Study on the Sensitivity of Bare Fiber Bragg Grating for Ultrasonic Frequencies Response Under Various Temperature

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Abstract. This work presents a study on the sensitivity of bare fiber Bragg grating (FBG) to detect ultrasonic frequencies under various temperature. Two infrared (IR) laser with excitation wavelength, \( \lambda=1310\text{nm} \) and \( \lambda=1550\text{nm} \) were employed. Various types of FBG with operating wavelength of 1546nm, 1550nm and 1554nm were used to identify the optimum design of sensor in detecting range of ultrasonic frequencies between 5kHz until 30kHz under various surrounding temperature from 20°C until 30°C. The principle of FBG vibration detection lies in the fact that spectral shift would occur due to the acoustic-induced variations in the medium. In this study, the ultrasonic signal had been investigated by monitoring the amplitude of optical output power. At 30°C, the bare FBG with operating wavelength of 1554nm using 1310nm light source exhibits the optimum performance in detecting ultrasonic vibration frequency, in which its sensitivity was obtained as \( \Delta P=0.10\text{dBm} \). We believe that the sensitivity of the proposed sensor can be enhanced by introduce nanomaterials onto the FBG or by altering the physical structure of FBG.

1. Introduction

Vibration sensors plays an important role in our daily life. Their applications cover many areas such as structural health monitoring of machinery and civil infrastructures [1, 2]. In principle, the vibration sensors respond to the environmental frequencies. In civil infrastructure and earthquake monitoring, ability to detect a low frequency is the main feature must be owned by the sensor [3, 4]. Meanwhile, for medical health status monitoring, the vibration sensors must able to respond with medium or high frequencies (from a few hundred hertz to several kilohertz) [5,6].

The development of various types of vibration sensors such as electrochemical sensors, electronic sensors, mechanical sensors and optical sensors proves their vital role in diverse areas [7-10]. Nonetheless, the interest in optical vibration sensor has grown considerably recently due to its immunity to electromagnet interference, less bulky, light weight and high sensitivity [11-13]. The optical sensors can be categorized into two types, namely fiber optics sensor and free space optics sensor [14-17]. In free space optics sensor, air acts as medium for light propagation. To enhance light intensity, prism coupling technique is deployed to ensure that at least 90% of light is coupled to the device [18]. Fiber
optics sensor used an optical fiber to propagate light. For vibration sensing, as the sample vibrates, part of light will be attenuated from the fiber resulting the losses in optical signal.

Few types of fiber optics vibration sensors have been introduced recently including Mach Zender interferometer sensor, nanomaterial coated fiber optics and fiber Bragg grating (FBG) [19, 20]. Fiber Bragg grating (FBG) displays an excellent criteria of vibration sensor due to its simple structure [21]. Lim et al. (2017) developed an FBG ruggedized vibration sensors that able to sense the low vibration signal generated by train movement [22]. A high-frequency system had been introduced based on FBG cantilever sensor and edge filter demodulation scheme to collect vibration signals of engine valves and oil nozzle [23]. Yu et al. (2016) found that the grating with 3mm length of FBG has a higher sensitivity when detecting high frequency ultrasonic wave [24].

The vibration sensors usually are practically used for outdoor application in which they are tend to expose to the environment issues such as temperature [25]. Lack of detail studies on the environmental factors effect on the FBG performance were carried out. This issue leads to the motivation of this study in which the relationship between ultrasonic vibration frequency and temperature of the surrounding medium on the performance of bare FBG is investigated. We believe that the output of this study will benefit in health monitoring field where a robust and reliable FBG sensor is introduced.

