مجلة جمعية الليزر العراقية
Iraqi Laser Society Journal
I.L.S.J.

Issue-2 2nd Year 2025

Construction of Heterodyne Detection System Utilizing Fiber Bragg Grating

Sawsan K. Fandi, Esraa K. AL-Gazzi, Suaad M. Ali, Aseel I. Mahmood

Ministry of Higher Education and Scientific Research/ Scientific Research commission Industrial Applications Research and Materials Technology Center, Laser and Optoelectronics Research and Technology Department, Baghdad, Iraq.

Email: sawsanfendi68@gmail.com

Abstract

In this study, a heterodyne detection system is designed and constructed to detect the wavelength shift between the reference and sensing signals that results from temperature changes. A laser diode 1550 nm optical source is employed as a reference arm. While the sensing arm is represented by Erbium Doped Amplifier Fiber (EDAF). Fiber Bragg Grating (FBG) is used as a tunable element to generate different wavelengths according to the change in temperature. The Optical Spectrum Analyzer (OSA) displays the intermediate signal (beat signal) which, represents the difference between reference and sensing signals. As the temperature rises, the wavelength shifts linearly to a longer wavelength, whereas the wavelength shifts toward shorter wavelengths with the decrease in temperature. In the temperature range of (30-80) degrees Celsius, from the linear relation of beat (intermediate) wavelength and beat frequency versus the temperature, wavelength Sensitivity (WS) and Frequency Sensitivity (FS) as well as the resolution for heterodyne detection system in the case of heating and cooling, are analyzed and calculated.

Keywords: Beat frequency, Fiber Bragg Grating, Heterodyne detection, Terahertz.

مجلة جمعية الليزر العراقية
Iraqi Laser Society Journal
I.L.S.J.

Issue-2 2nd Year 2025

بناء منظومة كشف هيتيرودايني باستخدام ليف محزز براك

سوسن خلف فندي ، اسراء كامل ، سعاد محمد علي ، اسيل ابراهيم محمود

وزارة التعليم العالي البحث العلمي/ هيئة البحث العلمي/مركز بحوث التطبيقات الصناعية وتكنولوجيا المواد

قسم بحوث وتكنولوجيا الليزر والكهروبصريات

Email: sawsanfendi68@gmail.com

الخلاصة

في هذه الدراسة، تم تصميم وبناء نظام كشف هيتيرودايني لاكتشاف انزياح الطول الموجي بين إشارات المرجع والإشارة المستشعرة الناتجة عن التغيرات في درجة الحرارة. يتم أستخدام دايود ليزري بطول موجي 1550 نانومتر كمصدر ضوء مرجعي. بينما يمثّل ذراع الاستشعار بواسطة ليف التضخيم المطعم بمادة الاريبيوم (EDAF). يتم استخدام ليف محزز براك كعنصر قابل للتعديل لتوليد أطوال موجية مختلفة وفقًا للتغير في درجة الحرارة. يعرض محلل الطيف البصري الاشارة الوسيطة التي تمثل الفرق بين إشارة المرجع والإشارة المستشعرة. مع ارتفاع درجة الحرارة، ينزاح الطول الموجي بشكل خطي نحو أطوال موجية أطول، بينما تحدث الازاحة نحو الأطوال الموجية الأقصر عند انخفاض درجة الحرارة. في نطاق درجات الحرارة من 30 إلى 80 درجة مئوية، تم تحليل وحساب حساسية الطول الموجي (WS) وحساسية التردد (FS) بالإضافة الى قدرةالتحليل لنظام الكشف بالهيتيرودايين في حالتي التسخين والتبريد استنادًا إلى العلاقة الخطية بين الطول الموجي والتردد مع درجة الحرارة.

الكلمات المفتاحية: تردد الازاحة، ليف محزز براك، الكشف الهيتيرودايني، تيراهيرتز.

Introduction:

Heterodyne detection or (coherent detection) is a detection method which was originally developed in the field of radio waves and microwaves. This technique is based on two separate sources with optical interference between them. The optical weak signal from a specific light source that caries the information to be measured (sensing signal) is combined with a powerful "local oscillator" signal (reference signal) [1,2]. The primary objective is to determine the frequency difference between these two light beams. Beat frequency (fB) or intermediate frequency which is a new generated frequency due to mix reference and sensing signals. The resulting mixing signal is then detected, often after filtering out the original signal and the local oscillator frequency. The frequency of the mixing signal is the sum or the difference of the frequencies of the signal and the local oscillator. The optical information embedded in this intermediate frequency signal encompasses frequency, amplitude, phase, and other parameters [3,4].

