

Dependence of dynamic range, linearity and sensitivity of fiber Bragg grating system on bonded sensor length

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This study aims to explain the effect of sensor length on dynamic range, linearity and sensitivity of fiber Bragg grating system. The sensing principle is based on tracking of Bragg wavelength shifts caused by the changes in loading condition. A simple experimental setup was utilized in which fiber grating was bonded on a Zinc plate using araldite as an epoxy on both sides of grating and an Optical Spectrum Analyzer to monitor the values of wavelength shift corresponding to the changing applying load. The dynamic range, linearity and sensitivity of fiber Bragg grating system in terms of wavelength shift and longitudinal strain are discussed. From the results, it is inferred that if the sensor length is smaller, then Bragg wavelength shift, longitudinal strain and dynamic range are larger and vice versa. It means that the fiber Bragg grating system is more sensitive to smaller sensor lengths and less sensitive to larger sensor lengths. A linear response has been observed between longitudinal strain and Bragg wavelength shift throughout the measured region.

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1. Introduction

Since the discovery of photosensitivity in germanium doped optical fibers which led to the formation of the first fiber grating by Hill *et al* [1] and the subsequent improvements in fabrication techniques by Meltz *et al* [2], there has been a significant increase in interest in the use of fiber Bragg gratings. Fiber Bragg gratings have a periodically altered refractive index to filter certain wavelengths while allowing others to pass. In an optical fiber Bragg grating the Bragg grating exists in the optical fiber and reflects a very narrow bandwidth of light that is centered at the Bragg wavelength in the transmission spectrum. Standard fiber Bragg gratings have periodic modulations in the refractive index of the fiber. Fiber Bragg grating sensors are used to measure various parameters which introduce a change in reflection wavelength of the fiber Bragg grating.

Recently, a strong demand on developing high performance structures, which are able to monitor the physical and mechanical properties such as temperature and strain during service condition, is appreciated as a "Smart structural health monitoring system" [3]. Fiber Bragg grating sensor has been recognized as a new non-destructive evaluation (NDE) technique to suit this purpose for all structural applications [4] and [5]. The tendency to use fiber Bragg grating sensor for strain sensing application is due to the ability of this sensor to measure strain locally with high resolution and accuracy. As the physical size of an optical fiber is extremely small compared with other strain measuring components, it enables to be embedded into structures for determining the strain distribution without influencing the mechanical properties of the host materials [6].

In this study, the dependence of dynamic range, linearity and sensitivity of fiber Bragg grating system on sensor length i.e. distance between two epoxy positions

has been demonstrated. Following the introduction, the operating principle, experimental setups, results and discussion are provided in this article.

2. Operating principle

Fiber Bragg gratings operate by acting as a wavelength-dependent filter/reflector formed by introducing a periodic refractive index structure within the core of an optical fiber. Whenever a broad-spectrum light beam impinges on the grating, will have a portion of its energy transmitted through, and another reflected off as depicted in Fig. 1.

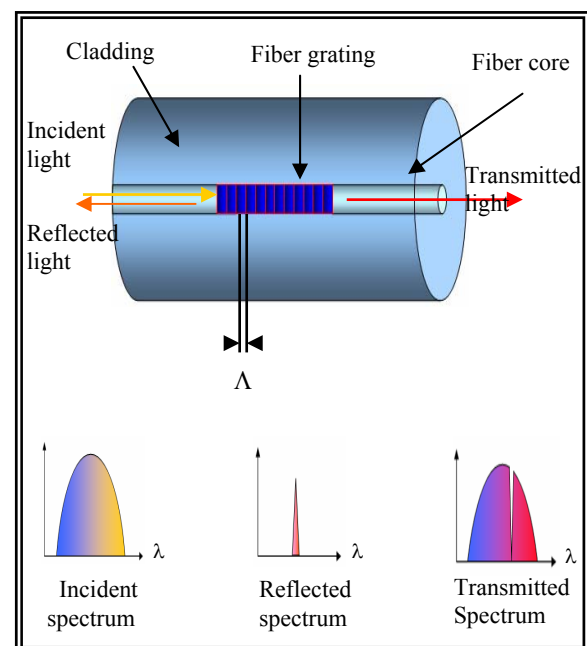


Fig. 1. Functional principle of FBG.