2. Materials and Methods

Figure 1 illustrates an experimental setup of this study. Two infrared (IR) excitation wavelength of light sources were deployed, namely 1310nm and 1550nm. The laser source was connected to the bare FBG. In this study, a term “bare FBG” refers to the FBG structure which is not coated with any materials. Three types of FBG with various operating wavelength namely 1554nm (FBG 1), 1546nm (FBG 2) and 1550nm (FBG 3) were used to investigate their influence on the optical output power. Length of grating area was fixed at 0.5mm. The FBGs have 0.3nm of bandwidth at 3 dB and their side lobe suppression ratio are less than or equal with 15 dB. Reflectivity of the FBG are less than or equal with 10%. The grating area of FBG was immersed into the DI water inside the ultrasonic bath.

To study the effect of ultrasonic vibration frequency in various temperature, the frequencies of water’s vibration were varied from 5kH to 30kHz with an increment of 5kH per reading. Meanwhile, values of water temperature were manipulated at 20°C, 25°C and 30°C. The second end of FBG was connected to an optical power meter to record the result. Note that, a single mode fiber (SMF) was also used in this study that act as a reference. The sensitivity of the sensor was determined by using equation (1) as expressed below:

\[
\Delta P \ (dBm) = maximum \ output \ power - minimum \ output \ power \quad (1)
\]

Figure 1: Experimental setup of FBG ultrasonic vibration sensor under various temperature
Table 1: List of variable parameters in this study

| Parameter                        | Description                        |
|----------------------------------|------------------------------------|
| Wavelength, \( \lambda \)        | 1310 nm, 1550 nm                   |
| FBG’s wavelength, \( \lambda' \) | 1546 nm, 1550 nm, 1554 nm          |
| Sample’s frequencies, \( f \) (kHz) | 5 kHz – 30 kHz                    |
| Liquid’s temperatures, (℃)       | 20 ℃, 25 ℃, 30 ℃                  |
| Types of fiber optics            | Operating wavelength               |
| FBG1                             | 1554nm                             |
| FBG2                             | 1546nm                             |
| FBG3                             | 1550nm                             |
| SMF                              | -                                  |

The sensitivity values between SMF and FBG was then compared. For the FBG sensor, various configuration of sensors with different wavelength and temperature were also investigated. Greater value of \( \Delta P \) indicates better sensor’s sensitivity. Table 1 summarizes all important parameters involved in this study.

3. Results and Discussions

3.1. Effect of ultrasonic frequencies on the optical output power under various sample’s temperature

Figure 2(a) shows a graph of optical output power versus frequency using 1310 IR light source for various types of fiber at water temperature of 20℃. The inconsistence output power within -3.84dBm and -3.93dBm were detected by FBG 1 as the frequencies were varied from 5kHz to 30kHz. No frequency changes were detected as FBG 2 was appointed, in which the output power remain at -3.47dBm for all frequencies. By using FBG 3 with operating wavelength of 1550 nm, small changes of optical power output were recorded between -3.35 dBm and -3.38 dBm. Figure 2(b) illustrates the pattern of optical power’s output versus frequency using 1550 nm light source at the same temperature. The optical output power for all FBGs including SMF did not exhibit any changes in which validate that the usage of 1550nm light source at 20℃ unable to detect difference in frequencies.

Figure 3 illustrates the graph of optical output power versus frequency at T=25℃ using 1310nm and 1550nm light source respectively. When \( \lambda=1310\)nm (Figure 3(a)), the reading of optical output power for FBG 1 and FBG 3 were consistence indicated both of them unable to detect the any changes of frequencies. Only FBG 2 able to detect the frequencies’ changes from 20 kHz to 25 kHz in which the optical power decreased from -3.38dBm to -3.47dBm. When the light source was changed to \( \lambda=1550\)nm (Figure 3(b)), all fiber optics including SMF did not show any respond with the increment of frequencies.