The electromagnetic fields due to the two beams of coherent light waves can be represent by [1-4]:

$$E1= AR \cos (\omega Rt +\theta 1) \quad ...1$$

$$E2= AS \cos (\omega St+\theta 2) \quad …2$$

In this context, E represents the electric field, while AR and AS denote the amplitudes of the reference and sensing signals, respectively. The symbol (θ) indicates the relative phase between the two signals, and ωS and ω R are the angular frequencies of the sensing and reference signals, respectively [1-4]. The principle of optical heterodyne detection involves generating a heterodyne beat signal by calculating the phase shift difference between the reference and sensing signals. High-frequency and constant components are filtered out, leaving the beat frequency. Consequently, the interference of the two waves with amplitudes AS and AR, and angular frequencies (ωS, ωR) produces an intensity modulation at the beat frequency, fB or Δf = |fs ± fR| (which is then detected as described in the equation (3) , The absolute value is used because beat frequency is always a positive value. The output electromagnetic waves of the interferometer are combined in a photodetector of Optical Spectrum Analyzer (OSA) then the generated intensity (I) is given by the total electric field square, as shown in equation(3)

[5- 7]

$$I = \underbrace{\frac{A_s^2+A_r^2}{2}}_{constant} + \underbrace{\frac{A_s^2}{2}\cos(2\omega_s t + 2\theta_1) + \frac{A_r^2}{2}\cos(2\omega_r t + 2\theta_2) + A_s A_r \cos((\omega_s + \omega_r)t + \theta)}_{High\ component} + A_s A_r \cos\left(\left(\underbrace{\omega_s - \omega_r}_{Beat\ signal}\right)t + \theta\right) \ldots\ldots\ldots\ldots\ldots 3$$

Figure (1) represents the optical heterodyne detection system, which includes two light sources (sensing and references sources), optical connections represented by optical fibers, OSA and photodetector to detect the signal optically and electrically, in addition to the presence of optical couplers.

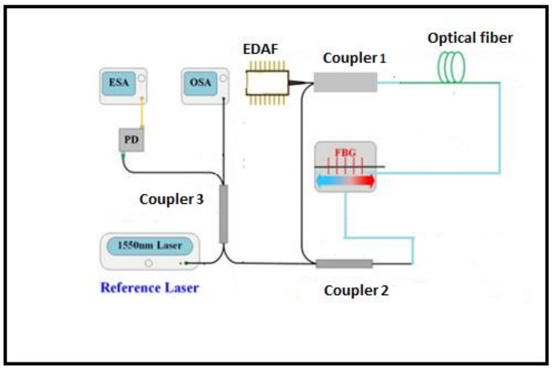

Fig. (1): Block diagram of heterodyne detection system [8].

We notice from the above figure presence Fiber Bragg grating (FBG) which represents a crucial component that can be defined as an optical fiber in which the refractive index within the core varies along its length, transitioning from high-index to low-index regions. This modulation of the refractive index enables the FBG to function like a mirror, reflecting specific wavelengths while transmitting others. Figure (2) represents the external shape of FBG [9].

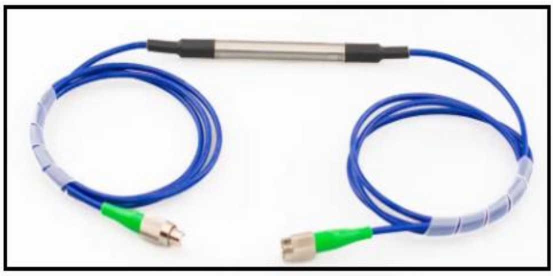

Fig. (2): External view of FBG.

FBGs are created by laterally exposing the core of a single-mode fiber to a periodic pattern of intense laser light. This exposure results in a permanent increase in the refractive index of the fiber's core, establishing a fixed index modulation that corresponds to the exposure pattern. This permanent modulation is referred to as a grating [10].

