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Selected paper

The Applications of FBG sensor for Real-time Strain Mapping of Thin Composite Plate under Point Loading

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FBG sensor technology has shown as great potential for structural health monitoring applications in recent decades. The integration of this optical sensor into composite structures accelerates the development of robust smart structures. This paper presents the use of embedded FBG sensor to view the real-time strain mapping of a thin composite under a point loading. The FBG interrogation system implements the match-filter method to convert wavelength variations into strain reading. In was found that, the FBG sensor system was very sensitive for different loading variations and able to update the strain value in real-time. At the end of this research, a prototype of online strain mapping system for thin composite plate, utilizing an embedded FBG sensor, has been built.

Keywords: FBG sensor; smart structures; structural health monitoring.

1. Introduction

Composite structures are often use by engineers to design modern structures, due to its high strength to weight ratio. However, composite structures generally have a very high probability of unexpected damage development during service. The damage formation must be monitored from the beginning before it heads towards structural failure which could result in substantial damage. The incorporation of composites into the critical application such as in aeronautics, outer-space exploration, building structures and wind turbines, ring a bell to the importance of a failure monitoring system. Therefore the introduction of structural health monitoring (SHM) is crucial to avoid the unforeseen event.

The assimilation of SHM systems in composite structures offers an ability to give the real time information of it circumstances under critical loading applications. It shows promising results especially with the integration of existing technology into SHM systems such as ultrasonic evaluation, Acoustic Emission method and Fiber Bragg Gratings (FBG) sensor. The integration of SHM into composite structures, also lead to the development of smart composite structures [1, 2]. Smart structures can be described as a concept a structure that can adapt in any changing surroundings. A smart structure can automatically 'order' a form of response; whether in the form of physical or chemical reaction, to ensure that it can survive in any situation without causing a major disaster to the components or the users.

FBG sensors have been used for SHM of fiber reinforced polymer composites efficiently for more than two decades [3]. The current advancement of the FBG sensor technologies offers chance for the implementation of sophisticated in-situ and robust SHM systems. This can be seen with the growing numbers of research efforts on health monitoring of composite structures using FBG sensors [4 – 8]. The ability to be integrated in between different layers of the composite structures, without significantly affects the mechanical properties is one of a great superiority of this optical sensor. This capability is difficult be

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achieved by conventional transducer such as piezoelectric and strain gauge. Moreover, the attractive properties such as immunity to electromagnetic fields; lightweight; low power attenuation over long distance transmission; high temperature sensing; survive in environmentally unfavorable conditions and multiplexing ability; are the other advantages of FBG sensors compared to the conventional transducer [9]. Besides, a single FBG sensor can provides the measurement of multiple parameters such as load/strain, vibration, and temperature [10].

There are a several researchers has done work on strain monitoring system based on FBG [13 – 15]. However, the research and development of a working prototype that is robust and low cost; is still ongoing. This is due to many grey area need to be explored such as a mathematical model for strain extrapolation; if minimum sensor is to be used. Therefore this present study utilized the good capability of FBG sensor to work as a sensitive strain sensor, to replace the conventional strain gauge. The aim of this research work is to create a real-time monitoring of composite structures under any loading conditions, therefore providing early warning of dangerous situation. At the end of the study, a full instrumentation system consists of FBG dynamic system, signal processing software and display has been developed. This system is robust and compact.

2. Notation

The notation used throughout the paper is stated below.

Symbol:

λ_B	Bragg wavelength
n	Effective refractive index of fibre core
Λ	Grating period
ε	Applied strain
C_s	Coefficient of strain
C_T	Coefficient of temperature

3. Principle of operation

The FBG sensors are fabricated in the core region of specially fabricated single mode low-loss germanium doped silicate optical fibers. The grating is the laser-inscribed region which has a periodically varying refractive index. This region reflects only a narrow band of light corresponding to the Bragg wavelength λ_B, which is related to the grating period Λ,

$$\lambda_B = 2n\Lambda \tag{1}$$

Where n is the effective refractive index of the grating. Any physical variable that can affect either the refractive index or the grating period can be measured using an FBG. In strain measurement the refractive index can be fixed, therefore leave the grating period to have linear relation with the strain. As consequence, the change in the measurand will corresponds to a change in the reflected wavelength (Bragg wavelength). The shift in the Bragg wavelength is positive when the FBG expands. Conversely, the Bragg wavelength shifts to negative when the FBG contracts. Any quantity that related to strain such as temperature, vibration and pressure, also can be measured. The relative change in the Bragg wavelength can be approximated as [12],

$$\frac{\Delta\lambda_B}{\lambda_B} = C_s\varepsilon + C_T\Delta T \qquad (2)$$

where C_s is the coefficient of strain, ε, C_T is the coefficient of temperature and ΔT is the change in temperature. The effect of temperature in the equation can be ignored since the strain has much greater value.

