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Development of FBG Sensors using Optiwave system software for structural health monitoring

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ABSTRACT *: Among the various types of FOSs (Fiber Optic Sensors), fiber Bragg gratings (FBGs) stand out as the most prominent technology for contact measurement of strain, vibrations and pressure. Fiber optic sensors (FOSs) are receiving a continuously growing interest in structural health monitoring (SHM) due to their many advantageous properties, such as: immunity to electromagnetic interference, intrinsic fire safety, low invasiveness, minimum aesthetic impact, possibility to send the data remotely using the same sensing fiber, etc. The popularity of FBG sensors is due to their valuable sensing properties: excellent balance between performance and complexity, possibility to work in less favorable signal-to-noise ratios than other types of optical sensors, predictable and memory-less dependence on temperature, and suitability for multiplexed optical sensor networks. Exploring and developing a novel sensing technologies with fiber brag grating sensors for structural health monitoring are the main objectives of this study. The present work focused on the study on principle and development of FBG sensors. A software OptiGrating has been used to simulate a FBG sensor, and the effect of strain and temperature on wavelength variation has been observed.*

KEYWORDS-*Fiber Bragg Grating (FBG), Fiber Optic Sensors (FOS), Strain measurement, Structural Health Monitoring, Optiwave Software*

I. INTRODUCTION

Structural monitoring/ Structural health monitoring (SHM) has attracted much attention in both research and development in recent years. SHM involves collecting and analyzing information obtained through measurements and analyses of a structure in order to evaluate its performance and to assess damage. Optical fiber sensors (OFSs) are receiving a continuously growing interest in structural health monitoring (SHM) due to their many advantageous properties, such as: immunity to electromagnetic interference, intrinsic fire safety, low invasiveness, minimum aesthetic impact, possibility to send the data remotely using the same sensing fiber [1]. Among the various types of FOSs, fiber Bragg gratings (FBGs) stand out as the most prominent technology for contact measurement of strain, vibrations and pressure.In normal optical fiber, the refractive index remains uniform along the fiber length such that when light enters at one end it passes through the fiber with almost no reflection. However, this is not the case for FBG. In FBG, a periodic structure of indentation in the fiber core (grating) causes a small amount of light to reflect [2]. That is, as light enters FBG, a narrow range of wavelength is reflected by the grating and the rest passes through the fiber. The Bragg wavelength is the center of this reflected wavelength. This phenomenon was first discovered by Hill et al. [3]. A longitudinal strain in FBG causes a linear shift in the reflection wavelength of FBG. This characteristic of FBG can be utilized to sense small movements or strains such as cracks created on the surface of a structure. Indeed, FBG sensors are currently employed in applications such as health monitoring in aerospace industry, structural analysis of large infrastructures, maintenance of historical buildings, geodynamics, and temperature sensing in harsh environment [4]. The popularity of FBG sensors is due to their valuable sensing properties: excellent balance between performance and complexity, possibility to work in less favorable signal-to-noise ratios than other types of optical sensors, predictable and memory-less dependence on temperature, and suitability for multiplexed optical sensor networks [5].A conventional FBG sensor system is composed of a broadband light source, FBGs, a wavelength interrogator, and system software. When the fiber is stretched, the Bragg period, changes which causes the reflected light's wavelength to shift. This shift provides enough information to detect the displacement, if the temperature is kept constant [6,7]. The changes in strain, temperature, and pressure, of fiber grating, alter both the effective refractive index and the grating period. When strain and pressure are exerted, the expansion or contraction of the grating periodicity and the photoelastic effect will shift the Bragg wavelength. The temperature change causes the Bragg wavelength shift through thermal expansion and contraction of the grating periodicity and through thermal dependence of the refractive index [8,9].

