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Research paperv

Sensitivity Improvement And Optomechanical Analysis Of Composite Material Using Fiber Bragg Grating Sensor Optomechanical Analysis of Composite Material Using Fibre Bragg Grating Sensor

Ibrar Jahan M.A[1], Dr. Rajini V Honnungar[2], Anup M Upadhyaya[3]

[1]*Research Scholar,Department of E&C Engg,RNS Institute of Technology Bangalore, India*
[2]*Associate Professor,Department of E&C Engg,RNS Instititute of Tehnology, Bangalore, India*
[3]*Assistant Professor,Dept of Mechanical Engineering,The Oxford College of Engineering, Bangalore, India*
**Corresponding author E-mail: upadhyayaanup74@gmail.com*

Abstract

This paper presents the design and simulation of FBG as a pressure sensor. Fiber Bragg Grating (FBG) coated with different materials and their sensitivity has been investigated. Using optomechanical equations strain and shift in wavelength values are calculated for a bare FBG and FBG coated with PMMA, polystyrene and aluminium. Bragg wavelength/center wavelength shifts when there is perturbation on the fiber gratings due to pressure or any external change. Design parameter is achieved by FBG spectral characterization. Using R-soft and Grating –Mod tool box grating length, modulation depth, grating pitch and other physical parameters are changed and simulation is carried out. In literature various methods are proposed for sensitivity improvement. In this work from the simulation results and sensitivity calculation it was noted that FBG coated with PMMA offers good sensitivity of 1.17µm/µε. Optomechanical simulation in Comsol multiphysics has also been investigated to obtain mechanical stress and strain with optical spectral response for metal embedded FBG sensor.Remarkable shift in wavelength is observed during the analysis. Linear displacement of fibre found with respect to arc length. Metal embedded FBG sensor is having tremendous application in aviation, automobiles,machine tools.

Keywords: *Fiber Bragg Grating, Layered composite, Optomechanical, PMMA, Sensitivity, Strain Monitoring,*

1.Introduction

A rapid progress has been made in optical based sensing systems (*Mihailov, 2012*) and devices.These devices have overcome the existing conventional approaches due to their immense benefits. The Fiber Bragg Grating (FBG) sensors (*Pinet, 2011*) are the most successful sensors compared to the other optical fiber based sensors due to their advantages like small size, immune to electromagnetic interference, multiplexing features,(*Guo, Xiao, Mirad, &Yao, 2011*) multi-parameter measurand capabilities, low loss, more secure etc. Temperature and pressure are the important parameters in analyzing the health of a composite materials (*Higuera, Cobo, Incera & Cobo,2011*) as these materials are used in satellites for space application, aircraft bodies, automobile industries. To monitor the health of these composite materials(*Zhang et al.,2001*) the traditional pressure sensors like strain gauges, mechanics, vibration wires are not suitable for harsh environment like explosive matters, chemicals. Using conventional methods it is not possible to realize measurement at multiple points and long distance monitoring.
Therefore pressure measurement using FBG sensor (*Guemes, Lopez, Crespo, 2013*) has grabed attention from research fraternity. FBG sensors can be embedded to composite materials or composite structure to determine their health, since these composite materials are used in various applications. This paper presents the design and simulation results of FBG pressure sensor coated with different materials. Reflectivity and sensitivity(*Liang, Chen, Huang, &Liu, 2014*) is compared. Optomechanical analysis of composite material is also performed by embedding the FBG on the composite structure.

2.Theory

A Fiber Bragg Grating is a periodic structure characterized by bragg wavelength. The center wavelength of the FBG in which the light relected from the grating is given by

$$\lambda_B = 2n_{eff}\,\Lambda \qquad (1)$$

Λ is the grating period and n_{eff} is the effective refractive index (*Shen, Yan, Xu, Tang, & Chen, 2015*). The Λ and n_{eff} depends on strain and temperature. The Bragg wavelength is sensitive to both the parameters. Since FBG as a pressure has been investigated grating length, modulation depth (*Mishra, Lohar, Amphawan, 2016*), grating pitch and other physical parameters are changed and simulation is carried out using R-soft Grating Mod simulation tool box (*Li, Prinz, Adams, 2003*). It is also required to calculate other parameters which is obtained using equation (2) to (5).

