OPTOELECTRONICS AND ADVANCED MATERIALS – RAPID COMMUNICATIONS Vol. 13, No. 5-6, May-June 2019, p. 290-294

Statistical analysis on impact of temperature to fiber Bragg grating sensor performance

H. HAROON*, A. KAREEM
Centre for Telecommunication Research & Innovation (CeTRI), Fakulti Kejuruteraan Elektronik Dan Kejuruteraan Komputer (FKEKK), Universiti Teknikal Malaysia Melaka (UTeM), 76100 Durian Tunggal, Melaka, Malaysia

This paper studied the feasibility of statistical approach to aid in the development of the fiber Bragg grating (FBG) temperature monitoring system using analysis of variance approach. Upon completion, the sensitivity of the sensor measured for DI water and palm oil is 0.00149 dBm/ ºC and 0.0273 dBm/ ºC, respectively. In terms of the wavelength shift, the sensitivity of 13.1 pm/ ºC and 25.29 pm/ ºC were achieved for DI water and palm oil, respectively. The coefficients of determination (R^2) for temperature variations relationships were 0.986 for DI water and 0.9806 for palm oil. This study showed the great potential of statistical approach in predicting the sensor device performance.

(Received September 26, 2018; accepted June 14, 2019)

Keywords: Fiber-optic, Fiber-optic sensor, Fiber Bragg grating, Temperature measurement, Sensor applications

1. Introduction

Fiber-optic sensor technology has experienced tremendous growth over the past four decades. Optical fiber refers to the medium associated with the transmission of information as light pulses along a glass or plastic optical fiber. A fiber-optic sensor (FOS) can be configured to be either intrinsic or extrinsic, based on the sensor location or operation. For an extrinsic FOS, the fiber will act as a delivery medium that transports light to or from the sensing element. The sensor will be less sensitive and mostly applied in temperature, pressure and liquid level measurements. For an intrinsic FOS, the light intensity will react to the changes of optical fiber refractive index, which self- converts the signal variations into a modulation of the light signal. The refractive index of optical fiber changes in relation to the environmental variations including temperature, stress, humidity, etc. Light can be modulated in the form of intensity, phase, and frequency or polarization [1-3].

The fiber Bragg grating (FBG) technology is one of the most promising choices for optical fiber sensors, due to their environmental ruggedness, versatility, compactness, simplicity in fabrication, and most importantly their responsivity. The technology has been applied in various applications including structural monitoring, infrastructure assessment, bio-medical, defense, etc. [4–7]. FBG technology offers the possibility of measuring or sensing different parameters such as rotation, bio-chemical, temperature, current, displacement/strain, humidity, roughness, acceleration, refractive index, acoustic, electric field, and magnetic field. Research in FBG technology has significantly opened up a wide opportunity in the development of optical sensors, driven by its outstanding properties [8-11].

FBG sensing operation is based on the dependence of its Bragg wavelength with local Bragg condition, which only light at a selective wavelength will be reflected back to the detector. These Bragg conditions are specified by the grating period and modal effective index. Performance of the sensor is mainly determined by the sensitivity (S). For temperature sensing, this can either be in units of nm/ ºC or dB/ ºC [12].

The bottleneck in developing high–efficiency FBG sensor is time consumed in the developing process. Therefore, fundamental improvement in device characterization is urgently needed. Several methods have emerged in fiber optic performance analysis, commonly based on device modeling, and then verified by multiples of repeated experimental measurements. In this report, we examined the feasibility of statistical analysis to aid the validation of the sensor modeling and analysis. Since, consideration for variabilities of device characteristics is an important aspect in circuit designs [13-14], different techniques like Taguchi or response surface models have been reported before [15-18].

In this study, the main task is to describe the performance of a temperature sensor using single-mode fiber optic fiber Bragg grating (FBG). We examined the temperature dependent response of FBG between 25 ºC to 75 ºC, working around 1550 nm wavelength. The performance of FBG as temperature measurement is discussed, to forecast its potential to be an alternative to the electronic sensor.

Experimental results from the laboratory measurements will be verified with statistical analysis where we will perform the analysis of variance to check the validity of the measurements. These tools are adapted to the study of temperature variations in order to statistically analyze the sensor performance. To the best of our knowledge, this is the first attempt to integrate statistical analysis in validating the performance of fiber-optic sensor. The study will be a significant endeavor as it serve as a future reference for other researchers on designing high performance fiber based sensor. The applications of this sensor includes temperature measurement in harsh environments, high degree multiplexing system and distributed measurement area.

