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Application of Packaging Technique in Fiber Bragg Grating Temperature Sensor for Measuring Localized and Nonuniform Temperature Distribution

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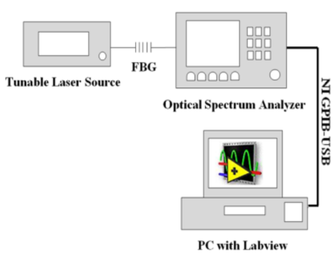
Graphical abstract



Abstract

The development of Fiber Bragg Grating (FBG) sensing technique has improved significantly especially in the sensor head design and real-time data acquisition technique. This paper presents the development of a simple and cost effective packaging technique that further enhances the performances of the FBG sensor. The packaged FBG sensor overcomes the nonuniform heat distribution of a bare FBG that causes eccentric response of FBG spectrum. Therefore, the packaged FBG sensor could be operated for a localized area with high temperature differential. The packaging also compensates the unwanted strain effect from the surrounding which makes temperature measurement become more accurate. The experimental works have been successfully carried out to demonstrate the system operation and the packaging functionalities. The temperature sensitivity coefficient of the bare FBG sensor measured in experiment is 10.05 pm/°C, while the packaged fiber sensor is 10.09 pm/°C, which are expected from the design.

Keywords: Optical Sensor; Fiber Bragg Grating; Labview; packaging; low cost

Abstrak

Perkembangan penderiaan teknik *Fiber Bragg Grating* (FBG) telah meningkat dengan ketara terutamanya dalam reka bentuk kepala penderia dan teknik pemerolehan data masa nyata. Kertas ini membentangkan pembangunan satu teknik pembungkusan yang mudah dan berkesan tetapi dengan kos yang rendah untuk meningkatkan prestasi penderia suhu FBG ini. Penderia FBG yang dibungkus mengatasi pengedaran haba tak seragam ke atas gentian yang tidak dibungkus, di mana penderia FBG yang tidak dibungkus akan menghasilkan respon yang tidak diingini pada spectrum FBG. Pembungkusan juga membatalkan kesan tekanan yang tidak diingini dari sekeliling untuk meningkatkan ketepatan pengukuran suhu pada penderia FBG. Kesimpulannya, kerja-kerja eksperimen telah berjaya dilaksanakan untuk menunjukkan operasi sistem dan fungsi pembungkusan. Sensitiviti suhu untuk penderia FBG yang tidak dibungkus ialah 10.05 pm/°C, manakala penderia FBG yang dibungkus ialah 10.09 pm/°C, seperti jangkaan daripada reka bentuk.

Kata kunci: Penderia Optik; Fiber Bragg Grating; Labview; pembungkusan; kos rendah

1.0 INTRODUCTION

Fiber Bragg Grating (FBG) has been widely accepted and applied in various of sensing and monitoring fields such as industrial sensing, biomedical device, mechanical [1, 2] and civil engineering [3], aerospace, and, oil and gas. Compared with other techniques, FBG sensor demonstrates a number of distinguishing advantages: wavelength encoded; self-referencing; linear output; small and lightweight; Wavelength Division Multiplexing (WDM) [4] and Time Division Multiplexing (TDM) compatibility; mass producible; durable; single and multi-point sensing [5]. Due to these superior advantages, FBG shows enormous potential of temperature, strain, pressure and radiation effect of sensing in smart structures and polymeric materials.

However, in reality, the bare fiber sensor head is very fragile and has low sensitivity [6]. Therefore the FBG sensor head must be protected by packaging technique to make them potential for sensing applications. Sensor packaging or coating has been the prominent method of improving the sensor response. Purposes of packaging for OFS are included improvement of transduction mechanisms allowing sensitivity enhancement to the corresponding perturbation, elimination of sensitivity to the undesired perturbations, provide reinforcement to bare fiber and tailoring the frequency response (for acoustic sensor) [7]. There are several work have been done in investigating the feasibility of packaging technique in optical fiber temperature sensor [8-12]. From the existing literature, the preferable solution for the fragility of bare FBG is through reliable FBG packaging or encapsulation technique. Three types of encapsulation techniques were developed for FBG strain and temperature sensors for practical applications in infrastructures [11]. A rigid probe technique was developed based on effective method of encapsulation of FBG sensor to be used in harsh and corrosive environments. These encapsulated FBGs demonstrated superior responsively, sensitivity, durability, and repeatability compared to the one without encapsulated. However, the encapsulation procedure in [11, 12] prove to be extremely complex and high cost because requiring specific equipment. In this paper, we propose a simple and low cost packaging technique with satisfied responsively, sensitivity and repeatability.

