Stress induced in optical fiber sensors embedded in composite materials by the lamination process

Tomasz R. Woliński[1], Piotr Lesiak[1], Robert Plaga[1], Mateusz Szeląg[1], Daniel Budaszewski[1] Andrzej W. Domański[1]
Anna Boczkowska[2], Ginu Rajan[3], Yuliya Semenova[3], and Gerald Farrell[3]

[1] Faculty of Physics, Warsaw University of Technology, Warszawa, Poland, wolinski@if.pw.edu.pl
[2] Faculty of Materials Science and Engineering, Warsaw Univ. of Technology, Warszawa, Poland, abocz@meil.pw.edu.pl
[3] Photonics Research Centre, Dublin Institute of Technology, Dublin, Ireland, gerald.farrell@dit.ie

Abstract: The influence of the lamination process on stress sensitivities of the composite structure incorporating optical fiber sensors with fiber Bragg gratings (FBGs) and polarimetric highly birefringent (HB) fibers has been investigated. Coating layers of the HB fibers are found to be responsible for performance of the embedded polarimetric sensors while the angular orientation of embedded FBGs written in HB fibers is responsible for the observed optical wavelengths shifts.

Key words: embedded optical fiber sensors, composite materials, optical wavelength metrology

1. BACKGROUND

Composite material structures are widely used in many fields of science and technology such as aerospace, marine, aviation and civil engineering industry.

The main advantage of such structures is their high strength, high creep and tensile resistance, as well as stiffness with less weight, even four times lowers than for steel. Due to their wide use, structural health monitoring technologies for composite structures have been studied extensively in order to assess the safety and the durability of the structures.

Composite structures are frequently subjected to external excitations over a variety of vibration frequency ranges. Such dynamic interference may cause the structures to suffer from fatigue damage and/or catastrophic failures if the excitation frequency approaches to the natural frequency of the structures. A typical composite fails in a sequence of transverse micro-cracking, delamination and fiber failure. Polymer matrix composites accumulate damage in a general rather than a localized fashion and failure does not always occur by the propagation of a single macroscopic crack.

The micro-structural mechanisms of damage accumulation including fiber breakage and matrix cracking, debonding, transverse cracking and delamination, occur sometimes independently and sometimes interactively, and the predominance of one or the other may be strongly affected by both materials variables and testing conditions [1-4].

Non-destructive evaluation (NDE) techniques have been developed to detect internal or invisible damage. To the traditional NDE techniques belong: ultrasonic scan, an eddy current method, X radiography, an acoustic emission method, and passive thermography. The NDE techniques are effective in detecting damages in materials and structures, but it is difficult to use them in operation due to the size and weight of the devices. Therefore, there is a strong interest in development of smart composite structures with integrated optical fiber sensors which would allow in-situ monitoring of both the manufacturing process and the service life.

Compared to the traditional NDE techniques, fiber-optic sensors offer unique capabilities as: monitoring the manufacturing process of composite parts, performing non-destructive testing once fabrication is complete, and enabling health monitoring and structural control. Due to their minimal weight, small size, high bandwidth, high sensitivity, immunity to electromagnetic interference, possibility to operate in a hazardous environment and in the presence of electric currents fiber-optic sensors offer significant performance advantages over traditional sensors. Furthermore, optical fibers are steadily becoming more cost-effective due to advances in the telecommunication and optoelectronic industries. There are three major types of optical fibers in current use: multimode stepped index or graded index, single-mode stepped or graded index fibers, and highly birefringent (HB) single-mode or few-mode polarization-maintaining (PM) fibers [5,6].

Composite structures are made of two or more components with significantly different physical or chemical properties and they remain separate and distinct in a macroscopic level within the finished structure. This feature allows for introducing optical fiber sensors into the composite material.