Many users exist for FBGs in today's fiber communication systems, which rely heavily on Dense Wavelength Division Multiplexing (DWDM) and optical amplification. Besides this, FBGs have found applications in sensor systems, which they stand out from all other technologies, in the performance, reliability & the cost. A FBG consists of a periodic modulation of the index of refraction along the core of an optical fiber. FBGs are created by exposition of a photosensitive fiber to an intensity pattern of UV light. Various types of simulation software packages are available on the Internet like PC-Grate, GratingMod, SPSS, FOGS, Optiwave (OptiGrating) etc for the simulation of a FBG sensor [10,11]. Complete documentation in the form of user guides and manuals are available as .pdf files and support is also available in the form of example model files. FBG model can be constructed using one of these software packages and simulated to evaluate grating efficiency for various grating shape parameters, number of plane sections and wavelengths. In this chapter, an optical FBG sensor model is being simulated with the help of advanced software modules such as the Optigrating and the modeled sensor is evaluated for the grating efficiency for various grating shape parameters, pitch, the number of plane sections and different wavelengths.The major objective of this study is exploring and developing a novel sensing technologies with fiber brag grating sensors for structural health monitoring.A software OptiGrating has been used to simulate a FBG sensor, and the strain and temperature effect on wavelength variation has been observed.

II. PRINCIPLE AND DEVELOPMENT OF FBG SENSORS

2.1. Principles of FBG Sensors

The basic working principle of FOS and FBG sensors is reflection and filtration of different wavelengths of light. One of the most commonly used and broadly deployed optical sensors is the fiber Bragg grating (FBG), which reflects a wavelength of light that shifts in response to variations in temperature and/or strain.. FBGs are constructed by using holographic interference or a phase mask to expose a short length of photosensitive fiber to a periodic distribution of light intensity. The refractive index of the fiber is permanently altered according to the intensity of light it is exposed to. The resulting periodic variation in the refractive index is called a fiber Bragg grating. When a broad-spectrum light beam is sent to an FBG, reflections from each segment of alternating refractive index interfere constructively only for a specific wavelength of light, satisfies Bragg condition of Eq (1), called the Bragg wavelength, is reflected, and the others passes the grating [2,3].

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

Where λ_B is the Bragg wavelength, n_{eff} is the effective refractive index, and Λ is the grating period. When strain is induced in an FBG, the Bragg wavelength is expected to have a proportional shift. The strain can be easily determined by analyzing the change of the wavelength. According to this principle, FBG sensors can sense the grating period change due to strain variation, and they can measure strain without the influence from noise and light intensity perturbation. The wavelength shift is proportional to strain, and absolute strain can be measured. A fiber Bragg grating has unique characteristics to perform as a sensor. For example, when the fiber is stretched or compressed, the FBG will measure strain. This happens essentially because the deformation of the optical fiber leads to a change in the period of the microstructure and, consequently, of the Bragg wavelength. There is also some contribution from the variation of the index of refraction, through the photoelastic effect.

Sensitivity to temperature is also intrinsic to a fiber Bragg grating. In this case, the main contributor to Bragg wavelength change is the variation of the silica refraction index, induced by the thermo-optic effect. There is also a contribution from the thermal expansion, which alters the period of the microstructure. This effect is, however, marginal given the low coefficient of thermal expansion of silica [12].

2.2.FBG Strain Dependence

The strain dependence of a fiber Bragg grating can be determined by differentiating the wavelength as given in equation (2) [13]:

$$\left|\frac{\Delta\lambda_B}{\lambda_B} = \frac{\Delta(n_{eff}\,\Lambda)}{(n_{eff}\,\Lambda}\right|_{T\,=\,\mathrm{Constant}} = \left(1 + \frac{1}{n_{eff}}\frac{\partial n_{eff}}{\partial \varepsilon}\right)\Delta\varepsilon = (1\ + p_e)\Delta\varepsilon = k_\varepsilon\Delta\varepsilon \tag{2}$$

Where: k_ε is strain sensitivity of the Bragg grating and p_e is photoelastic constant (variation of index of refraction with axial tension), and The p_e for the optical fiber it is approximately equal to - 0.212, which indicates that strain sensitivity of a FBG is given by the expression Eq. (3):

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - 0.212)\Delta\varepsilon = 0.788\Delta\varepsilon \tag{3}$$