The basic principle of a FBG-based sensor system lies in the monitoring of the wavelength shift of the returned Bragg-signal, as a function of the measurand. The reflected light signal will be very narrow and will be centered at the Bragg wavelength which corresponds to twice the periodic unit spacing Λ . Any change in the modal index or grating pitch of the fiber caused by strain or temperature will result in a Bragg wavelength shift. There are several ways in which fiber Bragg gratings (FBGs) function. An optical fiber Bragg grating operates as a sensor when change in a particular environmental variable like pressure, temperature, or stress are correlated with the shifts in reflected wavelength of the FBG. Some examples of standard fiber Bragg gratings specifications include a center wavelength of 650 nm – 1620 nm, 90% reflectivity, bandwidth 0.2 nm, and fiber length 1.5 meters.

3. Experimental work

In this work, the FBG system is comprised of Tunable Laser Source (TLS), coupler, matching sleeve box, optical spectrum analyzer (OSA) and optical fiber with prewritten gratings. For the strain monitoring purpose, load is directly transferred from host material to fiber core of the grating region by the action of strain [7]. This causes the length of the grating region to be changed and the resultant refractive index of the core section to vary accordingly. The mechanical properties of the structure are simply determined by measuring the reflected wavelength change from the system.

Experimental setup A for sensor length ~ 10 cm

A schematic experimental arrangement to measure the wavelength shift for sensor length ~10 cm is shown in Fig. 2. Fiber Bragg grating was bonded onto the material i.e. Zinc plate carefully using araldite as an epoxy. The two epoxies were made on either sides of grating. The distance between the two epoxies i.e. sensor length was 10 cm.

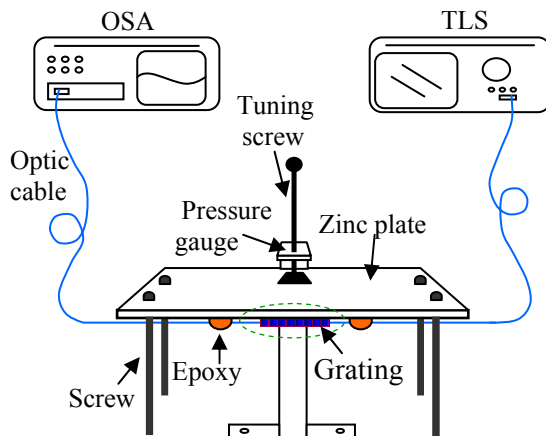


Fig. 2. A schematic of experiment setup to strain the zinc plate for sensor length ~10 cm.

The pressure gauge comprised of the tuning screw which was supported by a steel plate at the bottom. The fiber Bragg grating bonded material (Zinc plate) was supported by two screws at the end of the both sides of Zinc plate. With the use of optical table, the Zinc plate can remain straight and tightly fixed after application of the load. Once the components and equipments were ready to be used, Tunable Laser Source and Optical Spectrum Analyzer were preset. The light from Tunable laser source was launched into the optical spectrum analyzer through fiber Bragg grating. The tuning screw was turned to apply the load, followed by pushing the single sweep button from OSA. The elongation in the grating was produced by turning the screw gauge. The wavelength shift in the transmission spectrum was monitored against each gradually increasing value of load on the screen of Optical Spectrum Analyzer.

Experimental setup B for sensor length ~ 15 cm

A schematic experimental arrangement to measure the wavelength shift for sensor length ~ 15 cm is shown in Fig. 3. In experimental setup B all the experimental procedure is same as in experimental setup A except change of sensor length i.e. 15 cm.