2. THEORY

In HB PM optical fibers, any symmetric deformation effect (*X*) influences the propagation constant β in every fiber optic mode due to changes in fiber length L and both refractive indices of the fiber core and the fiber cladding. In a single-mode regime, this leads to changes in the phase difference $\Delta\Phi = \Delta\beta \cdot L$ between both polarizations of the fundamental LP_{01} mode along the fiber [6]:

$$\frac{\delta(\Delta\Phi)}{\delta X} = \Delta\beta\frac{\partial L}{\partial X} + L\frac{\partial(\Delta\beta)}{\partial X} \tag{1}$$

where X stands for temperature (T), pressure (p) or longitudinal strain (ε) defined as: $\varepsilon = \Delta L / L$.

The effect of longitudinal strain on mode coupling is to modulate the relative phase retardation between the two orthogonal polarizations in the LP_{01} mode. The general formula describing the birefringence sensitivity to strain can be expressed in terms of an experimental parameter T_ε describing the amount of strain ε required to induce a 2π phase shift of a polarized light observed at the output as [6,7]:

$$\Delta\beta(\varepsilon) = \Delta\beta^0 + \mathrm{sgn}\left[\frac{d(\Delta\beta)}{d\varepsilon}\right]\varepsilon\frac{2\pi}{T_\varepsilon L} \tag{2}$$

where $\mathrm{sgn}\left[\frac{d(\Delta\beta)}{d\varepsilon}\right]$ signifies unperturbated modal (polarization) birefringence of a fiber and the function has two values: + 1 or -1 depending on the sign of the changes in the relative polarization birefringence with strain and L is the total optical path of the fiber.

Under influence of the longitudinal strain the first term on the right-hand side of expression (1) is negligible with respect to the first, so it leads to:

$$\delta(\Delta\Phi) \cong \frac{\partial(\Delta\beta)}{\partial\varepsilon}L\varepsilon = \frac{\partial(\Delta\beta)}{\partial\varepsilon}\delta L \tag{3}$$

Hence the phase changes of the polarimetric responses are proportional to the absolute elongation δL and are independent of the length L of the sensing region. Under the influence of a longitudinal axial strain, the equation (3) can be approximated with the use of formulae (2) in terms of the only experimental parameter T_ε

$$\frac{\delta(\Delta\Phi)}{\delta\varepsilon} = \Delta\beta\frac{\partial L}{\partial\varepsilon} + \mathrm{sgn}\frac{d(\Delta\beta)}{d\varepsilon}\cdot\frac{2\pi}{T_\varepsilon} \cong \mathrm{sgn}\frac{d(\Delta\beta)}{d\varepsilon}\cdot\frac{2\pi}{T_\varepsilon} \tag{4}$$

For the HB fibers in which birefringence is caused by stress applying parts introduced in cladding close to the region of the fiber (i.e. bow-tie fiber) $\Delta\beta$ is nearly wavelength independent and chromatic dispersion of the modal birefringence is negligible. For any other types of the HB fibers (i.e. photonic crystal fibers) $\Delta\beta$ strongly depends on the wavelength and chromatic dispersion component should be added to the expression on the polarization mode dispersion. On the other hand, chromatic dispersion is longitudinal strain independent and polarization mode dispersion depends only on changes in birefringence. The PMD dependence on the longitudinal strain can be described according to the following equation [5]:

$$\frac{\Delta\tau}{L} \cong \frac{1}{ck}\left(\Delta\beta_L + k\omega\frac{d(\Delta n_{eff})}{d\omega} + \mathrm{sgn}\left[\frac{d(\Delta\beta)}{d\varepsilon}\right]\varepsilon\frac{2\pi}{T_\varepsilon L}\right) \tag{5}$$

where c is the light velocity in the vacuum, $\omega = 2\pi c/\lambda$ is the angular frequency of light.

This explains that PMD depends on the phase birefringence as well as on chromatic dispersion. From the formula (5) it is evident that changes in linear birefringence influence DGD in the HB fibers. In consequence, DGD increases linearly with longitudinal strain.