At each periodic change in refractive index, a small amount of light is reflected. When the grating period is approximately half the wavelength of the input light, all reflected light signals combine coherently to create a significant reflection at a specific wavelength. This phenomenon is known as the Bragg condition, and the wavelength at which this reflection occurs is referred to as the Bragg wavelength (λBragg). Light signals at wavelengths other than the Bragg wavelength, which are not phase-matched, remain essentially transparent [9,11].

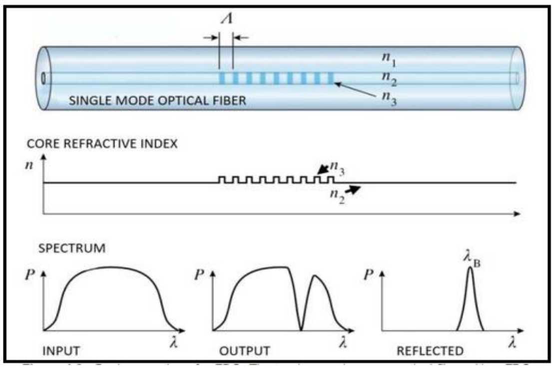

Fig. (3): The fundamentals of an FBG. An optical fiber with an FBG etched in its core is depicted in the top image. The refractive index of the core transformed into a periodic modulation is shown in the center figure. The input light spectrum, the resulting transmitted spectrum, and the spectrum reflected by the FBG are shown in the bottom image, from left to right.

Thus, light travels through the grating with minimal attenuation or signal variation. Only the wavelengths that meet the Bragg condition are impacted and strongly back-reflected. The capacity to precisely set and maintain the grating wavelength is a key feature and advantage of Fiber Bragg Gratings.

The basic principle governing the operation of a Fiber Bragg Grating (FBG) is Fresnel reflection, which occurs when light travels between materials with differing refractive indices, resulting in both reflection and refraction at the interface. The refractive index typically varies over a specified length. The reflected wavelength (λBragg) is determined by the following relationship. [4,11].

$\lambda_B = 2n_{eff}\,\Lambda$……………………….4

Where n_{eff} represents the effective refractive index of the fiber core, and Λ is the grating period. The effective refractive index measures the speed of propagating light in comparison to its speed in a vacuum [12-14]. n_{eff} influenced not only by the wavelength but also, in the case of multimode waveguides, by the mode of light propagation. For this reason, it is often referred to as the modal index [4,11].

Due to the temperature and strain dependence of the parameters n_{eff} and Λ the wavelength of the reflected component will change in response to variations in temperature and/or strain. This dependency is well established, enabling the determination of temperature or strain from the reflected FBG wavelength, as illustrated in Figure (4) [9].

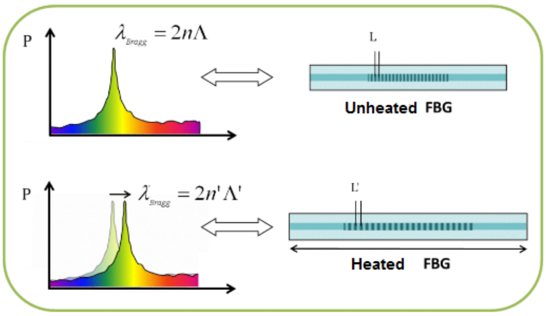

Fig. (4): FBG response as a function of temperature [9].

Numerous academics have thoroughly examined the heterodyne detection method using a range of methodologies.

In 2012, Jie Y. et al. used a semiclassical approach to explain heterodyne detection with two optical detectors. They showed that excess noise in the local oscillator can be canceled, and balanceddetector methods require less local oscillator power than traditional ones. An experimental demonstration of noise cancellation was provided.

In 2017, Marwa M. Sami et al. presented a heterodyne detection system using photonic crystal fiber (PCF) to detect temperature-induced wavelength shifts. The system featured a 1550 nm optical source, with a reference arm using PCF and a sensing arm with Fiber Bragg Grating. Results showed a linear wavelength shift-temperature relationship with a sensitivity of -65.83 pm/°C in the 30-70°C range.

In 2018, Shehab introduced a system combining a single laser source with a Fiber Bragg Grating (FBG) as a tunable source to achieve OHD, using single-mode fiber for the sensing arm.