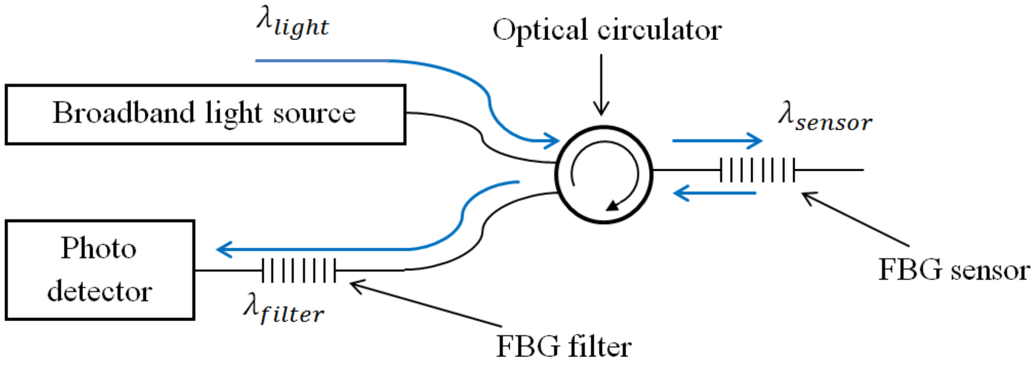
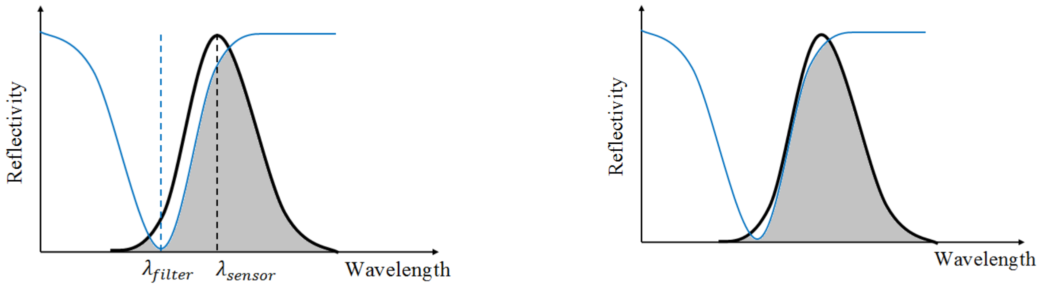


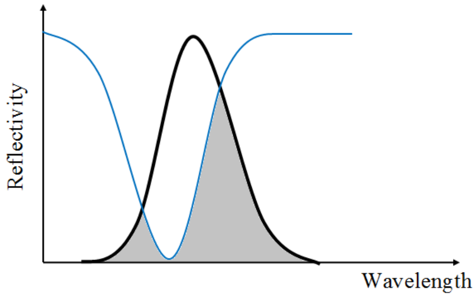
Figure 1: Schematic diagram of the optical components arrangement for the matched FBG filter system.

To perform as a strain sensor, the FBG sensor system in this work utilized the match-filters FBG sensors system. The arrangement of the system can be shown as in Figure 1. According to Figure 1, the light source will supply a broadband light in the range of 1500 nm – 1600 nm. The three ports optical circulator will direct the light into FBG sensor; which is placed onto physical measurand. The reflected light from the sensor; with a specific band, 1550 nm, will be directed by the circulator to go through the FBG filter.



(a) At strain free

(b) FBG sensor in tension



(c) FBG sensor in compression

Figure 2: The resultant of optical signals after passing through an FBG filter.

