

Temperature Sensor Based on Fiber Bragg Grating (FBG), Implementation, Evaluation and Spectral Characterization Study

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ABSTRACT: Optical fiber plays significant roles in optical communications, optoelectronics, and sensors. The FBG sensors exceed other conventional electric sensors in many aspects, for instance, immunity to electromagnetic interference, light weight, compact size, stability, flexibility, high temperature tolerance, and resistant to harsh environment. This paper provides the operating principle, implementation of a “strain-free” FBG temperature sensors head and spectral characterization study. High-resolution detection of the wavelength-shifts induced by temperature changes are achieved using optical spectrum analyzer. Both uniform Fiber Bragg Grating (FBG) temperature and Mach-Zehnder Interferometric (MZI) temperature sensors based on single mode fibers were implemented and investigated due to measurement of the Bragg wavelength shift. It has been shown from the results that the FBG is very sensitive to variations in temperature degrees over a temperature range of (5–70) °C and the sensitivity was (1-6 pm/0.1°C), also observed from the results, the relation between the shifted Bragg wavelength and temperature degrees was linear.

KEYWORDS: fiber-optic sensors, Mach-Zehnder Interferometer, Fiber Bragg Grating.

I. INTRODUCTION

In recent years, the fiber optics sensing of different based such as temperature, strain, vibration, acoustics, linear and angular position, pressure, humidity, viscosity, acceleration, electric field measurement, magnetic field measurement, chemical measurement and others, won the special attraction because of its feature like lightweight, small size, cylindrical geometry, robust to environment, size compacted, high in sensitivity, possibility of remote sensing, immune to electromagnetic interference and interface with radio frequency [1]. Several types of fiber optic sensors were reported, among them are fiber Bragg grating sensors, fiber optic interferometer sensors like Michelson, Fabry-Perot, Sagnac, and Mach-Zehnder, and others. Fundamentally, a fiber-optic sensor works by modulating one or more properties of a propagating light wave, including intensity, phase, polarization, and frequency, in response to the environmental parameter being measured. Extrinsic (hybrid) optical sensors use the fiber only as a mechanism to transmit light to and from a sensing element, while intrinsic optical sensors use the optical fiber itself as the sensing element. In this paper, FBG will be implemented as a temperature sensor and its spectral characteristics such as sensitivity and resolution will be studied and compared with another type which is a single mode Mach-Zehnder interferometer sensors based temperature. Fiber Bragg Grating (FBG) was discovered by Ken Hill and co-workers in Canada, nearly twenty years ago. FBG is a periodic or an aperiodic perturbation of the effective absorption coefficient and/or the effective refractive index of an optical waveguide. They typically reflect light over a narrow wavelength range, which satisfies the Bragg condition and transmit all other wavelengths, but they also can be designed to have more complex spectral responses [2].

II. FIBER BRAGG GRATING (FBG) SENSOR

One of the most commonly used and broadly deployed optical sensors is the fiber Bragg grating (FBG), which reflects a wavelength of light that shifts in response to variations in temperature and/or strain. FBGs are constructed by using holographic interference or a phase mask to expose a short length of photosensitive fiber to a periodic distribution of

light intensity. The refractive index of the fiber is permanently altered according to the intensity of light it is exposed to the resulting periodic variation in the refractive index is called a fiber Bragg grating as shown in Figure (1) [3].

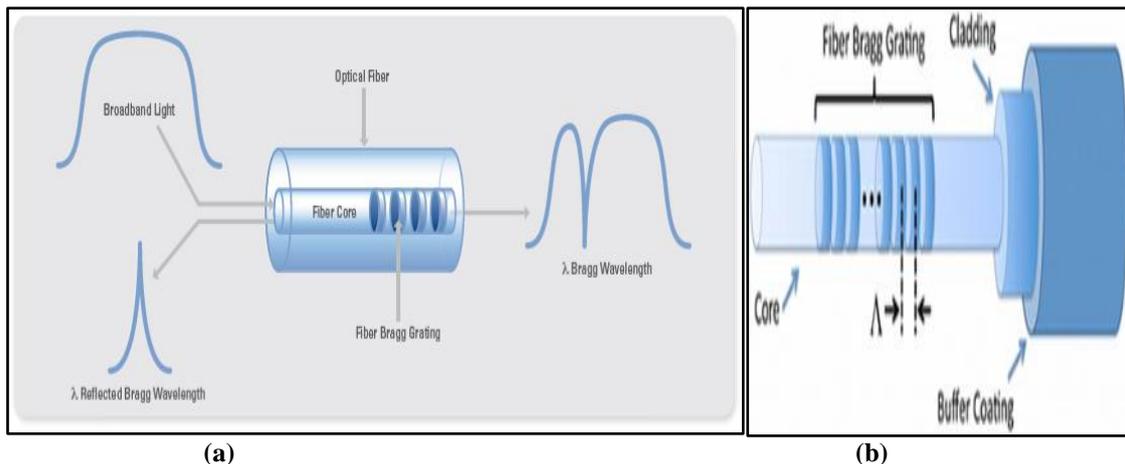


Figure 1. (a).Operation of an FBG Optical Sensor, (b). An Expanded View of an FBG