In 2019, A. Resen et al. present a new Optical Heterodyne Detection (OHD) method using Optisystem software, where Fiber Bragg Gratings (FBGs) are used in a system with a single light source. One FBG acts as a tunable source, and the other serves as a sensing element, with a photodetector combining the optical signals. The results that the researches obtained show a linear beat frequency shift in response to temperature, with a sensitivity of 2.24 GHz/°C.

In 2020, Ammar S. Alattar et al. presented an optical heterodyne temperature sensor system using Fiber Bragg Grating (FBG). Two techniques were tested: one with dual laser diodes and another with a tunable single laser source controlled by the FBG. Simulation results showed that the single-source design improved wavelength shift and sensitivity.

In 2020, Hedi B and Mustafa A.G. Abushagur described a temperature sensor using Fiber Bragg Gratings (FBGs) with heterodyne detection. One FBG serves as a reference and the other as a sensing element, with a Folded Mach-Zehnder interferometer to detect temperature-induced wavelength shifts. The sensor's dynamic range and sensitivity were also analyzed.

In 2020, Deyaa A. Resen et al. proposed an optical fiber sensor using the optical heterodyne technique (OHT), with a bandpass filter (BPF) as the reference and Fiber Bragg Grating (FBG) as the sensing element. The system detects interference between reflected signals for high-resolution measurement. Applied to temperature sensing, it achieved a sensitivity of 1.152 GHz/°C.

In 2022, Yanqi developed a fiber-based two-wavelength heterodyne interferometer for sensitive displacement measurement in inertial sensing. The system demonstrated a sensitivity of 7.5 pm/√Hz at 1 Hz, with algorithms proposed to address periodic errors.

In 2023, Chunxi proposed a dual-pulse heterodyne distributed acoustic sensor (DAS) system utilizing a semiconductor optical amplifier-based fiber ring laser. This approach simplifies the configuration by replacing the narrow linewidth laser and pulse modulator, enhancing the system's adaptability.

In 2024, Xiang proposed a photonic-assisted microwave frequency measurement (MFM) method based on optical heterodyne detection. The system combines a linearly chirped optical waveform and a multi-wavelength signal for efficient frequency measurements. In the current research, the Bragg grating is used as a tuning element to generate wavelengths as a result of its exposure to a range of temperatures within the optical heterodyne system.

Experimental Setup

The experimental setup of Implementation of Heterodyne Detection system utilizing Fiber Bragg Grating is illustrated in figure (5). In this experiment, two laser sources are used: the first is the Erbium Doped Amplifier Fiber

(EDAF) with 1550 nm as a wavelength, which represents the first arm. This source is injected into a (FBG) which is centered at a wavelength of 1551 nanometers. The second arm is represented by laser diode whose wavelength is close to that of the first source that (1547) nm as wavelength. These two optical sources are the key components of the heterodyne theory. The output optical signal, which represents the mixing of two signals is shown by the computer utilizing an Optical Spectrum Analyzer (OSA) type (Thorlabs) as demonstrated in figure (6) which represents the intensity of sensing signal, that enveloped by local oscillator, as a function of wavelength range for the two sources. All these devices and equipment in our experiment is connected to each other using three optical couplers.

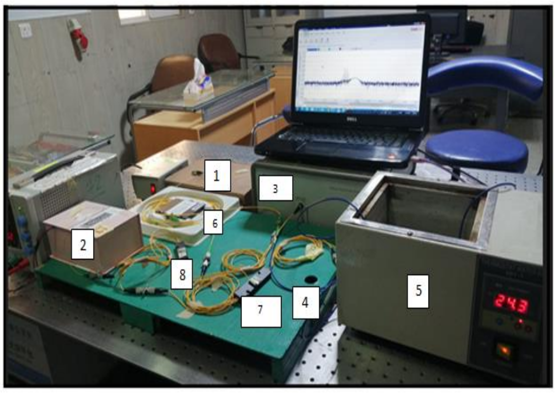

Fig.(5): The experimental setup of Implementation of Heterodyne Detection system that include:1: EDAF, 2: Laser diode, 3: OSA, 4: FBG, 5: water bath, 6,7 and 8 denote the optical couplers

