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Development of FBG Sensing System for Outdoor Temperature Environment

S. Daud[a,] *, M.A. Jalil[b], S. Najmee[c], Saktioto[d], J. Ali[e] and P.P. Yupapin[f]

[a, b ,c ,d, e] *Institute of Advanced Photonics Science, Nanotechnology Research Alliance,*
Universiti Teknologi Malaysia (UTM), 81310 Johor Bahru, Malaysia
[f] *Advanced Research Center for Photonics, Faculty of Science*
King Mongkut's Institute of TechnologyLadkrabang Bangkok 10520, Thailand

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Abstract

We have experimentally designed a practical pass-through type FBG temperature sensor. The objective of this study is to design and built a prototype outdoor fibre Bragg grating (FBG) temperature sensor system. Its performance is evaluated at different times of the day. In order to reduce the optical losses of the FBG system, the shortest optical fiber path used to connect the FBG system is 55.5m. It has a total connector loss 4.0dB and fibre loss of 0.3dB thus giving a total loss of the system as 4.3dB. The FBG sensor system is connected to the tunable laser source (TLS) and optical spectrum analyzer (OSA). The TLS is used to provide a broadband light source via a fibre optic cable of wavelength 1550nm. The OSA is used to display the transmission and reflection spectrum to give the Bragg wavelength λ_B, bandwidth and power dip. The output spectrum can be obtained through direct connection to the FBG. Result of transmission and reflection spectrum show the sensitivity which is calculated from the slope of the graph. The FBG temperature sensor system has an average sensitivity of 9.1 pm (°C)$^{-1}$ based on the transmission spectrum. It has an average sensitivity of 10.6 pm (°C)$^{\mathbf{-1}}$ based on the reflection spectrum.

***Keywords*:** Commercial fibre Bragg grating, transmission and reflection spectrum, outdoor system, sensitivity, Bragg wavelength.

1. Introduction

FBGs have been widely used as temperature, strain, or pressure sensors. The advantages of small size, light weight, electromagnetic immunity, and other benefits render these sensors extremely useful for implementation in civil and mechanical engineering. FBG sensors adopt light carrier and fibre-optic media, and the wavelength of reflected light from FBG changes with temperature and/or strain change [1-3]. Hill *et. al* developed fibre Bragg grating technology in 1978 [4]. FBG's are based on the principle of Bragg reflection [5]. Most of the present day fibre optic (FO) sensor heads that adopts fibre gratings use FBG's. The technology and applications of FBG's in

* Corresponding author. Tel.: +6075534077; fax: +6075566162.
E-mail address: suzairi_87@yahoo.com.

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temperature sensing have progressed rapidly over the last three decades [6]. The use of such a device for temperature sensor has been reported [7].

In practical engineering applications, temperature and strain changes correspond with the change of fibre grating center wavelength. Thus FBGs have a linear response with temperature and strain, and measurement errors can be accepted over small temperature range. When light propagates in fibre, the characteristic parameters of light wave including amplitude, phase, and polarization will change with external fields such as magnetic field, temperature and strain. As for the FBG, the center wavelength of reflected light is affected by temperature and strain applied onto the grating, which has been suggested and widely used as a sensing mechanism [8-10]. An FBG temperature sensor with a sensitivity of (16.5 ± 0.1) pm $(°C)^{-1}$ in the range of -60 °C to +150 °C at 1550.63 nm has been designed and developed by Ramesh *et. al* [11]. High birefringent (HiBi) FBG's for temperature sensing with sensitivity of (11.5 ± 0.1 pm $°C^{-1}$) have been reported [12]. Conventional hydrogen-loaded FBGs have a sensitivity of 0.0166 $nm(°C)^{-1}$ at low temperatures and 0.015 $nm(°C)^{-1}$ at temperature of 700 °C [13]. Temperature sensitivities of 0.009 $nm(°C)^{-1}$ at low temperature which changes to 0.0175 $nm(°C)^{-1}$ at temperatures of 1000 °C have also been reported [12]. In this paper, the objective is to design, develop and test the performance of an outdoor FBG temperature sensor system.

