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Investigating The Spectral Response of Fiber Bragg Grating (FBG) for Temperature Sensor Applications

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Abstract: In the field of sensor technology, the optical fibre sensor (OFS) has gained a lot of notoriety and prominence. It is frequently utilised to detect changes in the environment and react to outputs from other systems, such as those used in chemical analysis, industrial, and monitoring applications. A Fibre Bragg Grating (FBG) is a type of device in which a brief segment of optical fibre with a particular wavelength is reflected with light, while the Bragg reflector begins to grow and transmit all other wavelengths. The developing features and behaviours of temperature and strain sensors working on Fibre Bragg Grating using computer modelling are the focus of the current project. The main objective of this work is to examine the behaviour and properties of temperature sensors operating on Fibre Bragg Grating. The temperature sensor is utilised to measure and identify any temperature anomalies operating on the Fibre Bragg Grating that may cause mishaps or fires. This will reveal how temperature sensors may be demonstrated using Fibre Bragg Grating.
Keywords: Fiber Bragg Grating, Temperature Sensor, Bragg Wavelength, Wavelength Shift.

I. INTRODUCTION

A fiber-optic sensor is one that uses optical fibre both as an intrinsic sensor and as a method of processing extrinsic sensor signals that are relayed from the far sensor to the electronics. The three components of an optical fibre are the coating, cladding, and core. The cladding layer has an index of refraction of n_2 , and it was initially composed of a dielectric substance. The cladding material's index of refraction is lower than the core material's.[1]. Optical fibre sensors with a very wide bandwidth, resilience to electromagnetic interference, and a robust ability to operate in harsh temperature, toxic, and pressure situations.[2] One of the most interesting advancements in optical fibre sensing technology is the fibre Bragg grating (also known as fibre Bragg Grating) sensor, which has multiplexing capacity and is widely used in a variety of SHM.[3] A Fibre Bragg Grating functions as a sensor and has a unique character to follow. For example, the strain is determined by the Fibre Bragg Grating when the fibre is compacted. This occurs as a result of the optical fibre distortion, which modifies the microstructure's time adjustment. For a fibre Bragg grating, affectability of the temperature-sensitive material is also inherent. The temperature sensor acting in the Fibre Bragg Grating, where the Bragg wavelength shifted due to the change in refractive index is induced by the thermo-optic coefficient and the thermal-expansion coefficient, is similar to the strain sensors where the single-point sensors belong to and save the highlights the characteristics of small size, solidness, peak accuracy, and elasto-optic for the optical strain.[4] In the past several years, numerous studies have been conducted on Fibre Bragg Grating (Fibre Bragg Grating) by numerous researchers who have used simulation to use Fibre Bragg Grating as a strain and temperature sensor. The two main outcomes of Fibre Bragg Grating are the refractive index and the grating period. This study presents Fibre Bragg Grating and centres on its numerical theoretical demonstration and simulation using MATLAB, aided by simulation results that provide insight into the impacts of Fibre Bragg Grating.

Fibre Bragg Grating (FBG) have shown a great potential advantage in biomedical application over the past ten years [5] due to their prominent characteristics, which include their extremely small size, light weight, immunity to electromagnetic interference (EMI), electrical neutrality, and ability to be easily embedded into a structure without having any effects on the mechanical properties of the object under investigation[6][7].Fibre Bragg Grating was used as a photoacoustic (PA)detection method to detect the existence of tumours because of its capacity to transform the absorbed energy entirely into heat without producing PA signals caused by scattering particles[7]. Because it combines light contrast and ultrasonic resolution, the photoacoustic approach is unique[8]. This technique is used in tumour diagnosis because of its benefits, which include noninvasiveness, high detection sensitivity, and the ability to identify small element sizes[9],[10].