The resonance wavelength of FBG is formed by collective reflection or transmission of a group of grating pitch. Under a typical operation, it is required that the grating pitch experienced uniform changes of measurand (i.e the temperature) across the grating structure so that the grating period and the refractive index are also uniform. The uniformity of these parameters is important to ensure the shape of grating spectrum is maintained throughout the temperature measurement. Since length of FBG sensor is typically ranging from 0.5 cm to 2 cm, it contains thousands of grating pitch. This size could be too large for measurement of localized temperature, where a slight difference in temperature distribution across the grating structure could cause anomalies of the grating period and refractive index distribution. This effect cause distortion to the grating spectrum, and therefore, measurement of the wavelength to determine the temperature also could be erroneous. Therefore, packaging of FBG sensor seems to be the most practical method to overcome this problem.

This paper presents a simple and economical packaging technique based on copper tube that further improves the sensing performance of the temperature sensor. The packaging technique is used to compensate unwanted strain originated from the surrounding. More importantly, the packaging overcomes the nonuniform heat distribution of a bare fiber that causes eccentric behavior of FBG spectrum. The sensitivity of the FBG sensor is also increased due to the higher thermal expansion of the copper tube. This paper also presents the development of real-time data acquisition technique using a National Instrument GPIB-USB interface and Labview Software. The use of Labview software allows the Digital Signal Processing (DSP) to be performed in parallel to the data acquisition process. One main advantage is that, the functions of the system can be modified by only software changes, which is much simpler, quicker and inexpensive than replacing components in analog or digital circuit [13].

This paper is organized as follows; the first section is the introduction of FBG sensor and this project. In Section 2.0, we present the theory related to the characteristic of packaged FBG temperature sensor. Subsequently, Section 3.0 presents the experimental works in the term of real-time data acquisition system and the proposed packaging technique for FBG sensor and also the work flow of this project. Next, Section 4.0 presents the result and discussion of this project. Lastly, conclusion of this project presented in Section 5.0.

■2.0 THEORY: RESPONSE OF PACKAGED FBG TEMPERATURE SENSOR

The Bragg grating resonance wavelength, λ_B, which is the central wavelength of light back reflected from a Bragg grating. The shift in the Bragg grating wavelength $\Delta\lambda_B$, will be affected by the changes in temperature and strain. The relative shift of Bragg grating wavelength due to the temperature perturbation can be expressed as

$$\Delta\lambda_B = (\alpha + \xi) \cdot \lambda_B \cdot \Delta T \qquad (1)$$

where the α is thermal expansion coefficient of optical fiber, the ξ is thermo-optic coefficient of optical fiber, and ΔT is the change in external temperature at the FBG zone. For a general germanosilicate fiber, the value of α is 0.55×10^{-6} / °C, and the value of ξ is 6.67×10^{-6} / °C [14].

However, the thermal expansion coefficient can be altered alter when the bare FBG are packaged by some materials. Therefore, the relative shift of packaged Bragg grating wavelength due to the variation of temperature can be expressed as [16]

$$\Delta\lambda_B = [(\alpha + \xi) + (1-p_{eff})(\alpha_{sub} - \alpha)] \cdot \lambda_B \cdot \Delta T \qquad (2)$$

where the α_{sub} is thermal expansion coefficient of packaging material. p_{eff} is the effective photo-elastic coefficient and assumed to be 0.22.

■3.0 EXPERIMENTAL WORKS

The scope of this study covers the development of data acquisition program, hardware setup and packaging technique. A real-time data acquisition of FBG temperature sensor system is required to determine the temperature change from the wavelength shift in the transmission spectrum. The Labview-based system must able to record the important parameters of FBG spectrum throughout the experiment. This is important for the analysis and comparison between the result of bare and packaged FBG sensor head. Strategies and implementations of the packaging of the sensor are also discussed. As mentioned earlier, the packaging technique is needed in FBG sensor to make it practicable and enhance the accuracy of the FBG sensor.