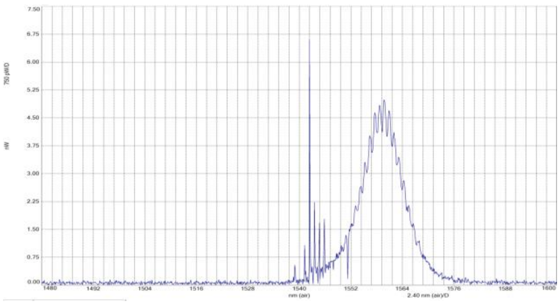

Fig. (6): The optical signal that represent the mixing of two sources.

Figure (7) represents five spectra for the frequencies corresponding to the varying Bragg wavelengths (λ_{Bragg}) at five different temperature values. These changes in wavelengths and their corresponding frequencies were adopted to calculate the Beat wavelengths, as well as the Beat frequencies.

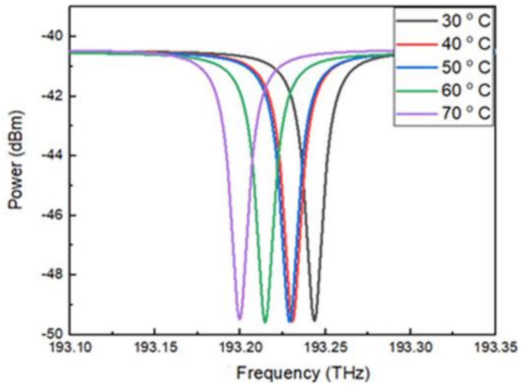

Fig. (7): The inverse relationship between maximum Bragg frequencies and temperatures

n an optical heterodyne detection system, Frequency Sensitivity (FS) or Wavelength Sensitivity (WS) are important characteristics referred to how the system responds to changes in the wavelength or frequency of the incoming optical signal. (FS) refers to the ability of the heterodyne detection system to detect small variations in the incoming signal's frequency. Also (WS) refers to how sensitive the system is to the changes in the wavelength of the incoming optical signal. Both (FS) and (WS) are crucial because this system typically operates by mixing two optical signals (local oscillator and sensing signal) producing a beat frequency or beat wavelength that represent the difference between the two signals.

To verify the relationship between temperature and beat frequency or wavelength, we first show how temperature influences the Bragg spectrum. This is achieved by adjusting the temperature between 30 and 70 degrees using water bath. During the experiment, the ambient temperature was approximately 30 °C, while the initial water temperature was 25°C. We recorded data as the water temperature gradually and steadily increased and then decreased.

Results and Discussions

Accurate measurements of Beat frequency or Beat wavelength changes brought on by temperature changes are essential in many spectroscopic applications to comprehend how the system behaves under various circumstances. Since heterodyne detection systems rely on the interference between the two signals, local and sensing signals, to identify subtle spectrum shifts, they are frequently utilized in this context to examine these changes with great accuracy.

Understanding how temperature affects frequency or wavelength is crucial for comprehending how the environment affects system performance. These impacts might be caused by internal device modifications or external environmental factors.

In order to improve measurement accuracy and result interpretation, this section will offer the figures that show how Beat frequency or Beat wavelength changes with variations with temperature in the heterodyne detection system. Figure (8) represents the relationship between Beat wavelengths as a function of temperatures. The results were obtained over the temperature range from (30 to 80) °C. It can be observed that the wavelength is linearly changed with the temperature over the entire range and increased with an increment of temperature. The observed red shift in the wavelength with increasing temperature is due to the combined effect of thermal expansion and the thermo-optic effect, leading to a proportional increase in wavelength.

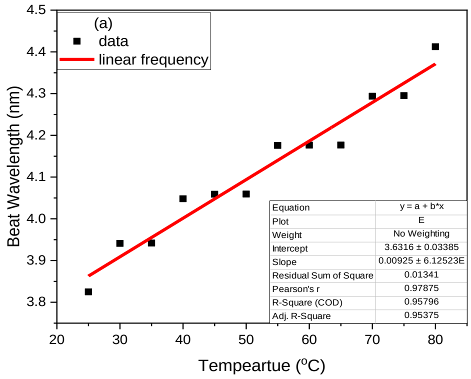

Fig. (8): The shift in Beat wavelength for different values of temperature in the case of heating.

