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Optical Fibre Sensor Using Frequency Beating Technique

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ABSTRACT

In this paper, a new method to realize the optical fibre sensor using an optical heterodyne technique (OHT) is proposed and numerically demonstrated. In this method, the bandpass filter (BPF) was utilized as a reference element and fibre Bragg grating (FBG) served as a sensing element. The wideband light is equally split and launched to sensing and reference elements. The reflected light of sensing element coherently interferes with the output of BPF inside 3-dB coupler. A photodiode detects the interfered signal and the beat frequency can be determined to achieve a high-resolution. To examine the proposed method, the scheme for temperature sensing is investigated. The Fabry-Perot narrow-bandpass filter type (F7 glass) serve as BPF. The results reveal that a good and fast response to temperature change with the sensitivity of 1.152 GHz/°C can be obtained.

Keywords: Bragg Grating Fibre, Fabry-Perot Narrow-Bandpass Filter, Interferometric Sensors, Optical Heterodyne Technique**.**

1. INTRODUCTION

Optical fibre sensors have been widely studied and developed, due to its numerous advantages such as small size, lightweight, immunity to electromagnetic interference, low cost, high durability, and multiplexing capability [1]. Accordingly, there are many techniques to realize optical fibre sensors. Fibre sensors are well known due to its wide range of applications in the monitoring of strain, temperature [2], and other mechanical, chemical [3], biomedical parameters, biomechanics and rehabilitation applications [4].

The optical heterodyne technique (OHT) is an interferometric technique that utilizes frequency or wavelength difference between two incoming signals [5, 6]. In optical sensing, OHT uses two signals with different wavelengths, where an incoming wave with a specific frequency, fs, which is mixed with a local wave with different frequency, fo using a 3-dB coupler. Inside the optical coupler, the waves interfere jointly to be detectable and analyzable by a photodiode that was placed at the output of the optical coupler. The photocurrent with a frequency difference called beat frequency (f_B) was received at the output part [7]. Several methods have been proposed to implement the OHT based on fibre sensors. Furthermore, there are several attempts to add elements for several purposes such as improving the performance of the system and reducing the cost and complexity. In 2012, Zhao et al. [8] proposed an OHT for a current sensor using nano-wire grid in-line polarizer. In 2018, Duan et al. [9] demonstrated a temperature sensor with high-resolution employing OHT technology by using a single-frequency fibre laser with narrow linewidth. The cost, complexity, and limited choices are the main problems in the previous works. In addition, OHT that uses two identical Bragg grating (FBG) has been proposed to measure

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temperature change [10]. In this technique, one of FBG was utilized as a reference signal and another FBG operated as a sensing element. The proposed sensor has instantaneously measured temperature over a wide dynamic range with good sensitivity. However, it needs to maintain the temperature of the reference arm at a specific value for ensuring accurate measurements.

In this paper, a new method for implementing optical heterodyne technique based bandpass filter (BPF) and FBG sensor was proposed. In this method, a Fabry-Perot narrow-bandpass filter acts as a reference element and uniform FBG was used as a sensing element to achieve OHT. Due to its response to the temperature is approximate nil, Fabry-Perot filter made of F7 glass was proposed as BPF for minimizing the effect of temperature on the reference element. The temperature of the sensing element was varied in order to examine the proposed sensor. The rate of beating frequency shift per centigrade is about 1.152 GHz, for the proposed system.

2. THEORETICAL CONCEPTS

The block diagram of the proposed OHT is shown in Fig. 1. The proposed system consists of wideband laser (193.1 THz), 3-dB coupler, BPF (as reference arms), FBG (as sensing arms), beam combiner and photodetector (PD). The process of generating frequency based on OHT represents a frequency beating or optical beating. A photodetector receives the mixed optical waves to obtain a photocurrent with f_B in front of the photodetector. The outcome photocurrent is given by equation 1 [7, 10]:

$$i = R[P_S + P_R + 2\sqrt{P_S P_R}\cos(2\pi(\mathrm{f}_S - \mathrm{f}_R)\,t + \phi_S - \phi_R)] \quad (1)$$

where R is detector responsivity, P_S and P_R represent the powers of sensing and reference signals, f_S and f_R are the frequency of the sensing and reference signals, ϕ_S and ϕ_R represent the phases of the two signals, which incident on the photodetector. The first term of equation 2, $R(P_S+P_R)$, generates the constant direct current and can be removed easily using bandpass filters. The heterodyne signal is then given by the alternating current:

$$I_{ac} = 2R\sqrt{P_S P_R}\cos(2\pi f_B + \phi_S - \phi_R)$$
(2)

where f_B is generated beat frequency and it equals to $f_S - f_R$ [11, 12], furthermore $f_B << f_S, f_R$ [7]. When the fields of both optical waves are overlapped with common polarization, the optical beat frequency can be achieved by [13, 14]:

$$f_B = \frac{c}{\lambda_S} - \frac{c}{\lambda_R} = \frac{\Delta\lambda c}{\lambda_S \lambda_R}$$
(3)

where c is the light speed in free space, λ_S and λ_R are the wavelength of the sensing and reference signals. Changes in the environments of the sensing element can vary Bragg frequency, for example, changing in temperature modifies the grating space and the index of refraction, leading to a shift in Bragg frequency [15-17].

