STRAIN SENSOR BASED ON FIBER BRAGG GRATING BONDED WITH GRAPHENE ON POLYMER PLATE

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To my dearest father, mother, my beloved wife, and my lovely children for their never-ending love, patience and support

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ABSTRACT

Fiber Bragg Grating (FBG) sensing has been intensively studied in the application of smart structures because of its immense advantages offered over those of the conventional sensors. In this study, the sensing characteristics of FBG bonded onto graphene and polymer plate are demonstrated under various mechanical deflections within the tension and compression modes. The sensing elements utilized for this purpose were 5 mm, 15 mm, 25 mm, and 35 mm FBG sensor bonded onto the surface of graphene with polymer plate. To accomplish these tasks, the lateral displacement was changed stepwise at different stress locations of 1 cm, 2 cm, and 3 cm applied away from the movable end of the FBGs, by which the curvature of the graphene with polymer plate is changed. An almost linear relationship between the sensitivity and deflection was observed for the FBGs bonded onto polymer plate and deflected at stress locations of 1 cm and 2 cm. However for the stress location of 3 cm it was deviated from being linear. Meanwhile FBGs bonded with graphene on polymer plate, the relation curves were also deviated from being linear. The sensitivity at 3 cm stress location for tension and compression modes was found to be larger than those for other applied stress locations and this is valid for both cases; graphene on polymer plate or on polymer plate only. It was also established that regarding the shift in Braggs wavelength center, both tension and compression processes are valid and comply with the physical observations. Moreover, for the FBGs bonded with grapheme on polymer plate, the sensitivity was increased upon the increment of grating length. It was also discovered that sensitivity of the FBG sensor for the small grating lengths of FBG (5 mm and 15 mm) was enhanced and it was observed that the response of compression mode is better than that of tension. However, for large grating lengths (25 mm and 35 mm), the tension mode response was found to be larger than that of compression. It was noticed that the hysteresis effect is significant in the tension mode and showed greater values in the large grating FBG. An interest linear relationship was determined between the optical and intensity (electrical) outputs.

ABSTRAK

Pengesanan parut gentian Bragg (FBG) telah dikaji secara intensif di dalam penggunaan struktur pintar disebabkan oleh banyak kelebihannya berbanding dengan pengesan konvensional. Dalam kajian ini, ciri pengesanan FBG yang dilekatkan pada grafin dan plat polimer telah ditunjukkan dalam pelbagai pemesongan mekanikal antara mod tegangan dan mampatan. Elemen pengesanan yang digunakan untuk tujuan ini adalah pengesan FBG 5 mm, 15 mm, 25 mm dan 35 mm yang dilekatkan pada permukaan grafin dengan plat polimer. Untuk melengkapkan tugasan ini, sesaran sisi telah diubah secara berperingkat pada lokasi tekanan yang berbeza iaitu 1 cm, 2 cm, dan 3 cm dari hujung FBG yang boleh digerakkan, yang mana kelengkungan grafin dengan plat polimer diubah. Satu hubungan yang hampir linear antara sensitiviti dan pemesongan telah diperhatikan bagi FBG yang dilekatkan pada plat polimer dan telah dipesongkan pada lokasi tekanan 1 cm dan 2 cm. Walau bagaimanapun, bagi lokasi tekanan 3 cm, keluk kaitannya menyimpang dari linear. Sementara itu FBG yang dilekatkan pada grafin dengan plat polimer, keluk kaitannya juga menyimpang dari linear. Sensitiviti pada 3 cm lokasi tekanan bagi mod tegangan dan mampatan didapati lebih besar berbanding dengan mod yang dikenakan pada lokasi yang lain dan ini benar bagi kedua-dua kes; grafin yang dilekatkan pada plat polimer atau hanya pada plat polimer sahaja. Selain itu juga, berkaitan anjakan dalam pusat gelombang Bragg, kedua-dua tegangan dan mampatan adalah sah dan mematuhi pemerhatian fizikal. Tambahan pula, untuk FBG dilekatkan dengan grafin pada plat polimer, sensitiviti FBG meningkat dengan bertambahnya panjang parutan. Juga diperolehi bahawa sensitiviti pengesan FBG dengan panjang parutan FBG yang kecil (5 mm dan 15 mm) telah dipertingkat dan dapat diperhatikan tindakbalas mod mampatan adalah lebih baik berbanding regangan. Walaubagaimana pun untuk panjang parutan yang besar (25 mm dan 35 mm), tindakbalas mod regangan didapati lebih besar berbanding mampatan. Ia nya juga mendapati yang kesan histeris adalah signifikan dalam mod tegangan dan menunjukkan nilai yang lebih besar dalam FBG yang parutannya besar. Suatu hubungan linear yang menarik telah ditentukan antara output optikal dan keamatan (elektrikal).