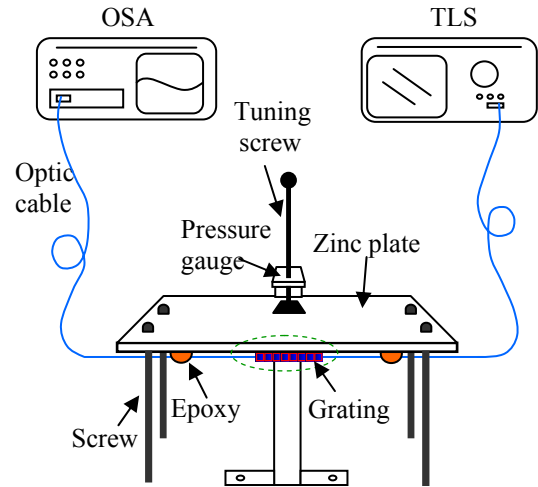
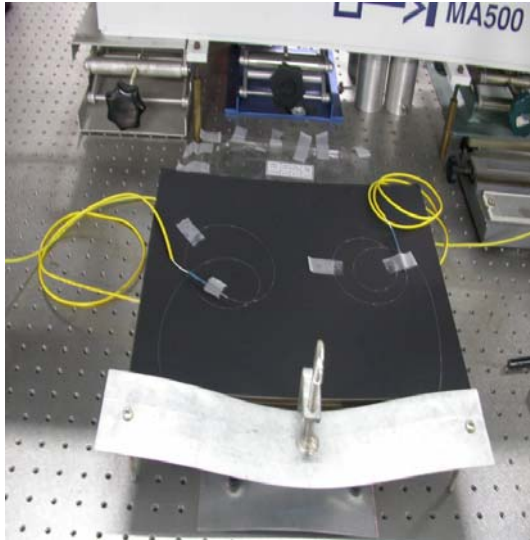


Fig. 3. A schematic of experiment setup to strain the zinc plate for sensor length ~15 cm.

The strain response arises due to both the physical elongation of the sensor (and corresponding fractional change in grating pitch) and the change in the refractive index due to photoelastic effects. Some photographs of experimental setup as shown in Fig. 4(a), 4(b). These include monitoring of wavelength shift from optical spectrum analyzer and close observation of applying load through screw gauge on the FBG bonded Zinc plate.



4 (a) Monitoring of wavelength shift (OSA)



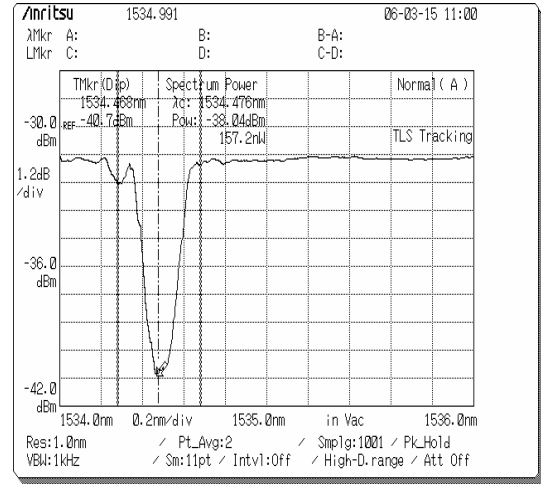
4 (b) FBG bonded and loaded zinc plate

Fig. 4. a, b. Photograph of experimental setup.

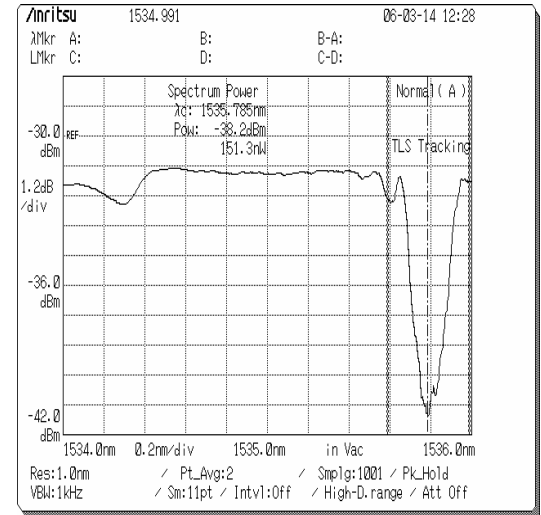
4. Results and discussion

4.1 Dynamic range of FBG sensor

For the experimental setup A, the Bragg wavelength λ_B and Bragg wavelength shift $\Delta\lambda_B$, were obtained using Optical Spectrum Analyzer after the FBG was strained during the load application by turning the screw gauge on the Zinc plate. The corresponding transmission spectra (first & last only) obtained from OSA show the tracking of Bragg wavelength shifts due to the changes in loading conditions with sensor length ~ 10 cm are shown in Fig. 5.