The strain sensitivity for a FBG at a bragg wavelength of 1550 nm is 1.2 pm/με

2.3.FBG Temperature Dependence

Similarly to the strain dependence of a fiber Bragg grating, the temperature dependence can be determined by differentiating the wavelength expression Eq. (4) [13]:

$$\left|\frac{\Delta\lambda_B}{\lambda_B} = \frac{\Delta(n_{eff}\,\Lambda)}{(n_{eff}\,\Lambda}\right|_{\varepsilon\,=\,\mathrm{Constant}} = \left(\frac{1}{\Lambda}\frac{\Lambda}{\partial T} + \frac{1}{n_{eff}}\frac{\partial n_{eff}}{\partial T}\right)\Delta T = (\alpha + \zeta)\Delta T = k_T\Delta T \quad (4)$$

Where: k_T = thermal sensitivity of the Bragg grating; α = coefficient of thermal expansion of the fiber; ζ = dependence of the index of refraction on temperature

For a temperature sensitivity approximation, we can assume that these values are constant for the temperature range:

$\alpha = 0.55\mathrm{x}10^{-6}/^{o}\mathrm{C}$; $\zeta = 5.77\ \mathrm{x}10^{-6}/^{o}\mathrm{C}$

Hence, the approximate thermal sensitivity is given by Eq. (5)

$$\frac{\Delta\lambda_B}{\lambda_B} = k_T\Delta\varepsilon = 6.32\lambda_B \quad (5)$$

The temperature sensitivity for a FBG at a bragg wavelength of 1550 nm is 9.8 pm/^{o}C

If the optical strain gauge is fixed to a rigid strain free structure, the temperature may change the index of refraction of the fiber, but its expansion is fixed by the structure. This is equivalent to consider the thermal expansion of a fixed fiber as α = 0. The temperature dependence of a fiber Bragg grating measuring strain is given in Eq. (6):

$$\frac{\Delta\lambda}{\lambda} = \zeta\Delta T \quad (6)$$

When measuring strain this temperature induced wavelength change is confused with strain. The measured strain that is actually caused by temperature is given in Eq. (7):

$$\frac{\Delta\lambda}{\lambda} = k\Delta\varepsilon = \zeta\Delta T \leftrightarrow \Delta\varepsilon = \frac{\zeta}{k}\Delta T \quad (7)$$

The cross-sensitivity to temperature (TCS) is therefore given by Eq. (8):

$$TCS = \frac{\Delta\varepsilon}{\Delta T} = \frac{\zeta}{k} \quad (8)$$

The effective strain should be calculated from the strain sensor as the strain measured by the strain sensor minus the effect of temperature on the strain FBG. This correction of the deformation does not take into account the effect of temperature on the deformation of the structure where the sensor is fixed on. To compensate also for the deformation of the structure due to temperature effects, the computation should be done considering the coefficient of thermal expansion (CTE) of the structure. To compensate the deformation of the structure due to temperature effect it is necessary to know the CTE value of the material of the structure where the sensor is fixed on. The strain values measured by the optical interrogator (data acquisition system) are the peak wavelengths of the narrow spectrum reflected by the fiber Bragg grating sensor. When strain at the optical strain sensor causes the wavelength to change, the interrogator detects a change in the peak wavelength that is proportional to the strain. The gauge factor or the sensor sensitivity specified on the sensor packaging is used as the proportionality factor [14,15].

III. SIMULATION, DESIGN AND EVALUATION FBG SENSOR

3.1. OptiGrating

OptiGrating is an implementation of the Coupled Mode Theory of optical gratings. This is a powerful tool for the analysis of coupling and reflection among guided modes of optical waveguides and fibers. OptiGrating also has specialized modules for simulating physical conditions such as temperature and strain on the grating. Simulation of a FBG sensor for minimum attenuation criteria has been worked on and given in this chapter. From the outcome of this, one can design a FBG sensor starting from the fundamental concepts using a software tool [14]. Using the simulation tools, it is possible to design the fiber Bragg grating sensor for strain measurement by first estimating approximately the grating pitch for maximum reflective power for a given interrogating wavelength and then characterizing the sensor by varying the grating pitch as it would change on application of strain and noting the decrease in reflected power for the chosen wavelength. So, before actually inscribing the grating in the fiber, simulation tools provide valuable help in optimizing the design parameters. FBG sensors are based on the fact that the Bragg wavelength changes with change in the pitch of the grating and the change in the refractive index [8]. Thus, any physical parameter (like temperature, strain) which causes changes in the above mentioned parameters can be sensed using a FBG, by measuring the shift in the Bragg wavelength or the change in reflection coefficient of a particular wavelength.