The optical output power from FBG 1 with \( \lambda=1310\)nm shows a good response at T=30℃ (Figure 4(a)). When frequency increased from 15kHz to 20kHz, the optical power dropped about 0.1 dBm from -3.93dBm to -4.03dBm. The usage of FBG 2 did not show any response as the fiber was immersed into the sample. Meanwhile, the optical power rose about 0.09 dBm when the frequency was increased from 5kHz to 10kHz with the deployment of FBG 3. Next, the excitation wavelength was replaced with \( \lambda=1550\)nm (Figure 4(b)). Obviously, FBG 3 and SMF did not show any significant changes as the frequency increased. Nonetheless, small changes about 0.02dBm and 0.03dBm were observed when FBG 1 and FBG 2 were used, respectively. The power changes were recorded with the increment of frequency from 15kHz to 25kHz.
Figure 2: Effect of ultrasonic frequencies on the optical power output for various types of FBG and SMF at 20°C (a) $\lambda=1310$ nm (b) $\lambda=1550$ nm
3.2. Analysis on the sensitivity of vibration sensor

A sensitivity analysis of the sensor was determined by using Equation 1. Figure 5 portrays the power losses, $\Delta P$ experienced by FBG 1, FBG 2 and FBG 3 as temperature varied at 20°C (Figure 5(a)), 25°C (Figure 5(b)) and to 30°C (Figure 5(c)). Note that better sensitivity sensor can be determined based on the greater value of $\Delta P$ because of the ability of FBG to detect changes in output power resulted by the optical losses. In comparison, the employment of light excitation wavelength, $\lambda=1310$ nm produced better sensitivity than $\lambda=1550$ nm. Apparently, temperature mainly affected the performance of FBG as
vibration sensor. Nonetheless, the output patterns were quite inconsistence with the increment of temperature. At 20°C, FBG 1 exhibits the best sensitivity with $\Delta P=0.09$dBm using $\lambda=1310$nm. The deployment of FBG 2 resulted the best sensitivity for frequency detection with $\Delta P=0.09$dBm when $T=25$°C. As the sample’s temperature was increased to 30°C, FBG 1 and FBG 3 with operating wavelength of 1554nm and 1550nm experienced great power losses of 0.10dBm and 0.09dBm. To summarize, the optimum design for ultrasonic vibration frequency sensing can be obtained by employing FBG with operating wavelength of 1554nm using 1310nm IR laser source. The sensor exhibited its best performance at surrounding temperature of 30°C.

The principle of FBG vibration detection lies in the fact that spectral shift would occur due to the acoustic-induced variations in the medium. The amplitude, frequency, phase, and polarization of the ultrasonic signal are influenced by the condition of the sensing medium [26]. In this study, the ultrasonic signal had been investigated by monitoring the amplitude of output power. Based on analysis, we found that bare FBG is insufficient to detect the ultrasonic vibration. Although the FBGs show respond as the frequency change, unfortunately only small changes can be detected. Obviously, the selection of the operating wavelength of FBG mainly affect the output. Note that the usage of FBG 1 with operating wavelength of 1554 nm at $T=30$°C by using 1310nm IR light source resulted the best sensitivity of vibration sensor. Additional nanomaterials such as metal coated onto the bare FBG to generate surface plasmon resonance (SPR) is believed can enhance the sensing properties of the fiber [27]. The structural properties of the fiber can be altered by using an etching technique to decrease the thickness of cladding area so that more evanescent waves will propagate from the fiber in order to amplify the sensitivity of our proposed sensor [28, 29].

Figure 5: Analysis on the sensitivity of FBG based on optical power losses, $\Delta P$ (a) $\lambda=1310$ nm (b) $\lambda=1550$nm
4. Conclusions
In conclusion, bare FBG shows the best sensing properties by using 1310nm IR light source with the fiber’s operating wavelength of 1554nm. The proposed sensor exhibits its optimum performance at T=30°C as the ultrasonic vibration frequencies were varied between 5kHz until 30kHz with maximum sensitivity of ΔP=0.10dBm. For future work, the bare FBG will be coated with sensing nanomaterials such metals, metal oxide or graphene oxide to enhance the intensity of evanescent field.

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