3.1 Real-Time Data Acquisition of FBG Temperature Sensor System

In this project, a Labview-based data acquisition system is developed to interrogate FBG temperature sensor. The setup of the system is shown in Figure 1. The system consists of a sensing FBG, Optical Spectrum Analyzer (OSA) Anritsu model MS9710B, a desktop computer and a National Instrument GPIB-USB cable. A 20 mm FBG was fabricated on SMF-28 hydrogen loaded fiber by UV scanning through a phase mask with no apodization applied. The grating was written by a 244 nm frequency doubled Argon ion laser at output power of 150 mW and scanning speed of 3 mm/min [15]. Table 1 shows the specifications and setup of the device and equipments.

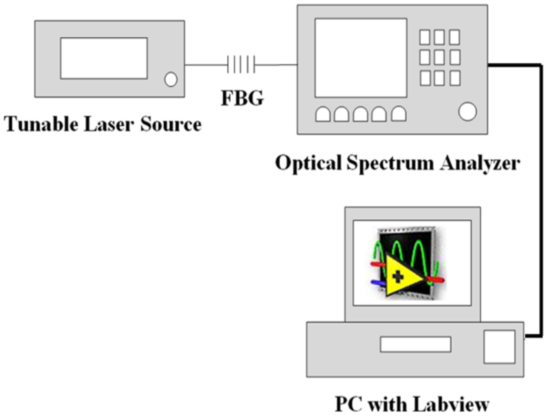
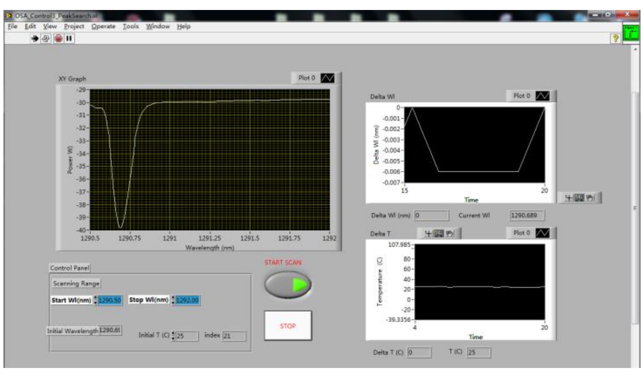


Figure 1 Experimental setup

Table 1 Specifications and setup

Device	Specification
Fiber Bragg Grating (FBG)	Single Mode Fiber (SMF-28) Central Wavelength : 1528 nm Length: 20 mm Peak reflectivity: ~ 99%
Tunable laser source	1550 nm SLD Light Source Operating Wavelength : 1400-1600 nm
OSA (Anritsu MS9710B)	Measurement range : 600 – 1750 nm Wavelength accuracy : 50 pm (1530-1570 nm)
NI GPIB-USB Cable	Full speed 12 Mb/s USB Signaling Transfer Rates Greater than 880 kbytes/s



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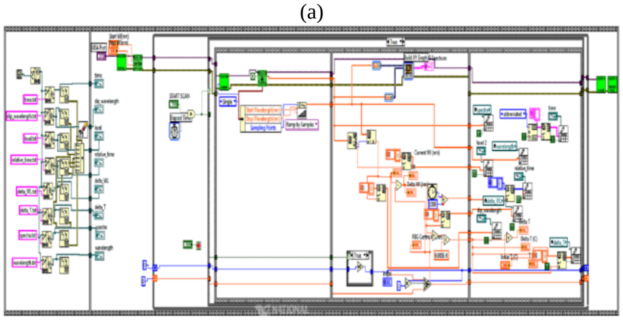


(b)

Figure 2 Labview program for data acquisition program; (a) graphical user interface and (b) code to control OSA and to record data