3.2. Fibre Bragg Grating Design and Simulation using OptiGrating

FBG is a longitudinal periodic variation of the index of the refraction in the core of an optical fiber. When it has been interrogated, the fiber bragg grating with a defined strain, the effect of wavelength shift leading to refractive index variation to be measured. The spacing of the variation is determined by the wavelength of the light to be reflected. In this research the physical parameter as strain to be sensed using a Fiber Bragg Grating sensor, this can further consider other parameters such as rotation, acceleration, electric field & magnetic field measurement, temperature, pressure, displacement, acoustics, vibration and linear and angular position, stress, strain, humidity viscosity and chemical measurements in which, the refractive index could also be included. This software provides facility to plot the graphs between the wavelengths vs. reflective power to find the efficiency of the FBG sensor, which can also be used for experiment design and analysis.

The FBG can be designed by selecting suitable core, inner cladding and outer cladding as per requirement. The central wavelength, radia photosensitivity, index etc can be suitably entered in the software for designing FBG as shown in Fig. 1. On verification of the wavelength versus Transmittivity/Reflectivity a curve will be obtained as shown in Fig. 2, where the blue line indicates reflection spectrum and redline indicates for transmission spectrum for a uniform grating. The OptiGrating software available in the Optical Laboratory of School of Electrical Sciences, IIT Bhubaneswar was used for the study. The transmission spectrum can be broadened by chirping the grating as shown in Fig. 3. The delay and dispersion can also be observed using the software as shown in Fig. 4 and 5 respectively.

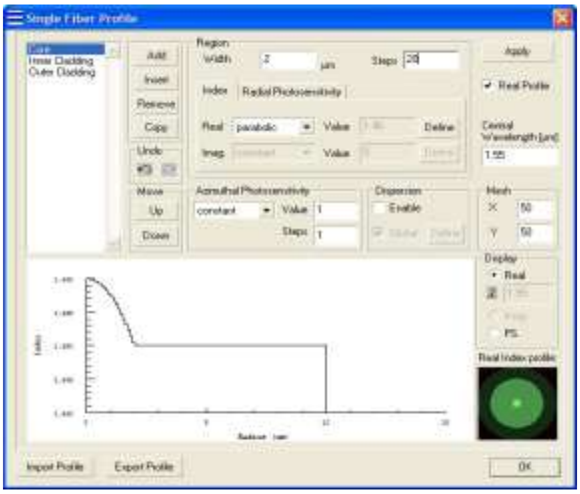


Fig. 1 Fibre Bragg Grating Design

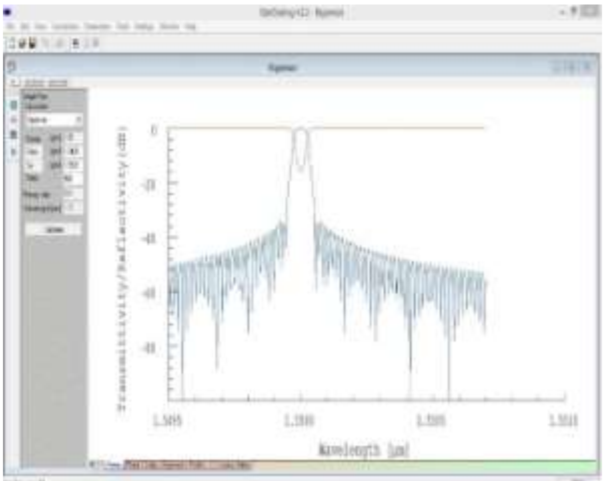
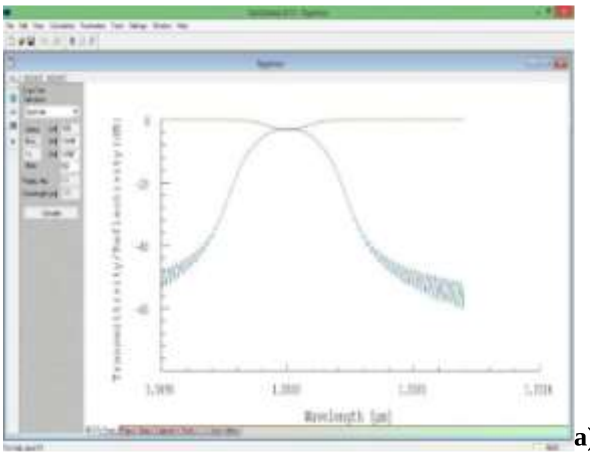
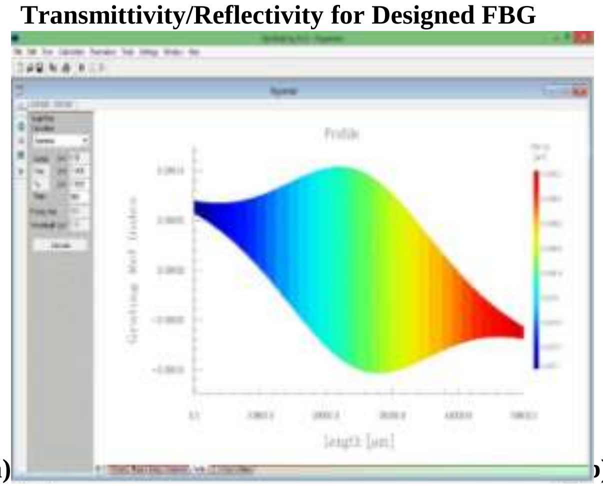


