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Performance simulation and design comparison of optical heterodyne temperature sensor based on Fiber Bragg Grating

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Abstract. In this work, an optical heterodyne temperature sensor system had been designed using Fiber Bragg Grating (FBG). Two techniques implemented. The first standard design uses dual laser diodes LDs as a laser sources that satisfy the condition of beat frequency range. The second new heterodyne optical system designed to get tunable source from single laser source using FBG, which is used as tunable element. By controlling the ambient temperature of the FBG, the wavelengths and their ranges can be controlled in way that satisfies the condition of beat frequency range. Mach-Zehnder interferometer (MZI) sensing technique had used with FBG element in both reference arm and sensing arm. Then the new modified heterodyne optical system had done by utilizing FBG in both reference arm and sensing arm with single source. A comparison study of results by using Optisystem software shows that, the modification of the second design provides better performance by increasing the wavelength shift and the sensitivity of the modified heterodyne temperature sensor.

Keywords: Fiber optics sensors; FBG-Fiber Bragg grating; Heterodyne; Beat frequency, Optisystem software

1. Introduction

Over the years, a wide range of optical fiber sensors became devices of choice for many applications. Fiber sensors with variety principles of operation and techniques, such as changing in intensity, polarization phase, or wavelength shift, used to detect temperature, pressure, strain, refractive index and different measurands [1]. One of the most widely used wavelength-based sensors is the Fiber Bragg gratings sensors (FBGs). Chain of grating planes formed through the fiber due to a photo-induced periodic refractive index modulated structure in the FBG core, [2]. The reflected Bragg wavelength is sensitive to a range of physical parameters such as strain, temperature, or pressure [3]. There are different sensing mechanisms using optical fibers that bring differentiated performance such as the sensitivity of a fiber-grating sensor is less than that of a fiber interferometer [4]. There are many



ways to improve the sensitivity of the fiber interferometer by choosing the appropriate structure. The common types of interferometers are the Michelson interferometer (MI), Fabry-Pérot interferometer (FPI), Sagnac interferometer (SI) and Mach-Zehnder interferometer (MZI) [5]. The most prevalent type is the MZI fiber sensor [6, 7]. Figure (1) shows the internal structure and working principle of FBG temperature sensor.

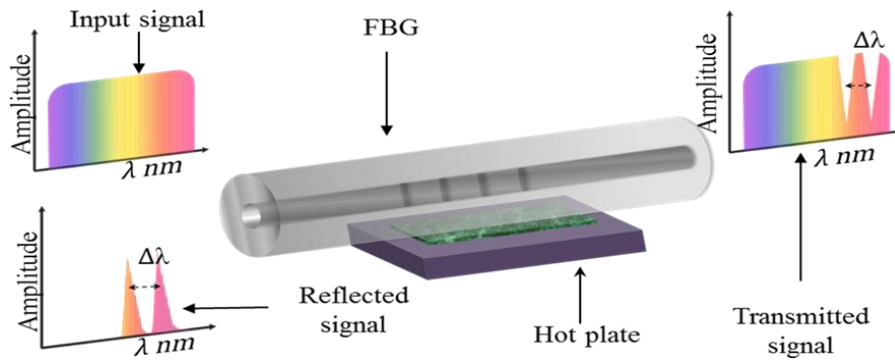


Figure 1. The working principle of FBG temperature sensor.

The reflected Bragg wavelength beam from the FBG is given by [8]:

$$\lambda_B = 2n_{eff}\Lambda \quad (1)$$

Where: λ_B the Bragg wavelength, n_{eff} is the effective index of refraction of the core material and Λ is the grating period. FBG temperature sensor principle work is, the variation in the wavelength $\Delta\lambda_B$ or, and intensity ΔI as a function of the change in the refractive index δn due to thermal effects. Bragg wavelength change is given in equation (2), [9]:

$$\frac{\delta n}{\delta T} = \frac{\Delta\lambda_B}{\lambda_B} \frac{n}{\Delta T} - kn\alpha_{glass} \quad (2)$$

The optical fiber temperature sensor based on MZI, where the change in temperature ΔT of the environment causes a phase change $\Delta\phi$, which results from fiber thermal expansion α and a perturbation of the fiber refractive index which given by [9].

$$\Delta n = \frac{\lambda}{2\pi L} \Delta\phi - n\alpha \Delta T \quad (3)$$

The concept in optical heterodyne detection is to introduce a heterodyne beat signal which related to the difference of phase shift between the reference signal and sensing signal, the high frequency components and constant components out are filtered, leaving (beat) frequency. As a result of this shift, the interference of the two waves of amplitudes (A_s , A_r) and angular frequencies (ω_s , ω_r) produce an intensity modulation at the beat frequency, $\Delta f = f_1 - f_2$, which is then detected according to equation [10].