The figure clearly shows that the wavelength shift is in the direction of longer wavelengths (red shift) with increasing temperatures. Most sample points fall inside or near the best-fitting line, as shown by the test data, this suggests that within the temperature range of 30 to 80 °C, the system may achieve steady operation with linearity (0.95).

To validate the accuracy of the optical heterodyne method all of the data was measured from OAS were converted from wavelength domain to frequency domain as shown in figure (9).

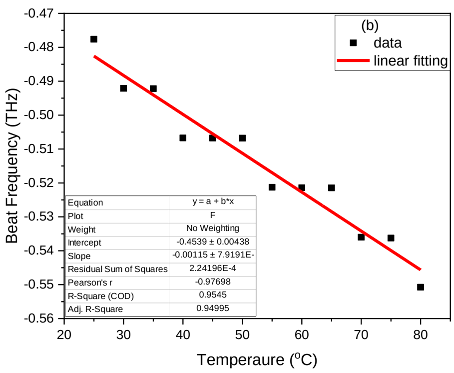

Fig. (9): The inverse relationship between Beat frequency and temperature in the case of heating.

The frequency drops as the temperature rises, according to the graph's inverse linear relationship between the two variables. It is evident that the behavior stays almost constant, suggesting that temperature has a steady and reliable impact on frequency. The nearly graph's good straight-line fit demonstrates the system's precision and stability in heterodyne detection with linearity (0.95). Figures (10) and (11) represent the behavior of the Beat wavelength and Beat frequency in case of decrement of temperature (the cooling) in the system.

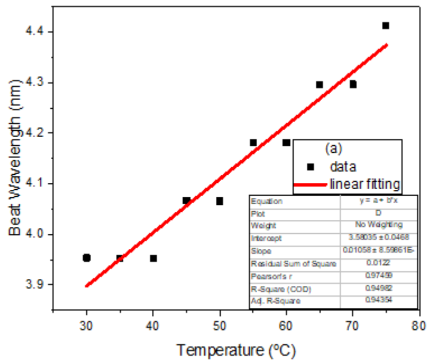

Fig. (10): The wavelength shifts for different values of temperature in the case of cooling.

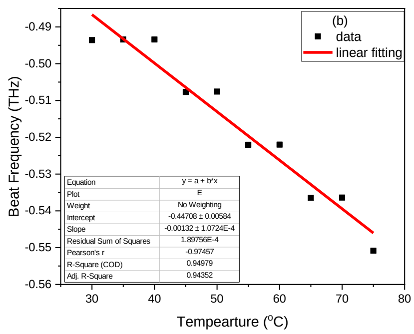

Fig. (11): The inverse relationship between the frequency and temperature in the case of cooling.

The two figures in the case of cooling behave similarly to the earlier ones (in the case of heating), which is to say that when the temperature drops, the wavelength decreases and the frequency increases.

The scientific definitions of FS and WS were given above. Mathematically and in heterodyne detection they may now be described as the wavelength or frequency change as a function of temperature change, which is equivalent to the slope of the straight line that results from the wavelength or frequency change with temperature variation. Based on the aforementioned data, (WS) and (FS) have been determined to be (9.25Pm/^{o}C) and (-0.00115THz/^{o}C) in the case of heating and (10.58 Pm/^{o}C) and (-0.00132 THz/ ^{o}C) in the case of cooling respectively. The minus sign accompanying the values of frequency sensitivity indicates the inverse relationship between the frequency and temperature.

The ability of a heterodyne detection system to discriminate between two closely spaced frequencies or wavelengths is referred to as *Resolution (R).* In essence, it is the shortest wavelength variation that the system can accurately detect and quantify. Here, (R) is calculated to be (1.08×10^{-3} ^{o}C), (1.05×10^{-3} C) in the case of heating and cooling respectively.

Small values of (f_B) mean that it is possible to distinguish between the very close wavelengths in the heterodyne detection system. The spectral line width of (f_B) is extremely tiny, usually in the Terahertz range; this indicates that (f_B) is contained within the Radio Frequency (RF) range. It may convey the same information as the original signal despite having a tiny line width. This facilitates the transmission of high-frequency data over a lower frequency channel, or within the radio frequency range, which is easier to manage and helps increase the accuracy of spectral measurements.