3.Strain Calculation

The central wavelength of FBG changes for an applied longitudinal strain change and the wavelength shifts is given by

$$\Delta\lambda_{bragg} = \lambda_{bragg} (1-\rho_e) \Delta\varepsilon \quad (2)$$

ρ_e is the photoelastic coefficient of the fiber.

$$\rho_e = (n_{eff}^2/2) [\rho_{12}-(\rho_{11}+\rho_{12}) \nu] \quad (3)$$

ρ_{11} and ρ_{12} are the components of the strain optic tensor coefficients and ν is the Poisson's ratio.
For a applied pressure the strain along the fiber can be calculated as shown below.

$$\epsilon = \frac{P(1-2\nu)}{E} \quad (4)$$

P is the pressure, ε is the strain, E young's modulus of the material and ν is the poisson's ratio.

n_{eff} Calculation: The fiber is designed to be a single mode fiber. Dispersion equations are used to calculate the coefficient 'b' and n_{eff} is given by,

$$V\sqrt{1-b} = m\pi + 2tan^{1}(\sqrt{(\frac{b}{1-b})}) \quad (5)$$

V = 2.405 (V number), m = 0 (mode 0) is the fundamental mode of the energy field.
The calculation of n_{eff} is given by,

$$b = \frac{n_{eff}^2 - n_2^2}{n_1^2 - n_2^2} \quad (6)$$

n_{eff} is effective refractive index, n_1Core refractive index and n_2 Clad refractive index of the given fiber.
In this work a bare silica FBG and FBG coated with three different materials namely PMMA (Poly Methyl Methacrylate), Polystyrene and Aluminium are considered. Above equations are used to calculate strain values for a given pressure and shift in wavelength. FBG1 bare silica FBG with core Ge doped silica and the clad is pure silica. FBG2 with core Ge doped silica and the clad is PMMA coated.FBG3 with core Ge doped silica and the clad is Polystyrene coated. FBG4 with core Ge doped silica and the clad is Aluminium coated. Table1. below shows the various parameter values for four different FBG's.

Table 1.FBG parameter values

Parameters	FBG1	FBG2	FBG3	FBG4
Core RI-n_1	1.465	1.465	1.465	1.465
Clad RI-n_2	1.45	1.48	1.59	1.44
Effective RI n_{eff}	1.458	1.284	1.348	1.453
Young's Modulus-E	66.3GPa	3 GPa	3.3 GPa	72 GPa
Poisson's ratio-ν	0.15	0.34	0.353	0.33
Strain optic tensor coefficients- (ρ_{11}, ρ_{12})	(0.133,0.252)	(0.3,0.297)	(0.32,0.31)	(0.12,0.27)
Photoelastic coefficient - ρ_e	0.2893	0.2425	0.2784	0.3373

4.Results And Discussions

FBG as pressure sensor to monitor the health of composite materials has been investigated . For this purpose different pressures are considered and using equation (2), (3) and (4) strain values, shift in wavelength and grating period are calculated. Table 2. shows the values for strain, shift in wavelength and grating period values for bare FBG. Figure 1 and Figure 2 shows the graph of reflected power vs wavelength for bare FBG, it can be observed there is a shift in the wavelength.

Table 2. Strain, shift in wavelength and grating period values for FBG1

Pressure (Pascal)	Strain(10^{-5})	$\Delta\lambda_{BS}$ (10^{-11})	Λ (Pitch) (practical)	Λ (Pitch) (theoretical)
0.4903	0.5176	0.572	0.5305334609	0.5315520302
0.9806	1.0353	1.140	0.5305354131	0.5315539781
1.4709	1.553	1.710	0.5305373716	0.5315559328
1.961	2.070	2.28	0.53053933	0.5315578875
2.452	2.588	2.85	0.5305412915	0.5315598423
2.942	3.106	3.221	0.5305425665	0.5315611145
3.432	3.623	3.99	0.530545209	0.5315637517
3.923	4.141	4.561	0.5305471738	0.5315657099
4.413	4.66	5.13	0.5305491265	0.5315676612
4.903	5.176	5.701	0.5305410913	0.5315696193