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Optical fibre that has been specially designed can be used to create sensors. The core refractive index of the optical fibre meant for sensor applications is different from the core and cladding of a conventional fibre only a very small fraction of the fibre [11]. Usually, in that little area of the optical fibre core, a periodic structure is inserted. This part of the fibre core is called Fibre Bragg Gratings (FBG) because it reflects particular light wavelengths. The effective refractive index of a dielectric waveguide is periodically changed when the waveguide's characteristics are changed on a regular basis [12], [13]. On the other hand, a DBR is a structure made up of several alternating layers of materials with different refractive indices. The FBG, which is a periodic wavelength-scale modification of the refractive index, is encoded in the fibre core segment. Light that satisfies the Bragg condition at a specific wavelength is reflected by Bragg gratings. When forward and back propagation modes couple at a particular wavelength, a grating experiences this reflection [14]. When a particular requirement, such as the Bragg condition, between the vectors of the light waves and the vector number of the grating is met, the coupling coefficient of the modes is at its highest:

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

The Bragg wavelength, the diffraction order m, the grating period, the core's effective refractive index, and the effective wavelength of light. The working concept of the fibre Bragg grating is shown in Figure 1.

There is an infinite number of possible Bragg wavelengths for a single FBG. Equation (1) suggests that for a given value of m, the diffraction order Bragg wavelength varies. In fact, due to a huge spectral difference between the two, only one or sometimes two Bragg resonance wavelengths are used. Assuming the first Bragg wavelength, m=1550 nm, is 1550 nm, the second Bragg wavelength of the grating will be twice as short, at 750 nm. Nevertheless, the sources used for fibre typically have a spectral range of only 100 nm. If the refractive index modulation in FBG is not sinusoidal, as it normally is, then additional Bragg peaks could appear. For instance, the Fourier spectrum of a rectangular grating has many modulation frequencies, which can lead to multiple Bragg peaks. despite the fact that most fiber-based gratings have essentially sinusoidal index modulation. There are several FBG structures; however, the experiment and analysis in this paper used a uniform FBG to test how well an FBG functions as a sensor.Extra Bragg peaks may show up if the refractive index modulation in FBG is not sinusoidal as it usually is. For example, a rectangular grating's Fourier spectrum contains a large number of modulation frequencies, which can result in several Bragg peaks, even though the index modulation of the majority of fiber-based gratings is essentially sinusoidal. Although there are several FBG structures, the experiment and analysis in this work tested the sensor performance of an FBG using a uniform FBG.

II. THE FUNDAMENTALS OF FBG SENSING PRINCIPLE

The Fibre Bragg Grating (FBG) is a single mode fibre having periodic refractive index modulation along its core, as seen in figure 1. When a single mode optical fibre is subjected to intense UV radiation, the reflective index of the fibre core rises, creating a fixed index modulation known as a grating[9]. Since the period of the grating area is approximately half that of the wavelength of the input light, as shown in equation (2) [4][6][11], the wavelength that is reflected when the FBG is subjected to a particular wavelength is known as the Bragg's wavelength, or maximum reflectivity.

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

where Λ is the FBG period, λB is the Bragg grating wavelength in the free-space centre wavelength of the input light that will be back-reflected from the FBG, and neff is the effective refractive index of the fibre core. The remaining fraction of the light is likewise transmitted by the fibre.

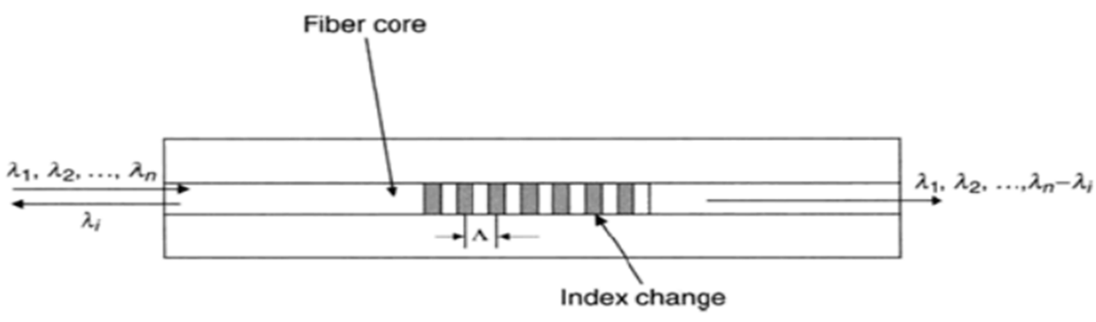

Figure 1: Schematic diagram of a fiber Bragg grating. [17]