$$I = \underbrace{\frac{A_s^2 + A_r^2}{2}}_{\text{Constant}} + \underbrace{\frac{A_s^2}{2} \cos(2\omega_s t + 2\theta_1) + \frac{A_r^2}{2} \cos(2\omega_r t + 2\theta_2) + A_s A_r \cos((\omega_s + \omega_r)t + \theta)}_{\text{High component}} + \underbrace{A_s A_r \cos((\omega_s - \omega_r)t + \theta)}_{\text{Beat signal}} \quad (4)$$

Where Θ is an angle between the wave fronts. Compared with the direct detection, the heterodyne detection technique is highly sensitive and has better accuracy. Thus, it is beneficial for weak signal detection. This is the most essential advantage [10]. The optical homodyne and heterodyne detections were known as the difference of the optical frequencies of the two-mixed field. The signal-to-noise ratio of the heterodyne detection is worse than that with homodyne detection [11]. Several studies

have focused on the optical homodyne and heterodyne detections methods. They are allowing us to compare the measurement performance of both configurations specially, in weak signal detection [12]. Eudum Kim et al [13], proposed temperature sensing technique through utilizing the optical beating. A peak wavelength of the sensing laser varies due to temperature fluctuation. Moreover, with limitation of the optical spectrum analyzer's (OSA) spectral resolution (sub-nm), it is uneasy to measure the exact amount of the wavelength fluctuation. Therefore, an electrical spectrum analyzer (ESA) and two lasers were utilized for gotten the wavelength shift. In addition, Haijin Fu et al [14], presented a novel measurement method of nonlinearity. It is free from the type of heterodyne laser interferometer and the motion state of the target, by employing double-channel quadrature demodulation and substituting the external reference signal with internal ones. The results carried out and refer that the proposed method accomplishes better accuracy above 2 pm. In this paper, we present a new modified heterodyne optical system for obtaining an optimized temperature sensor.

2. Simulation Aspect

In this work, a standard homodyne optical system technique was designed and simulated by Optisystem 15.0 software. FBG used as a temperature sensor depend on measuring the reflected FBG wavelength shift that detected as a function of temperature variation within range of (25-100 C). In this case single source used with MZI interferometer technique. The block diagram shown in Figure (2). While Figure (3) shows the Optisystem software layout of designed circuit.

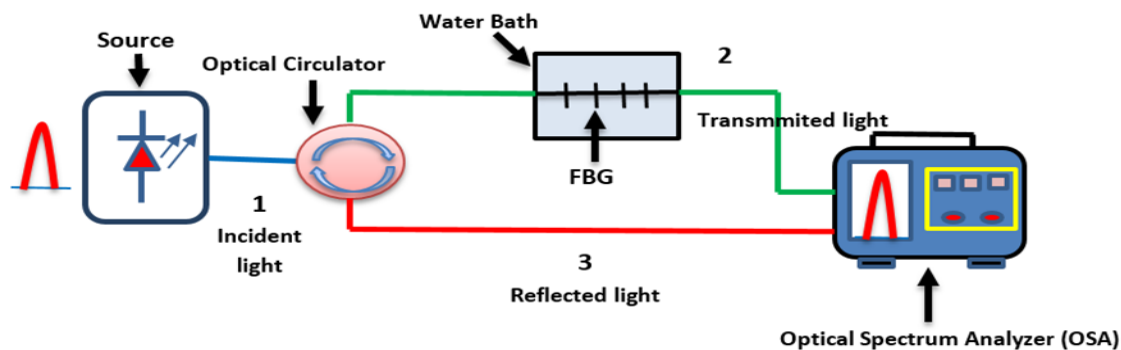


Figure 2. Block diagram of Optical homodyne FBG temperature sensor.

