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Research paper

Tunable Optical Wavelength Interferometer Heterodyne System from Single Laser Source Using Fiber Bragg Grating

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Abstract

In this work, a new heterodyne optical system had been designed to get tunable source from single laser source using Fiber Bragg Grating (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 satisfy the condition of beat frequency range. First SMF had been used in both reference arm and sensing arm. Then the system had been modified by utilizing of Photonic Crystal Fiber (PCF) in both reference arm and sensing arm. This modification provides better performance efficiency by increasing the wavelength shift of the temperature sensor. The achieved sensitivity for range from room temperature to 85 ° C was 52.01 pm/°C for model that's used SMF and 68.17 pm/°C for model that's used PCF in both reference and sensing arm. The importance of the idea is that it can be employed as a new technique in the heterodyne detection systems that have become widely applicable applications.

Keywords: *Fiber optics sensors; Fiber Bragg gratings; Heterodyne; Photonic crystal fibers; Tunable source.*

1. Introduction

Tunable lasers play important roles in optical sensing, in origin most of tunable lasers were developed for optical communication systems were successfully used in sensing fields [1]. These include various temperature-tuned distributed feedback (DFB) lasers, external cavity tunable diode lasers [2], Multi-section distributed Bragg reflector lasers [3], and MEMS-based tunable VCSELs [4].

Fiber Bragg Gratings (FBG's) has received extensively interest and greatly contributed to the development of photonic sensing where the Bragg wavelength of FBG is very sensitive to the surrounding environment, fiber telecommunication system and fiber Bragg Lasers [5, 6].

FBG couple light from a forward propagating mode in to a backward or counter propagating guided mode at the Bragg wavelength λB. This is the wavelength for the Bragg reflection, which is the phenomenon by which a single large reflection can result from coherent addition of many small reflections from weakly reflecting mirrors spaced a multiple of hall of the wavelength apart The equation relating the grating periodicity and the Bragg wavelength depends on the effective refractive index of the transmitting medium, neff and is given by [7]:

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

Where Λ grating period.

The temperature sensing of Bragg grating occurs principally through the temperature effect on the index of refraction and to a lesser extent through the expansion coefficient. It is noteworthy that temperature sensitivity can be enhanced or mulled by proper bonding to other materials. The maximum operating temperature may be around (500 ˚C); however, this may depend on the fabrication condition of the Bragg grating [8]

The wavelength sensitivity of Bragg grating is governed by the elastic-optic and thermo-optic properties. the theoretical analysis shows that if there is a short period grating with period Λ under influence change ΔT[9]:

$$\frac{d\lambda_B}{dT} = 2\left[\Lambda \frac{d\lambda_B}{dn_{eff}}\frac{dn_{eff}}{dT} + n_{eff}\frac{d\lambda_B}{d\Lambda}\frac{d\Lambda}{dT}\right] \qquad (2)$$

From the above equation, it can be seen that the contribution to the thermal induced shift is a function of change in refractive index with temperature d_{neff}/dT while the waveguide effect is dependent on the variation in grating period with temperature.

The shift in Bragg wave grating center wavelength due to temperature can be given by [9]:

$$\Delta\lambda_B = \lambda_B(\alpha_\Lambda + \alpha_n)\Delta T \qquad (3)$$

Where $\alpha_\Lambda = \left(\frac{1}{\Lambda}\right)\left(\frac{\delta\Lambda}{\delta T}\right)$, The thermal expansion coefficient for the fiber (approximately 0.55×10-6 1/˚C for Silica).

While $\alpha_n = \left(\frac{1}{n_{eff}}\right)\left(\frac{\delta n_{eff}}{\delta T}\right)$ Represents the thermal – optic coefficient, which is approximately equal to (8.6*10-6 1/˚C) for the Germanium – doped, Silica – core fiber [9].

Fiber Bragg grating laser sensors are classified according to their principle of operation into two categories: wavelength encoding sensor and polarimetric heterodyning sensor. The first one converts the measurand into a corresponding change in the operation wavelength of the laser. The narrower linewidth (typically several megahertz or hundreds of kilohertz) permits higher resolution