2. FBG Operating Principle

A light source that has a wideband spectrum is launched into the FBG sensor. Inside the FBG, the optical wave is partially reflected from one end grating. However, the optical waves that are partially reflected from each part constructively interfere with each other only for a specific wavelength at the Bragg wavelength. Hence, for a broadband source only a narrow spectrum at the Bragg wavelength is reflected. The other wavelength components are transmitted through the FBG. The Bragg wavelength is given by

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

where n_{eff} is the effective refractive index of the fibre core and Λ is the grating period. This equation forms the basis for any wavelength-modulated FBG sensors. FBG can be used as a strain or temperature sensor heads. Assuming an isothermal condition, the Bragg wavelength change, $\Delta\lambda_B$ upon strain and temperature changes can be expressed [8] as

$$\Delta\lambda_B = 2(\Lambda\frac{\partial n_{eff}}{\partial L} + n_{eff}\frac{\partial\Lambda}{\partial L})\Delta L + 2(\Lambda\frac{\partial n_{eff}}{\partial\lambda} + n_{eff}\frac{\partial\Lambda}{\partial\lambda})\Delta\lambda + 2(\Lambda\frac{\partial n_{eff}}{\partial T} + n_{eff}\frac{\partial\Lambda}{\partial T})\Delta T \tag{2}$$

where T is the temperature and L is the length of strain effect. According to Equation (2), the second term represents the temperature effect on an optical fibre. A shift in Bragg wavelength due to the thermal expansion, changes the grating spacing and changes the index of refraction. Omitting the first term which represents the strain effect, the Bragg wavelength change, $\Delta\lambda_B$ for temperature difference/variation, ΔT can be written as

$$\Delta\lambda_B = \lambda_B(\xi + \alpha)\Delta T \tag{3}$$

where $\alpha = \left(\frac{1}{\Lambda}\right)\left(\frac{\partial\Lambda}{\partial T}\right)$ is the thermal coefficient ($0.55 \times 10^{-6}\ {}^0C^{-1}$) and $\xi = \left(\frac{1}{n}\right)\left(\frac{\partial n}{\partial T}\right)$ represents the thermo-optic coefficient ($8.6 \times 10^{-6}\ {}^0C^{-1}$) for the germanium-doped silica core fibre[14].

3. Experiment

Figure 2 shows the experimental set-up for the outdoor temperature based on a commercial FBG.

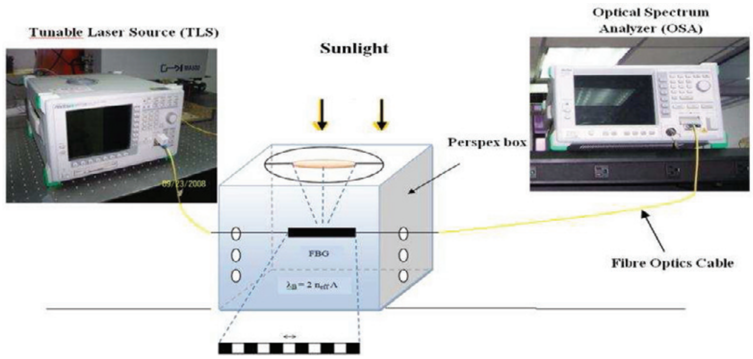

Figure 2: The experimental set-up for the transmission wavelength spectrum

The FBG sensor system is connected to a TLS and OSA. The TLS is used to provide the broadband light source via a 1550 nm FO cable. The OSA is used to display the transmission and reflection spectrum to obtain $\lambda_{B,}$ bandwidth and power dip. The transmission spectrum can be obtained through direct connection to the FBG as shown in Figure 2. The reflection spectrum is obtained by using a (2x2) 3-dB coupler. Initially, the transmission and reflection spectrum of the commercial FBG with center wavelength 1553.865 nm, bandwidth of 0.24 nm and 98% > Reflectivity > 97% is measured at room temperature of 23 °C. These readings are then benchmarked for the Bragg wavelength shift. The FBG system is then placed on the roof top of the Physics Building at C21, UTM. The effect of outdoor temperature variation (27 °C to 42 °C) on the FBG sensor is observed by monitoring the $\Delta\lambda_B$ via OSA.