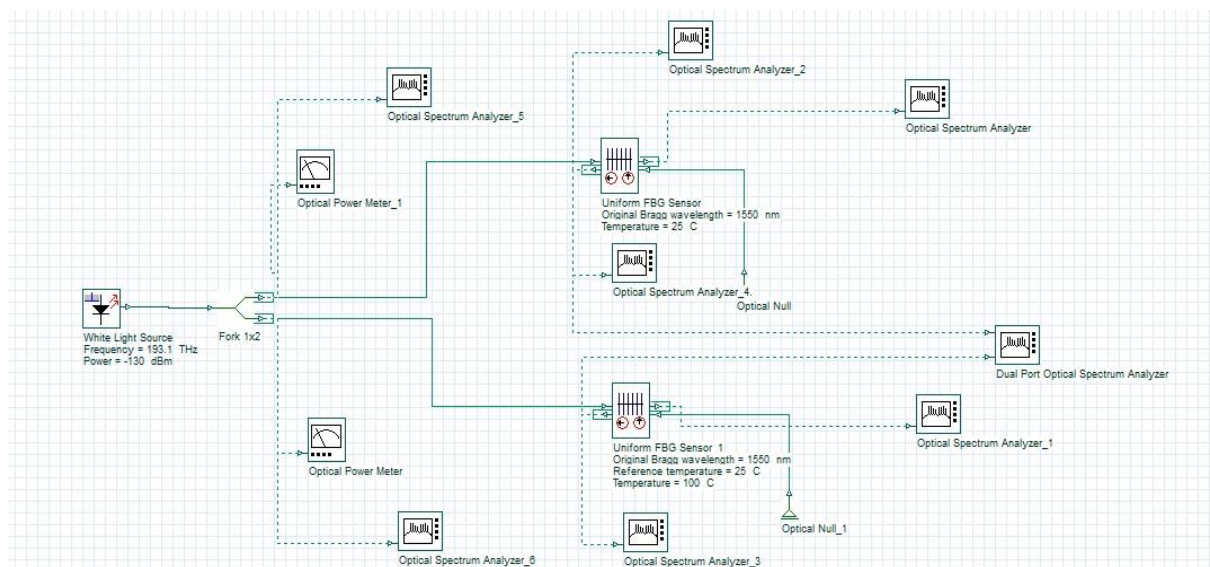


Figure 3: Optical homodyne system using FBG temperature sensor.

A heterodyne detection through MZI interferometer technique by using two optical sources has used in this work for measuring the Bragg wavelength shift. In such temperature sensors, the reflected wavelength shifts were detected. It induced by the temperature changes in the sensing FBG element. The block diagram shown in Figure (4).

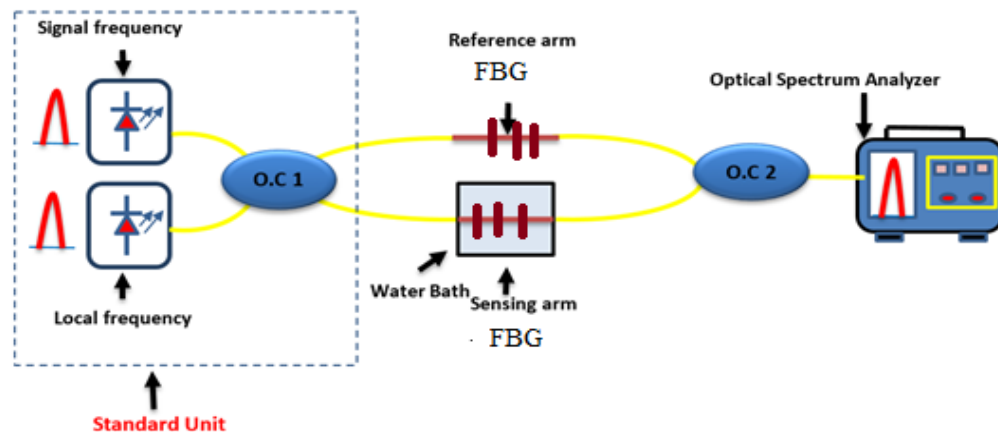


Figure 4: Block diagram of Optical heterodyne FBG temperature sensor.

The designed optical heterodyne system based temperature sensor was simulated using Optisystem 15.0 software is shown as block diagram in Figure (5).

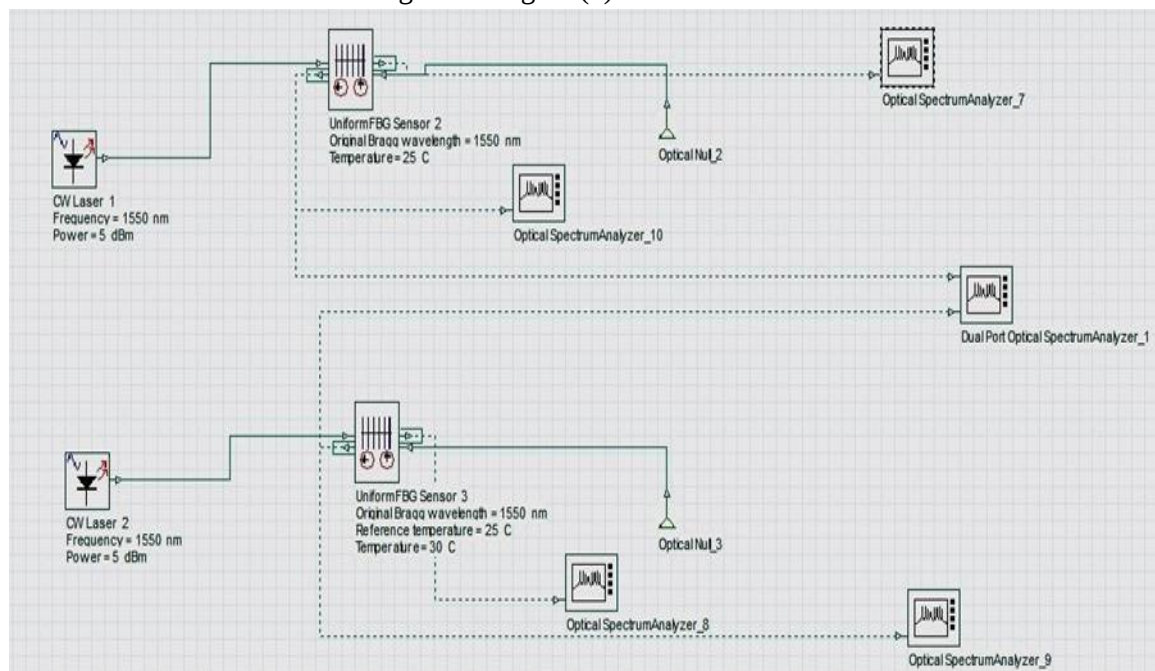


Figure 5: Optical heterodyne system using FBG temperature sensor using dual LD sources.