Bragg wavelength = 1534.468 (nm)



Bragg wavelength = 1535.785 (nm)

Fig. 5. Transmission spectra for sensor length ~ 10 cm.

The operating principle is that the grating reflects different wavelength component of the signal for different section along the grating. It is also clear from the transmission display that the values of Bragg wavelength and hence the Bragg wavelength shift are gradually increased by increasing the applied load. If the applied load is uniform, then the Bragg wavelength shifts occur without modification of the initial spectrum shape.

The longitudinal strain for the experimental setup A was calculated against each value of Bragg wavelength shift using the following equation:

$$\varepsilon = \frac{\Delta\lambda_B}{\lambda_B (1 - \rho_\alpha)} \quad (1)$$

where p_e is an effective strain-optic constant defined as $p_e = n^2/2 [p_{12} - \nu (p_{11} + p_{12})]$

where p_{11} and p_{12} are components of the strain optic tensor, n is the index of the core, and ν is the Poisson's ratio. For a typical optical fiber $p_{11} = 0.113$, $p_{12} = 0.252$, $\nu = 0.16$ and $n = 1.482$. The Bragg wavelength λ_B is 1534.991 nm.

The dynamic range is calculated in terms of longitudinal strain and wavelength shift under variable

load conditions and at a constant temperature of 25 °C. It is ranging from 0 to 1.317 nm in the Bragg wavelength shift as a function of longitudinal strain ranging from 0 to 1100.356 $\mu\epsilon$ for a 1534.991 nm grating with a sensor length ~ 10 cm

For the experimental setup B, the Bragg wavelength λ_B and Bragg wavelength shift $\Delta\lambda_B$, were obtained using Optical Spectrum Analyzer after the FBG was strained during the load application by turning the screw gauge on the Zinc plate. The corresponding transmission spectra (first & last) obtained from Optical Spectrum Analyzer to show the tracking of Bragg wavelength shifts due to the changes in loading conditions with sensor length ~ 15 cm are shown in Fig. 6.

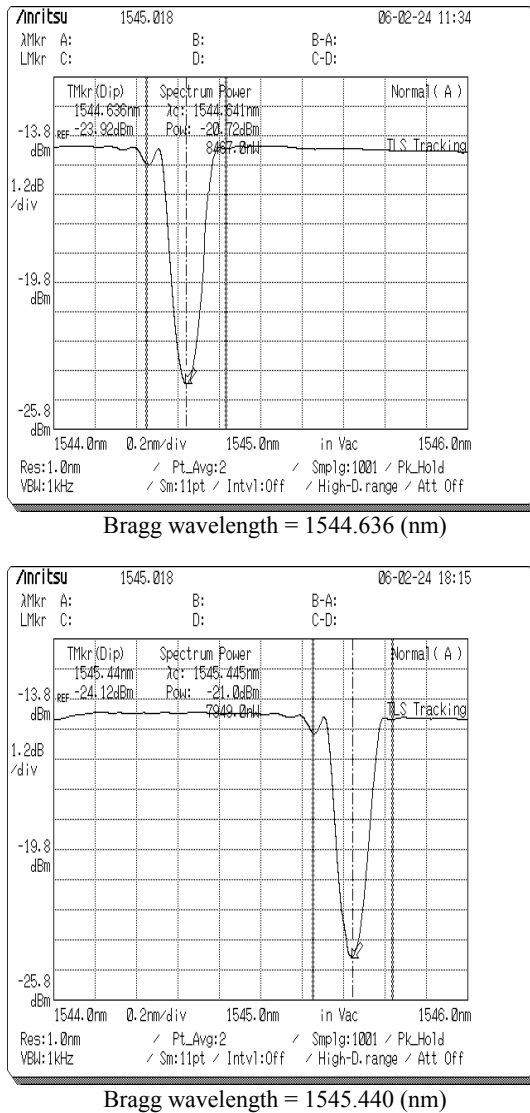


Fig. 6. Transmission spectra for sensor length ~ 15 cm.