Consider a clamp-clamp position of thin composite sample with an embedded FBG, connecting to FBG system as shown in Figure 1; and having a point force in the center of the plate. The FBG sensor will experience the stretching or compression due to the bending of the sample, depending on the location of the sensor. Meanwhile, the FBG filter is let to be secured and without any strain. The resultant optical signal, at strain-free, which is observed at the end of FBG filter, can be illustrated by the shaded area in Figure 2(a). Meanwhile Figures 2(b) and 2(c) show how the overlapped area increase or decrease due to strain variations. Consequently, there will be a variation to the optical signal before reaching the photodiodes (PD), thus causing a significant change to the output current of the PD. A photodiode or photo detector (PD) is the important components in the optical receiver part. A PD absorbs the photons from the incoming light signal and converts it into electrical signals.

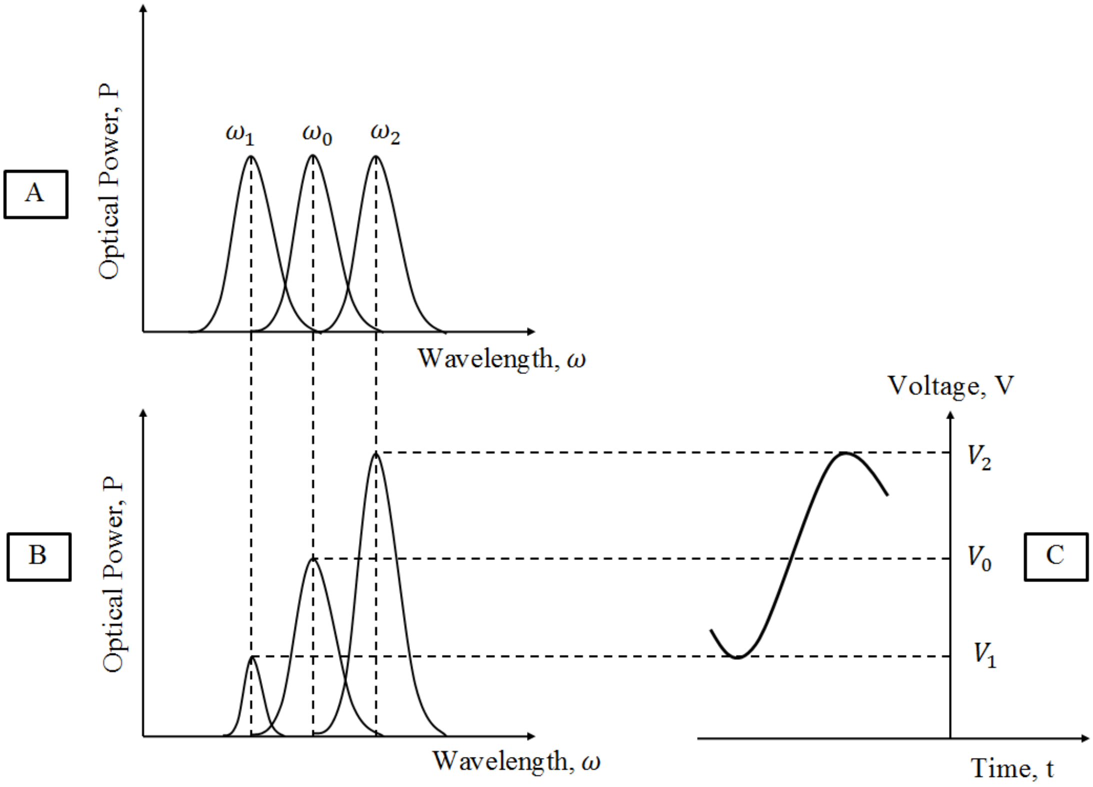


Figure 3: Demodulation of the NIR-FBG spectral shift for the fixed NIR-FBG filter system.

Figure 3 illustrates the demodulation of the NIR-FBG spectral shift due to the bending (or compression) of the composite sample. The spectral shifts of the NIR-FBG sensor, labeled as A in the Figure 10, will cause optical power variations (labeled as B) as the optical signal passes through the NIR-FBG filter. Consequently, this will cause the changes in the voltage reading (labeled as C) if viewed from the signal viewer.