Among the optical fiber sensors, fiber Bragg grating (FBG) sensors are the one widely used and considered as the most popular technology for implementing in health monitoring systems. Main advantages of FBGs over other optic sensor schemes are its low cost, good linearity, wavelength multiplexing capacity, resistance in harsh environments and transduction mechanism which eliminates the need for referencing as in interferometric sensors [5-9]. FBG sensor technology is now on the verge of maturity after almost three decades of active research and development in this field. Efforts are now concentrating on delivering complete FBG sensor systems including front-end electronics.

The grating typically has a sinusoidal refractive index variation over a defined length [10]. The reflected wavelength (λ_B), called the Bragg wavelength, is defined by the relationship:

$$\lambda_B = 2n\Lambda \tag{6}$$

where n is the effective refractive index of the grating in the fiber core and Λ is the grating period.

Fiber Bragg gratings can be used as sensing elements in optical fiber sensors. In a FBG sensor, the measurand causes a shift in the Bragg wavelength, $\Delta\lambda_B$. The relative shift in the Bragg wavelength, $\Delta\lambda_B/\lambda_B$, due to an applied strain (ε) is approximately given by:

$$\frac{\Delta\lambda_B}{\lambda} = C_s\varepsilon \tag{7}$$

where C_S is the coefficient of strain.

The stress-induced (ε) elongation of the sample in the function of the deflection is given by following formulae:

$$\varepsilon = 6\frac{s\cdot d}{L^2} \tag{8}$$

where: s – deflection, d – distance between fiber layers, L – length of the sample.

In recent years, many experiments and research have been carried out on laminated composites to obtain optimal mechanical properties [11-18]. Composite properties are highest in the orientation direction of fibers. In practical application, most of the structures are not loaded in a single direction, it is necessary to orient fibers in multiple directions. This demands evaluation of mechanical properties for different fiber orientations. The fiber weight fraction is an important parameter influencing the mechanical properties of composites.

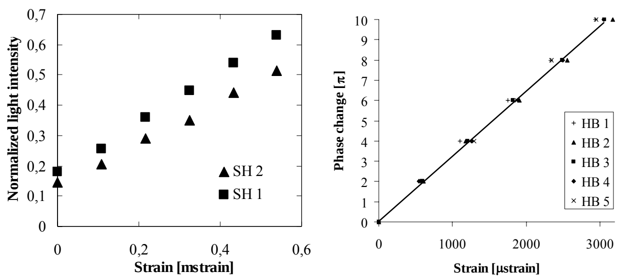
An alternative technology is based on highly birefringent polarization-maintaining fiber-based fiber-optic sensors. HB PM sensors known as polarimetric fiber sensors utilize polarization (phase) modulation within fibers to sense external perturbations and have attracted great interest over the last decade [6]. In HB fibers, the difference between the phase velocities for the two orthogonally polarized modes is high enough to avoid coupling between these two modes. Fibers of this type have a built-in, well-defined, high internal birefringence obtained by designing the core and/or cladding with a noncircular geometry, or by using anisotropic stress induced by stress elements running along the length of the fiber.

We have already proposed [19-21] a novel hybrid optical sensing approach based on two different types of embedded optical fiber sensors working in a complementary fashion: HB fiber polarimetric sensors and FBG sensors, so as to provide in-situ measurements of strain, temperature or vibration frequency. This novel hybrid approach to sensing has not been utilized before and has the advantage that the two different sensor types are used in a complementary manner so as to overcome the limitations of the individual sensors. The objective is to develop effective methods for the monitoring of composite structures based on this hybrid optical sensing technique.

In this paper we present initial experimental results of the influence of the lamination process on performance (stress sensitivities) of the composite structure incorporating a hybrid system of optical fiber sensors with FBGs written within the HB fibers and also two types of polarimetric HB fiber sensors.