Figure 2 shows the graphical user interface and code of the Labview based data acquisition system. Note that the Labview code which is shown in Figure 2(b) is executed in sequential manner. The first step (from left hand side) the code creates the filenames for the required data. Then, the program initializes the OSA using Virtual Instruments (VIs) provided by the manufacturer. The VIs allow certain OSA parameters to be controlled from PC such as the start wavelength, stop wavelength, single or continuous scanning and resolution. However, most of the parameters are kept constant, where can only be changed during offline. This is to ensure that the setting and data are consistent throughout the measurement. The next sequence is to obtain the full FBG transmission spectrum data which consists of the wavelength and power. From the transmission spectrum, the program searches the minimum value of the power. The dip corresponds to the FBG center wavelength. The change of FBG center wavelength from initial value allows us to determine the temperature change in real-time using the equation (1) or (2). Finally, the all the data are saved in the hard drive of the computer for offline analysis. The use of Labview-based data acquisition automated the process of recording the FBG parameters from the OSA, hence avoiding any human errors during reading. This process can be precisely set to be repeated in every few seconds. Therefore, the timing can be synchronized with other types of sensors used in the experiment. The main parameter is the full transmission spectrum of FBG, which is continuously recorded and processed by the computer. From the analysis of full spectrum measurement in each cycle, the wavelength shift is determined and subsequently the temperature change is calculated.

3.2 Strategizing and Applying the Sensor Packaging Process

Packaging technique applied on the FBG temperature sensors is not only aimed for enhancement of the response, but also to ensure the survival of the sensor and its packaging throughout the measurement process. The main aspect is the type of the coating material with high thermal conductivity so that the heat can be conducted across the grating structure fast and efficiently. Copper possesses many desirable properties for packaging purpose compared with other conventional materials. Apart from its high thermal conductivity, copper has the advantages of corrosion resistant, good thermal expansion, high allowable stress resistant and internal pressure resistant. With high bulk modulus of 140 GPa, the packaged sensor will be insensitive the unwanted strain originated from the surrounding.

The filler material for the copper tube that is used to enhance the contact between the sensor and coating wall should be ready with suitable viscosity, so that the process of injecting the material can be done with ease. More importantly, the material should also possess relatively high thermal conductivity. As for this work, a heat sink compound RS503-357 with thermal conductivity of 0.65 W/m°C is selected. The cost for heat sink compound is increased for higher thermal conductivity. All materials used in the experiments are selected so that it could sustain the minimum and maximum expected temperatures to be measured. For this work, the sensor is tested in a boiling water, hence, the range of temperature is between the room temperature and the boiling point of water i.e. 100 °C. The packaging of sensor to sustain up to 180 °C, limited by the rubber sleeve operating temperature range.

Other considerations taken in account are to provide a rugged and robust packaging so that the FBG sensor can be easily handled without worrisome and could be further employed in harsh environment. It is extremely important to provide sufficient protection to the egress/ingress points, where the optical fiber is in contact with the sharp end of the copper tube. For this case, rubber sleeve was found to provide sufficient protection and flexibility to optical fiber during handling and deployment. When bent, this tube produces a rounded bend rather than sharp or v-shaped bends, thus ensuring the survival of the optical fiber when small-diameter bending inside the structure is required.

Figure 3 shows the schematic of the FBG sensor packaging. The copper tube used for packaging has the length of 4 cm, which create additional 1 cm at both ends and 2 cm for FBG. In the packaging procedure, the bare FBG was loosely placed at the center of a copper tube and then the position is fixed by small amount of glue applied to the fiber ends. This step is to ensure the grating section has a direct contact with the inner wall of the copper tube whilst maintaining the flexibility of grating section. Then heat sink compound was slowly injected into the slot of the copper tube. At the 1 cm buffer zone of both ends, the rubber sleeves were used to give extra protection to the ingress/egress points which are the most vulnerable parts. Finally, strong glue was applied to fix the position of the rubber sleeves as well as contain the heat sink compound in the copper tube. The glue was left to dry before the sensor can be tested. The copper tube is then cleaned from the remaining of the heat sink compound. The FBG sensor and heat sink compound consolidated very well with the copper tube and the surface cosmetic looked very good after treatment. Specifications of the materials used in the sensor packaging are outlined is Table 2.