The longitudinal strain for the experimental setup B was calculated against each value of Bragg wavelength shift using equation 7. In this case the Bragg wavelength λ_B is 1545.018 nm. The dynamic range is calculated in terms of longitudinal strain and wavelength shift under variable load conditions and at a constant temperature of

25 °C. It is ranging from 0 to 0.874 nm in the Bragg wavelength shift as a function of longitudinal strain ranging from 0 to 725 $\mu\epsilon$ for a 1545.018 nm grating with a sensor length ~ 15 cm. From the calculations obtained from experimental setup A and B, it is clear that the dynamic range for longitudinal strain and wavelength shift have larger values for smaller sensor length i.e. 10 cm and vice versa.

4.2 Linearity of FBG sensor

The longitudinal strain, ϵ that is obtained from the calculation above is increasing linearly corresponding to the increasing value of Bragg wavelength shift. It is observed that the Bragg wavelength has shifted through with negligible proportions, in length elongation of fiber grating. Therefore, the plots for experimental setup A and B between longitudinal strain and the Bragg wavelength shift can be drawn as a straight line and are shown in Fig. 7(a) and 7(b) respectively.

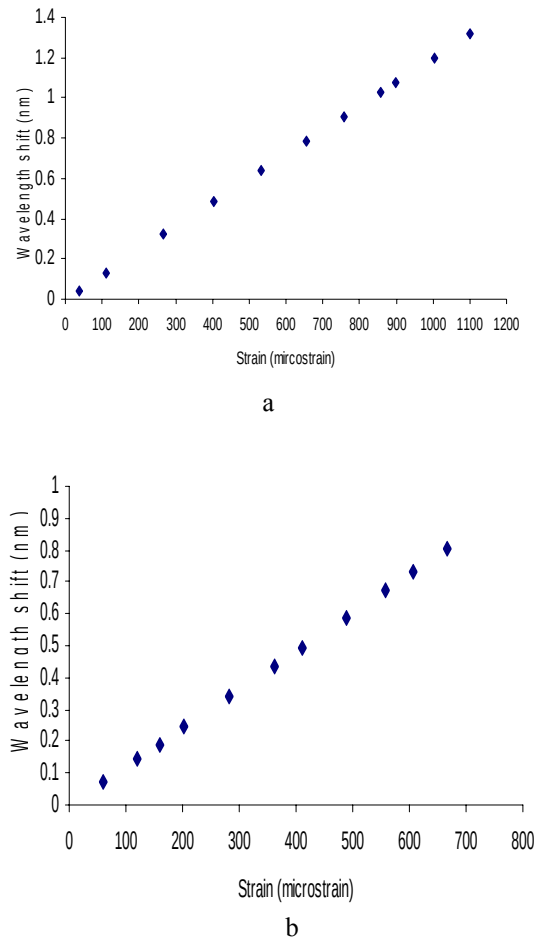


Fig. 7 (a), 7(b). Longitudinal strain versus Bragg wavelength shift for experimental setup A and B, respectively.

The Fig. 7(a) shows the plotting of results obtained under variable load conditions having a shift ranging from 0 nm to 1.317 nm in the Bragg grating wavelength as a

function of longitudinal strain ranging from 0 to 1100.356 $\mu\epsilon$ at a constant temperature of 25 °C for a 1534.991 nm grating with a sensor length $\sim$ 10 cm.

The Fig. 7(b) above shows the plotting of the results obtained under variable load conditions having a shift ranging from 0 nm to 0.874 nm in the Bragg grating wavelength as a function of longitudinal strain ranging from 0 to 725 $\mu\epsilon$ at a constant temperature of 25 °C for a 1545.018 nm grating with a sensor length $\sim$ 15 cm. The comparison plot for experimental setup A & B between longitudinal strain and wavelength shift can also be drawn and shown in Fig. 8.