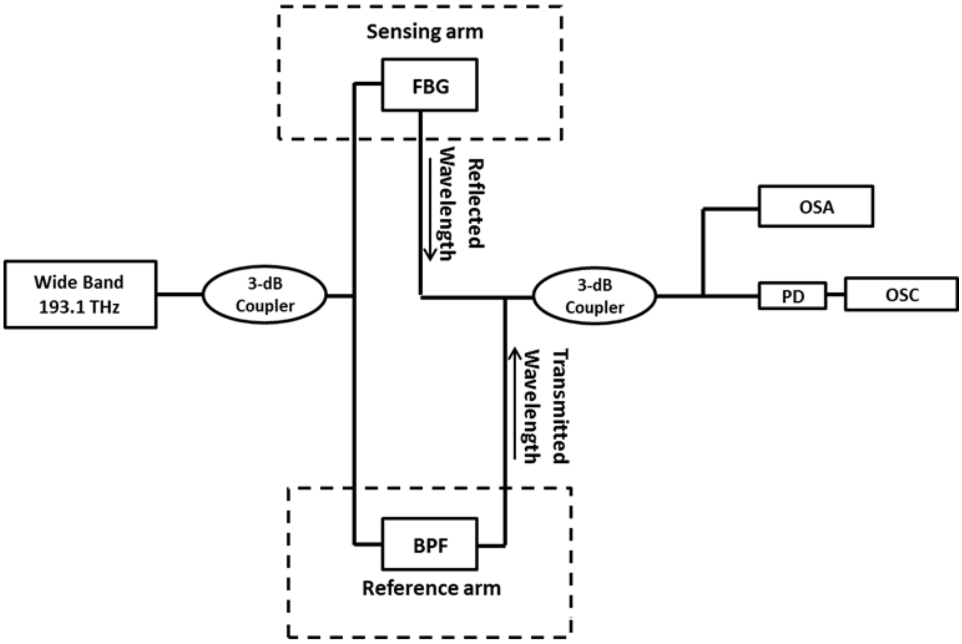

Figure 1. Block diagram of the proposed sensor. OSC represents oscilloscope and OSA is an optical spectrum analyzer.

The temperature change can be expressed as a function of beating frequency by [9, 18]:

$$\Delta T = \frac{f_B}{(\alpha+\xi)\frac{c}{\lambda_S}} \tag{4}$$

where α and ξ represent thermal-expansion and thermo-optic coefficients of the FBG, respectively. For standard FBG, α and ξ are $\sim 1.1\times10^{-6}/^{o}C$ and $\sim 8.3\times10^{-6}/^{o}C$, respectively. Based on equation 4, the resolution of the proposed sensor is mainly governed by the linewidth of the light source. The effect of linewidth on temperature measuring can be described as in Eq. (5):

$$\delta T = \frac{1}{(\alpha+\xi)\delta\nu} \tag{5}$$

3. PROPOSED SENSOR SETUPS

Setup of the proposed system is shown in Fig. 2. The proposed sensor comprises of a wideband optical source centred at 193.1 THz, narrow BPF and FBG sensor. The BPF that represents the reference element was modelled with a bandwidth of 5 GHz and centre frequency (f_{BPF}) of 193.1 THz while the FBG that acts as sensing element is set with a reflected frequency of 193.252 THz, and linewidth of 5 GHz. After the light beam launched to the first coupler (C_1), the reflected beam of FBG was led through C_1. All Bragg transmitted frequencies were blocked by BPF, except the allowed frequencies. Both of transmitted frequency of BPF and the reflected frequency of FBG were mixed inside second optical coupler (C_2). Finally, the combined signal was detected at the end of C_2 by a photodiode (PD) and was converted to an electrical signal. The detected signal was displayed by an oscilloscope (OSC). This study proposed the Fabry-Perot made of F7 glass with 5 GHz bandwidth as BPF, because its response to the temperature is almost nil [19, 20]. The relationship between environmental changes and frequency shift can be obtained by using a sensing element according to the equation 4, when the transmitted frequency of BPF is fixed.