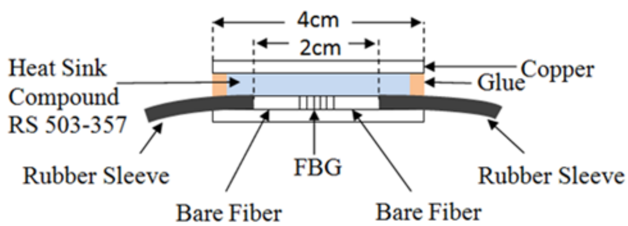


Figure 3 Schematic of FBG sensor packaging

Table 2 Specification of the packaging material

Material	Specification
Heat sink compound RS503-357	Material : Zinc Oxide Thermal conductivity : 0.65W/m°C Boiling point : >275°C Melting point : 1970°C
Copper tube	Thermal conductivity: 401W/m°C Operating temperature range: -50 - 200°C Tube inside diameter: 2.8mm Tube outside diameter: 4mm Bulk modulus: 140 GPa Melting point: 1084 °C
Rubber sleeve	Material : Silicone Rubber Operating temperature range : -65 - 180°C Sleeve diameter : 1mm Wall thickness : 0.5mm
Glue	Faster Super Glue, SG-F-3ML

3.3 Experiment Flow

The experiments were carried out in two phases; the bare fiber sensor head and packaged fiber sensor head. The same FBG with Bragg wavelength is 1528 nm was used throughout the experiment for fair comparison. The functionality of the FBG temperature sensor was tested by continuous heating of the sensor underwater from room temperature up to the boiling point. A thermometer was used as a reference reading. Reading from FBG sensor and thermometer was compare based on the relative time of the process. For both bare and packaged sensors, two cases were examined; uniform heat test and nonuniform heat test. In the uniform heat test, the whole sensor was submerged to the normal operating condition where the heat can be evenly distributed in the whole grating structure. On the other hand, for the nonuniform heat test, only half length of the grating is submerged underwater. The partial heating on the grating will test the performance and response of FBG sensor when there are anomalies of heat distribution across the grating section. Figure 4 summarized the flow of experiment.

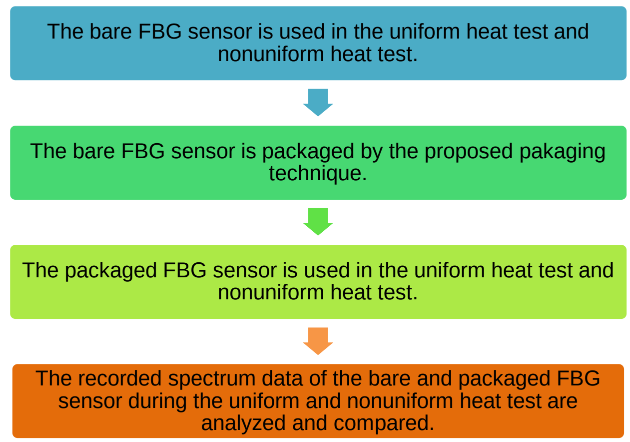


Figure 4 Flow of the experiment

4.0 RESULTS AND DISCUSSION

Figure 5 shows the temperature sensitivity coefficient of the bare and packaged FBG temperature sensor. The central Bragg wavelength of the bare FBG is 1528 nm. According to the equation (1), the theoretical value of temperature sensitivity coefficient of the bare FBG temperature sensor is 11.03 pm/°C. But from the figure 5(a), the temperature sensitivity coefficient is 10.05 pm/°C, which is different from the theoretical value. This is because the type of fiber we used is not germanosilicate fiber. From the equation (1), we can see the index change ($\alpha + \xi$) is the dominant effect in temperature sensitivity [16], and this caused the big difference between the theoretical and experimental result. For the packaged FBG temperature sensor the central Bragg wavelength is changed to 1528.46 nm. This is due to the stress residue created by the external packaging material. The expansion coefficient of the copper is 17×10^{-6}/°C. Therefore, according to the equation (2) the sensitivity coefficient of the packaged FBG temperature sensor is 30.64 pm/°C. Since the grating section is loosely placed i.e. not rigid inside the tube, the effect of higher thermal expansion of the copper tube is not prominent. However, there is still a small increase of sensitivity coefficient of the packaged FBG to 10.09 pm/°C that could be observed. To significantly enhance the sensitivity, strong contact between the FBG sensor and the copper is required so that the effect of higher thermal expansion can be transferred to the FBG.