4. Results and Discussion

During the designing and developmental stage for the FBG temperature sensor system, it is necessary to determine the shortest length of SMF-28 fibre in order to minimize optical losses. The shortest FO path used to connect the FBG system is 55.5 m with a total loss of 4.3 dB. The commercial FBG sensor head supplied by QPS Photonics Inc, Canada has its Bragg wavelength centered at 1553.865 nm. The measured center wavelength is 1552.805 nm. Figures 3 and 4 shows the reflection and transmission spectra obtained due to the effect of outdoor temperature. The Bragg wavelength shift with external temperature is clearly observed for both the transmission and reflection spectrum. This is due to the perturbations of the gratings resulting in a shift in the Bragg wavelength in either the transmitted or reflected spectra. As the outdoor temperature changes due to environmental conditions, thermal expansion in the grating occurs. Due to this thermal expansion, the FBG refractive index changes. This causes a variation in the FBG wavelength. The variation in $\Delta\lambda_B$ is monitored through the transmission or reflection spectrum from the OSA. The reflection method offers some advantages over the transmission method. In reflection, only the light that matches the Bragg condition of the grating is measured over relatively small background intensity. Figure 5 and 6 shows the Bragg wavelength shift $\Delta\lambda_B$ versus outdoor temperature obtained from both the transmission and reflection spectra. Results show the linearity of the FBG sensing system. There is a good correlation between temperature changes and Bragg wavelength shift obtained from the experimental set-ups. A linear response has been observed between temperature changes and Bragg wavelength shift throughout the measured region. The slope of $\Delta\lambda_B$ versus T gives the FBG sensor sensitivity. The FBG temperature sensor system has an average sensitivity of 9.14 pm $(°C)^{-1}$ and 10.58 pm $(°C)^{-1}$ respectively based on the transmission and reflection spectra. Theoretically, the change in Bragg wavelength $\Delta\lambda_B$ for a given wavelength 1552.805 nm due to change in temperature, ΔT is calculated using Equation (3) which gives a sensitivity of 13.2 pm $(°C)^{-1}$. It can be seen that there is a good agreement between the experimental results, the theoretical calculation and the typical temperature sensitivity [15].