The information encoded on the original signal is still carried by the intermediate frequency, despite it being within the radio frequency range. The information is preserved when the original frequency is changed to the intermediate frequency, but the frequency is lowered to make it easier to detect and process many applications, including spectroscopic systems, radar systems, and wireless communication applications, depend on the heterodyne system for high-precision frequency and signal detection. The use of Beat frequency, which has a narrow line width but conveys the same information, improves detection capabilities while maintaining spectral accuracy. Therefore, the Beat frequency in this system serves as a tool that combines the convenience of managing radio frequencies with the precision of the signal.

Conclusion

In the heterodyne detection system, the spectral line width of (fB) is very narrow, usually in the Terahertz range allow for the separation of very close wavelengths. This makes it easier to handle and improves the precision of spectral measurements by enabling the transmission of high-frequency data via a lower frequency. This preserves the information from the original signal while improving the efficiency of detection and processing, even though it is in the radio frequency range. Also, this investigation into the heterodyne detection system looked at how temperature changes affect both frequency and wavelength. The findings demonstrated that the wavelength varies linearly with temperature, rising at higher temperatures and falling at lower ones. Additionally, it was noted that frequency varies inversely with temperature. By modifying wavelength and frequency in response to external variables, this behavior can help optical heterodyne detection systems operate at their best.

Conflict of Interest:

The authors declared no conflict of interest.

References

[1] Hedi B, Mustafa A.G. Abushagur, "Heterodyne detection for Fiber Bragg Grating sensors", Article in Optics & Laser Technology · July 2000.

[2] Jie Y. et al., "A Balanced Optical Heterodyne Detection for Local-oscillator Excess-noise Suppression",Article in Proce edings of SPIE - The International Society for Optical Engineering · November 2012.

[3] Ammar S. Alattar et al., "Performance simulation and design comparison of optical heterodyne temperature sensor based on Fiber Bragg Grating", IOP Conference Series: Materials Science and Engineering 2020.

[4] Deyaa A. Resen et al., "Design System of Optical Heterodyne Detection Based on Temperature Sensor". 2nd International Conference on Sustainable Engineering Techniques (ICSET 2019).

[5] Marwa M. Sami et al. , "Design And Implementation Of Heterodyne Detection Based On Photonic Crystal Fiber Sensor", Article in Advances in Natural and Applied Sciences · June 2017.

[6] Deyaa A. Resen et al. , "Optical Fibre Sensor Using Frequency Beating", International Journal of Nanoelectronics and Materials Volume 13, No. 2, Apr 2020.

[7] Hely, G., et al., "Micrometric displacement sensor based on the strain of a fiber Bragg grating with heterodyne detection of intensity in a Mach Zehnder interferometer", IOPJournal of Physics: Conf. Series, 792(1): p.1-6,2017.

[8] Duan L. et al., "High-Resolution Temperature Sensor Based on Single-Frequency Ring Fiber Laser via Optical Heterodyne Spectroscopy Technology", Journal, Sensors 2018.

[9] Abdollah Malakzadeh et al., "Simultaneous measurement of temperature and strain based on peak power changes and wavelength shift using only one uniform fiber bragg grating", journal of optical and quantum Electronic, 2021.

[10] Huang J. et al., "A fiber Bragg grating pressure sensor and its application to pipeline leakage detection," Advances in Mechanical Engineering 5 (2013) 590451

[11] Marcelo M. Werneck et al. "Fiber Bragg Grating :theory , fabrication, a application", PSIE, the international society for optics and photonics, 2017.

[12] Shehab, A., et al., " Tunable Optical Wavelength Interferometer Heterodyne System from Single Laser Source Using Fiber Bragg Grating", International Journal of Engineering & Technology, 7(4): pp. 3086–3089, 2018.

[13] Chnxi Z. et al., "Dual pulse heterodyne distributed acoustic sensor system employing SOA-based fiber ring laser", Frontiers in Physics, vol.11, 2023.

[14] yange Z. and Felipe G. "Fiber-based two-wavelength heterodyne laser interferometer", optics express, vol.30, No. 21, 2022.