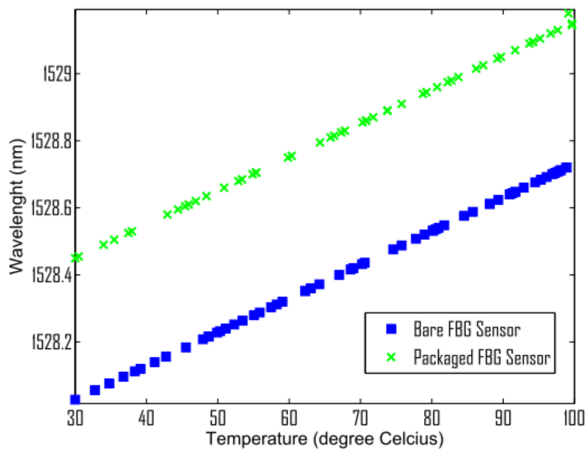
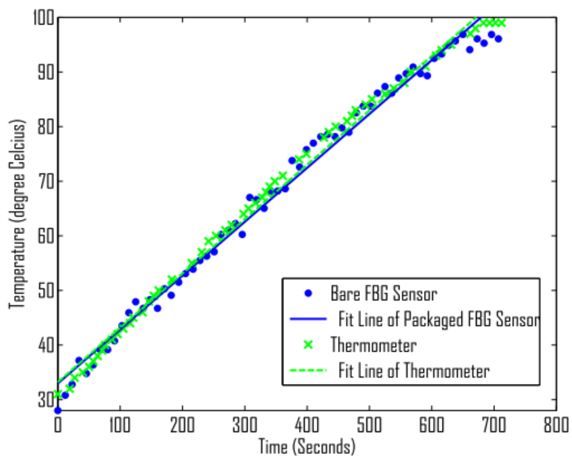
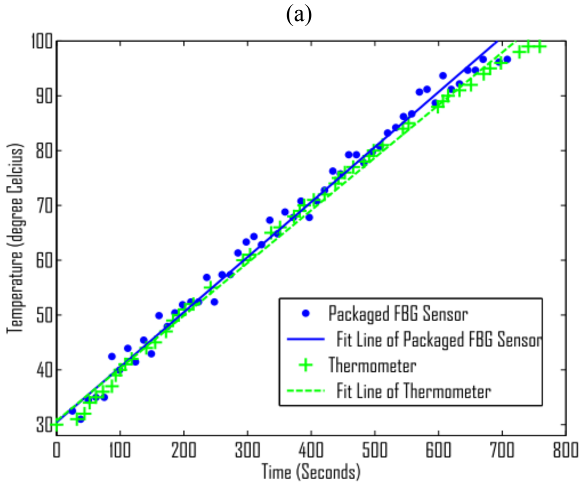


Figure 5 Temperature characteristics curve of bare and packaged sensor



(a)

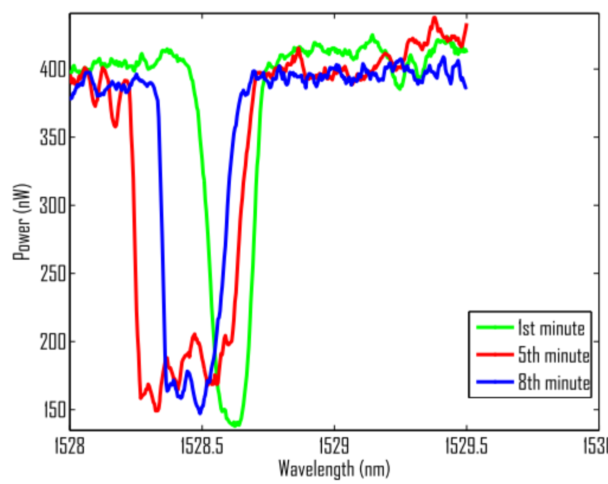


(b)

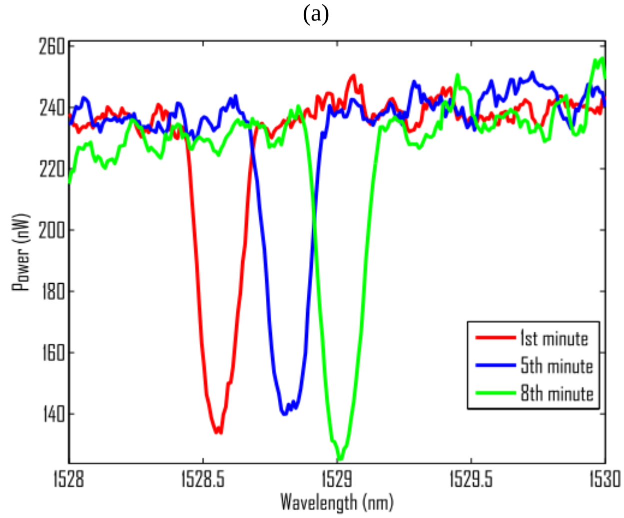
Figure 6 Temperature measurement of (a) bare FBG sensor, and (b) packaged sensor