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LIST OF SYMBOLS

ϵ - Longitudinal strain
ϵ_{ax} - Axial strain
β - Fiber core propagation constant
$d\delta$ - Vertical displacement (deflection)
$d\theta$ - Angle between x axis and tangent to the deflection curve
δn_{eff} - Index change spatially averaged over a grating period
$\Delta\beta$ - Wave vector detuning
$\Delta\lambda_{FB}$ - Wavelength bandwidth
E - Young modulus of the beam
F - Force
ϕ - Diameter of the single mode fiber grating
$\phi(z)$ - Grating chirp
h - Thickness of the beam
I - Cross-section moment of inertia of the beam
K - Curvature
k_f - Wave vector of the scattered spectrum
k_i - Wave vector of incident spectrum
k_g - Wave vector of grating
κ - Coupling constant
L' - length of the cantilever
L - Total length of Grating
$M(x)$ - Bending moment applied to the beam
n_{eff} - Effective refractive index of the grating in the fiber core
ν - Poissons ratio
ν' - Fringe visibility of the index change
Λ - Grating spacing
λ_B - Bragg wavelength
P_B - Reflection power
P_{op} - Optical power

p_e	-	Effective photoelastic
p_{ij}	-	Tensor of strain−optic
R	-	Reflectivity
ρ	-	Radius of curvature
S	-	Coupling coefficient
S_j	-	Strain vector
V_{out}	-	Output voltage
x_f	-	Distance to the center of the FBG to the fixed end of the cantilever

LIST OF ABBREVIATIONS

AWG	-	Arrayed-Waveguide
CFRLs	-	Carbon Fiber Reinforced Laminates
DGD	-	Differential Group Delay
CWDM	-	Coarse Wavelength Division Multiplexing
DWDM	-	Dense Wavelength Division Multiplexing
DFB	-	Distributed Feedback
DIC	-	Digital Image Correlation
EMI	-	Electromagnetic Interference
ISHM	-	Integrated Structural Health Monitoring
IFOS	-	Intelligent Fiber Optic System
FBG	-	Fiber Bragg Grating
FWHM	-	Full width at half maximum
GFRP	-	Glass Fibre Reinforced Polymer
MCVD	-	Modified Chemical Vapor Deposition
MFBG	-	Microfiber Bragg Grating
NPP	-	Nuclear Power Plant
OSA	-	Optical Spectrum Analyzer
PDL	-	Polarization Dependent Loss
PMD	-	Polarization Mode Dispersion
RFI	-	Resin Film Infusion
SHM	-	Structural Health Monitoring
TRDS	-	Transmit Reflect Detection System
WDM	-	Wavelength Division Multiplexing

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

In the last couple decades, the scientific community has witnessed a great development in the production and utilization of small sized, light weight, flexible and economical friendly devices thanks to the continuous research works performed by the scientists. Very recently, Fiber Bragg Grating (FBG) sensors have received considerable attention and have been subjected to intensive research works. Fiber Bragg grating (FBG) is a type of distributed Bragg reflector constructed in a short segment of optical fiber that reflects particular wavelengths of light and transmits all others. The achievement of this unique property is by the creation of a periodic variation in the refractive index of the fiber core, which generates a wavelength specific dielectric mirror (Othonos and Kalli, 1999). The formation of permanent gratings in an optical fiber was first demonstrated by Hill *et al.* (1978), at the Canadian Communications Research Centre (CRC) (Hill and Meltz, 1997; Morey *et al.*, 1990).

Based on their unique characteristics, FBGs have proven to be ideal for a variety of applications such as dynamic strain, pressure measurement, temperature of a full scale pre-stressed concrete bridge made with high performance concrete during the construction process, buildings, piles, bridges, pipelines, tunnels, and dams (Matin *et al.*, 2005; Lin *et al.*, 2002; Li *et al.*, 2004). It is also used for maintenance inflight monitoring and space vehicles, marine and medical science ((Miesen *et al.*, 2011; Chan *et al.*, 2006). Its application has also been extended to provide online monitoring of cracks or leaks in reactor vessel head penetration of Nuclear power plant (NPP) (Seo *et al.*, 2009). According to literature, its wide application area has been mainly attributed to its ability to keep its reflectivity under radiation exposure (Lee *et al.*, 2010b), its immunity to electromagnetic interference, applications in remote sensing, stability in harsh environments, multiplexing capability, high sensitivity, wide dynamic range and simplicity.

