Investigation on fiber optic sensor using FBG for various temperature and liquid density

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Abstract. There are several issues that present in conventional sensor including its accuracy, safety, durability and RF effect. These issues could be minimized with the implementation of fiber optic sensor. This project is to design and implement optical sensor using FBG for various temperature and liquid density sensing. The FBG sensor was submerged in liquid substances to determine the sensing conditions. The available pigtail was connected to the circulator, 1550nm laser source and optical spectrum analyzer (OSA). The data regarding temperature and density sensing captured from OSA were observed and analyzed. It is found that the relationship between the change in temperature and the change in wavelength is virtually linear in both environments making FBG a good candidate for sensing temperature.

1. Introduction

Few years back, the ability of fiber optic sensors (FOS) has been improved to substitute conventional sensors for acoustics, vibration, electric and magnetic field measurement, acceleration, rotation, temperature, pressure, linear and angular position, strain, humidity, viscosity, chemical measurements and a host of other sensor applications [1]. These sensors can be used in high voltage, high temperature, or corrosive environments due to its dielectric property.

Fiber optic sensor technology has been a major user of technology associated with the optoelectronic and fiber optic communications industry. In the early days, most commercially successful FOS were squarely targeted at markets where existing sensor technology was marginal or in many cases nonexistent. The inherent advantages of FOS, which include their ability to be lightweight, very small size, passive, low-power, resistant to electromagnetic interference, their high sensitivity, their bandwidth and their environmental ruggedness were heavily used to offset their major disadvantages of high cost and end-user unfamiliarity.

Fiber Bragg gratings (FBG) are optical device with sensing elements where the core of an optical fiber is written by ultraviolet (UV) lasers. In addition to all the benefits of the FOS, these devices have an inherent ability to self-reference and can easily be multiplied over a single fiber. Its field of action ranges from structural health monitoring to the incorporation of intelligent materials and can even be introduced in bio application [1].

The FBG sensor operation principle lies in the monitoring of the wavelength shift of the optical signal reflected by the grating, which is known as Bragg wavelength. Bragg wavelength, \( \lambda_{Bragg} \) is the wavelength of the reflected signal, which is a function of the monitored parameter such as strain,
temperature, etc., is correlated to the effective refractive index of the fiber core, \( n_{\text{eff}} \), and the grating period, \( \Lambda \) by:

\[
\lambda_{\text{Bragg}} = 2n_{\text{eff}}\Lambda
\]  

(1)

From equation (1), Bragg wavelength is influenced by changes in the grating period for strain sensors or the effective refractive index for temperature sensors. The relationship between the strain and temperature variation and the wavelength of Bragg is given in equation (2), where the first term represents the strain effect on \( \lambda_{\text{Bragg}} \) and the second term describes the temperature effect [1]:

\[
\Delta \lambda_{\text{Bragg}} = \lambda_{\text{Bragg}}(1 - \rho \alpha)\Delta \varepsilon + \lambda_{\text{Bragg}}(\alpha + \xi)\Delta T
\]  

(2)

where \( \Delta \lambda_{\text{Bragg}} \) represents the change in the Bragg wavelength, \( \rho, \alpha \) and \( \xi \) are the photo-elastic, thermal expansion and thermo-optic coefficients of the fiber respectively. \( \Delta \varepsilon \) is the change in strain and \( \Delta T \) is the change in temperature.

2. Methodology

FBG is used as optical sensor to investigate the temperature variation and density in liquid substances using simple experimental setup. This setup consists of a light source, hotplate, circulator, FBG and OSA. The sensor device was tested in water and palm oil. Laser diode is used to generate broadband light through optical temperature sensor. The operating wavelength of the laser diode is around 1550 nm to 1560 nm. Bragg wavelength can reach circulator in port 1 through port 2. Port 3 circulator is connected to Anritsu MS9740A OSA.

The temperature and liquid density are the parameters considered in this project. The sensor device was tested in various temperature and different liquid density. Figure 1 shows the simple experimental setup using FBG as FOS in this project. FBG was connected to the optical source, circulator and OSA. A beaker filled with liquid solution is placed on top of the hotplate. The distance between the surface of liquid substances and the FBG is about 5 cm constantly. The temperature is observed by using thermometer inside the beaker to record the temperature change of the solutions along the heating process. The temperature of solutions varied from 30 to 95 °C. Thus, thermal expansion is produced in the grating and the refractive index variation of the FBG.