Series of measurement have been carried out in order to verify the temperature response of bare and packaged sensor correspond to the actual temperature. The measurement is then compared to the measurement obtained from the thermometer. Figure 6(a) and 6(b) show the temperature measurement of bare fiber and packaged fiber respectively. The result clearly indicates the temperature measurements for bare and packaged fiber are quite similar to the reading of the thermometer. There are minor peak fluctuations of the FBG spectrum that caused temperature fluctuation. One of the reasons is that the low wavelength resolution of the OSA. Furthermore, the low scanning speed of the OSA could also cause small irregularity to the measured spectrum as the temperature could change during between each scanning step. By using high speed tunable optical filter with high resolution, the aforementioned problem can be minimized. Adjustment on the coefficient for the packaged fiber is made to compensate the higher thermal expansion of the copper tube and the heat sink compound. The higher thermal expansion of the copper tube also enhances of the sensitivity of the packaged sensor. The increase of temperature is almost linear with the relative time taken.

Figure 7(a) and 7(b) show the transmission spectra of bare and packaged sensors for the nonuniform heat test. There are multiple peaks and spectrum broadening in the bare fiber due to the nonlinear chirping of grating. Apparently, this multiple peaks lead to error in temperature measurement. Meanwhile, for the packaged sensor, the shape of the transmission spectrum is undistorted by the nonuniform heat distribution test. The result is shown in Figure 8 verifies that the measurement of packaged FBG sensor under nonuniform test is comparable to the reading of the thermometer. The functionality of the copper tube packaging for heat conductor is evident as the sensors pick up the highest temperature from the nonuniform heat test.



(a)



(b)

Figure 7 FBG transmission spectra at different stages of experiment in nonuniform heat test for (a) bare FBG sensor, and (b) packaged FBG sensor

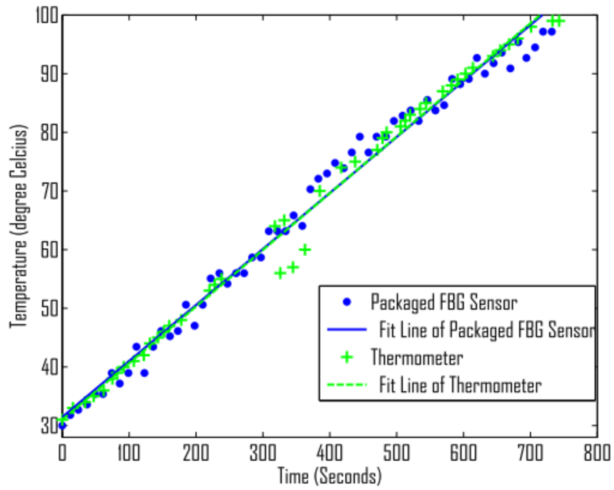


Figure 8 Temperature measurement of packaged FBG in nonuniform heat test

■5.0 CONCLUSION

In this work, a Labview based data acquisition system for temperature measurement of FBG sensor has been successfully developed. Functionality of measuring the correct temperature is also demonstrated. The response of FBG temperature sensor for a localized and nonuniform heat measurement has been investigated, whereby the spectrum of bare FBG sensor is distorted in nonuniform heat test and could not give the correct temperature reading. This is due to the anomalies of grating period and refractive index distribution. To overcome this problem, a simple and economical FBG packaging technique is proposed and experimented. The temperature sensitivity coefficient of the bare FBG is 10.05 pm/°C, which is slightly different to the theoretical value of 11.03 pm/°C as the germanosilicate fiber is not being used in experiment which assumed in the equation (1). The temperature sensitivity coefficient of the packaged FBG, is 10.09 pm/°C which is slightly higher than the bare fiber and lower than the theoretical value of packaged fiber. This result is expected since the packaging is not rigid which reduce the contact between fiber and packaging material, consequently the effect of packaging is not evident. Result shows that the packaged FBG sensor gives the correct temperature reading while the bare FBG sensor gives an error reading in the nonuniform heat test. Furthermore, the sensitivity of the FBG sensor could further enhanced due to the higher thermal expansion of the packaged material. This sensing performance in conjunction with the existing advantages of fiber optic sensor is highly desirable by many practical applications.