Finally, to get a modified heterodyne optical system via using tunable source from single laser source using FBG as tuneable element. A new modified MZI is made in which the light from the 1550nm LD is launched into the single-mode fiber and split by a coupler into the two arms of the MZI interferometer of single-mode fibers with two inscribed identical Bragg gratings shown as block diagram in Figure (6).

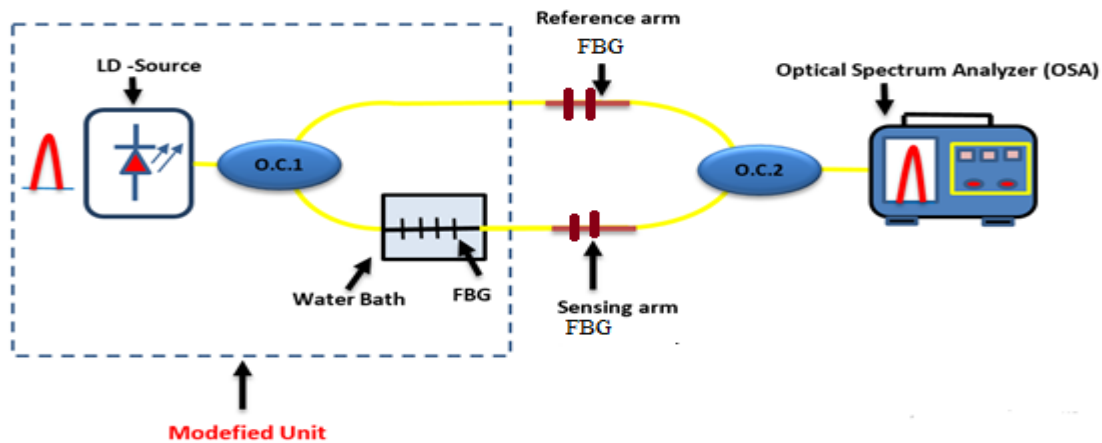


Figure 6: Block diagram of new modified Optical heterodyne temperature sensor.

By controlling the ambient temperature of the FBG, the wavelengths and their ranges can be controlled in way that satisfies the condition of beat frequency range. The designed new modified optical heterodyne system based temperature sensor was simulated by using Optisystem 15.0 software is shown as block diagram in Figure (7).

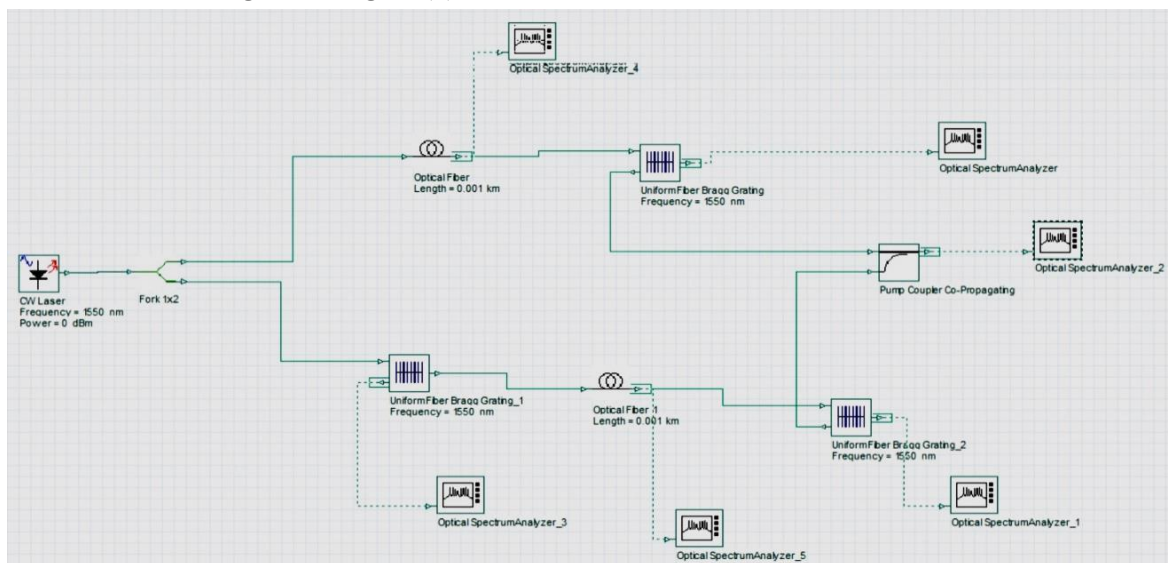


Figure 7: A new modified Optical heterodyne system using FBG temperature sensor using single LD source.