Two quantities in (1), namely temperature and strain, are susceptible to changes in external conditions.Effective index of the core ,n_{eff} and grating period Λ are these parameters. When the temperature varies, the thermo-optic effect causes the effective index to change, whilst the glass thermal expansion causes the period to vary. When strain is applied, effective index changes as a result of the elasto-optic effect, whereas period changes as a result of the glass's elasticity, both of which are explained by Hooke's law. The overall Bragg wavelength will change by λ_B as a result of the effective index and period of the grating shifting as a result of strain and temperature changes. Therefore, the Bragg condition will produce an equation (3):

$$\lambda_B + \Delta\lambda_B = 2\cdot(n_{eff} + \Delta n_{eff})\cdot(\Lambda + \Delta\Lambda)$$
$$= 2(n_{eff}\cdot\Lambda + n_{eff}\cdot\Delta\Lambda + \Lambda\cdot\Delta n_{eff} + \Delta n_{eff}\cdot\Delta\Lambda) \quad (3)$$

Since the final part of the formula represents the multiplication of two little amounts, it can be ignored. We shall arrive at the formula for the change of Bragg wavelength after including accounting for (1):

$$\Delta\lambda_B = 2(n_{eff}\cdot\Delta\Lambda + \Lambda\cdot\Delta n_{eff}) \quad (4)$$

If any of the previously mentioned parameters changes, the Bragg wavelength will also change. By contrasting the related Bragg wavelength shift with the reference, one may identify the alteration.

III. REFLECTION AND TRANSMISSION OF LIGHT IN FIBER BRAGG GRATING

As observed in the below image, the refractive index of the fibre core varies with a period of . Λ The part of light whose wavelength coincides with the fiber wavelength When a broad spectrum light source is discharged into one end of the fibre, the remaining light will pass through to the other end, and the bragg grating will be reflected back to the input end. This reflection phenomena is explained in the diagram that follows.