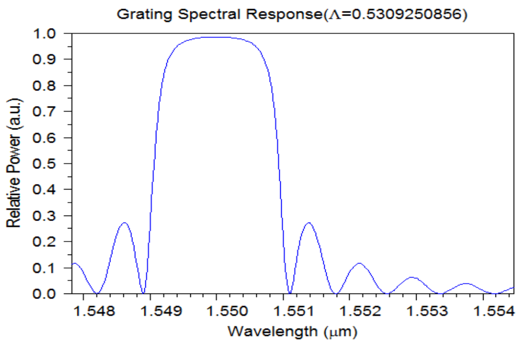


Figure 1. Reflected power vs wavelength

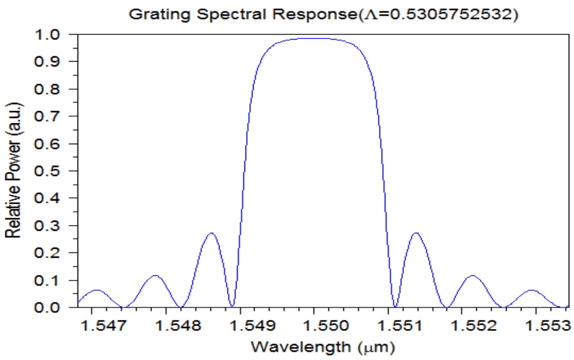


Figure 2. Reflected power vs wavelength

Table.3 shows the values for strain, shift in wavelength and grating period for a FBG2. The considered FBG has Ge doped silica as core and the clad is coated with PMMA material[Poly Methyl Methacrylate]. Figure 3. and Figure 4. shows the graph of reflected power vs wavelength for FBG2.

Table 3.Strain, shift in wavelength and grating period values for FBG2

Pressure (Pascal)	Strain (10^{-4})	$\Delta\lambda_{BS}$ (10^{-9})	Λ (Pitch) (practical)	Λ (Pitch) (theoretical)
0.4903	0.523	0.0614	0.529417	0.6035827
0.9806	1.046	0.1220	0.529439	0.6035830
1.4709	1.570	0.1840	0.529460	0.60358327
1.961	2.093	0.2456	0.529482	0.60358351
2.452	2.618	0.3074	0.529503	0.60358375
2.942	3.138	0.3684	0.529524	0.60358398
3.432	3.661	0.4298	0.529546	0.60358422
3.923	4.185	0.4916	0.529567	0.60358446
4.413	4.707	0.5526	0.529589	0.60358470
4.903	5.230	0.6140	0.529610	0.60358494

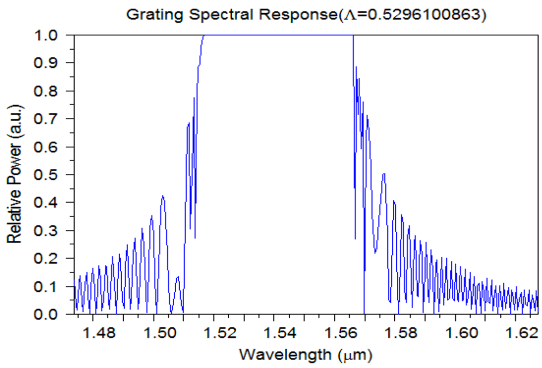


Figure 3. Reflected power vs wavelength

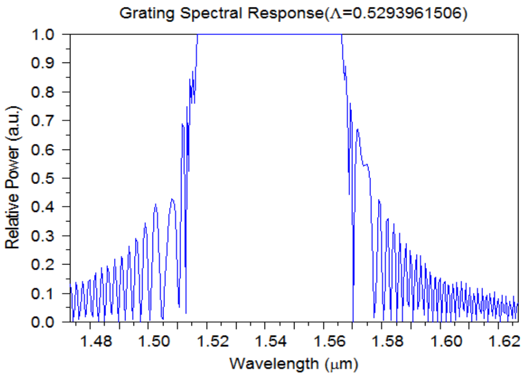


Figure 4. Reflected power vs wavelength

Table.4 shows the values for strain, shift in wavelength and grating period for a FBG 3. The considered FBG has Ge doped silica as core and the clad is coated with polystyrene. Figure 5. and Figure 6. shows the graph of reflected power vs wavelength for FBG3.