Fig. 2 Wavelength Versus Transmittivity/Reflectivity for Designed FBG



a)



)

Fig. 3 (a) Transmission Spectrum and (b) Grating Refractive Index due to Chirping

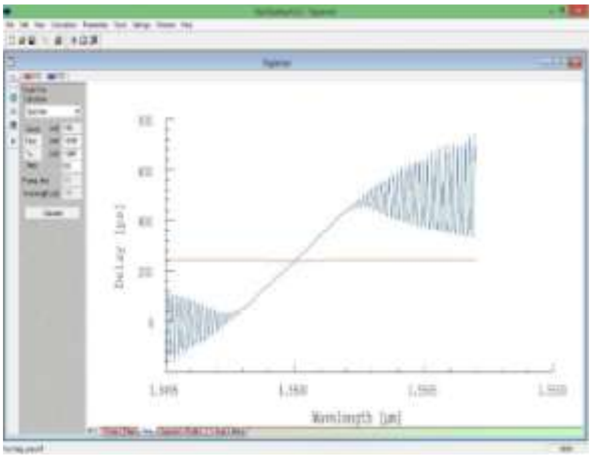


Fig. 4 Delay in the Designed FBG

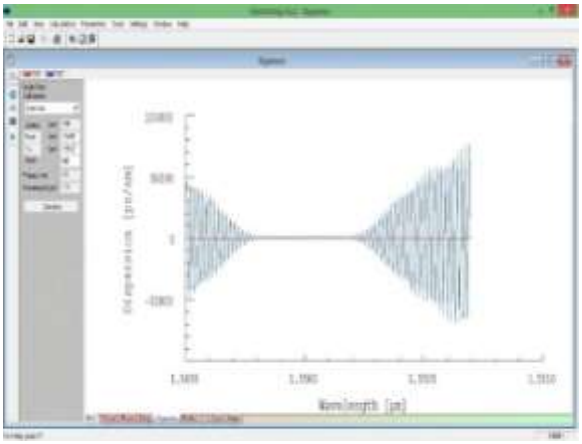


Fig. 5 Dispersion Measurement in the Designed FBG

3.3. Use of OptiGrating for Strain Analysis in the Designed FBG

The OptiGrating software can be used for observing the change in the wavelength pattern, delay, dispersion and grating reference index for different strain. The effect of temperature on measurement of strain can be observed. Under a uniform strain, linearly and Gaussian variable stain condition the shift in wavelength and pattern can be observed in the design FBG for calibration before use. The variables can be entered in the software as shown in Fig 6