In the past decade, several researchers have tried to enhance the sensitivity of FBGs by taking out different methods. For example, (Seo *et al.*, 2009) reported that the cantilever sensor exhibited a high sensitive resonance frequency spectrum. Subsequently, (Lee *et al.*, 2010b) used a Cu-coated fiber to develop a FBG acoustic sensor for integrated structural health monitoring (ISHM) of nuclear power plant (NPP). By carrying out a full 3-D numerical analysis and experimental verification of an acoustic sensor in the frequency range 0.5-30.0 kHz, (Moccia *et al.*, 2011), reported the first evidence of the resonant behaviour of an underwater acoustic sensor constituted by an FBG coated by a ring-shaped material. Furthermore, an FBG device can easily replace the dependence on piezo ceramic (PZT, or lead zirconate titanate $(\mathrm{Pb[Zr_x, Ti_{1-x}]O_3})$ strain gage to convert an deflection into an output voltage. This is because the electronic parts of the strain gages are subjected to continuous harm and degradation when immersed in water. In addition, the wiring that is a characteristic of strain gage makes the final device heavy and bulky. This can also be simplified by the use of FBG (Kleckers, 2009; Moccia *et al.*, 2011).

On the other hand, various methods have been undertaken by researchers to produce the tension and compression in the FBGs. (Fayed *et al.*, 2010) used fast Changeable Electromagnetic Force, while (Mavoori *et al.*, 1999) employed magnetic actuator, and (Iocco *et al.*, 1999) utilized piezoelectric actuator. Furthermore, motorized actuator was used to produce axial strain (tension or compression) by Mavoori *et al.* (1999). Alternatively, other researchers (Goh *et al.*, 2003) applied beam bending method, of which a cantilever beam with applied lateral strain is used to produce the tension and compression (Qin *et al.*, 2001; Kang *et al.*, 2012; Yu *et al.*, 1999; Feng *et al.*, 2016). Specifically, liner displacement measurement is an important area of interest, in which a number of FBG strain sensor configurations have been demonstrated (Mizutani and Groves, 2011; Waldbjørn *et al.*, 2014; Yau, 2014).

The selection of suitable materials presenting high flexibility and excellent curvature deviation for the purpose of producing a systematic deflection in the FBGs is of great importance. Graphene sheet has very high mechanical strength and can be stretched by as much as 20%. Ma *et al.* (2012) emphasized that with such unique characteristics of graphene, it is possible to build miniature pressure and acoustic sensors with high sensitivity and dynamic range. Therefore, interested by the enhanced properties of graphene, this research work was conducted to report on and analyse the performance of Fiber Bragg Grating (FBG) bonded onto the graphene with polymer plate substrate at different applied stress locations. The FBG is bonded with graphene on polymer plate to represent a physical cantilever, by which the deflection in the free end of the cantilever is achieved within the range of μm. As such, upon having the applied linear lateral displacement, the curvature of the graphene with polymer plate is subjected to increase or decrease. This variation in curvature is imperatively transferred to the FBG, which results in a tension or compression in the FBG architecture. The Bragg wavelength and area under the reflection spectrum are varied based on the stress applied to the FBG. This deviation process is repeated for different grating lengths of FBGs and the results are analysed and compared considering the tension and compression modes. Finally, attempts to deduce an empirical equation that is best fitted to correlate the reflected output voltage and optical power are presented.

1.2 Problem Statement

In order to analyse the performance of Fiber Bragg Grating FBG bonded onto graphene substrate, it is required to design and test a number of optical fiber sensors while utilizing FBG as the main sensing element. There is a need of using polymer plate as cantilever and to be bonded FBG onto the graphene sheet so that a suitable deflection is obtained by changing the lateral displacement concurrently with the increased or decreased tension and compression in the FBG's grating period. Nevertheless, the effect of changing stress location on the response of FBG sensor is remained to be highly important while investigating the effect of tension and compression on the sensing performance of FBG. Additionally, it is questionable how to utilize difference grating lengths of FBG to enhance the sensitivity of FBG sensor. Furthermore, the existence of an inexact correlation between optical and reflected intensity (electrical) outputs of FBG sensors requires rigorous research work to be done in order to determine such correlation. Considerably, it can be possible to utilize the electrical response of FBG devices instead of their optical related behaviours in the real life applications, especially in the field of environmental monitoring and alarm system.