2. Methodology

In this study, we utilized commercially available silica fiber based FBG with Bragg resonance set at 1550 nm. This FBG has a reflectivity of >80% and bandwidths of <0.5 nm at ~1550 nm. The experimental setup for temperature measurement used in this work is shown in Fig. 1.

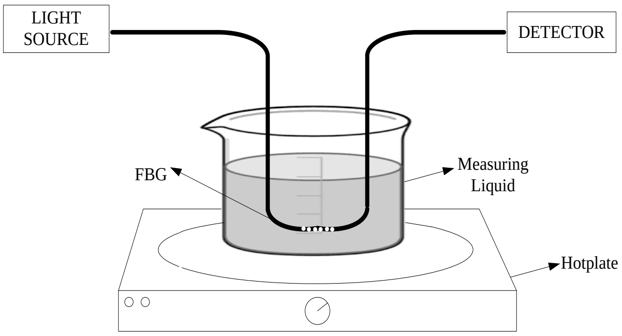

Fig. 1. Setup for FBG based temperature measurement

The FBG utilized in this study is shown as in Fig. 2. The FBG sensor system is connected to a laser source and an optical power meter (OPM). The OPM is used to measure the output optical power and shifted wavelength of the output. The FBG sensor system is then dipped into a measuring liquid, where the beaker is placed on the hotplate. The length of the FBG is about 1.5 m, with sensing probe at the middle of the fiber. The liquid in the beaker will be heated using a hotplate to increase the temperature of the solution. Origin Pro 8 software is used to plot the output results into a graph. Two liquid samples were taken into account which is the distilled (DI) water and palm oil solution, where the readings for each solution were repeated three times. The average readings were taken as the final results. The sensor probe was cleaned with acetone liquid and dried prior to another liquid testing.

The performance of the FBG sensor system is investigated based on the temperature effect on optical output power and wavelength shift. Analysis of the results is emphasized on the adjusted coefficient of determination (R^2), F-test and P-test value, in order to validate the modeling results. R^2 is frequently used to determine the accuracy of the models, as it provides an estimate of the strength of the correlation between the model and response variable. R^2 is calculated to measure the goodness of fit. In this study, the focus is to study the output power and wavelength affected by the temperature changes. Meanwhile, F-test compares two variances, by dividing them. These two variances were calculated from the unfitted model and fitted model. The overall F-test determines whether the relationship of the model parameters is statistically significant. In addition, P-test can also help to determine the significance of the results. P-value of 0.05 can be concluded that there 5% probability that the output (Y) will not change as a result of the variation in the input (X). Hence, in our case, the value of less than 0.05 shows that the temperature variation has a strong interaction with the output power or wavelength shift [18-20]. All the statistical analyses and results are calculated using Origin Pro 8 Software.

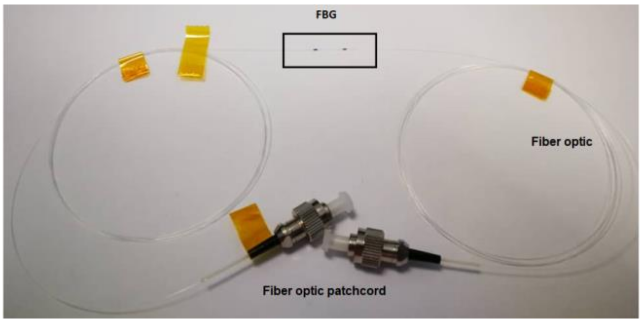

Fig. 2. Fiber optic cable with FBG

3. Results and discussion

Fig. 3 depicts the best-fitting curve for the optical output power obtained due to the effect of temperature variations. The reading obtained from OPM is the optical output power for DI water with the light source transmitted at the wavelength of 1550 nm. Temperature range used for the experiment is from 25 °C to 75 °C. From the graph, it can be seen that the optical output power, P_o decreases from -5.21 dBm to -5.29 dBm as the temperature increases. The mathematical description of the proposed sensor performance can be predicted as:

$$P_o\,(\text{dBm}) = -0.00149 \ \text{x}\ t\,(^{\circ}\text{C}) \ -5.179 \qquad (1)$$

which reflects the dependency of output power, P_o and temperature, t.

The adjusted R^2 value of 98.6 % obtained concludes that the model has good fit and accuracy. The sensitivity of the FBG-based temperature sensor can be estimated by fitting the slope of the experimental data, which from Fig. 3, the sensitivity observed is 0.00149 dBm/ ºC. The analysis of variance for the temperature effect experiment for DI water is shown as in Table 1.