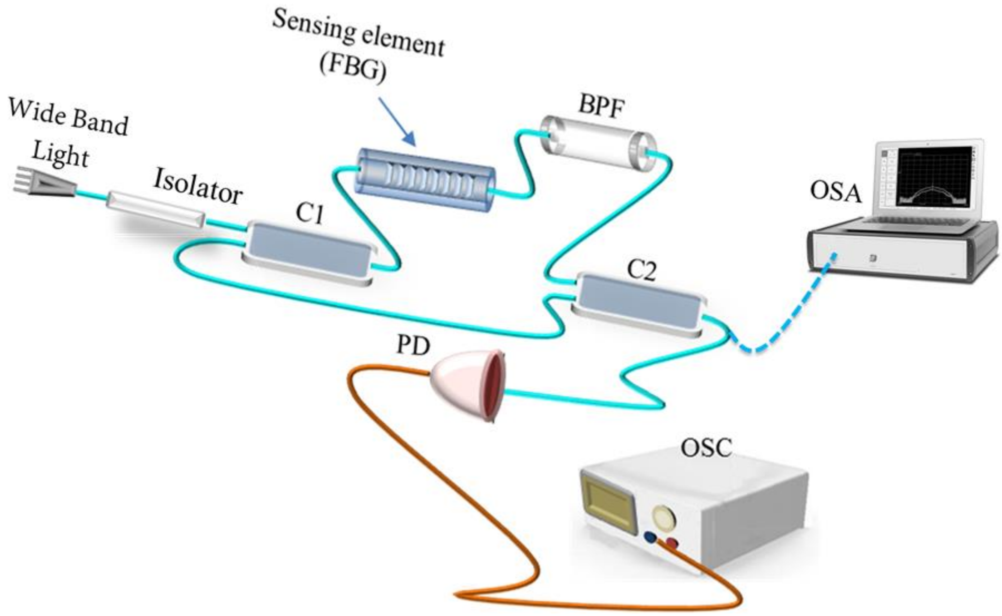

Figure 2. Proposed optical sensing system.

4. RESULTS AND DISCUSSION

In this section, the performance of the proposed system utilizing OHT is numerically demonstrated using VPItransmisionMaker software. To investigate the performance of the proposed optical sensor, the sensing element that is sensitive to temperature were considered. Figure 3(a) shows the optical spectrum of the combined signal at the output of the proposed sensor before the incident on photodiode when the temperature is changed over a range from 0 to 100°C. The Bragg frequency shift due to thermal expansion comes from the modification of the grating spacing and the refractive index. This work used wavelength shift per one centigrade which is approximately 14 pm/°C [21, 22]. In order to show the change in beating frequency as the temperature is varied, the detected signal by PD is displayed on the oscilloscope. The change of beat frequency, f_B is demonstrated in Figure 3(b) for different values of temperature. The shift in f_B comes from the increase in the difference between sensing and reference signal as a function of T as is illustrated in equation 3. Although the frequency shift in Figure 3(a) seems linear, the accurate measurements for beating frequency show nonlinear behaviour. This resulted from a thermo-optic effect.

In order to explore the performance of the proposed sensor, Table 1 displays the effect of increasing the temperature from 0 to 100°C on the optical frequency and beating frequency. It can be noted that the optical frequency decrease with increasing temperature while the beating frequency is increased.

Table 1 Effect of changing temperature on the optical frequency and beat frequency

T (°C)	f (THz)	f_B (GHz) (Analytical)	f_B (GHz) (Numerical)
0	193.06	40	45.8
20	193.0252	74.8	71.4
40	192.9905	109.5	91.7
60	192.9557	144.3	107
80	192.9209	179.1	128.1
100	192.8862	213.8	161