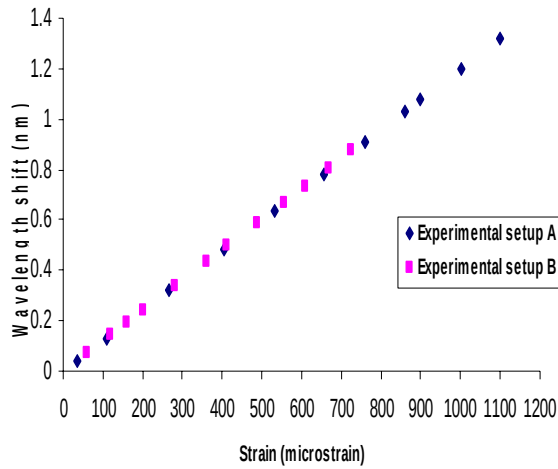


Fig. 8. Longitudinal strain verses Bragg wavelength shift.

The figure above shows the linearity of the fiber Bragg grating system. There is an excellent agreement between longitudinal strain and Bragg wavelength shift obtained from two experimental setups. A linear response has been observed between longitudinal strain and Bragg wavelength shift throughout the measured region.

4.3. Sensitivity of FBG sensor

According to the results, it is shown that the Bragg wavelength shift and longitudinal strain vary with sensor length under the same loading and temperature. If the sensor length is smaller, then the shift in the Bragg wavelength and longitudinal strain are larger and vice versa. It means that the fiber Bragg grating system is more sensitive for smaller sensor length i.e. 10 cm and less sensitive for larger sensor length i.e. 15 cm. In Fig. 9, the longer columns show larger values of Bragg wavelength shift or, in other words, more sensitivity of the fiber Bragg grating system and shorter columns show smaller values of Bragg wavelength shift or, in other words, less sensitivity of the fiber Bragg grating system.

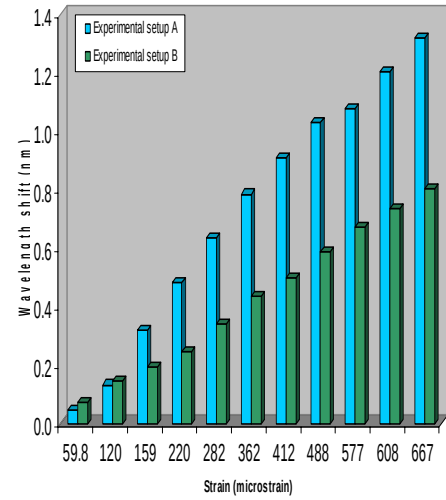


Fig. 9. Longitudinal strain versus Bragg wavelength shift.

The results show that there is a correlation between theoretical and experimental data for the sensitivity of the fiber Bragg grating system. Results of transmission spectrum and reflectivity of light in fiber Bragg grating system have been found to have a relationship with Bragg wavelength when monitoring the strain effect and applying temperature on an optical fiber Bragg grating. This corresponds to the change in the grating spacing and the refractive index of a fiber. Therefore, a shift in the Bragg wavelength is remarkable. The good linear relationship between longitudinal strain and Bragg wavelength shows the potential of using device (FBG) sensing applications for bridges, buildings, water tanks, load monitoring etc.

5. Conclusions

A simple fiber Bragg grating sensing system to observe the effect of sensor length on the dynamic range, linearity and sensitivity in terms of Bragg wavelength shift and longitudinal strain has been demonstrated. The proposed technique is based on the use of fiber Bragg grating for sensing and the whole system is able to maintain the low cost and high commercialization. The potential applications for this fiber Bragg grating sensing system include long term structural health monitoring, short term condition assessment of structure and seismic vibration response structures. From the results, it is concluded that if the sensor length is smaller, then Bragg wavelength shift, longitudinal strain and dynamic range are larger and vice versa. It means that the fiber Bragg grating system is more sensitive to smaller sensor lengths and less sensitive to larger sensor lengths. A linear response between longitudinal strain and Bragg wavelength shift has been observed throughout the measured region. Having a capability of linear response, the fiber Bragg grating sensor can also be used for optical sensing as a high temperature sensor, fire alarm sensor, vibration sensor, and pressure sensor.

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