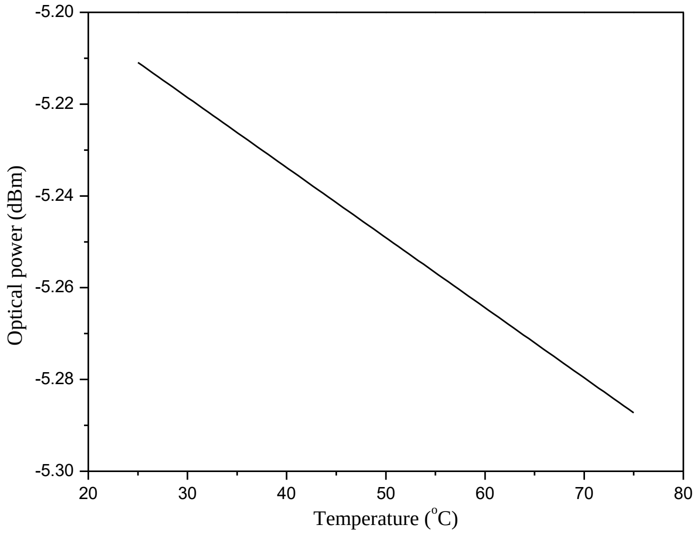

Fig. 3. Relationship between temperature variations with optical output power for DI water

Table 1. Analysis of variance for temperature effect experiment on output power for DI water

	Sum of Squares	Mean Squares	F-value	P-value
Observed Output Power	0.00642	0.00321	355.767	<0.01
Error	$7.21678E^{-5}$	$9.02098E^{-6}$		
Total	0.00649			

Based on the statistical analysis of the best fitting graph of the optical power, as shown in Table 1, with a high value of F and P value < 0.05, we can deduce that the optical power significantly affect by the temperature variations, which as the temperature increases, the power received reduced.

The effect on the wavelength shift, Δλ versus the applied temperature, *t* is observed as in Fig. 4. It can be clearly seen that abrupt change happens after the temperature of the water is increased beyond 50 °C. Starting from 50 °C, the sensitivity of the sensor in terms of wavelength shift is 13.1pm/ °C. The overall performance of the sensor towards temperature changes is modeled by Equation 2.

$$\Delta\lambda_{water}\,(\text{nm})=0.0415\ \text{x}\ t\,(^{o}\text{C})+0.0543\ \text{x}\ t^{2}(^{o}\text{C})+71.7207 \quad (2)$$

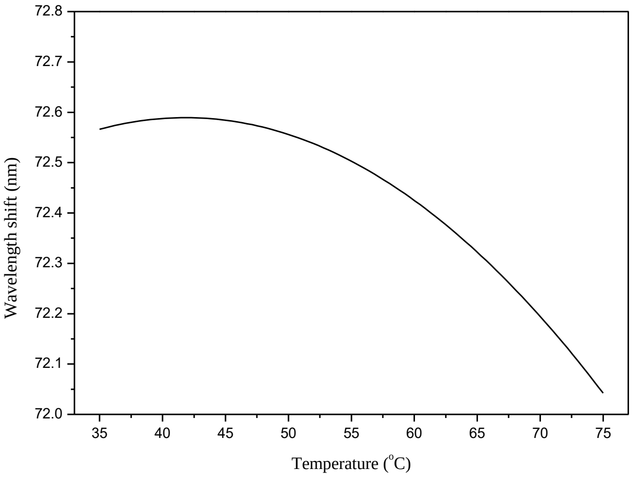

Fig. 4. Relationship between temperature variations with wavelength shift for DI water

The analysis of variance of the model is summarized as in Table 2. Note that, the values of F is greater than 1 and the error observed from P-value is less than 5%, hence the model is said to be sound. It testifies that the fitting model as shown in Fig. 4 is significant and practical to be considered in designing the temperature sensor.

Table 2. Analysis of variance for the temperature effect on wavelength for water

	Sum of Squares	Mean Squares	F-value	P-value
Observed Output Power	0.24897	0.24897	7.27823	0.0429
Error	0.17103	0.03421		
Total	0.42			

To examine the feasibility of the FBG sensor to detect temperature changes in different liquid solutions, the same sensor is immersed in palm oil liquid which has the refractive index of 1.46. The palm oil is selected as it is an edible oil, commonly used in daily life of South Asians. The best linear fitting of the graph is shown as in Fig. 5. Again, it can clearly be seen that as the temperature increased, the received power become smaller.