3. Results and discussion

To achieve the idea of the proposed work of the **first case**, a homodyne FBG temperature sensor results within range (25-100 °C) are shown in Figure (8a). Moreover, the wavelength shift according to temperature variation between two temperature values (peak at 1550nm) at (25°C) and (peak at 1551nm) at (100°C) are shown in Figure (8b). The wavelength shift value for this temperature range is equal to (1 nm). When temperature increased from 25 to 100° C, there was a significant deviation in the difference frequency arising from the homodyne optical interference of the reference arm and other generated by sensing arm. Figure (9) shows the difference between the two wavelengths (or frequencies) versus applied temperature. The sensitivity of this sensor is about 12.75 pm/°C, which is the same as [15].

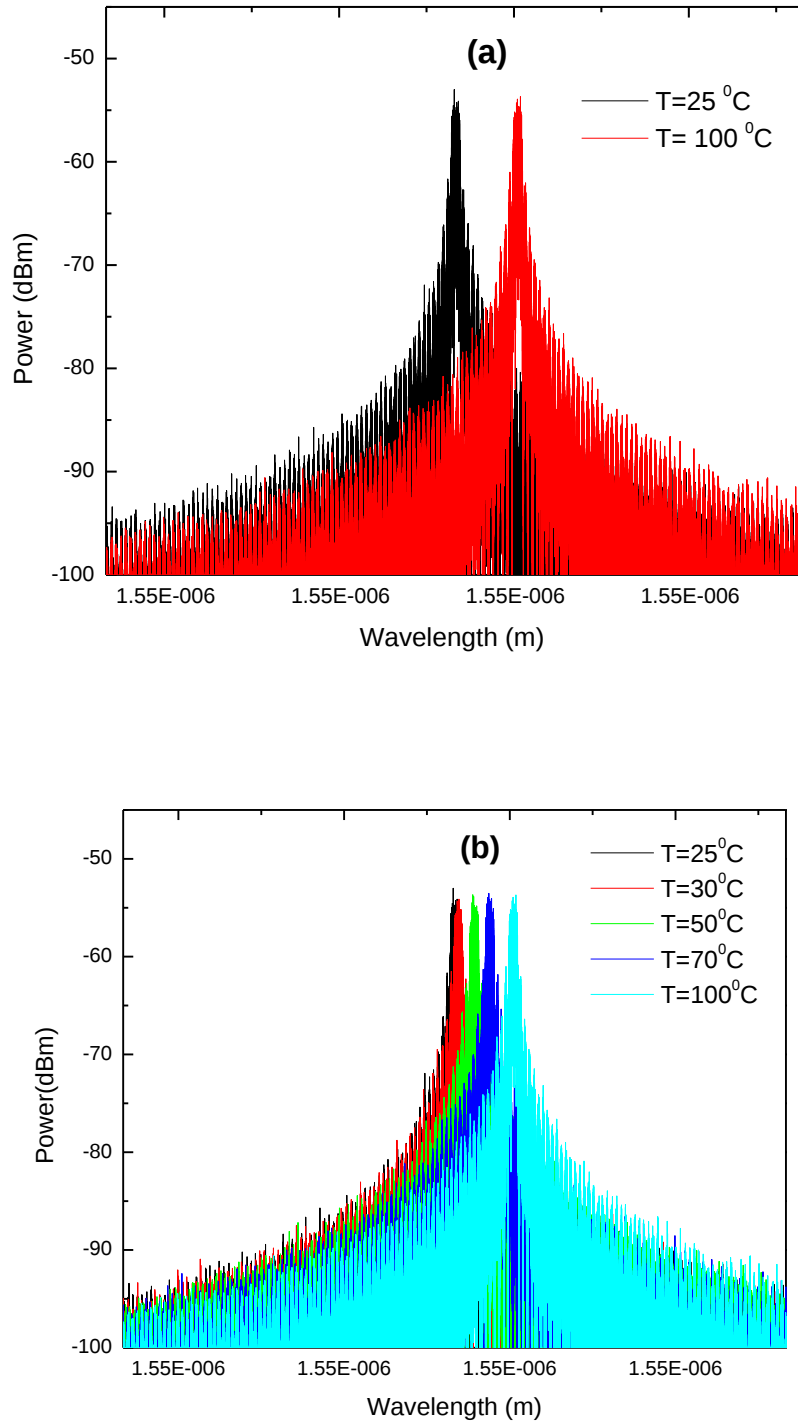


Figure 8: Homodyne optical FBG temperature sensor wavelength shift vs. temperature variation range (a) (25-100°C), (b) for selective temperature degrees.