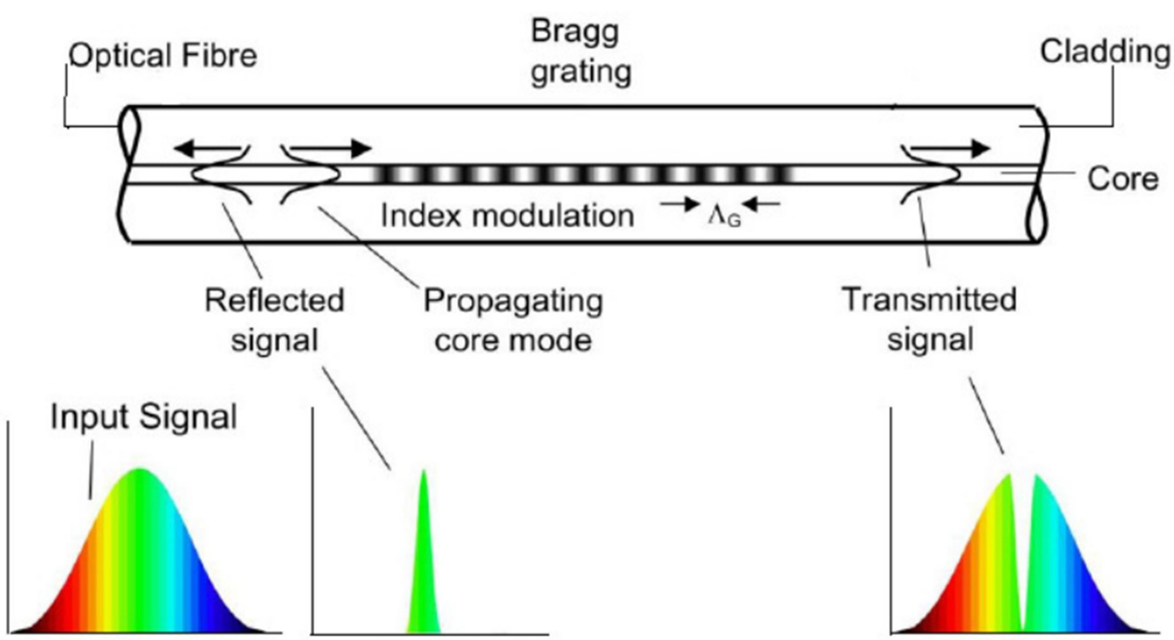

Figure 2 : The reflection and Transmission Spectrum of an FBG. [18]

The necessity of momentum conservation in the Bragg grating condition leads to the following equation:

$$2\left(\frac{2\pi n_{\text{eff}}}{\lambda_B}\right) = \frac{2\pi}{\Lambda} \quad (5)$$

where neff is the effective refractive index of the fibre core and λB is the wavelength of light reflected by the Bragg grating.

The basic principle behind the functioning of fibre Bragg gratings (FBGs) is Fresnel reflection. when two mediums with different refractive indices come together and allow light to reflect and refract. The fibre Bragg grating will typically show a sinusoidal variation in refractive index over a specified length. As seen in Figure 3, Δλ, where δn0 is the fluctuation in the refractive index (n3-n2) and η is the fraction of power in the core, determines the bandwidth, or the distance in wavelengths between the first minima.

$$\Delta\lambda = \left[\frac{2\delta n_0 \eta}{\pi}\right] \lambda_B \tag{6}$$

IV. WORKING PRINCIPLE OF FIBER BRAGG GRATING

A single mode fibre core is regularly exposed laterally to a powerful UV laser light pattern, creating an optical sensor called an FBG. The fiber's core's refractive index steadily increases as a result of the exposure, producing fixed index modulation known as grating spacing. The grating within the fibre optic core, as shown in the image below, is in charge of transmitting all other light while reflecting a certain input light wavelength that is referred to as the Bragg wavelength (Bragg related to grating period). Using the equation, we can determine the Bragg wavelength.

$$\lambda_{Bragg} = 2\ \eta\ \Lambda \tag{7}$$

When a change in physical features occurs, an interrogation unit, as depicted in the above picture, detects the shift in the reflected Bragg wavelength, which is determined by equation.

$$\Delta\lambda_{Bragg} = [(1 - p_e).\varepsilon + (\alpha + \zeta).\Delta T]\ \lambda_{Bragg} \tag{8}$$

Where p_e is the strain-optic coefficient, T is the change in temperature, induced strain, thermal expansion coefficient, and thermo-optic coefficient are all present. According to the equation above, temperature and strain both affect Bragg shift. P_e = 0.22 and various coefficients are known for silica fibre.

V. FBG EQUATIONS FOR TEMPERATURE MEASUREMENT

The Bragg wavelength shift is given by the following equation.

$$\Delta\lambda_{Bragg} = 2\left(\Lambda \frac{\partial \eta_{eff}}{\partial T} + \eta_{eff} \frac{\partial \Lambda}{\partial T}\right) \times \Delta T \tag{9}$$

$$\Delta\lambda_{Bragg} = \lambda_{Bragg}(\alpha + \zeta) \times \Delta T \tag{10}$$

For fused Silica,

$$\alpha = \frac{1}{\eta_{eff}} \frac{\partial \eta_{eff}}{\partial T} = 8.8 \times 10^{-6} \tag{11}$$

$$\zeta = \frac{1}{\Lambda}\frac{\partial \Lambda}{\partial T} = 0.55\times 10^{-6} \tag{12}$$

Bragg wavelength temperature sensitivity,

$$\frac{\Delta\lambda}{\Delta T} \tag{13}$$

VI. METHODOLOGY

One of the most crucial and significant parts of the Fibre Bragg Grating simulation is setting the parameter. In this simulation, the main Fibre Bragg Grating parameter is left at its default settings. However, it is crucial to set the specification setting where the sensor shows the effect only after identifying any changes caused by strain and temperature differences.