When a broad-spectrum light beam is sent to an FBG, reflections from each segment of alternating refractive index interfere constructively only for a specific wavelength of light, called the Bragg wavelength, described in equation (1). This effectively causes the FBG to reflect a specific frequency of light while transmitting all others.

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

Because the Bragg wavelength is a function of (Λ), the spacing between the gratings known as the grating period. FBGs can be manufactured with various Bragg wavelengths, which enable different FBGs to reflect unique wavelengths of light. Changes in strain and temperature affect both the effective refractive index n and grating period Λ of an FBG, which results in a shift in the reflected wavelength. The change of wavelength of an FBG due to strain and temperature can be approximately described by equation (2):

$$\frac{\Delta\lambda_B}{\lambda_B} = k\epsilon + \alpha_\delta\Delta T \tag{2}$$

$\Delta\lambda_B$ = Bragg wavelength shift, k =gage factor = $1-p$, where $p=0.22$, $k=0.78$,
 ϵ =strain, α_δ =changing in index of refraction, ΔT = changing in temperature[4].

The first expression describes the impact of strain on the wavelength shift, the second expression describes the impact of temperature on the wavelength shift. Because an FBG responds to both strain and temperature, so for sensing temperature, the FBG must remain unstrained. Using packaged FBG temperature sensors make to ensure the FBG inside the package is not coupled to any bending, tension, compression, or torsion forces.

III.MACH-ZEHNDERINTERFEROMETER (MZI) SENSOR

Fiber optic interferometer sensors also have been widely deployed owing to their special characteristics. Mach-Zehnder fiber optic interferometer sensor operates on the interference effect between two beams that propagate through different optical paths of a single fiber or two different fibers. It can be seen that the beam splitting and combining components are required in any configuration of the fiber optic interferometers. The incident light is split into two arms by a fiber splitter and then recombined by a fiber combiner. Early MZIs had two independent arms, which functioned as the sensing arm and the reference arm, respectively. The phase shift due to temperature is obtained by the following equation:

$$\frac{d\phi}{dT} = \frac{2\pi}{\lambda} \left[n \frac{dL}{dT} + L \frac{dn}{dT} \right] \tag{3}$$

Where $d\phi$ symbolizes the phase shift, λ represent the wavelength of light, n is the refractive index, dT and dL are variation in the temperature and elongation respectively, L is the fiber interaction length, since:

$$\alpha = \frac{dL}{dT \cdot L} \text{ and } \beta = \frac{dn}{dT} \quad (4)$$

Then:

$$\frac{d\phi}{dT} = \frac{2\pi}{\lambda} L(n\alpha + \beta) \quad (5)$$

Where α is thermal expansion, β is thermo-optic coefficient [5], [6].

According to above equations , the refractive index change given by the following equation

$$dn = \frac{\lambda}{2\pi L} d\phi - n\alpha dT \quad (6)$$

IV. EXPERIMENTAL WORK

a. Characterization of FBG Sensor:

To characterize the FBG sensor, a single mode fiber-pigtailed laser diode, FC/PC, center wavelength about (1530 nm-1590 nm) , output power approximation 1.59 mW, output current around 29.4 mA was launched into input terminal (1) of optical fiber circulator, while the transmitted terminal (2) was connected to the fiber Bragg grating which emerged in amicroprocessor-controlled water bath boiler HH-1,temperature Range: (0-100) $^{\circ}$ C, and the outputreflected signal through the third terminal (3) of circulator connected to the Monochromator / Spectrograph (Zolix DlnGaAs1700 InGaAa Detector) model Omni- λ Series, focal length 500 (mm).The whole block diagram of theexperimental setup is shown in the Figure 2.