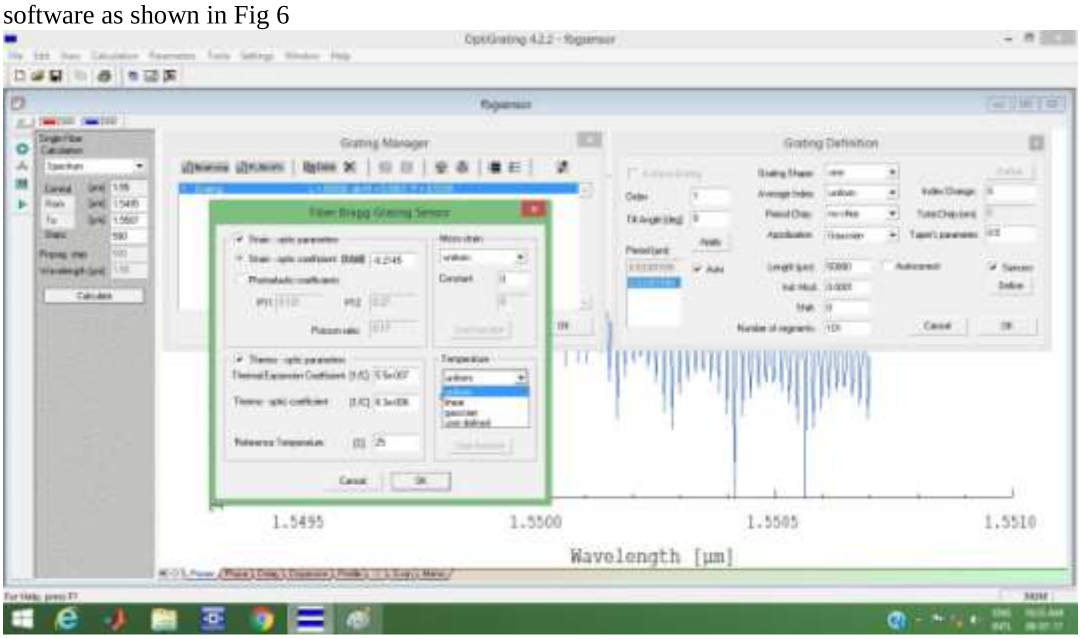


Fig. 6 Application of the Designed FBG for Checking Effect of Variables

The designed FBG sensor has been checked for giving a uniform strain micro-strain of 400 µε and variable strain from -200 µε to 200 µε at constant temperature (25°C) and variable temperature conditions (0-50°C). This lead to the shift of bragg wavelength as shown in Fig. 7 and 8 respectively. Also, the variable grating index was obtained for variable strain as shown in Fig. 9. This software also helps in addressing the cross sensitivity of temperature and strain.

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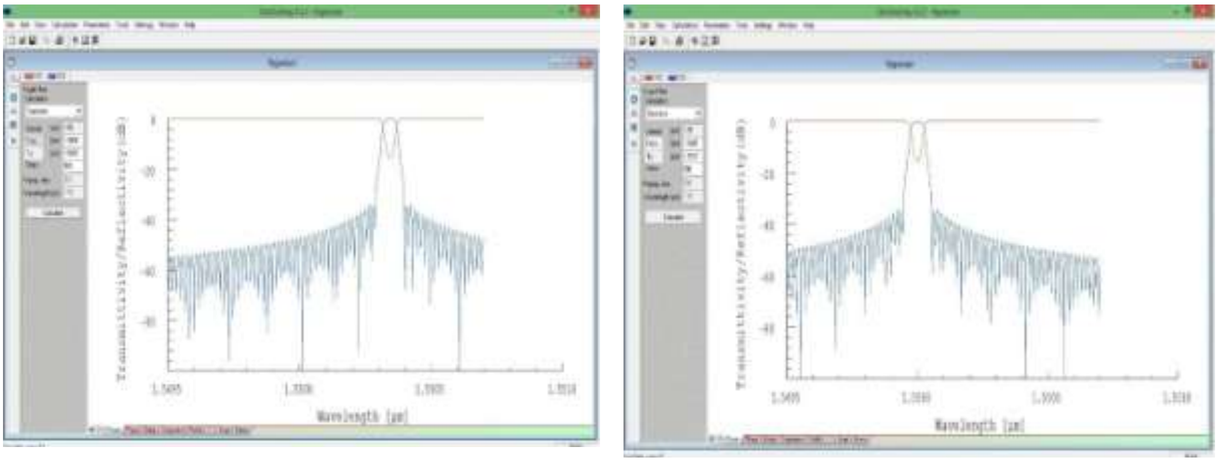