4. Experimentation

In order to demonstrate the application of FBG sensors for real-time strain mapping, an experiment was prepared. A 300 mm x 150 mm sample of woven Gl/epoxy resin laminates (8 layers) was fabricated by hand lay-up method, as shown in Figure 4. A 1550 nm FBG sensor was embedded during the lay-up and was placed between the 7th and 8th layer of the laminates. The most outer layer was chosen, to ensure the FBG sensor get the maximum strain during loading, thus increase the sensitivity.

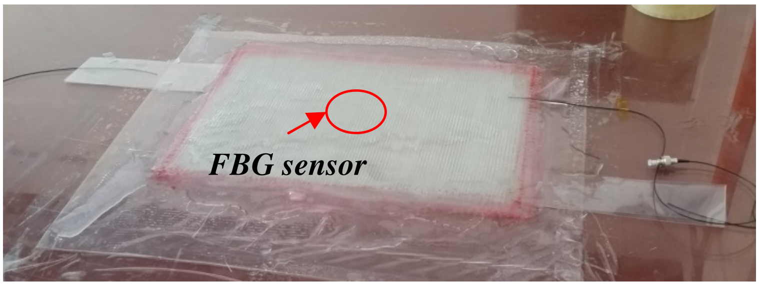


Figure 4: Composite sample was cured for 24 hours in room temperature, and atmospheric pressure.

The FBG sensor system was set up as the arrangement in Figure 1. The broadband light source supplies a continuous light source with power 20mW. Both FBGs; the sensor and the filter, have the reflectivity of 99.9%. This is to ensure the FBG sensor can reflect most light at 1550nm wavelength. The conversation of the wavelength shift into optical power variation was explained in previous section.

The PD is connected to analog input National Instrument DAQ, NI 9234 for data acquisition. MATLAB software was used as the virtual instrumentation tool. The optical circulator and FBG filter were secured in special boxes to eliminate the risk for fiber damage. The light source, optical circulator, FBG filter and photodiodes were arranged in one system, as shown in Figure 5.

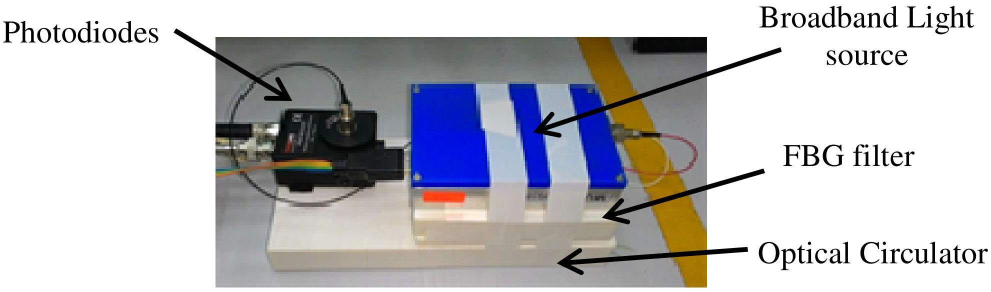
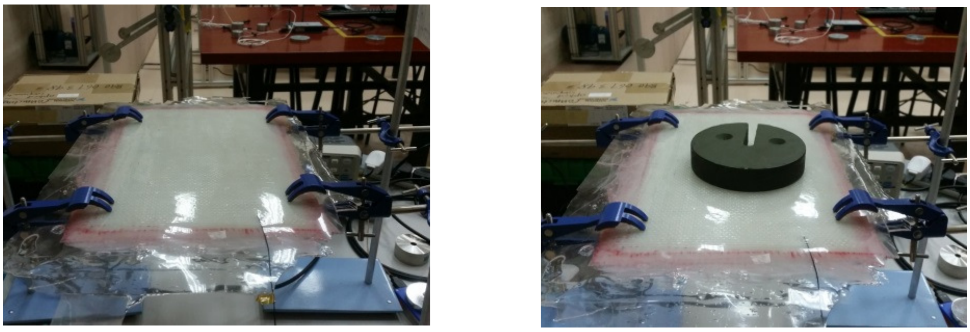


Figure 5: The arrangement of the optical components.

To illustrate the effectiveness of the system, a MATLAB program was written to create a friendly graphical user interface (GUI) to display the real-time strain mapping of the composite sample, under a specific load. The artificial sample in the MATLAB was created with 10 x 10 elements; with four fixed locations. The strain distribution was predicted based on the voltage reading from a single FBG sensor which located in the middle of the plate. In order to calculate the approximate strain throughout the plate, quadratic extrapolation algorithm was used.