![Figure 1. Experimental setup](image)

This experiment is to observe the characteristics of Bragg wavelength on the performance in various temperature and density through the wavelength, bandwidth and the sensitivity of the FBG. The sensitivity of the FBG is determined using the slope steepness of the graph plotted from the data achieve.
The Bragg wavelength shift is dependent on temperature and the relationship between the temperature variation is given in the equation (3):

\[ \Delta \lambda_B = \lambda_B (\xi + \alpha) \Delta T \]  

where \( \Delta \lambda_B \) is the Bragg wavelength shift, \( \lambda_B \) is the Bragg wavelength of the FBG, \( \xi \) is the thermo-optic coefficient \((8.6 \times 10^{-6} \, ^\circ C^{-1})\), \( \alpha \) is thermo-expansion coefficient \((0.55 \times 10^{-6} \, ^\circ C^{-1})\) and \( \Delta T \) is the change in temperature respectively.

The optical source was turned on to provide a broadband light. OSA is used to observe the Bragg wavelength shift of FBG. All transmission and reflection spectra inside the OSA were observed and recorded.

For the temperature sensing, the solution which is water and palm oil were observed and analyze by using various temperature ranging from 30 °C to 95 °C. This temperature was set up by using a hot plate machine. The reason why temperature variation limit is 95 °C because the boiling point of water is 100 °C. The boiling point of water is difficult to achieve due to longer time needed. For density parameter, the solution which is water and palm oil is observed based on its characteristic of density. The refractive index of liquid substances is observed and measured to determine the ratio of speed of light in vacuum with speed of light in medium. Refractive index of liquid substances was measured using refractometer. Table 1 shows the details of liquid substances.

| Liquid Substances | Density (kg/m³) | Refractive Index | Boiling Point (°C) |
|-------------------|----------------|-----------------|-------------------|
| Water             | 1000           | 1.3333          | 100               |
| Palm Oil          | 980            | 1.4636          | 300               |

FBG verification is necessary before the experiment can be conducted. The FBG manufactured spectrum is shown in Figure 2. It was used for reflection spectra as the initial reference reading of each measurement. The Bragg wavelength or center wavelength was measured as 1550.109 nm with 0.283 nm bandwidth.

Figure 2. Reflection spectrum by manufacturer
3. Result and Discussion
Two different type of liquid substances were chosen which are water and palm oil. This was used to determine the effect of density of liquid substances towards the performance of FBG. Data were obtained from the experiments conducted in water and palm oil. From the data obtain in water and palm oil, the Bragg wavelength pattern is increase as temperature increase while bandwidth has no change in value and shape. For water, the wavelength shifts from 30 °C until 95 °C is 0.7630 nm, close to the wavelength shifts for the palm oil which is 0.7487 nm.

Table 4 shows the Bragg wavelength for every 5°C for water and palm oil substance. Both water and palm oil show increment in Bragg wavelength with temperature. It can be said that at the same temperature, the shift in Bragg wavelength is higher for palm oil compare to water.

| Temperature, T (± 1°C) | Bragg Wavelength shift, ΔλB (± 0.01nm) |
|-----------------------|--------------------------------------|
|                       | Water                                | Palm Oil                           |
| 30 – 35               | 0.064                                | 0.052                               |
| 35 – 40               | 0.066                                | 0.075                               |
| 40 – 45               | 0.046                                | 0.070                               |
| 45 – 50               | 0.052                                | 0.057                               |
| 50 – 55               | 0.062                                | 0.044                               |
| 55 – 60               | 0.059                                | 0.041                               |
| 60 – 65               | 0.065                                | 0.061                               |
| 65 – 70               | 0.064                                | 0.043                               |
| 70 – 75               | 0.050                                | 0.045                               |
| 75 – 80               | 0.053                                | 0.063                               |
| 80 – 85               | 0.057                                | 0.058                               |
| 85 – 90               | 0.069                                | 0.068                               |
| 90 – 95               | 0.056                                | 0.071                               |

The average results for both liquid substances had no significant difference. Thus, it can be concluded that different density with increasing of temperature does not affect the Bragg wavelength shift.