Table 4 .Strain, shift in wavelength and grating period values for FBG3

Pressure (Pascal)	Strain (10^{-4})	$\Delta\lambda_{BS}$ (10^{-10})	Λ (Pitch) (practical)	Λ (Pitch) (theoretical)
0.4903	0.4368	0.4885	0.492144	0.5749439
0.9806	0.8736	0.977	0.4921457	0.5749620
1.4709	1.3104	1.465	0.4921473	0.5749801
1.961	1.747	1.954	0.4921489	0.5749982
2.452	2.211	2.473	0.492151	0.5750175
2.942	2.621	2.931	0.492152	0.5750345
3.432	3.057	3.419	0.492153	0.5750526
3.923	3.495	3.909	0.492155	0.5750708
4.413	0.4368	4.396	0.492156	0.5750888
4.903	0.8736	4.885	0.492158	0.5751070

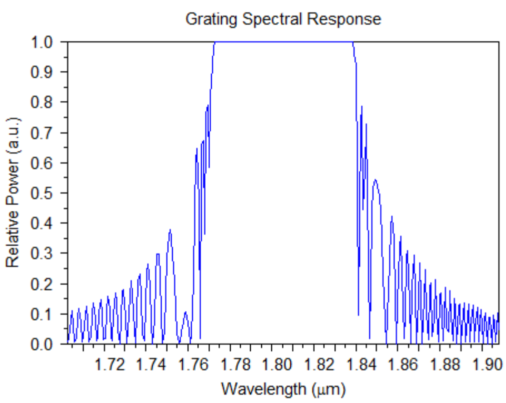


Figure 5. Reflected power vs wavelength

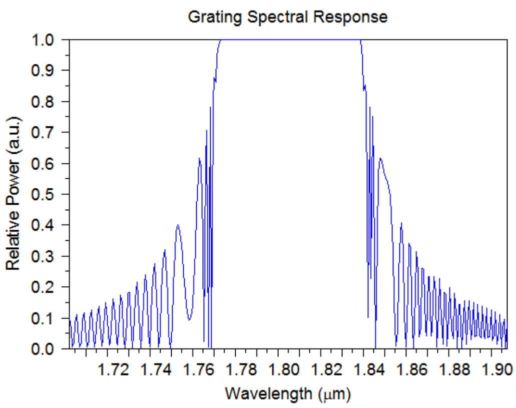


Figure 6. Reflected power vs wavelength

Table.5 shows the values for strain, shift in wavelength and grating period for a FBG 4. The considered FBG has Ge doped silica as core and the clad is coated with aluminium. Figure 7. and Figure 8. shows the graph of reflected power vs wavelength for FBG4.

Table 5. Strain, shift in wavelength and grating period values for FBG4

Pressure (Pascal)	Strain (10^{-6})	$\Delta\lambda_{BS}$ (10^{-11})	Λ (Pitch) (practical)	Λ (Pitch) (theoretical)
0.4903	2.3153	0.2378	0.5325920139	0.53338003
0.9806	4.6306	0.4756	0.5325928397	0.53338085
1.4709	6.9456	0.7134	0.5325936655	0.53338167
1.961	9.2598	0.9511	0.532594491	0.53338248
2.452	11.578	1.1893	0.5325953182	0.53338330
2.942	13.892	1.427	0.5325961397	0.53338412
3.432	16.205	1.664	0.532596958	0.53338494
3.923	18.524	1.902	0.5325977845	0.53338576
4.413	20.838	2.14	0.532598611	0.53338657
4.903	23.152	2.378	0.5325994375	0.53338739

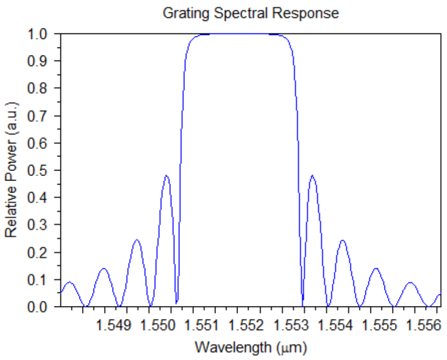


Figure 7. Reflected power vs wavelength

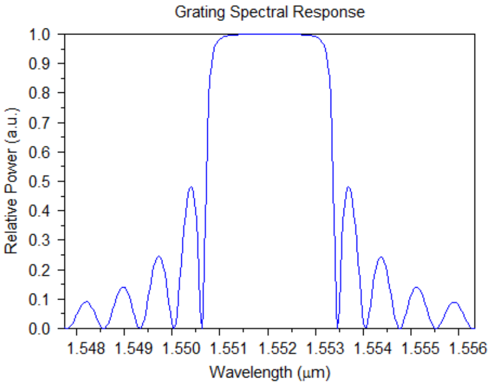


Figure 8. Reflected power vs wavelength

Sensitivity is calculated for all the four FBG's and it is noted that PMMA coated FBG offers better sensitivity.Table 6 . shows the sensitivity of coated FBG