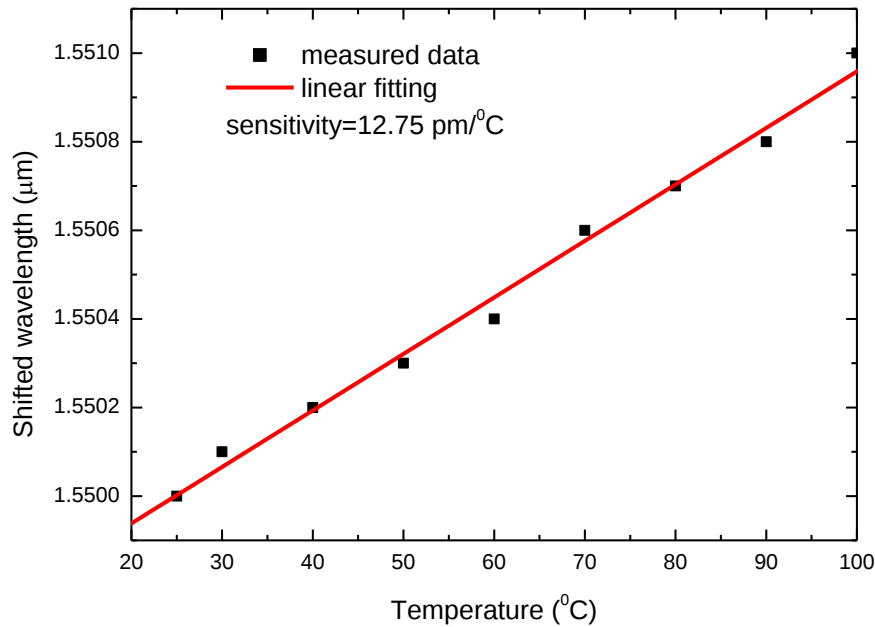


Figure 9: The shifted wavelength versus applied temperature.

Second case, a standard heterodyne FBG temperature sensor using dual sources results within range (25-100 °C) are shown in Figure (10a). Also, the beat frequency in range of (wavelength scale) according to temperature variation between two temperature values (peak at 1550nm) at (25°C) and (peak at 1551.12nm) at (100°C) are shown in Figure (10b). The beat frequency shift value in range of (wavelength scale) for this temperature range is equal to (1.12 nm).