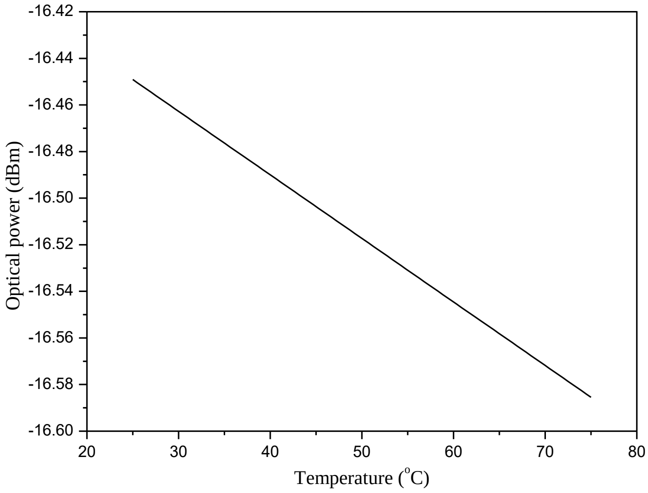

Fig. 5. Relationship between temperature variations with optical output power for palm oil solution

The sensor performance was then modeled and expressed as a function of the optical output power and temperature variations as shown in Equation 3.

$$P_o\,(\text{dBm}) = -0.0273\text{x } t\,(^\circ\text{C}) - 16.38 \qquad (3)$$

The adjusted R^2 value of 98.06% shows a good accuracy of the model. The slope of the graph reflects the sensitivity of the sensor for oil, determined as 0.0273 dBm/ °C, which shows that palm oil solution has better sensitivity in detecting temperature changes compared to DI water.

Analysis of variance for the fitted graph as shown in Fig. 5 is portrayed in Table 3. A high F-value and small P-value, indicate that there is no problem with the experiment validity.

Table 3. Analysis of variance for the temperature effect experiment on output power for palm oil

	Sum of Squares	Mean Squares	F-value	P-value
Observed Output Power	0.02045	0.02045	506.25	<0.01
Error	$3.63636E^{-4}$	$4.0404E^{-5}$		
Total	0.02082			

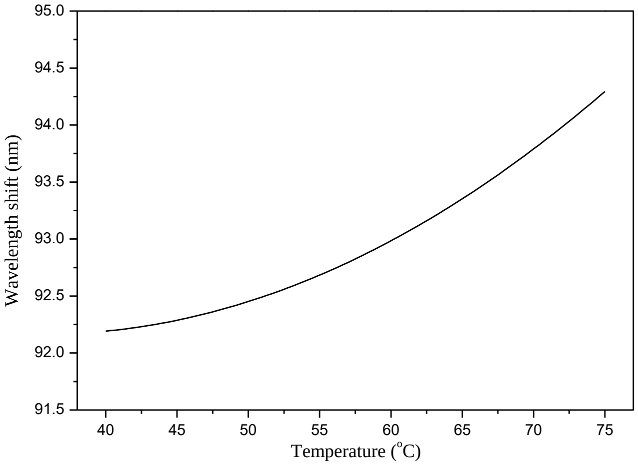

Fig. 6. Relationships of temperature variations with wavelength shift in palm oil solution

Fig. 6 describes the amount of wavelength shift corresponding to the temperature variations. The resonant wavelength shift is directly proportional to the temperature changes with the average sensitivity of 25.59pm/ °C, measured from 50 °C to 75 °C. The relationship of the wavelength shift and temperature variations modeled by can be the polynomial curve fitting as in Fig. 6, can be represented by Equation 4 as below.

$$\Delta\lambda_{oil}\,(\text{nm}) = -0.0966\text{x } t\,(^\circ\text{C}) + 0.00136 \text{ x } t^2\,(^\circ\text{C}) + 93.876 \qquad (4)$$

The analysis of variance for the wavelength shift effect of palm oil is summarized in Table 4. Note that the F-value is higher than 1 and the error is about 2.9%. Clearly, the P-value is small in this case. Therefore, we can conclude that temperature significantly contributes to the wavelength shift, and the model represented by equation 4 is well fitted and highly accurate.