Table 6 Comparison and sensitivity improvement

Coating material on FBG	Sensitivity (μm/με)
Bare FBG	1.10
PMMA	1.17
Polystyrene	1.11
Aluminium	1.02

5.Strain Monitoring In Layered Composite Structre Using Embedded Fbg Sensors

Axial Strain developed in core part of FBG sensor is used to obtain the spectral response. Layered metal parts embedded with FBG having main application in structural health monitoring in the field of automobile, aerospace as well as in many machine tool industries[10]. Silver coated FBG is embedded in two metal layers like nickel and aluminium. Model is constructed in ANSYS Multiphysics shown in Figure 9 and Figure 10, Figure 12. Desccritization of model is necessary to carry out the simulation shown in Figure 11. Constructed model is meshed in COMSOL Multiphsics. Suitable boundary conditions i.e fixed is assigned in COMSOL Multiphsics for one end of fibre and longitudinal load is applied at the other end. Number of elements in the region of core part of layered mode is increased to maintain the accuracy of deflection..Simulation is carried out in COMSOL Multiphsycis with 8GB RAM to solve it for 2,89,234 elements. Silver coated layer of 5 micrometer thickness is meshed fine to increase the accuracy of result.

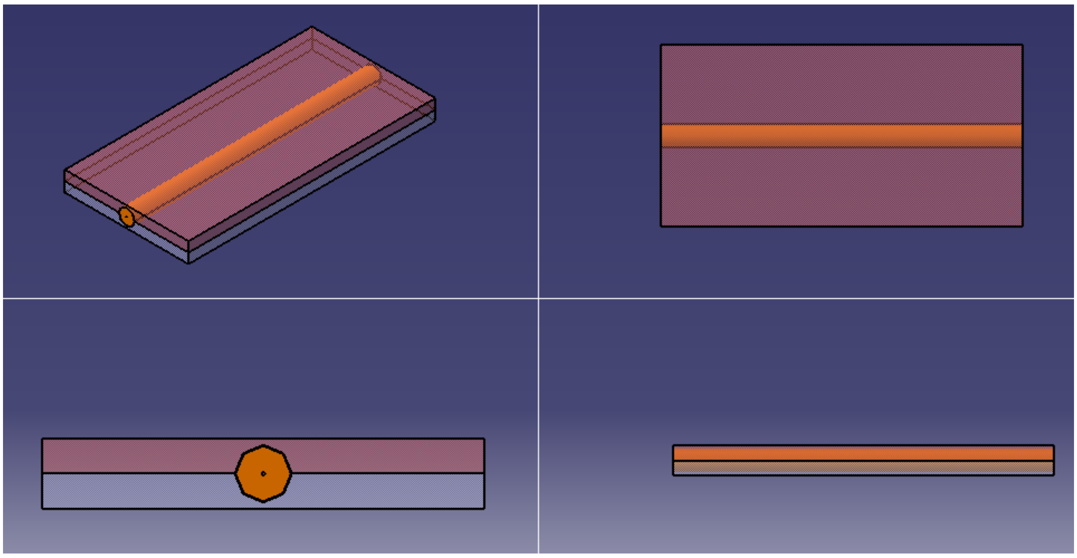


Figure 9. Metal Embedded FBG in different view

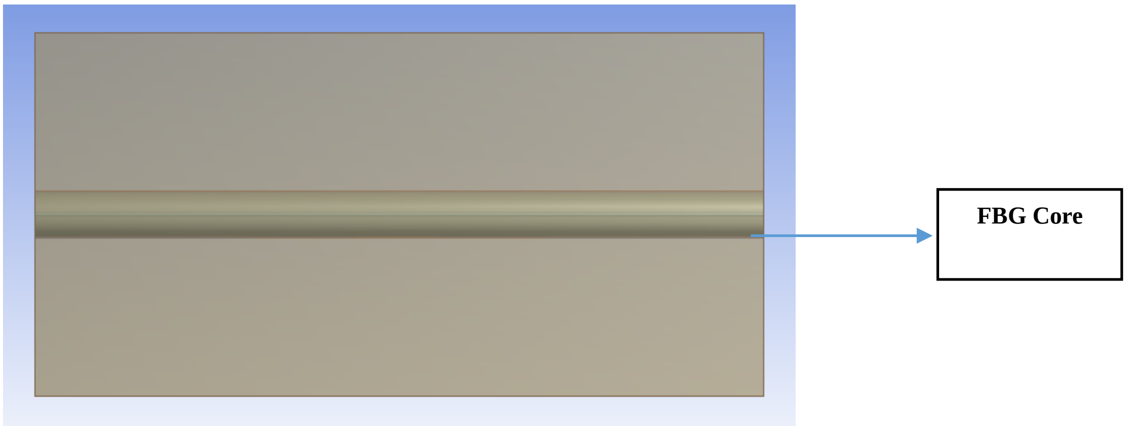
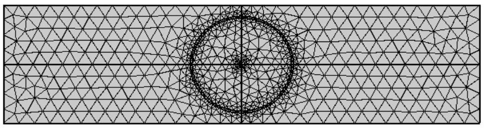


Figure 10. Transparent view of core part in FBG sensor model

Modelling Data

Core Dimension: 8.2µm
Length of Fibre 2000 µm
Cladding diameter: 125 µm
Coating layer of silver: 5 µm

Dimension of Metal Layer
Width 300 µm
Depth =80 µm
Height = 2000 µm



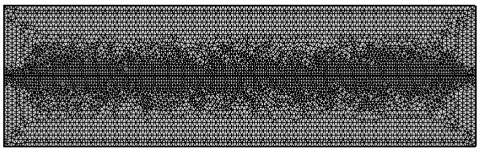


Figure 11. (a) Front View **Figure 11.**(b) Side view

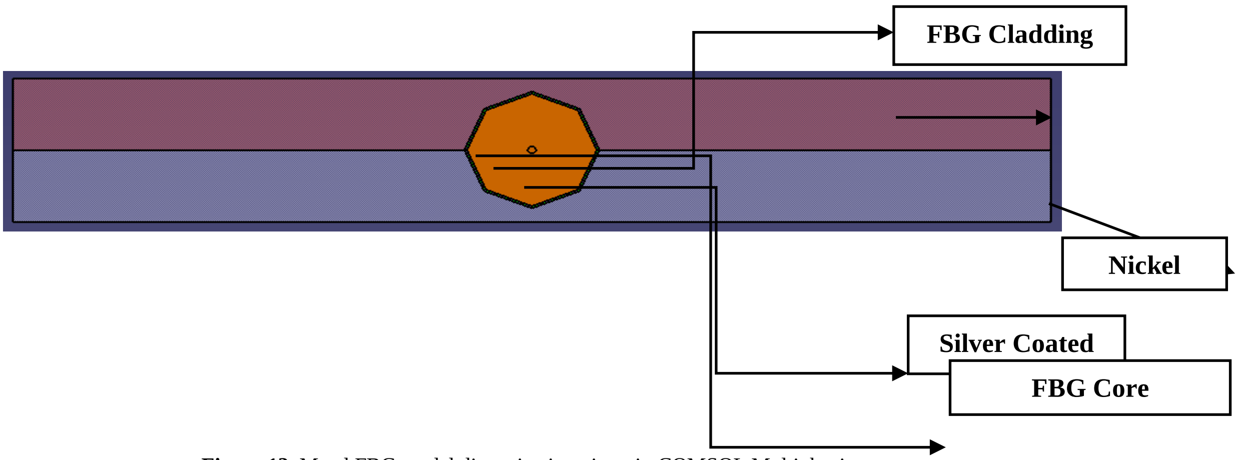


Figure 12. Metal FBG model discretization views in COMSOL Multiphysics

Table 7. Force vs strain values

Sl.No	Total Force	Strain
1	1N	0.02
2	2 N	0.05
3	3N	0.08
4	4N	0.1
5	5 N	0.13
6	6 N	0.16
7	7N	0.19
8	8 N	0.22