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References

[1] A. I. Azmi, Raju and G. D. Peng. 2012. Progressive Failure Monitoring of E-Glass/Vinylester Curve Composites Using Embedded FBG Sensors. *Proceedings of Third Asia Pacific Optical Sensors Conference*. 8351: 835138.

[2] Y. B. Lin, K. C. Chang, J. C. Chern and L. A. Wang. 2005. Packaging Methods of Fiber-Grating Sensors in Civil Structure Applications. IEEE *Sensor Journal*. 5(3): 419–423.

[4] A. I. Azmi, D. Sen, J. Canning and G. D. Peng. 2011. Intensity-Type Vibration Sensor Based on Multiple Subchannels Sensing Scheme. Proceedings of IQEC/CLEO Pacific Rim 2011. 2023–2035,

[4] X. Xu. 2006. Improving the Performance of FBG Sensing System. Master Thesis, School of Electrical, Computer and Telecommunications Engineering, University of Wollongong,

[5] W.-H. Wang, Y.-J. Feng, W.-Q. Shi, Z.-Y. Xiong, S.-D. Li, W.-N. Wu, *et al*. 2009. Analysis of Packaging Material Impacting on FBG Temperature Sensors. *2009 International Conference on Optical Instruments and Technology: Advansed Sensor Technologies and Applications*. 7508: 750810–1.

[6] A. I. Azmi. 2012. Development of Fiber Grating-Based Sensing Techniques and Application in Mechanical Enginering. PhD Thesis, School of Electrical Engineering and Telecommunication, The University of New South Wales, Sydney.

[7] V. F. David Barrere, J. Villatoro, S. Sales, and V. Pruneri. 2012. Packaged Optical Sensor Based on Regenerated Fiber Bragg Gratings for High Temperature Applications. *IEEE Sensor Journal*. 12(1): 107–112.

[8] Y. G.-Q. SONG Li-Jun. 2010. The Packaging Technique About FBG Temperature Sensor. *2010 Second International Conference on Communication Systems, Networks and Applications*.

[9] J. L. P.Wang, C. Li, W.Chen and H. Ahao. 2011. Temperature Sensing Experiment of Fiber Bragg Grating Packaged by Copper Capillary Without Strain. Proceedings of Conference on Optoelectronics and Microelectronics Technology. 69–72.

[10] Zhou, Graver, Hsu and OU. 2003. Techniques of Advanced FBG Sensors: Fabrication, Demodulation, Encapsulation and Their Application in the Structural Health Monitoring of Bridges. *Pacific Science Review*. 5: 116–121.

[11] P. S. Reddy, R. L. N. Saiprasad, D. Sengupta, M. Saishankar, K. S. Narayana, and P. Kishore. 2011. Encapsulated Fiber Bragg Grating Sensor for High Temperature Measurements. *Optical Engineering*. 50: (11): 114401–114406.

[12] A. I Azmi, I. Leung, X. Chen, S. Zhou, Q. Zhu, K. Gao, P. Childs and G. D. Peng. 2011. Fiber Laser Based Hydrophone Systems. *Photonics Sensor*. 1(3): 210-221.

[13] Jung J, Nam H, Lee B. 1999. Fiber Bragg Grating Temperature Sensor With Controllable Sensitivity. *Applied Optics*. 38(13): 2752–2574.

[14] A. I. Azmi, D. Sen, W. Sheng, J. Canning and G. D. Peng. 2011. Performance Enhancement of Vibration Sensing Employing Multiple Phase-Shifted Fiber Bragg Grating. *Journal of Lightwave Technology*. 29(22): 3453–3460.

[15] Q. C. a. P. Lu. 2008. Fiber Bragg Grating and Their Applications as Temperature and Humidity Sensors. *Atomic, Molecular and Optical Physics*. L. T. Chen, Ed. ed: Nova Science Publishers, Inc. 235–260.