Parameters	Symbols	Standard
Effective Refractive Index	n_{eff}	1.43535
Grating Period	Λ	536 nm
Strain-Optic Constant	ρ_e	0.22
Coefficient	k	0.78
Refractive Index Change	F	0.0003
Thermo-Optic coefficient	α	7.18×10^{-6}
Thermal-Expansion coefficient	β	2.5×10^{-6}

Table 1: Fundamental Parameters in the Fiber Bragg Grating

Parameter	Unit	Standard				
Fiber Bragg Grating wavelength range	nm	1548 - 1552				
Fiber Bragg Grating length	nm	1	2	3	4	5
Peak reflectivity	%	30	70	80	90	90
Strain range	$\mu\varepsilon$	± 8000				
Strain sensitivity	pm / $\mu\varepsilon$	1.15				
Strain resolution	$\mu\varepsilon$	0.40				
Temperature range	°C	25 - 250				
Temperature sensitivity	pm / °C	17.3				
Temperature resolution	°C	0.05				

Table 2: Specifications of Parameters in the the Fiber Bragg Grating

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VII. RESULTS AND DISCUSSION

The temperature increase are used to measure the Bragg wavelength shift. If temperature variations rise, the Bragg wavelength shift indicates an increase. When the Bragg wavelength shift continues to climb until 12.48745, the temperature change increased to 250 °C.

Temperature change, ΔT (± 1°C)	Bragg wavelength, λ_B (± 0.10nm)	Bragg wavelength shift, $\Delta\lambda_B$ ($\pm 0.00001nm$)
25	1548.60	1.24584
50	1549.00	2.49234
75	1549.40	3.73947
100	1549.80	4.98725
125	1550.20	6.23567
150	1550.60	7.48474
175	1551.00	8.73445
200	1551.40	9.98481
225	1551.80	11.23580
250	1552.20	12.48745