3. EXPERIMENTAL

In recent years, many experiments and researches have been carried out on laminated composites to obtain optimal mechanical properties [22-24], but the influence of the lamination process on the strain sensitivity of HB fibers embedded in composite material has remained underexplored.



A B

Fig. 1. Comparison between strain sensitivities in two laminated HB sensors: (A) 2 *side-hole*, (B) 5 *bow-tie* fibers

In our experiment, the composite material sample was 250 mm long, 35 mm wide and 2.5 mm thick. To measure the influence of the lamination process on the fiber sensor three HB fibers with written FBGs (Nos. 4, 5, 7) and placed in different layers of the composite material have been used. Additionally, two types of the HB fibers have been embedded in the same layer of the composite material, i.e. *side-hole* and *bow-tie* fibers (see Fig.2).

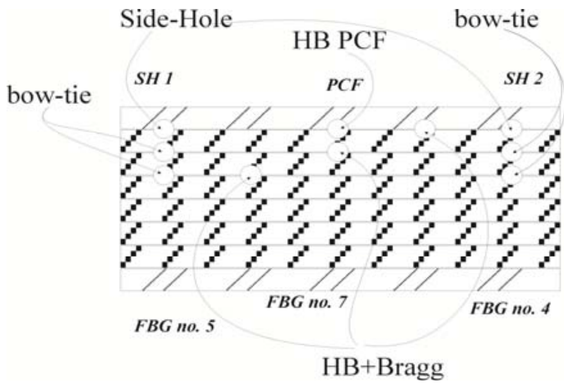


Fig. 2. Cross-section of the composite material sample with optical fibers embedded inside.

Measurements performed for the HB *side-hole* fiber sensors show that strain sensitivities are different in the HB sensors after the lamination process in comparison to the original values (Fig. 1A). Our previous results [21] made for a sample with 5 HB *bow-tie* fiber sensors placed in one composite layer indicate that all results were similar (Fig. 1B).

After lamination process influence of the transversal pressure on the *side-hole* fiber has been observed. These two experiments suggest that a type of the fiber coating layer can be responsible for behavior of the fiber inside the composite material. The HB *side-hole* fiber is coated by only one hard-coating layer and transversal pressure can be easily transmitted to the sensing fiber to modify its internal birefringence. However, the HB *bow-tie* fiber has two coating layers (hard and soft), so this second layer can be easily influenced by any lateral force and in consequence birefringence of the *bow-tie* fiber does not change (see Fig. 3.).

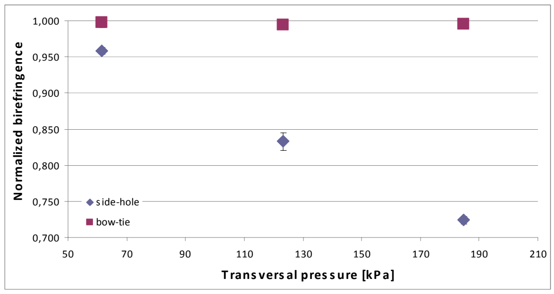


Fig. 3. Comparison of birefringence change in *side-hole* and *bow-tie* fibers in composite material under transversal pressure

In the further research we have investigated the dependence of axial orientation of the fiber optic sensor sensitivity as a function of axial stress induced by the load. It gives us possibility to optimize the orientation of the optical fibers to obtain the best sensitivity. The key issue in these smart structures in a type of the coating layer surrounding the optical fiber. We claim that stiffness of the coating layer surrounding the optical fiber as well as composite layers have a contribution to the sensitivity of the fiber optic sensors embedded inside the investigated composite element. In this part of the research two types of optical fibers have been used. The first type of the optical fiber was commercially available bow-tie HB1500 surrounded by two coating layers with different stiffness. The second optical fiber were three experimental side-hole HB optical fibers with single-coating layers with different stiffness. The measurements were made for optical fibers with and without coating layers.