sensing. Taking advantage of an imbalanced interferometer, a slight change in optical frequency induced by external perturbations can be measured through phase detection. The second one relies on a beat signal from two orthogonal polarization lasing modes. When the cavity is perturbed, the beat frequency changes due to the variation of intracavity birefringence. An extremely weak change of (10 -8) in cavity birefringence can induce a beat-frequency variation of megahertz order, which is easy to detect due to the nature of the heterodyning sensor. The polarimetric heterodyning fiber grating laser sensor is important not only because of their high sensitivity to external perturbations, but also because the signal extraction is much easier and simpler regarding the beat frequency is in the RF domain, which does not require expensive wavelength measurement for wavelength-encoding sensors [10]. The polarimetric heterodyning sensor was first demonstrated by Kim et al. [11]. In their proposed sensor, applied lateral force is measured by detecting a beating frequency change. However, the multi-longitudinal-mode output causes unstable RF spectrum and is not beneficial for multiplexing because of the existence of multiple frequency components. Further efforts were carried out to reduce the number of longitudinal modes [12]. Wu et al. [13] submitted a synthetic-wavelength based heterodyne interferometer of optical frequency combs with wide consecutive measurement range for absolute distance measurement, this system realize an accuracy of 75nm in 350mm consecutive measurement range. Gonzalez et al. [14] presents a strain FBG sensor, they obtain a measurements in micrometer scales by heterodyne detection of intensity in optical fiber Mach- Zehnder interferometer, the sensitivity of the submitted design was 0.77pW/µm with displacement size of 480 µm in dynamic range from 0µm to 488µm.
The concept in optical heterodyne detection is to introduce a heterodyne beat signal was 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 produces an intensity modulation at the beat frequency, $\Delta f = f1 - f2$, which is then detected [15].
When the two beams of light interact with each other, the light field is [16]:

$$E = E_1 + E_2 \qquad (4)$$

The output signal from detector is proportional with described as following:

$$I = [E_{1+} E_2]^2 \qquad (5)$$

$$I = [(A_s \cos(w_s t + \theta_1)) + (A_r \cos(w_r t + \theta_2))]^2 \qquad (6)$$

$$I = \frac{A_s^2 + A_r^2}{2} + \frac{A_s^2}{2}\cos(2w_s t + 2\theta_1) + \frac{A_r^2}{2}\cos(2w_r t + 2\theta_2) +$$

$$A_s A_r \cos((w_s + w_r))t + \theta)$$

$$+ A_s A_r \cos((w_s - w_r)t + \theta) \qquad (7)$$

Compared with the direct detection, the heterodyne detection technique has a high sensitivity and more accuracy, which is extremely beneficial for weak signal detection this is the most basic advantage [16].

2- Experimental Work

In this work, a new heterodyne optical system was designed to get tunable source from single laser source using FBG as tunable element. By controlling the ambient temperature of the FBG, the wavelengths and their ranges can be controlled in way that satisfy the condition of beat frequency range. The system is stable when temperature is applied to the fiber. The operating principle of the proposed work is as follows. An optical source (Laser diode) of wavelength1550 nm and optical power circa600 µW was connected to the input of 50-50 optical coupler. The first output arm is represented the reference with the same wavelength of the laser source, then this arm is modified (which is explain later) by adding piece of Photonic Crystal Fiber (PCF) spliced between two equal lengths of Single Mode Fiber (SMF-28). While, the sensing arm is integrating to the FBG , also for the modified system , a piece of PCF is added to form iteration of SMF – FBG – SMF – PCF – SMF configuration, then a range of temperature degrees were added to this arm by immersion the sensing arm in water bath as it is clear in figure 1.

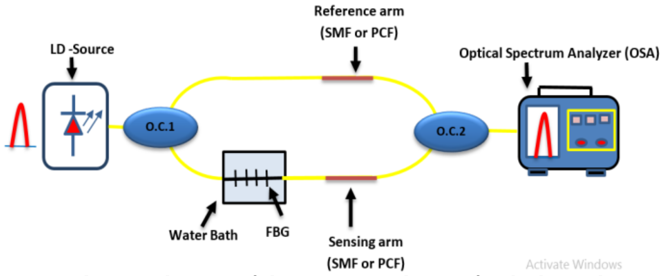
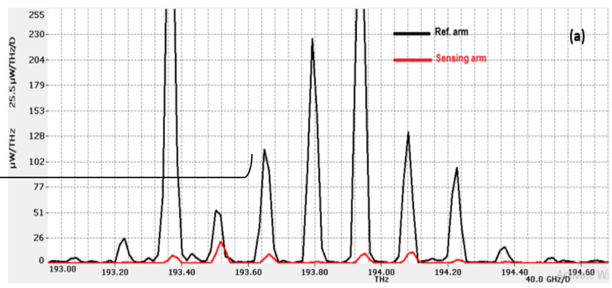


Fig. 1: Schematic diagram of the experimental setup for the heterodyne system.