1.3 Research Objectives

The main purpose of the current research work is to investigate the strain-sensitivity performance of FBGs under various deflection conditions of tension and compression when the FBGs are bonded onto the polymer plate or a combination of graphene and polymer plate. The aim can be achieved by the follows tasks:

1. To construct an FBG-bonded sensor configuration to be ready for analysing its performance.
2. To obtain the response of FBG-bonded onto graphene and polymer plate at difference stress locations.
3. To determine the effect of tension and compression on the sensing performance of FBG-bonded with graphene on polymer plate.
4. To analyse the sensitivity of these FBG sensors by utilizing difference grating lengths.
5. To find the correlation between optical and reflected intensity (electrical) outputs of FBG-bonded with graphene on polymer plate.

1.4 Significance of the research

The displacement sensors are receiving considerable attention in both academia and industry. In structural health monitoring SHM, FBG sensors are routinely used for monitoring strain and temperature (Dong *et al.*, 2001; Kahandawa *et al.*, 2012). Unlike strain and temperature, displacement is not a directly measurable quantity using bare FBG sensors. By utilizing the strain response of FBG to its equivalent Braggs wavelength, displacement sensors were developed and reported by researchers (Rajan, 2015). In addition, the method of depending on piezo ceramic (PZT, or lead zirconate titanate ($\mathrm{Pb[Zr_x, Ti_{1-x}]O_3}$) strain gage to convert a deflection into an output voltage directly can easily be replaced by the use of the proposed FBG device. This is because the electronic parts that are used for multiplexing and the related telemetry are subjected to continuous harm and degradation when they are immersed in water. But this degradation is rarely occurred during the utilization of FBG sensors. Furthermore, the wiring that is a characteristic of strain gage makes the final device heavy and bulky, whereas this can be simplified by the use of FBG. Specifically, this research is tailored to improve and analyses the sensitivity of different grating lengths of FBG bonded onto graphene sheet and finding a correlation between the output voltage and optical power. This can be accomplished by using oscilloscope instead of optical spectrum analyzer (OSA). As OSA is a costly instrument, the utilization of oscilloscope gives a substantial cost reduction and simplicity of use. Hence, the system can be a viable tool to be used in several applications like environmental monitoring and alarm system.

1.5 Scope of the research

This study only considers four different grating lengths of FBGs (1550.071 nm) having 5 mm grating, (1549.390 nm) having (15 mm and 25 mm) grating length and (1548.990 nm) having 35 mm grating length. the FBGs are classified as lateral linear displacement sensors along with utilizing an external power source (ALS-18-B-FA ASE) with a spectral range from 1452 nm to 1652 nm, operating at maximum power of (1.83 mW). The FBG will be bonded with graphene on polymer plate and made it as a cantilever deflected at its free end. This causes the curvature of the polymer plate to increase or decrease, which imperatively transfers the curvature onto the FBG and results in producing a tension or compression in the FBG architecture. The reason why graphene sheet has been selected was because of its high mechanical strength and stretchability to about 20%. By changing the displacement in linear translation stage (in amount of $\mu\mathrm{m}$), the reflection spectrum of the disturbed FBG will be obtained in two ways; i) by using a high-speed photo diode together with an oscilloscope, ii) second by using an optical spectrum analyzer (OSA). The lateral displacement was changed from 0 to 7500 $\mu\mathrm{m}$ in steps of 500 $\mu\mathrm{m}$.

1.6 Structure of Thesis

This thesis is comprised of five chapters and it is structured as follows; Chapter1 provides the background of the study, problem statement, objectives of the study, significance of the study and scope of the study. In Chapter 2, the related literature review of the FBG optical sensors are presented, while Chapter 3 is devoted to focus on the research methodology. Specifically, it started with introducing the methodology of the preparation of the FBG-bonded with graphene on polymer plate. In addition, it described the measurement of the FBG-bonded Sensors and the ways of analysing the performance FBG-boned Sensors. In Chapter 4, which includes the results and discussion part, the results of the output voltage of FBG-bonded sensors are studied for both substrates (polymer plate and graphene with polymer plate) at different stress locations under tension and compression process. There are done in order to estimate the optimum substrate and stress location. Furthermore, the output voltage for different grating lengths of FBG is analysed and targeted to determine a correlation between the output voltage and optical power. Finally, Chapter 5 draws the main conclusions of this study followed by the future research recommendations.

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