The experimental setup consisted of two rotating tables in which an investigated optical fiber was placed (see Fig. 4.).

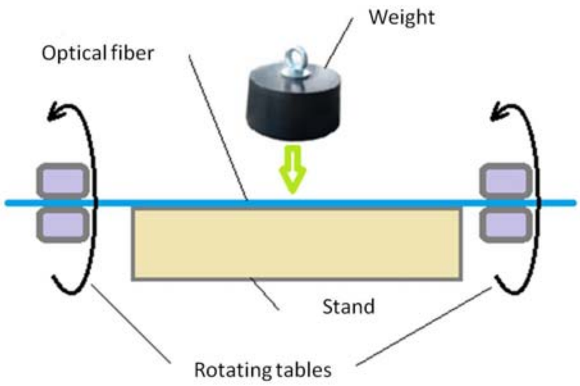


Fig. 4. Experimental setup for sensitivity measurements as a function of axial orientation of the birefringence axis under the influence of induced strain.

The investigated optical fiber was laying on the surface with very small elasticity. The axial stress was induced by the weight 625 grams.

The optical fiber was rotated in the setup every 10 degrees and axial stress was induced on it. Using the data acquisition program the Stokes parameters were registered and analyzed.

The results are presented in Fig. 5 and 6.

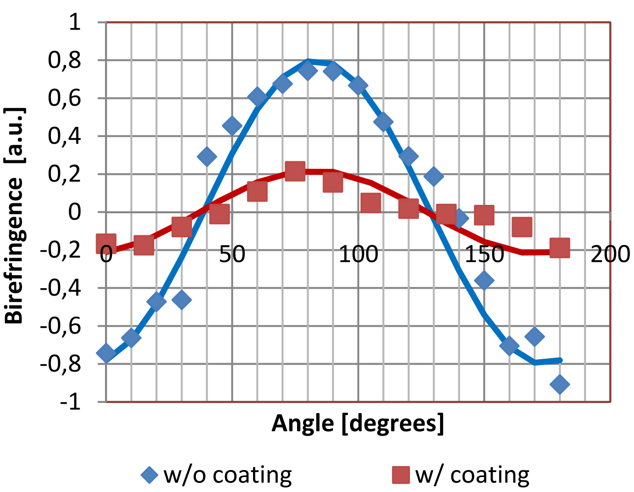


Fig. 5. Birefringence change in the bow-tie optical fiber as a function of birefringence axis orientation under the axial stress.

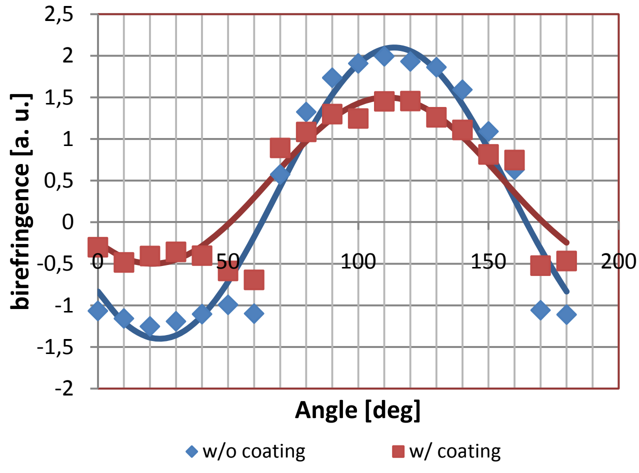


Fig. 6. Birefringence change in the side-hole optical fiber as a function of birefringence axis orientation under the axial stress.

From our measurements we can conclude that sign of the birefringence depends on axial orientation of the birefringence axis. Also the sensitivity of the optical fiber without coating layer is much better than for the same optical fiber surrounded by the coating layer. We have also noticed that side-hole optical fiber is much sensitive than bow-tie optical fiber sensor.