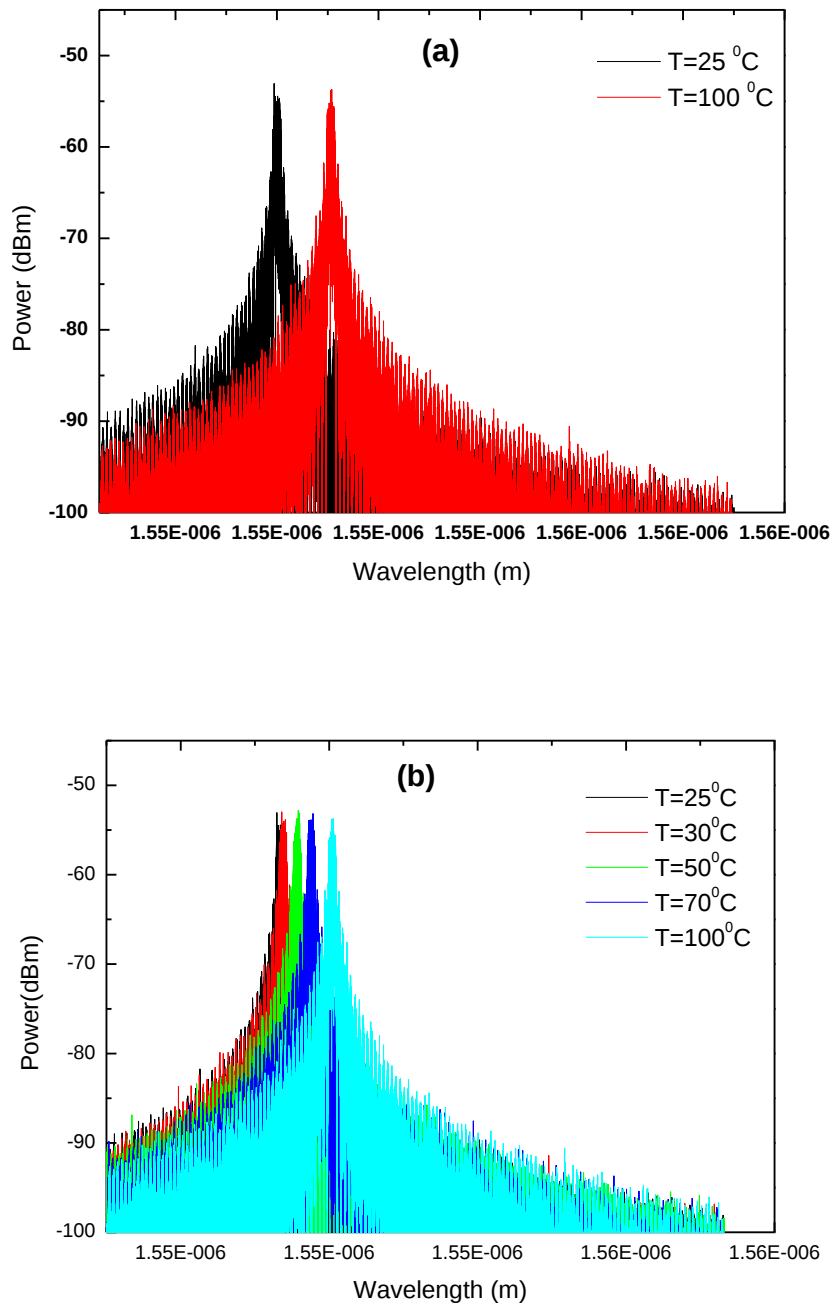


Figure 10: Heterodyne optical FBG temperature sensor with dual source beat frequency shift in range of (wavelength scale) vs. temperature variation range, (a) (25-100°C), (b) for selective temperature degrees.

When temperature increased from 25 to 85 °C, there was a significant deviation in the difference beat frequency arising from the heterodyne optical interference of the reference arm and other generated by

sensing arm. Figure (11) shows the difference between the two wavelengths (or frequencies) versus applied temperature. The sensitivity of this sensor is circa 13.12 pm/°C.

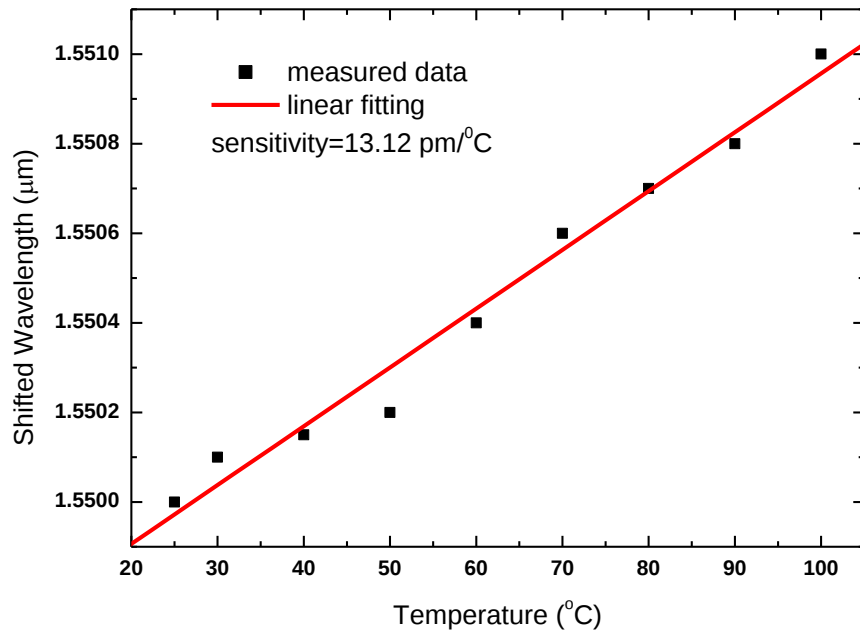


Figure 11: The shifted beat wavelength versus applied temperature.

Third case, a modified heterodyne FBG temperature sensor using single sources results within range (25-100 °C) are shown in Figure (12a). The beat frequency in range of (wavelength scale) according to temperature variation between two temperature values (peak at 1550nm) at (25°C) and (peak at 1556nm) at (100°C) are shown in Figure (12b). The beat frequency shift value in range of (wavelength scale) for this temperature range equal to (6 nm).