The output from the two arms then connected to the two arms of 50-50 optical coupler, and the output to the high accuracy Optical Spectrum Analyzer (OSA-Thorlabs 203). First, a spectrum had been recorded in room temperature, then the FBG part in the sensing arm immersed in controlled temperature water bath to get different degrees of temperature in this work we reach to 85 ∘C. Then the spectrum also recorded to each temperature degree.

3-Results and Discussions

To achieve the idea of the proposed work, first we compare the emission spectrum of the reference arm with the output spectrum of the sensing arm at room temperature to ensure that the frequency of the two signals are identical. The beat frequency is circa 11.798 GHz. Figure 2 shows the emission spectrum at room temperature using SMF (a) for the reference arm and for the sensing arm, (b) the amount of frequency difference between the arms.



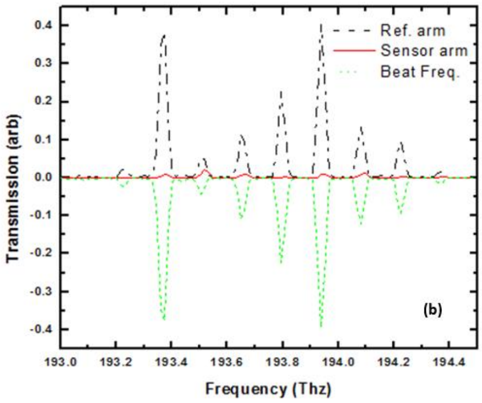


Fig. 2. Emission spectrum at room temperature using SMF (a) for the reference and sensing arms at R.T. (b) the amount of frequency difference between the two arms.

When temperature increased from room temperature to 85 ° C, there was a significant deviation in the difference frequency arising from the heterodyne optical interference of the reference arm and other generated by sensing arm. Figure 2 a shows the transmission spectrum at R.T and 85 °C. While figure 3 b shows the difference between the two wavelengths (or frequencies) versus applied temperature. The sensitivity of this sensor circa 52.01 pm/°C.

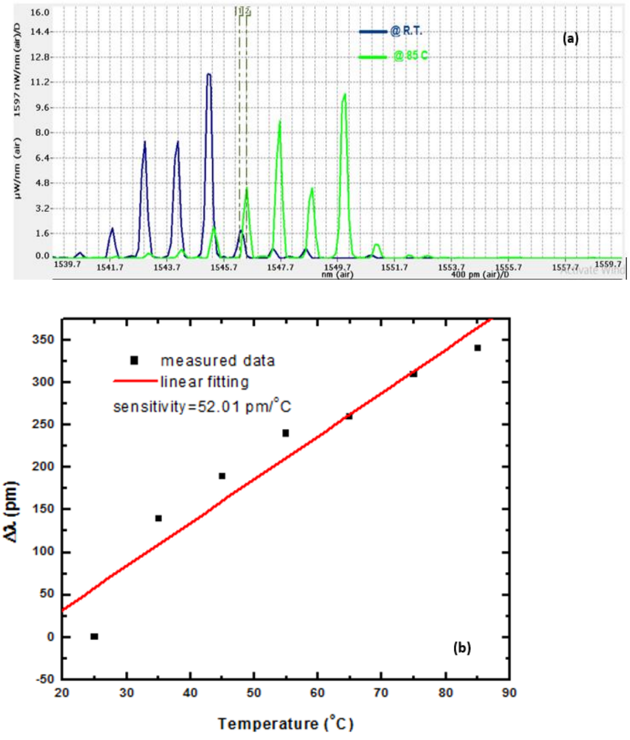


Fig. 3: (a) The emission spectrum within room temperature range and temperature of 85 ° C, (b) the wavelength difference versus applied temperature.

By controlling the ambient temperature of the fiber Bragg grating, the wavelengths and their ranges can be controlled by which the principle of optical harmony and synthesis of the wavelengths within the available permutations is determined by the spectral bandwidth of this single laser source and by the frequency of the signals The window and the reflector are sufficiently symmetrical so that their difference or frequency (beat frequency) is within the range required to achieve the hydrodynamic detection principle without the need for a second source.

Further enhancement were achieved by adding few mm's of PCFs in both reference and sensing arm, figure 1.