Table 5: Temperature Change with a Bragg Wavelength Shift

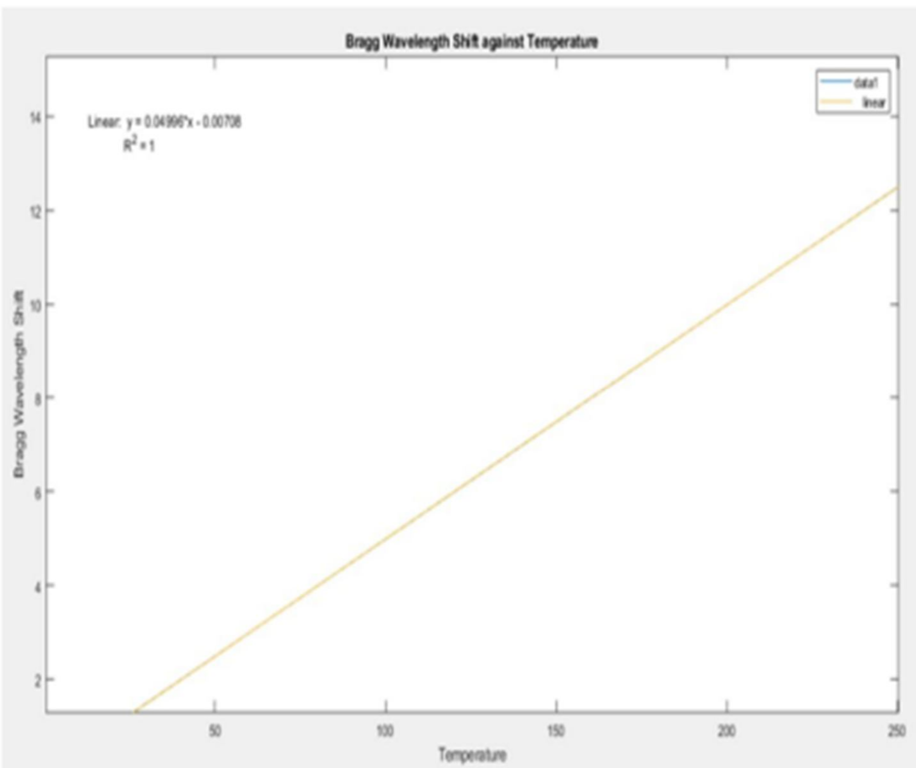

Figure 3 : Graph Temperature against Bragg Wavelength Shift

VIII. SPECTRAL REFLECTIVITY DEPENDENCE ON VARIOUS GRATING LENGTH

A graph showing the dependency of spectral reflectivity on various grating lengths, L = 1mm, 2mm, 3mm, 4mm, and 5mm, is displayed. The outcome displays how the spectral reflectivity varies for L = 1 mm, 2 mm, 3 mm, 4 mm, and 5 mm grating lengths, while the changes in the refractive index were fixed at $\Delta n = 0.0003$. The reflectance increased as the grating length increased. When the refractive index changes were set to remain constant at $\Delta n = 0.0003$, the spectrum reflectivity increased to 99.08% when the grating length increased to 5mm.

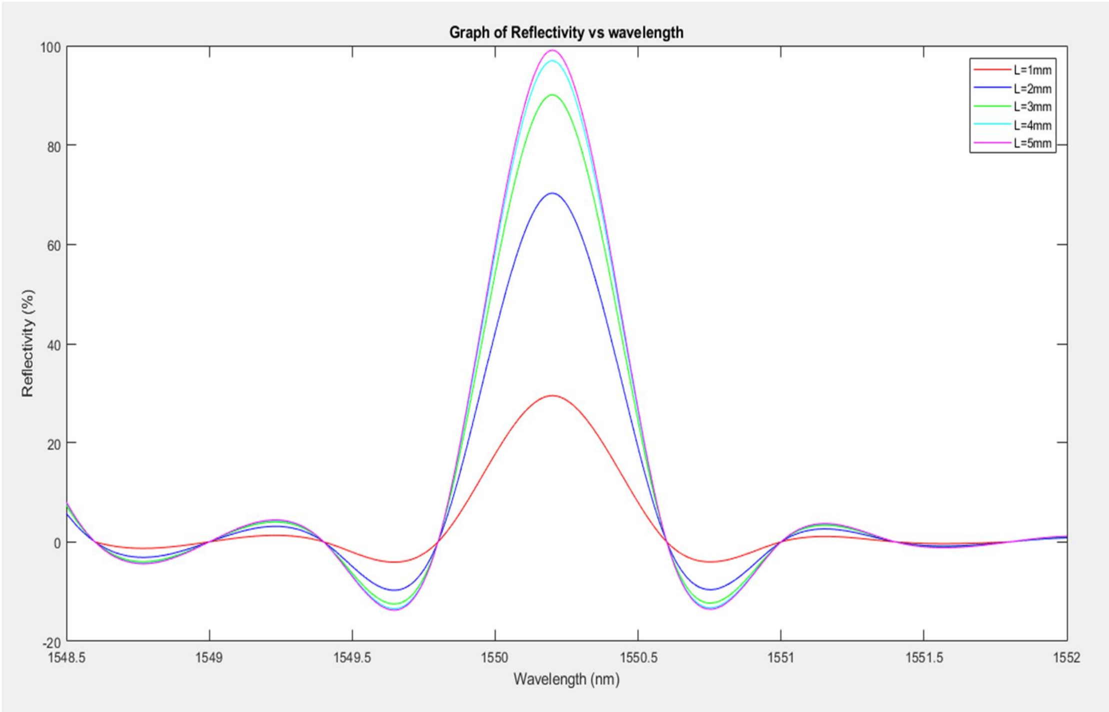

Figure 4: The Fiber Bragg Grating reflection spectrum with a refractive index shift of Δn = 0.0003 with varying grating lengths