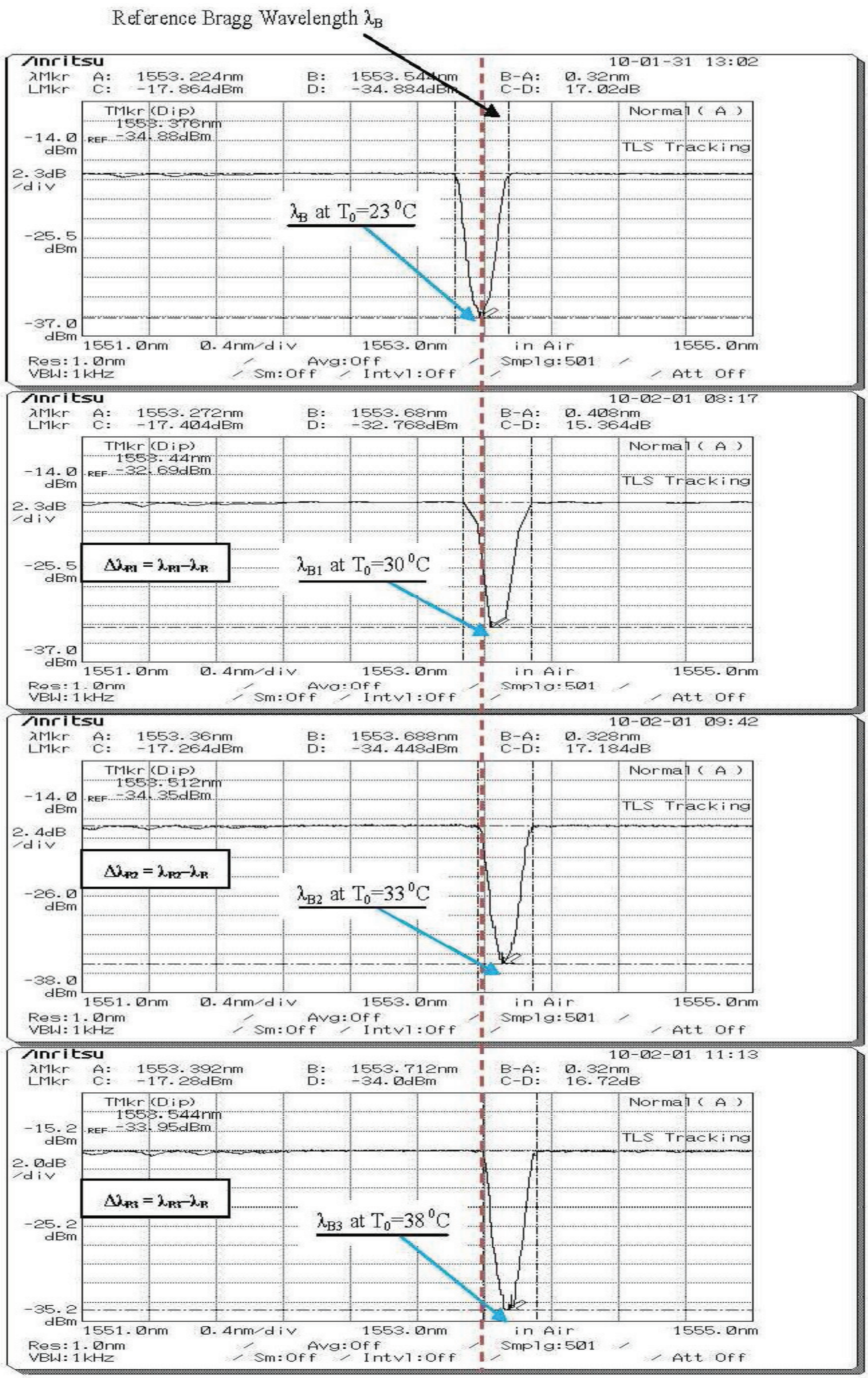

Fig 3: FBG Transmission Spectra

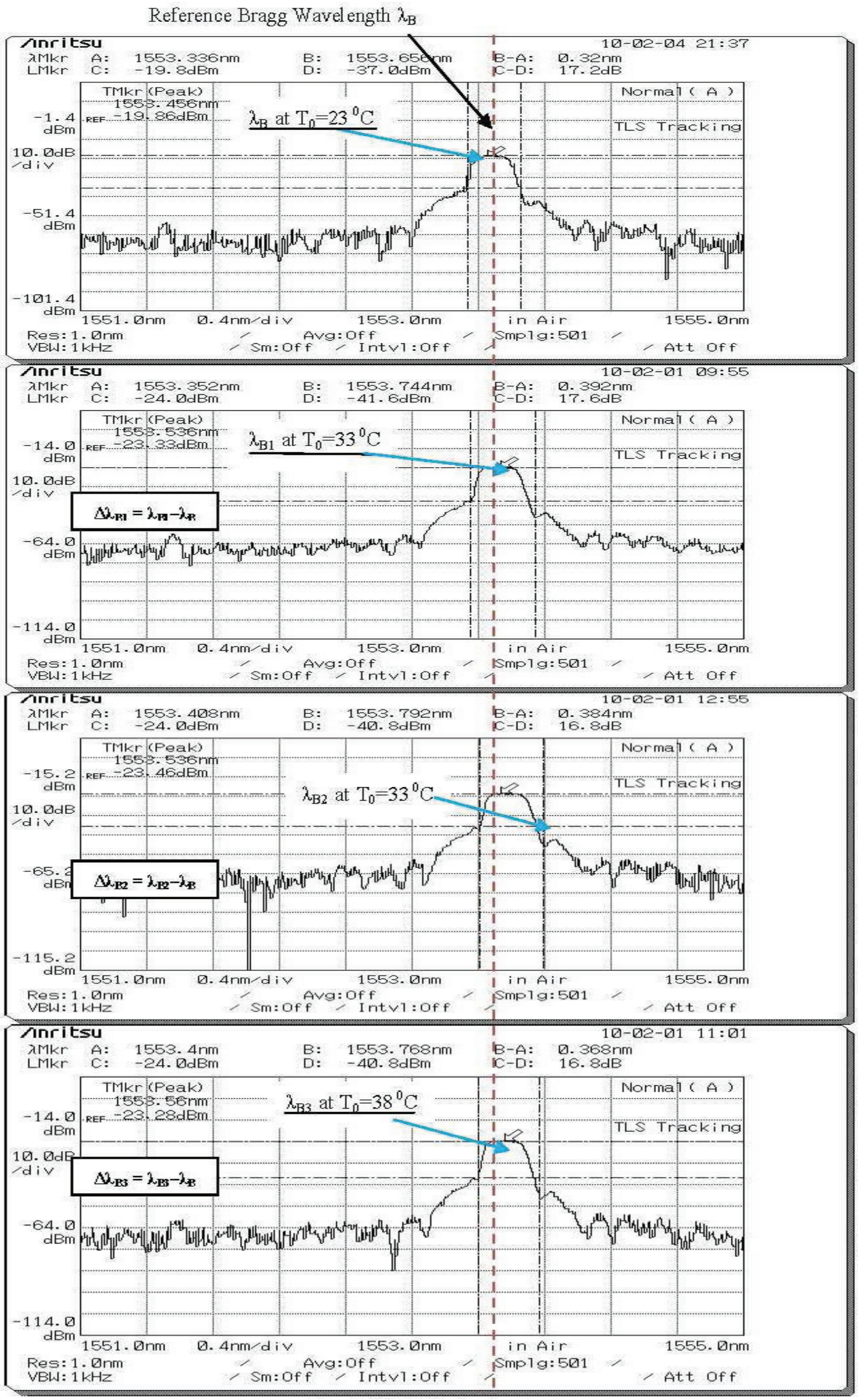

Fig 4: FBG Reflection Spectra

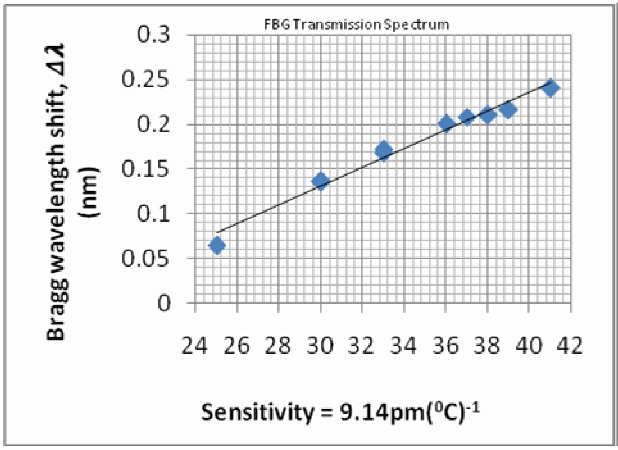

Fig 5: Transmission spectrum

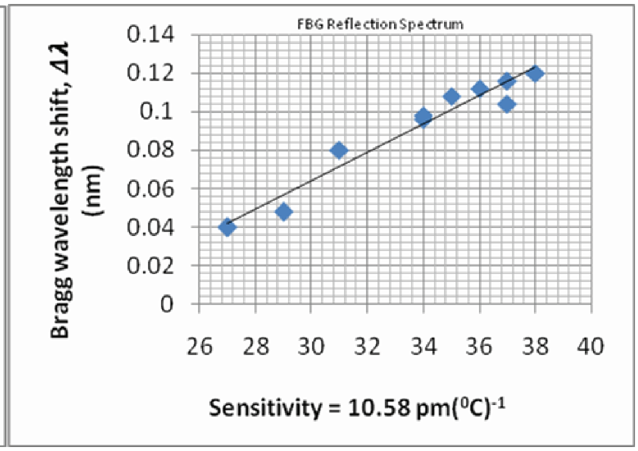

Fig 6: Reflection spectrum

5. Conclusion

An outdoor temperature sensor system using a commercial FBG has been designed, developed and its performance has been tested. The specifications or characteristics of the FBG temperature system is summarized in Table 1.

Table 1: Specifications of the tested FBG temperature sensing system

No	Characteristics		
1	SMF-28 FO length		(55.5 ± 0.1) m
2	Total Fibre Loss Connector loss Fibre Loss		(4.3 ± 0.1) dB (4.0 ± 0.1) dB (0.3 ± 0.1) dB
3	FBG sensor length		(3.0 ± 0.1) cm
4	Bragg wavelength λ_B (Manufacturer QPS Photonics Inc, Canada)		1553.865 nm
5	Bragg wavelength λ_B (Measured)		1552.805 nm
6	Bandwidth		0.24 nm
7	Reflectivity		98% > R > 97%
8	Average sensitivity		
	Mode	Reflection Spectrum	10.58pm(°C)$^{-1}$ ±0.02 %
		Transmission Spectrum	*9.14 pm(°C)$^{-1}$ ± 0.02%*
9	λ_B versus T : Linear Response		OSA uncertainty error 0.02% from manufacturer.

An excellent linear response has been observed between the temperature changes and $\Delta\lambda_B$ throughout the variable outdoor temperature from 27 °C to 42 °C. Thus with this capability of linear response, the FBG sensor can be used for outdoor temperature sensing.

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