Fig. 7 Shifting of Bragg Wavelength due to Variable Strain (Constant Temperature)

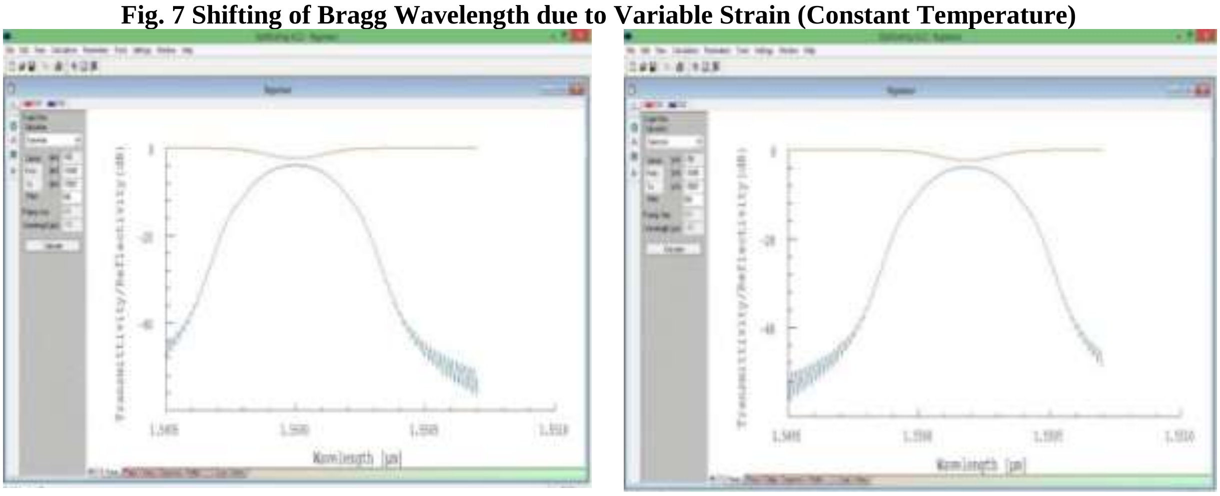

Fig. 8 Shifting of Bragg Wavelength due to Variable Strain (Variable Temperature)