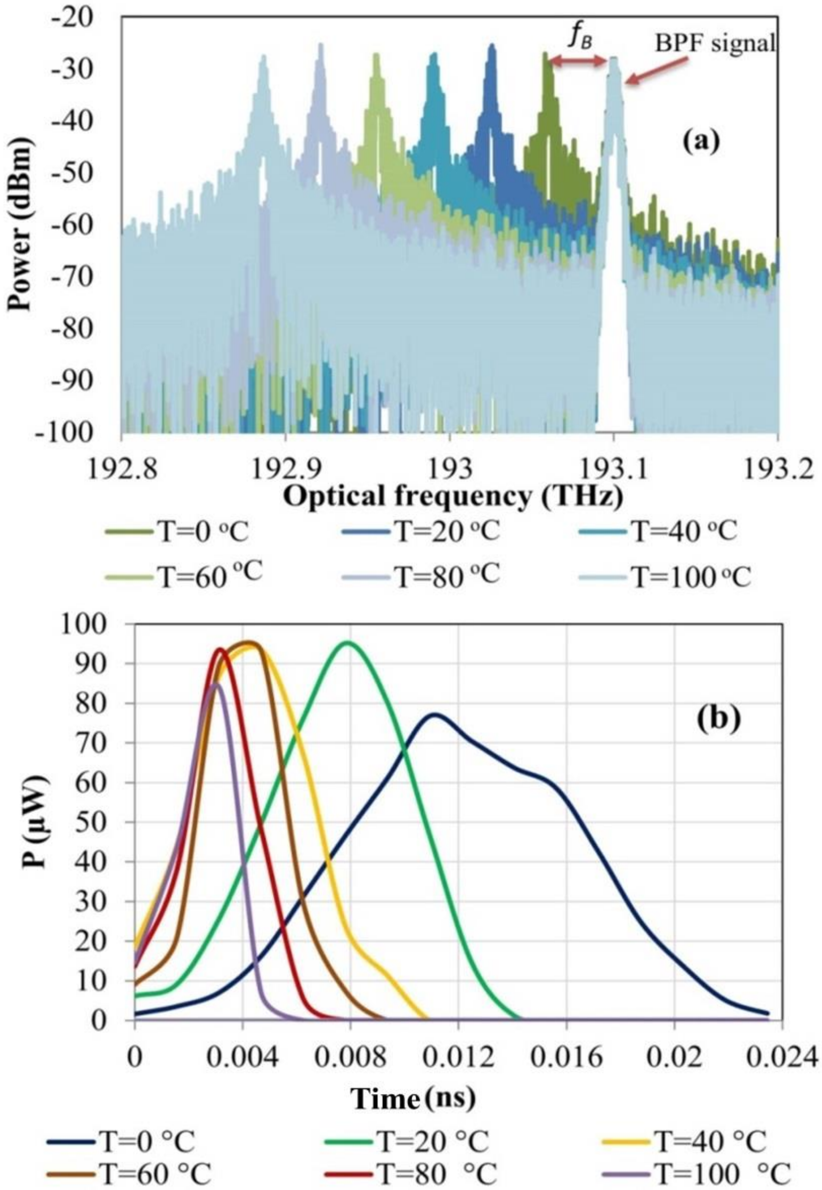

Figure 3. Effect of changing temperature on the performance of the proposed sensor where: a) optical spectra, and b) beat frequency f_B shift.

Figure 4 shows the beating frequency f_B as a function of temperature. The results were obtained over the temperature range from 0 to 100°C. It can be observed that the beat frequency that analytically calculated is linearly changed with the temperature over the entire range. However, because the simulation setup takes into account the effect of thermo-optic, numerical results are not exactly matched the analytical results. The numerical rate of shifting beating frequency per changing in temperature is about 1.152 GHz/°C. In addition, the resolution can be determined by using equation 5 and it records about 21×10^{-6}/°C.

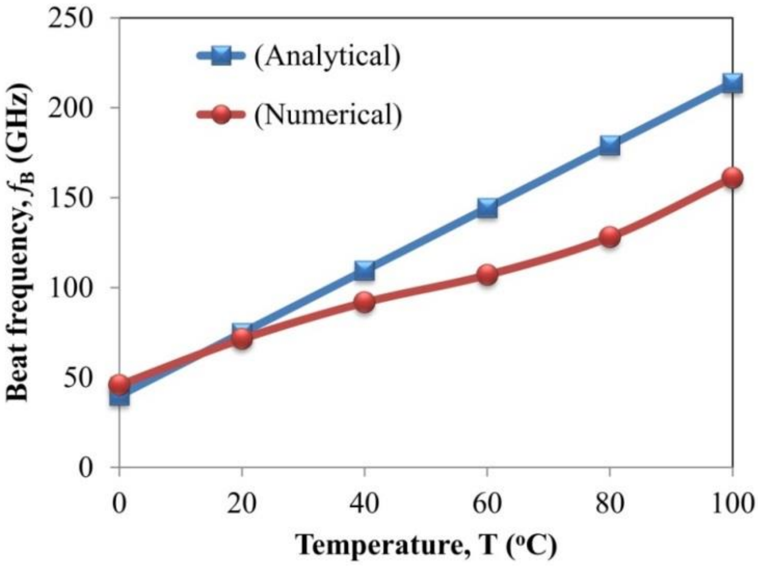

Figure 4. Relationship between T (°C) and f_B (GHz) of the OHT system.

5. CONCLUSION

The new efficient approach to interrogate the optical sensors based on optical heterodyne technique (OHT) has been proposed. In the proposed system, the output light of both optical sensing and reference arms inherently interfere inside the output coupler. The photodiode receives the interfered light and the oscilloscope measure the beat frequency. To explore the performance of the proposed method, the scheme for temperature sensing has been numerically demonstrated using VPItransmisionMaker software, in which F7 glass Fabry-Perot has been used as BPF because its response to temperature change is approximately nil. The results reveal that a good and fast response to temperature change with a sensitivity of 1.152 GHz/°C can be obtained. Furthermore, the proposed OHT has been built to reduce system complexity.

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