3.1 Bragg Wavelength
Equation (3) shows that the Bragg wavelength shift is dependent on temperature. When the temperature increase, the shift in Bragg wavelength increase and vice versa. Based on the data from the experiments, it is in agreement with the theory that temperature of liquid substances increase with increment of Bragg wavelength. As conclusion, Bragg wavelength shift is directly proportional to the change in temperature for water and palm oil substance as depicted in Figure 3. From the graph, it shows that the water and palm oil is increase linearly as temperature increases.
3.2 Bandwidth
Table 6 shows the data collected for the bandwidth of FBG measured in water and palm oil.

Table 3. Bandwidth measured in water and palm oil in various temperature

| Temperature, T (± 1°C) | Bandwidth, d (± 0.01nm) Water | Palm Oil |
|------------------------|-------------------------------|----------|
| 30                     | 0.29                          | 0.30     |
| 35                     | 0.29                          | 0.30     |
| 40                     | 0.29                          | 0.30     |
| 45                     | 0.29                          | 0.30     |
| 50                     | 0.29                          | 0.30     |
| 55                     | 0.29                          | 0.30     |
| 60                     | 0.29                          | 0.30     |
| 65                     | 0.29                          | 0.30     |
| 70                     | 0.29                          | 0.30     |
| 75                     | 0.29                          | 0.30     |
| 80                     | 0.29                          | 0.30     |
| 85                     | 0.29                          | 0.30     |
| 90                     | 0.29                          | 0.30     |
| 95                     | 0.29                          | 0.30     |

The bandwidth of the FBG in water and palm oil are 0.29 nm and 0.3 nm respectively. Based on the data taken, the bandwidth value has no significance difference and dramatic changes in value and shape. Thus, it can be concluded that the bandwidth of the FBG is constant in different temperature environment. The difference of bandwidth in both experiments is 0.01 nm which is very small value.

3.3 Sensitivity of Fibre Bragg Grating
The sensitivity of fiber is defined as the ability to respond for affective changes in certain environments, which implies the susceptibility of a system to the changes surrounding it. Thus, temperature sensitivity of the FBG sensor was investigated in terms of how sensitive the sensor is toward temperature change. In principle, lower sensitivity indicates better susceptibility.
Based on Figure 4 and Figure 5, the graph show that Bragg wavelength shift over temperature for the FBG sensing in water and palm oil respectively. Sensitivity can be determined by calculating the gradient or the slope steepness of the graph. The average sensitivity of FBG can be obtained by calculating the countable slope steepness of the graph plotted. From the graph plotted, the relationship between Bragg wavelength and temperature in both liquid substances is directly proportional. The sensitivities of FBG in water and palm oil were calculated and measured. The sensitivity of FBG in water is found to be 0.0117 nm °C⁻¹ with the y-intercept at 0.3471 nm. The sensitivity of FBG in palm oil is 0.011 nm °C⁻¹ with the y-intercept at 0.3185 nm. From the observation, the difference in density of water and palm oil does not affect the Bragg wavelength. This is because there is no significance difference on sensitivity between two liquid substances.
The accuracy of the FBG temperature can be affirmed by examining the theoretical value and compare with the measured value. From the graph plotted in Fig. 6, the sensitivity of FBG was calculated and measured which is 0.0142 nm °C⁻¹ and y-intercept at 0.4255 nm wavelength. Based on the experiments in different type of liquid substances in density, the temperature sensitivity of FBG sensor is measured in water is 0.0117 nm °C⁻¹ (1.17%) and in palm oil is 0.011 nm °C⁻¹ (1.1%) whereas the theoretical temperature sensitivity is measured to be 0.0142 nm °C⁻¹ (1.42%).

4. Conclusion
The project on investigation of fiber optic sensor using FBG for various temperature and liquid density was successfully design and developed. The process of heating for various temperature in different density has been done with the parameter of 30 °C to 95 °C in water and palm oil. It can be concluded that the Bragg wavelength shift is dependent on temperature. When temperature increase, the Bragg wavelength increase. This shows that Bragg wavelength shift is directly proportional to the temperature. The sensitivity between different type of density which is water and palm oil has been observed. There is no significance value between palm oil and water. Thus, density of liquid substances does not affect the Bragg wavelength. From this, it can be concluded that temperature sensor can be used in different density of liquid substances.

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