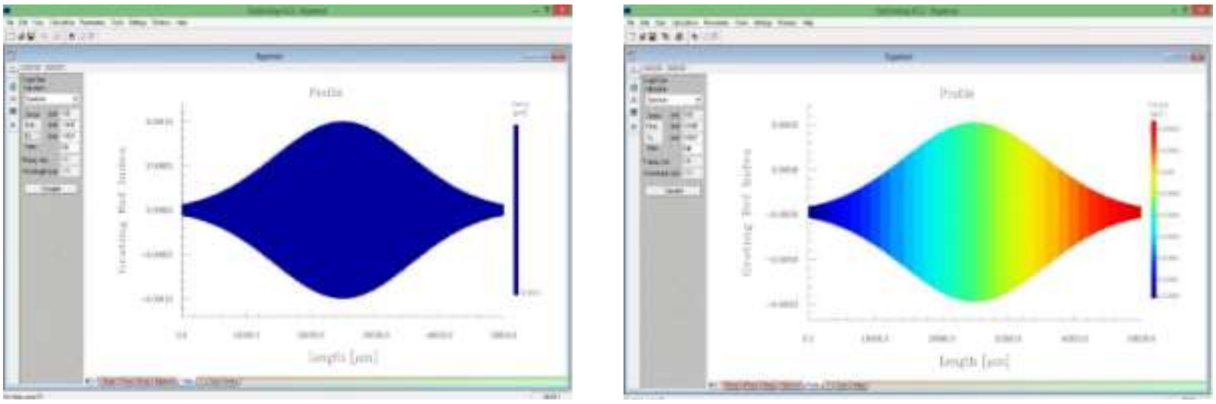

Fig. 9 Shifting of Bragg Wavelength due to Variable Strain

IV. CONCLUSIONS

The present work has provided a greater opportunity to understand the SHM and utilization of optical fiber sensors for measurement of any structural variation.The OptiGrating which is a very advanced software could be utilized to simulate and design a FBG sensor. The utilization of the software for FBG sensors could be studied and the effect of strain and temperature variations on the wavelength, delay, dispersion and grating index could be observed. The application of constant and variable strain on the change in wavelength pattern has been observed to check the effectiveness and property of the designed sensor. Also the effect of temperature variation on the FBG sensor has been checked. It was found that the FBG sensor designed and developed can be effectively utilized for application of structural health monitoring of real structures.

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REFERENCES

[1] Y. Zou, X. Dong, G. Lin, R. Adhami, "Wide Range FBG Displacement Sensor Based on Twin-Core Fiber Filter", *J. Lighwave Technol.,* Vol. 30, pp. 337-343, 2012.

[2] G. Meltz, W. Morey, W. Glenn, "Formation of Bragg grating in optical fiber by the transverse holographic method", *Opt Lett,* Vol. 14, pp. 823–825, 1988.

[3] K. O. Hill, G. Meltz, "Fiber Bragg Grating Technology Fundamentals and Overview", *J. Lightwave Technol.,* Vol. 15, pp. 1263-1276, 1997.

[4] N. Singh, S. C. Jain, A. K. Aggarwal, R. P. Bajpai, "Fibre Bragg grating writing using phase mask technology", *J. Scientific Ind. Res.,* Vol. 64, 108-115, 2005,

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

[6] B. O. Guan, H. Y. Tam, X. M. Tao, X. Y. Dong, "Highly stable fiber Bragg gratings written in hydrogen-loaded fiber", *IEEE Photonics Technol. Lett.,* Vol. 12, pp. 1349-1351, 2000.

[7] H. N. Li, D. S. Li, G. B. Song, "Recent applications of fiber optic sensors to health monitoring in civil engineering", *Eng. Structures,* Vol. 26, pp. 1647-1657, 2004.

[8] R. Aneesh, M. Maharana, P. Munendhar, H.Y. Tam, S.K. Khijwania, "Simple temperature insensitive fiber Bragg grating based tilt sensor with enhanced tenability", *Appl. Optics,* Vol. 50, pp. E172-E176, 2011.

[9] H. Y. Au, S. K. Khijwania, H. Y. Fu, W. H. Chung, H. Y. Tam, "Temperature-Insensitive Fiber Bragg Grating Based Tilt Sensor With Large Dynamic Range," *J. Lightwave Technol.,* Vol. 29, pp. 1714-1720, 2011.

[10] H. Bao, X. Dong, L. Y. Shao, C. L., Zhao, S. Jin, "Temperature insensitive 2-D tilt sensor by incorporating fiber Bragg gratings with a hybrid pendulum", *Optics Communications,* Vol. 283, pp. 5021-5024, 2010.

[11] K. Ni, X. Dong, Y. Jin, H. Xu, "Temperature-independent fiber Bragg grating tilt sensor", *Microwave Optical Technol Lett.,* Vol. 52, pp. 2250-2252, 2010.

[12] S. A. Vasil'ev, O. I. Medvedkov, I. G. Korolev, A. S. Bozhkov, A. S. Kurkov, E. M. Dianov, "Fibre gratings and their applications", *Quantum Electronics,* Vol. 35, pp. 1085-1103, 2005.

[13] S. W. James, M. L. Dockney, R. P. Tatam, "Simultaneous independent temperature and strain measurement using in-fibre Bragg grating sensors," *Electronics Lett.,* Vol. 32, pp. 1133-1134, 1996.

[14] W. Jin, W. C. Michie, G. Thursby, M. Konstantaki, B. Culshaw, "Simultaneous measurement of strain and temperature: Error analysis", *Optical Eng.,* Vol.36, pp. 598-609, 1997.

[15] I. Giles, M. Mondanos, R. Badcock, P. Lloyd, "Distributed Optical Fibre Based Damage Detection in Composites", *Proceedings of SPIE, Sensory Phenomena and Measurement Instrumentation for Smart Structures and Materials,* pp. 311–321, 1999.