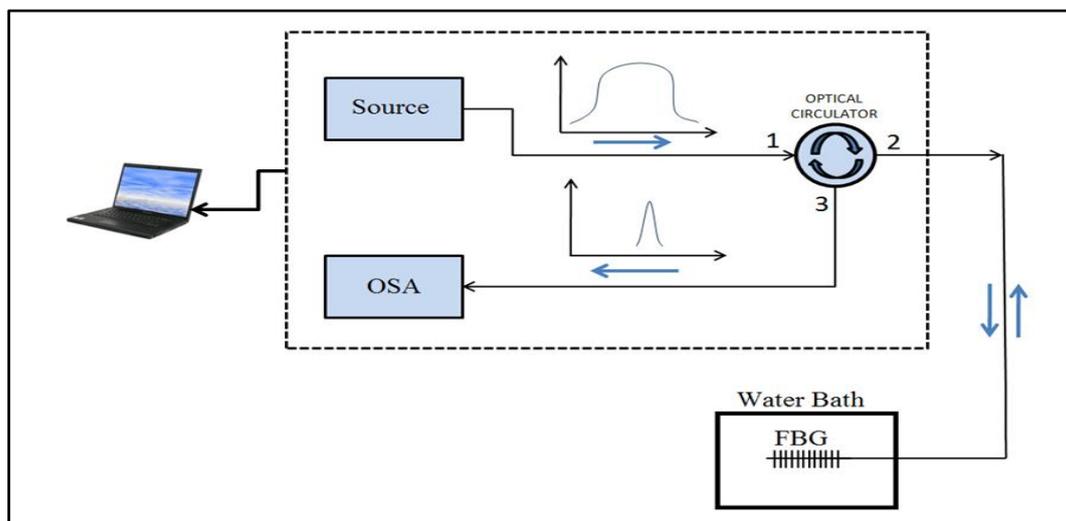


Figure 2. Block diagram of FBG temperature sensor setup.

For testing the FBG used here, the water temperature in the water bath was first changed from (5 – 70) $^{\circ}$ C with a step of 5 $^{\circ}$ C, the temperature decreased from (70 – 35) $^{\circ}$ C with a step of 5 $^{\circ}$ C .

The Bragg wavelength was taken as the center of the zero transmission region of the spectrum The spectral response (wavelength shift and the amplitude of the reflected signal of the FBG as a function to temperature variation) was noted using the optical spectrum analyzer. The observed transmission spectra and the change of the Bragg resonance wavelength as a function of increasing temperature are shown in Figure (4).

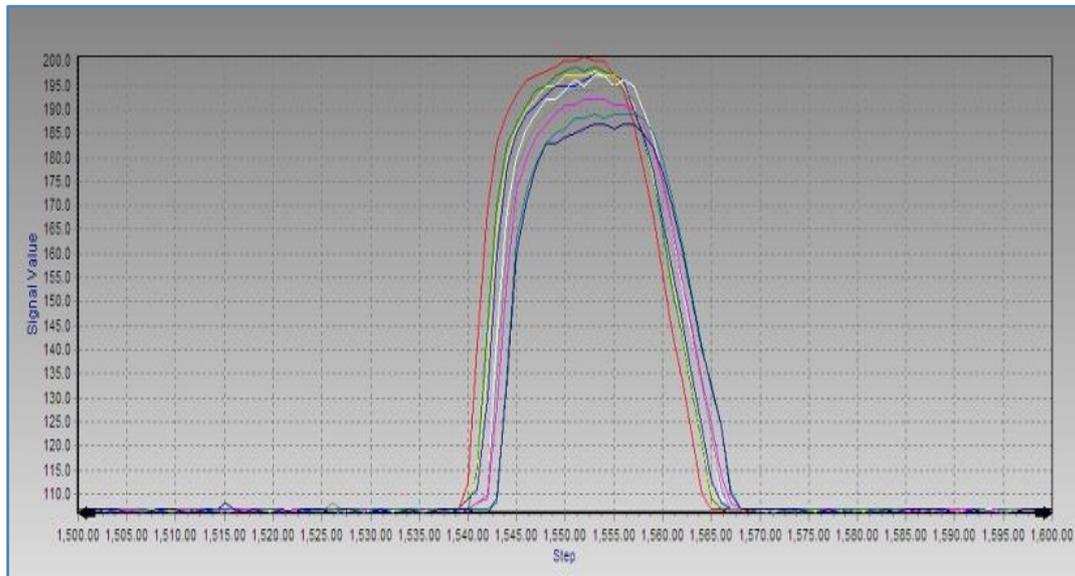


Figure 4. Wavelength shift and the amplitude of the reflected signal of the FBG as a function to temperature perturbation.