(a) (b)

Figure 6: Composite sample (a) without loading; (b) and with 2 kg load.

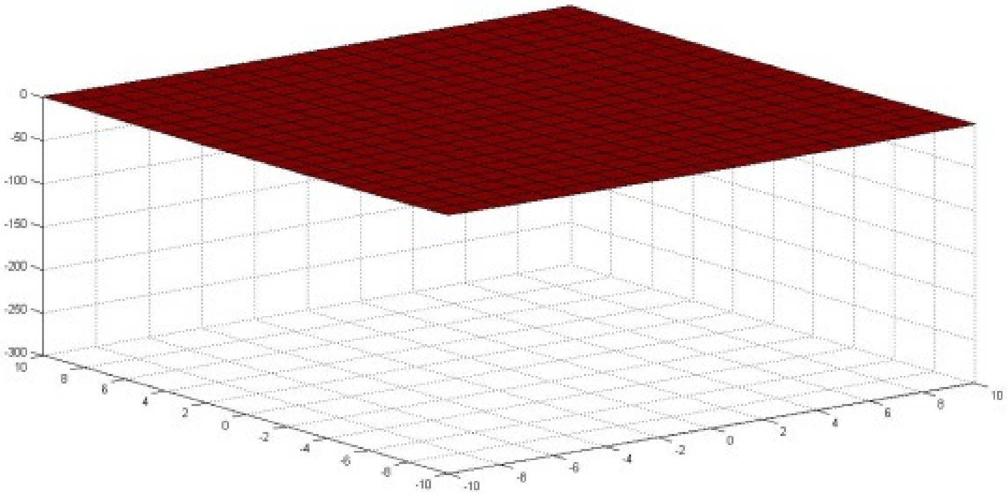


Figure 7: Illustration from MATLAB GUI for unload sample.

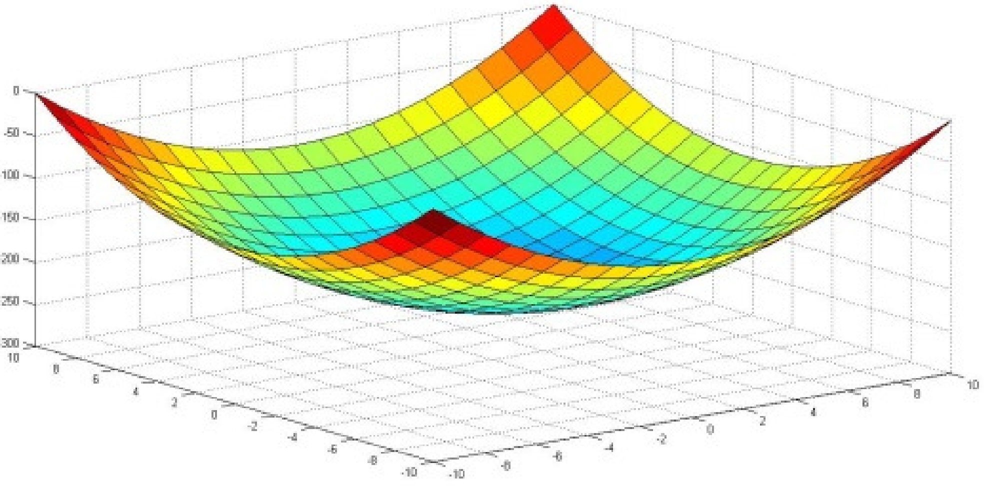


Figure 8: Illustration from MATLAB GUI for loaded sample as in Figure 5(b).

The composite sample prior to the loading can be shown by the Figure 6a; and the corresponding illustration from GUI can be seen in Figure 7. Meanwhile, Figure 6b shows a 2 kg load was applied in the mid of the sample. The mapping illustration due to the loading can be shown in Figure 8.

5. Conclusion

This study successfully presents the application of embedded FBG sensors for SHM of composite laminates. The embedded sensors can be used for static analysis and dynamic response measurement. The result offers the possibility of having the smart structures that can be utilized in many engineering applications such as, aircraft, automotive, infrastructures and etc.

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