Table 4. Analysis of variance for the temperature effect on wavelength for palm oil

	Sum of Squares	Mean Squares	F-value	P-value
Observed Output Power	3.62303	1.81152	14.416	<0.02893
Error	0.37697	0.12566		
Total	4			

4. Conclusions

In this work, an FBG-based temperature sensor was developed. When the temperature was increased to 50 °C, an excellent sensing performance was achieved. The performance of the sensor device in responding to temperature variations was investigated and analyzed for two different types of liquid solutions, which is DI water and palm oil. It is observed that the sensor performance in palm oil solution demonstrates higher sensitivity. Upon completion, the sensitivity of the sensor towards output power measured for DI water and palm oil is 0.00149 dBm/ ⁰C and 0.0273 dBm/ ⁰C, respectively. The higher sensitivity of FBG, the better the performance of the FBG sensor. In term of interaction with temperature to wavelength shift, with temperature change of 1 ⁰C, the operating wavelength will be shifted by 13.1 pm for water and 25.59 nm for palm oil solution. Liquid with higher refractive index leads to larger sensitivity. The significant findings which are based on statistical analysis should make as an important reference in designing an improved FBG for temperature sensor applications. Furthermore, the proposed design and theoretical formula we establish in this paper can be used for remote, real-time, high precision and early warning monitoring of extreme temperature fluctuations in any environmental monitoring. The study can be further improved by employing more robust statistical design methods such as Taguchi or Response Surface Method. Overall, the results of this study highlight the potential of statistical approach to be used in designing and optimizing fiber-optic sensor performance.

Acknowledgement

Our thanks to Universiti Teknikal Malaysia Melaka (UTeM) for the support.

References

[1] H. Haroon, S. S. Khalid, Journal of Advanced Review on Scientific Research **36**(1), 1 (2017).
[2] H. Haroon, S. K. Idris, M. Y. Yusoff, A. S. M. Zain, H. A. Razak, F. Salehuddin, M. Z. N. Syaimaa, Electronic and Computer Engineering (JTEC) **10**(2-5), 131 (2018).
[3] L. Mi, X. Fang, Appl. Sci. **8**, 107 (2018).
[4] G. Laffont, R. Cotillard, N. Roussel, R. Desmarchelier, S. Rougeault, Sensors (Basel) **18**(6), 1791 (2018).
[5] H.-Y. Chang, C.-H. Yeh, C.-Y. Huang, M.-Y. Fu, C.-W Chow, W.-F. Liu, Sensors and Materials **30**(1), 23 (2018).
[6] Y. Hu, C. Hong, Y. Zhang, G. Li, International Journal of Distributed Sensor Networks **14**(5), 12 (2018).
[7] X. Qiao, Z. Shao, W. Bao, Q. Rong, Sensors **17**(3), 429 (2017).
[8] Z. Zhang, C. Liu, Photonic Sensors **7**(4), 345 (2017).
[9] E. Oromiehie, B. G. Prusty, P. Compston, G. Rajan, Advanced Manufacturing: Polymer & Composites Science **3**(2), 52 (2017).
[10] E. Oromiehie, B. G. Prusty, G. Rajan, P. Compston, 2016 IEEE Sensors Applications Symposium (SAS), Catania, 1 (2016).
[11] D. Chen, L. Huo, H. Li, G. Song, Sensors **18**, 2586 (2018).
[12] W. Talataisong, R. Ismaeel, G. Brambilla, Sensors **18**, 461 (2018).
[13] H. Haroon, M. Bidin, H. A. Razak, P. S. Menon, N. Arsad, Z. F. M. Napiah, Proc. of 2011 IEEE Regional Symposium on Micro and Nano Electronics 380 (2011).
[14] J. J.-Sik Yoon, Advances in Condensed Matter Physics **2018**, Article ID 2426863 (2018).
[15] H. Haroon, H. A. Razak, N. N. A. Aziz, ARPN Journal of Engineering and Applied Sciences **11**(5), 3212 (2016).
[16] R. Suliman, A. F. Mitul, L. Mohammad, G. Djira, Y. Pan, Q. Qiao, Results in Physics **7**, 2232 (2017).
[17] N. Mohammadian, S. M. Ghoreishi, S. Hafeziyeh, S. Saeidi, D. Dionysiou, Nanomaterials **8**, 316 (2018).
[18] T. Revathi, R. Jeyalakshmi, N. P. Rajamane, J. Baskarasundararaj, International Journal of Chem. Tech. Research **11**(01), 13 (2018).
[19] J. Wang, C. Wang, W. Zhang, Appl. Sci. **8**, 1693 (2018).
[20] H. Hazura, F. Aliman, A. S. M. Zain, A. R. Hanim, F. Salehuddin, S. K. Idris, M. Z. Nor Syaimaa, Journal of Telecommunication, Electronic and Computer Engineering (JTEC) **10**(2-5), 125 (2018).

---

*Corresponding author: hazura@utem.edu.my