This achieved by spliced equal length of ESM-12B -PCF (Thorlabs) in both reference and sensing arms. Sensing arm has a different wavelength from the reference arm this is due to connecting it to FBG, the sensing arm was applied to temperature change from R.T. to 85°C, while the reference arm is kept isolated. In addition, as we compare the emission spectrum of the reference arm with the output spectrum of the sensing arm at room temperature to ensure that the frequency of the two signals are identical. The beat frequency is circa 10.112 GHz, as is clear in Figure 4, which is show the emission spectrum for both reference and sensing arm at R.T. (b) the frequency difference between the arms.

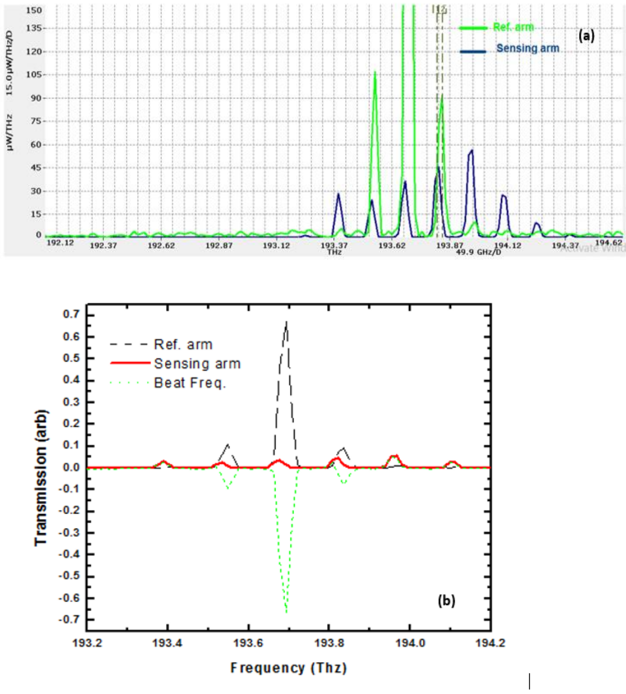
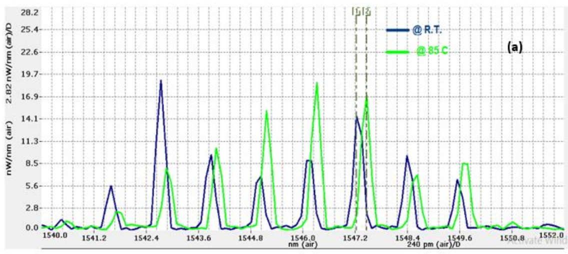


Fig. 4: Emission spectrum at room temperature using PCF (a) for the reference and sensing arms at R.T. (b) the amount of frequency difference between the two arms.

So the sensing arm of the temperature sensor was consist of SMF-FBG-SMF-PCF-SMF in order. Similarly, the interference spectra of the temperature sensor have been recorded and analyzed as the applied temperature applied from R.T. to 85°C. Figure 5 a and b clarify the emission spectrum of designed system in R.T. and 85°C and the wavelength difference versus applied temperature, from the results we could notice that there is a linear shift in the peaks of the interference spectrum towards the longer wavelengths as the temperature rise. The sensitivity was 68.17 pm/°C.



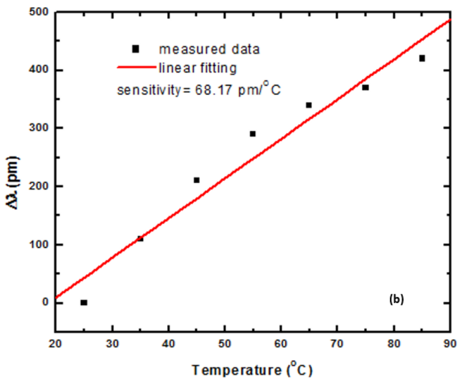


Fig. 5: (a) The emission spectrum within room temperature range and temperature of 85 ° C, (b) the wavelength difference versus applied temperature.

4- Conclusions

In this work, FBG had been used as a tunable element to design a new heterodyne optical system to get tunable source from single laser source. The implementation of a single laser source to generate two specific wavelengths gives stability in performance as well as reducing costs and requirements. This system chrectrized by its high sensitivity.

Here, first, we use SMF in both reference and sensing arm then modification had been done by replacing PCF instead of SMF in both reference and sensing arm, which provides better performance efficiency by increasing the wavelength shift of the temperature sensor. The error rates which is lead to instability resulting from losses and the impact of design and surrounding noise can be exceeded by laser sources. 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. The importance of the idea is that it can be employed as a new technology in heterodyne detection systems that have become widely applicable for rapid and sensitive topographic imaging by detecting the synthetic heterodyne group.

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