Since FBG sensors had no coatings so the stress induced by the lamination process could be clearly observed in our experiment. As is shown in Table 1 and also in Fig. 3, the Bragg wavelength shift strongly depends on the position of the fiber sensor in the composite material (the shift is bigger for the FBG sensors placed close to the centre of the sample). Additionally, results are different for both: slow and fast birefringent axes. This suggests that orientation of the polarization axes of the HB fibers embedded in the composite material should be taken into account.

Tab. 1. Optical wavelength shifts for three FBGs after lamination process of the composite material

	FBG no. 5	FBG no. 7	FBG no. 4	
Fast axis	0.63 ± 0.05	0.28 ± 0.05	0.10 ± 0.05	Δλ [nm]
Slow axis	0.58 ± 0.05	0.28 ± 0.05	0.14 ± 0.05	

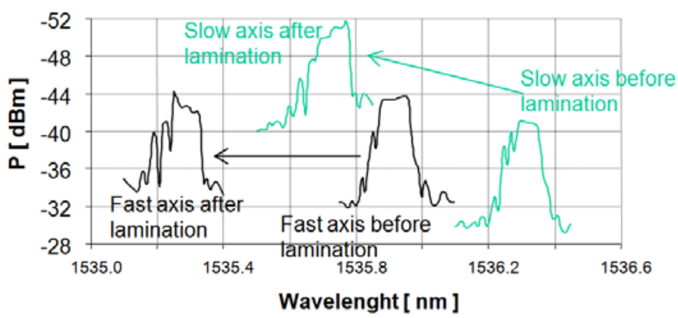


Fig. 3. Influence of the lamination process on the FBG wavelength

4. CONCLUSIONS

Influence of the lamination process on stress sensitivities of the composite structure incorporating optical fiber sensors with FBGs written within the HB fibers and polarimetric HB fiber sensors has been investigated.

To conclude coating (buffer) layers of the HB fibers are responsible for performance of the embedded polarimetric sensors and the angular orientation of embedded FBG sensors written in HB (uncoated) fibers is responsible for observed optical wavelengths shifts.

The proposed hybrid configuration can be effectively used for more reliable strain and temperature measurements and can be implemented in a wide range of sensing applications. Additionally we have investigated the influence of axis angular orientation of the HB optical fibers embedded into composite material sample under external axial stress and also investigated the influence of coating layer on sensitivity of the optical fiber sensors.

AKNOWLEDMENTS

This work has been supported by the Polish National Centre for Research and Development (NCBiR 436/2009 and 437/2009) and by Enterprise Ireland under the European SSES ERA-NET MATERA research project.

REFERENCES

[1] R. S. Reid, G. Zhou, Impact Behavior of Fiber-Reinforced Composite Materials and Structures, CRC Press, 2003.

[2] X. E Gros, Current and Future Trends in Non-Destructive Testing of Composite Materials, Ann. Chim. Sci. Mat. 2000 (25) 539-544.

[3] Encyclopedia of Smart Materials, vol. 2, edited by Mel Schwartz, Wiley, New York 2002, pp. 715 – 760.

[4] D. P. Garg, M. A. Zikry, G. L. Anderson.; Current and potential future research activities in adaptive structures: an ARO perspective, Smart Mater. Struct. 2001 (10) 610-623.

[5] A. W. Domanski, P. Lesiak, T. R. Wolinski: Longitudinal strain induced birefringence in highly birefringent fiber for dynamic compensation of polarization mode dispersion Acta Physica Polonica A, no. 2-3, vol. 103, pp. 221-227, 2003

[6] T. R. Woliński. Polarimetric Optical Fibers and Sensors, Progress in Optics, ed. Emil Wolf (North Holland, Amsterdam), vol. XL, pp. 1-75, 2000.

[7] T. R. Woliński. Polarization Phenomena in Optical Systems, in Enc. Opt. Engineering, ed. R. Diggers, M. Dekker, New York 2003, pp. 2150-2175).