The dependence of the red-shift of the resonance wavelength of the FBG on the increasing temperature was measured to be $0.0091 \text{ nm}^\circ\text{C}^{-1}$. From equation 2, the expected sensitivity for 1550nm Bragg grating is approximately equal to $13.7 \mu\text{m }^\circ\text{C}^{-1}$. Figure (5) show experimental results of a Bragg grating center wavelength shift as a function of temperature.

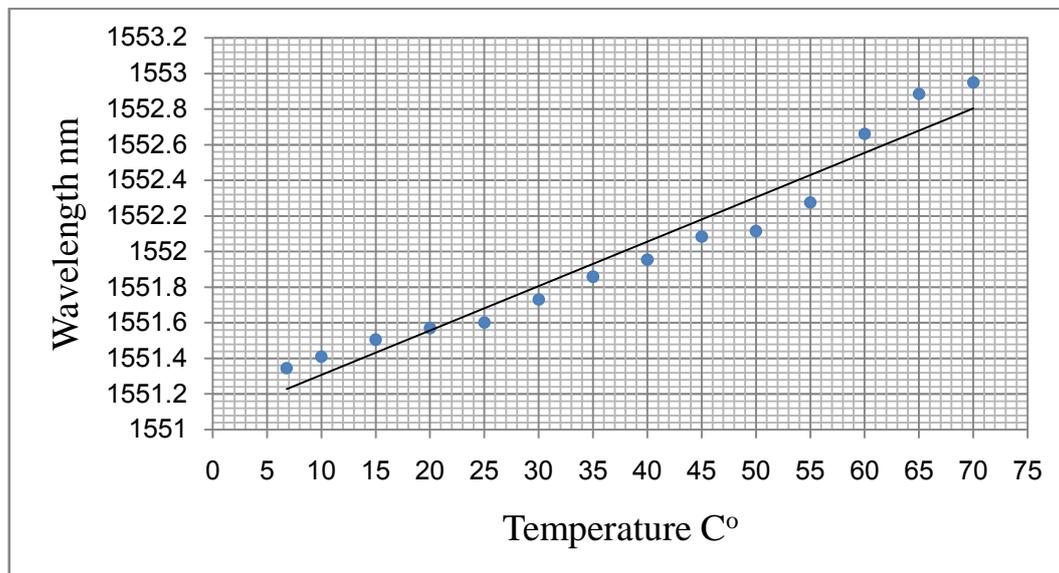


Figure 5. Peak reflection from the Bragg grating at different temperatures

The spectrum of grating was noted for different temperatures. A particular wavelength was selected from the spectrum as shown in table (1), at which the change in temperature was reflected by a corresponding change in the amplitude of transmission as shown in Figure (5), at selected wavelengths (1546 – 1556) nm the FBG can be used as a temperature sensor for the temperature range of (5–70)°C only. This can implement as calibration curve for such sensor.

T °C	λ_B nm	T °C	λ_B nm	T °C	λ_B nm
6.8	1551.3462	30	1551.7308	55	1552.2756
10	1551.4103	35	1551.8590	60	1552.6603
15	1551.5064	40	1551.9551	65	1552.8846
20	1551.5705	45	1552.0833	70	1552.9487
25	1551.6026	50	1552.1154		

Table (1). Bragg wavelength under variable temperature.

This is because to further increase in temperature, the transmission becomes 100% of these wavelengths. However, for higher temperature sensing applications, one has to use the FBG at different wavelengths. Based on the transmission spectra of the higher temperatures suitable wavelengths.

The major advantage of such calibration curves is that the change in temperature can be measured using a detector and a single wavelength source instead of a spectrum analyzer and a tunable laser source. In order to measure temperature, we can use as many FBG as necessary, in different Bragg wavelengths; the only precaution is that each FBG's spectrum should not overlap with its neighbor during its displacement when the temperature varies. To obtain the largest range for five FBGs we distributed them along the available range of most FBGs interrogators, that is, 1530 nm-1570 nm.

b. Characterization of (MZI) Sensor:

The experiment consist of (5mW) He-Ne laser at (633nm) wavelength, efficiently coupled into fiber core using a (5mm) focal lens through (1:2) single mode fiber coupler with 50% coupling ratio in order to splitting the light to two identical output beams so achieve interference pattern between them, and finally the output of our experiment takes by two ways, first of them is from screen, and the other is via USB beam profiling CDD camera. The whole block diagram of experimental set up is shown in the Figure 6.

