical Fiber Bragg Gratings", Iraq J. Electrical and Electronic Engineering, Vol.12, pp.85-95, 2016.

[4] T. Habisreuther, T. Elsmann, A. Graf, and M. A. Schmidt," High-Temperature Strain Sensing Using Sapphire Fibers With Inscribed First-Order Bragg Gratings", IEEE Photon. Journal, Vol. 8, 2016.

[5] Accessed Feb. 24, 2016. [Online]. Available: http://www.fbgs.com/applications/strain-sensing.

[6] P. Moyo, J. M. W. Brownjohn, R. Suresh and S. C. Tjin, "Development of fiber Bragg grating sensors for monitoring civil infrastructure," Eng. Struct., vol. 27, pp. 1828–1834, 2005.

[7] M. Silva-Lopez, A. Fender, W.N. MacPherson, J.S. Barton, J.D.C. Jones, D. Zhao, D.J. Webb and L. Zhang, I. Bennion,"Strain and temperature sensitivity of a single-mode polymer optical fibre", 17th Inte. Conf. on Optical Fibre Sensors, Proceedings of SPIE Vol. 5855, (SPIE, Bellingham, WA, 2005).

[8] Yu, J. M., Tao, X. M., and Tam, H. Y. Trans-4-stilbenemethanoldoped photosensitive polymer fibers and gratings. *Opt. Lett*. 2004; 29: 156–158.

[9] Keiser, G. (2000). *Optical Fiber Communications*. 3rd ed. McGraw-Hill, Boston, USA.

[10] Scholze, H. (1991). *Glass; Nature, Structure, and Properties*, Springer-Verlag, New York, USA.

[11]Sirkis, J. S. Unified approach to phase-strain-temperature models for smart structure interferometric optical fiber sensors: part 1, development. *Opt. Eng*. 1993; 32**:** 752-761.

[12]Kersey, A. D., Davis, M. A., Patrick, H. J., Blanc, M. L., Koo, K. P., Askins, C. G., Putnam, M. A., and Friebele, E. J. Fiber grating sensors. *J Lightwave Technol*. 1997; 15: 1442–1462.

[13]I. Haggmark," Fiber Bragg Gratings in Temperature and Strain Sensors", B.Sc thesis, Royal Institute of Technology, 2014.

[14]A. Othonos, K. Kalli, "Fiber Bragg Grating-Fundamentals and Applications in Telecommunications and Sensing," Artech House, Boston, 1999.