[8] J. Wojcik et al. Prototype of the side-hole HB optical fiber, Proc. SPIE 3731, pp. 88-93, 1999.

[9] K. .Schroeder et al, A fiber Bragg grating sensor system monitors operational load in a wind turbine rotor blade, Meas. Sci. Technol., 17, 2006, 1167-1172

[10] R. M. Measures, Structural monitoring with fiber optic technology, Academic Press, 2001

[11] G. Hedge, A. Asundi, Performance analysis of all-fiber polarimetric strain sensor for composities structural health monitoring, NDT&E International 39, 2006, 320-327

[12] A. W. Domański, M. Karpierz, M. Sierakowski, M. Świłło, T. R. Woliński; Polarimetric Optical Fiber Sensor with Compensated Birefringence for Dynamic Strain Measurement, Proc. SPIE, 1997, vol. 3189, pp. 83-85,

[13] W. J. Bock, A. W. Domański, High Hydrostatic Pressure Optical Fiber Sensor, US Patent No. 4920261, 1990,

[14] W. J. Bock, A. W. Domański, High Hydrostatic Pressure Sensing using highly birefringent optical fibers, Int. J. Optoelect, 1989, Vol. 4, No. 3-4, pp. 295-300,

[15] A. W. Domański, T. R. Woliński; W.Bock, Polarimetric Optical Fiber Sensor – state of the art and future, Proc SPIE, 1994, vol. 2341, pp. 21-28,

[16] W. J. Bock, T. R. Woliński; R. Wiśniewski, US Patent No 5187983, 1993.

[17] M. Rodzewicz, A. Boczkowska, S. F. Awietjan, K. .J. Kurzydłowski; Degradation of mechanical properties of CFRP under dynamic loads, Composites 6(2006)2, 27-31

[18] D. Witemberg-Perzyk, M. Perzyk, A. Boczkowska; Strain History Effects on Failure Stress of Glass Fabric Reinforced Polycarbonate Composite, Advances with Composites 2005, Naples (Italy), 11-14 October 2005, ed. I. Crivelli Visconti, AMME-ASMECCANICA p.49-51

[19] A.W. Domanski, P. Lesiak, K. Milenko, D. Budaszewski, M. Chychlowski, S. Ertman, M. Tefelska, T.R. Wolinski, K. Jedrzejewski, L. Lewandowski, W. Jasiewicz, J. Helsztynski, and A. Boczkowska, "Comparison of Bragg and Polarimetric Optical Fiber Sensors for Stress Monitoring in Composite Materials", Acta Physica Polonica A, no. 3, vol. 116, pp. 294-297, 2009.

[20] P. Lesiak, G. Rajan, Y. Semenova, G. Farrell, A. Boczkowska, A. Domanski, and T.R. Wolinski, "A hybrid highly birefringent fiber optic sensing system for simultaneous strain and temperature measurement", Photonics Letters of Poland, vol. 2 (3), 140-142, 2010.

[21] G. Rajan et. all., "A Photonic Crystal Fiber and Fiber Bragg Grating Based Hybrid Fiber Optic Sensor System", accepted for IEEE Sensors Journal.

[22] K. S. C. Kuang, R. Kenny, M. P. Whelan, W. J. Cantwell, and P.R. Chalker, "Embedded fiber Bragg grating sensors in advanced composite materials", Composite Science and Technology, vol. 61, pp. 1379-1387, 2001.

[23] J.A. Guemes, J.M. Diaz-Carrilo Menendes, "Measurement of strain distribution in bonded joints by fiber Bragg gratings", Proc. SPIE; vol. 3330, pp. 264–71, 1998.

[24] J.A. Guemes, J.M. Diaz-Carrilo Menendes, "Response of Bragg grating fiber-optic sensors when embedded in composite laminates", Composite Science and Technology, vol. 62, pp. 959-966, 2002.