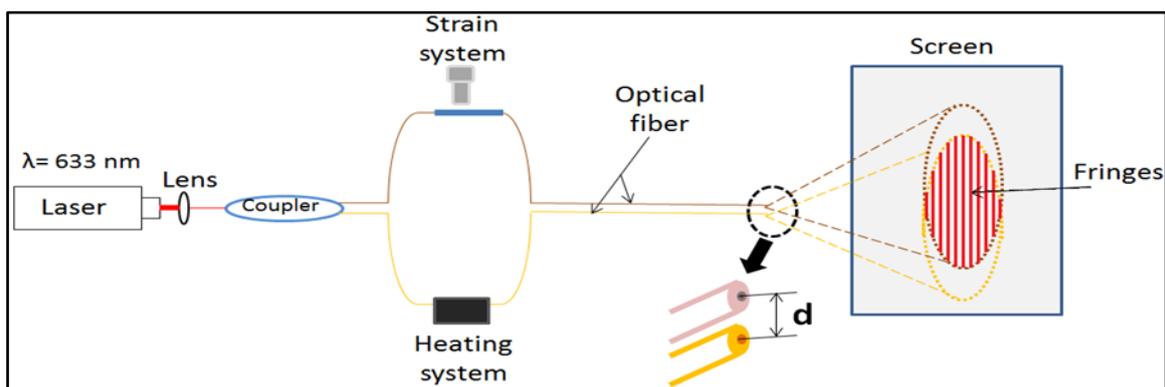


Figure 6. Block diagram of (MZI) sensor experimental set up

First, the interference pattern has taken on screen and by CCD camera at room temperature as shown in Figure (7). When the temperature increases fringes moved to one of directions, while opposite its direction when the temperature decreased.

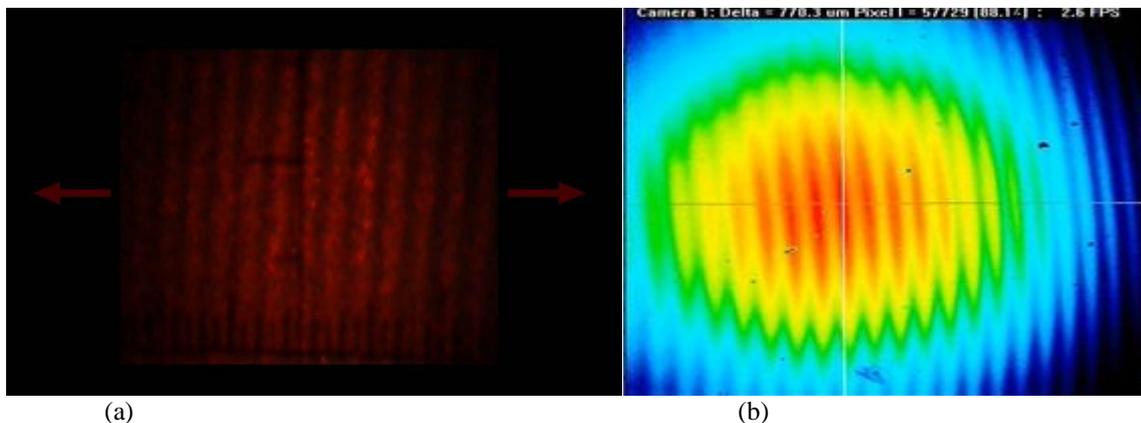


Figure 7. Interference pattern on (a) screen, (b) by beam profile CCD camera.

For testing the (MZI) sensor used here, the environment air temperature was first changed from (25 – 40) °C with a step of 5 °C. The phase difference related to change in refractive index calculated according to equation (7), as shown in Table (2).

T °C	$\Delta\phi*2\pi$	dn	T °C	$\Delta\phi*2\pi$	dn
28	9.50	1.6211	33	43.75	7.6434
29	17.75	3.0717	34	48.75	8.5226
30	24.75	4.3026	35	53.50	9.4017
31	31.50	5.4895	36	57.50	10.061
32	38.25	6.6763	37	61.25	10.721

Table 2. Temperature effect on phase difference related to change in refractive index.

A linear relation between Temperature variations according to phase difference which related to variation of refractive index as shown in Figure (8), can be used as a calibration and sensitivity curve for such sensor.

V. CONCLUSION

Fiber Bragg gratings as temperature sensor has been reviewed and demonstrated, which possess many unique advantages over conventional techniques. The FBG was characterized to get either the reflection or transmission spectrum which was as expected from the specification sheet. The FBG is calibrated to be used as a temperature sensor within the range (20 – 70)°C. The used fiber Bragg grating (FBG) in this work is very sensitive to the variation of the temperature degrees, the sensitivity was (1-6pm/0.1°C). The relation between the applied temperature and shifting Bragg wavelength was linear. The sensitivity of the Bragg wavelength to temperature arises from the change in the refractive index of the optical fiber.

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