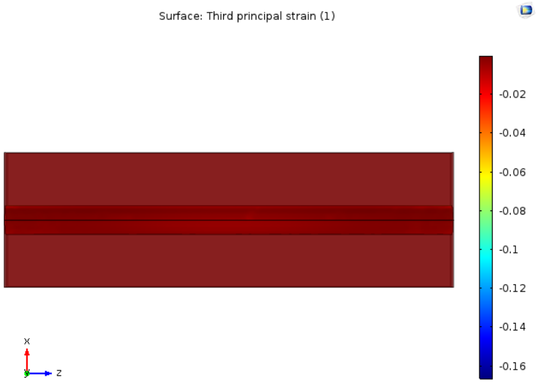


Figure 13. Sample Strain for 1N

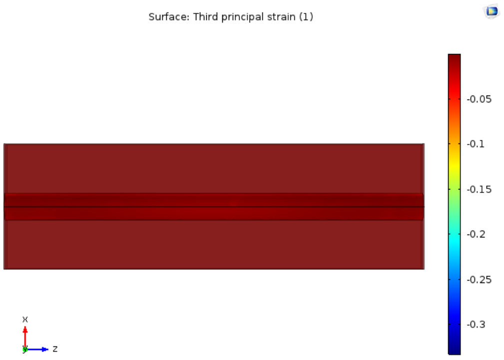


Figure 14. Sample Strain for 2N

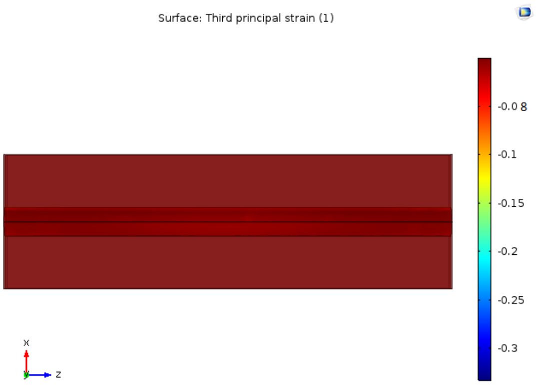


Figure 15. Sample Strain for force of 3N

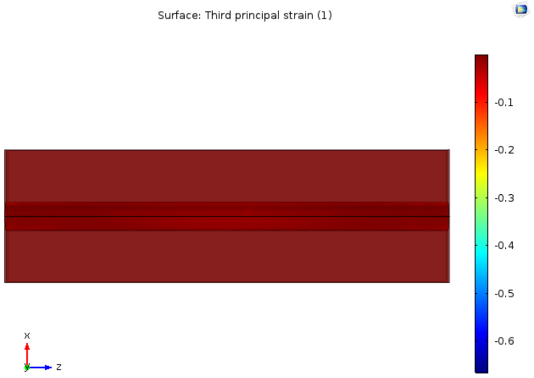


Figure 16. Sample Strain for force of 4N

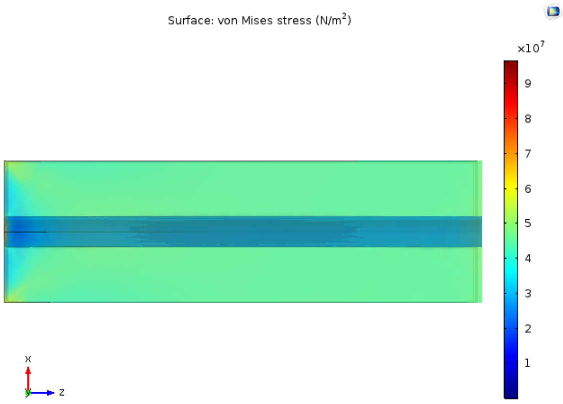


Figure 17. Sample stress visualization of model

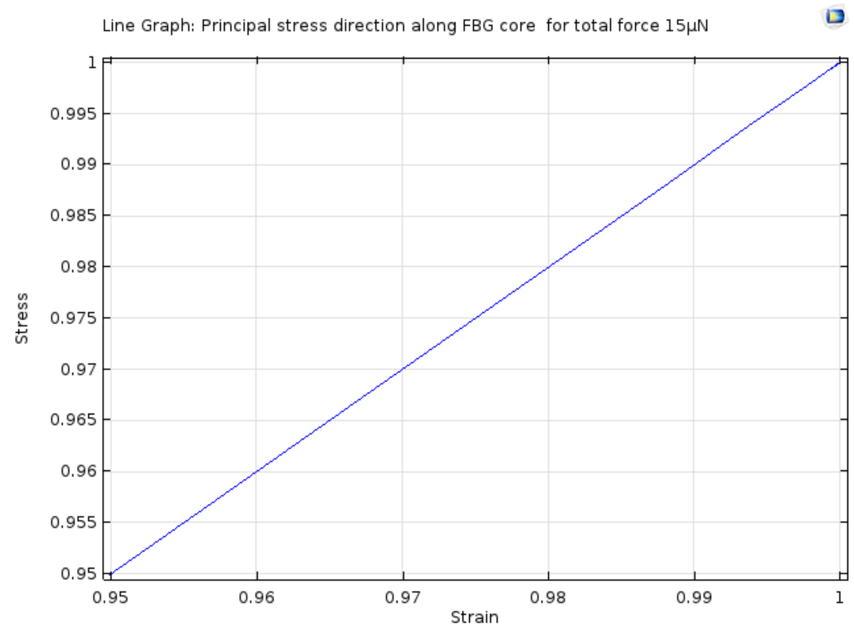


Figure 18. Sress – Strain Diagram for metal embedded FBG

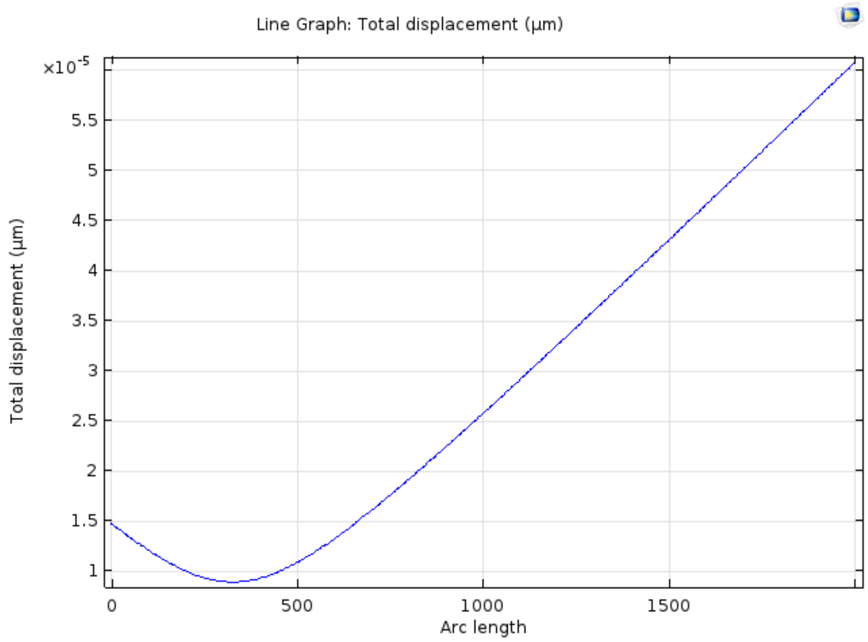


Figure 19. Displacement along the fibre for force 1N

Optomechanical simulation in Comsol multiphysics to obtain mechanical stress and strain with optical spectral response have been investigated for metal embedded FBG sensor, various strain values obtained is shown in Table 7 and Figure 13 to Figure 17 .Total force of 1 Newton to 5 Newton applied longitudinally to FBG embedded metal layer.Gradual increase in strain value has been observed during the analysis. There will be remarkable shift in wavelength is found when fibre was under load and without load. Linear relationship between stress and strain exhibits hookes law. Stress and strain realtion obtained is shown in Figure 18. Linear 1near curve obtained for total displacement versus arc length describes incremental displacement along the fibre shown in Figure 19. Topographical data shows a strain changes in core of FBG model embedded in metal layer.

6.Conclusion

This paper contains the design and simulation of diffenent FBG sensors for pressure measurement. A comparative study of a bare FBG and FBG coated with different materials namely PMMA, polystyrene and aluminium is done. The choice of coating materials is based on Young’s modulus of material, higher the young’s modulus the material is more rigid and such materials will not be able to detect the strain or residual stress developed in composite materials. It is observed that PMMA has low Young’s modulus and offers better sensitivity of 1.17μm/με.This work also includes the optomechanical simulation to obtain the mechanical stress and strain with optical spectral response of an embedded FBG sensor. Such analysis helps to monitor the health of composite materials or structures which are used in aircraft, automobile, machinery parts etc.

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