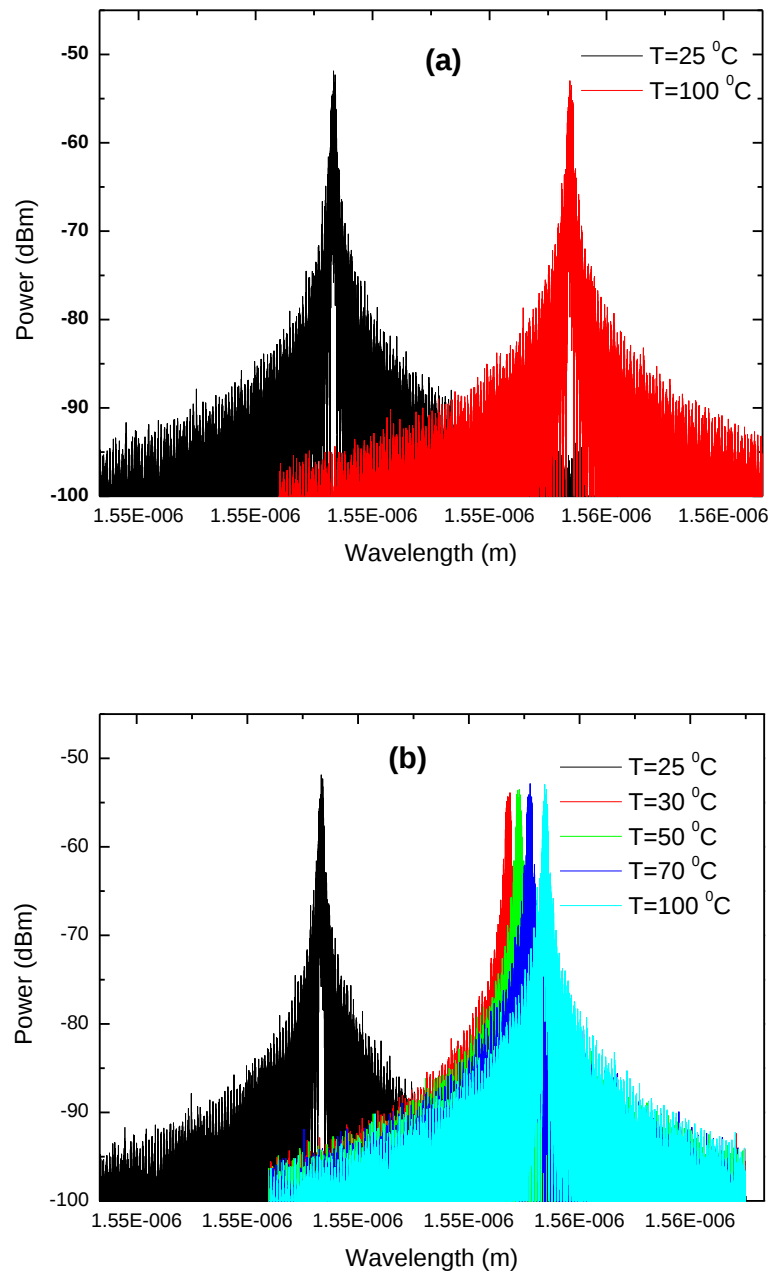


Figure 12: A modified heterodyne optical FBG temperature sensor with single source beat frequency shift in range of (wavelength scale) vs. temperature variation range (a) (25-100°C), (b) for selective temperature degrees.

When temperature increased from 25 to 85 °C, there was a significant deviation in the difference beat frequency arising from the modified heterodyne optical interference of the reference arm and other generated by sensing arm. Figure (13) shows the difference between the two wavelengths (or frequencies) versus applied temperature. The sensitivity of this sensor is circa 67.63 pm/°C, which is four times higher than that of 14.74 pm/°C high-resolution heterodyne temperature sensor [16].

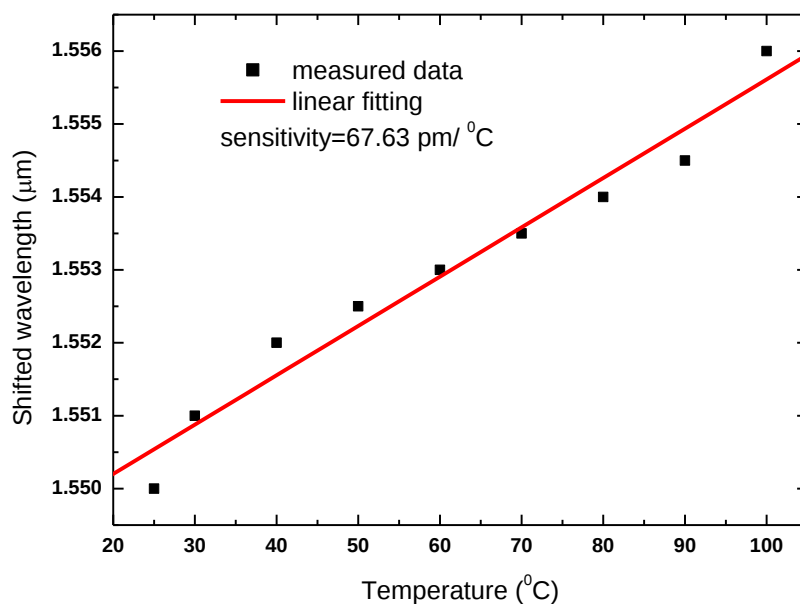


Figure 13: The shifted beat wavelength versus applied temperature.

4. Conclusions

In this work, FBG used as FBG element to design a modified heterodyne optical system to get tenable source from single laser source to generate two specific wavelengths gives stability in performance, reducing costs and requirements. This system characterized by its high sensitivity. Any undesirable effect can be calibrated by ensuring that it reflects on both frequencies generated from the same laser source is the same value and therefore does not affect its output compared with the use of different sources that are difficult to control and calibrate the factors affecting them in the same amount. Finally, the sensitivity of the modified heterodyne FBG temperature sensor is about 67.63 pm/°C.

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5. References

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