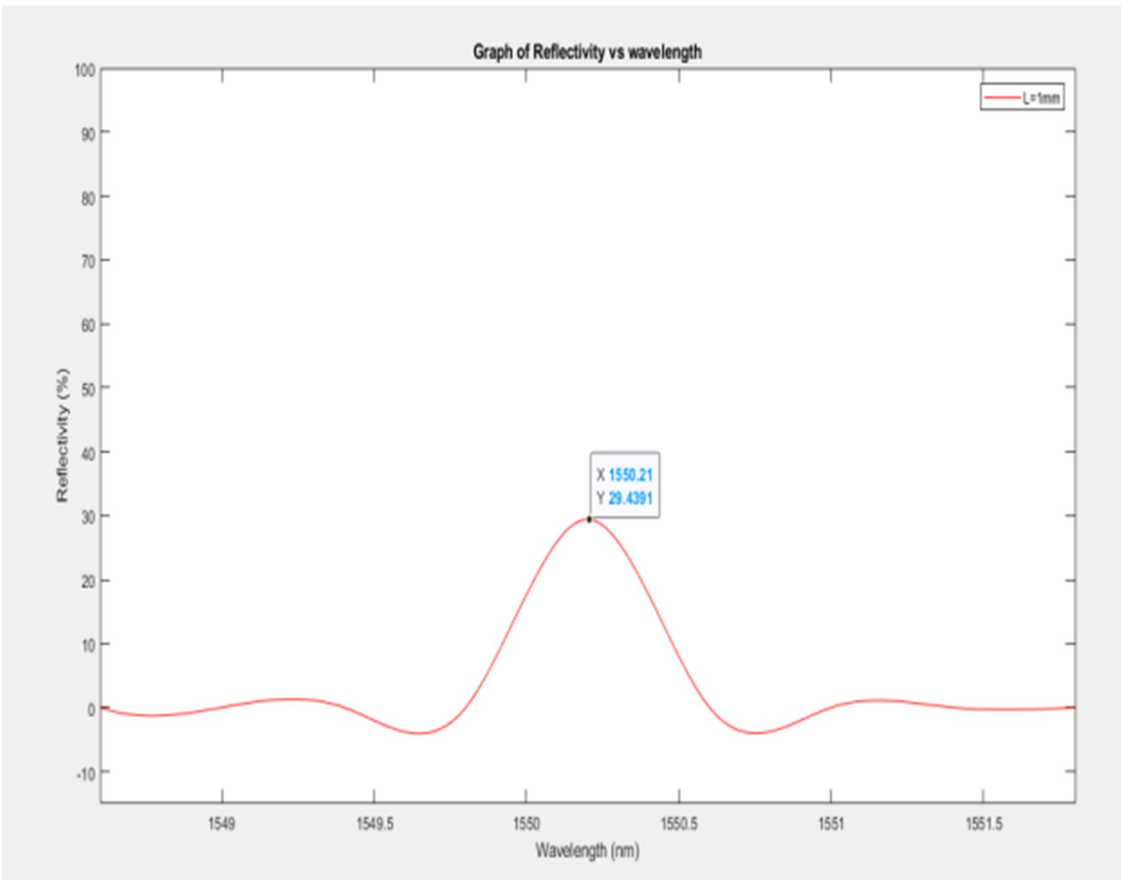

Figure 5: The reflection spectrum of Fiber Bragg Grating with grating length, L = 1mm at refractive index change of Δn = 0.0003 with peak reflectivity, R = 29.44%

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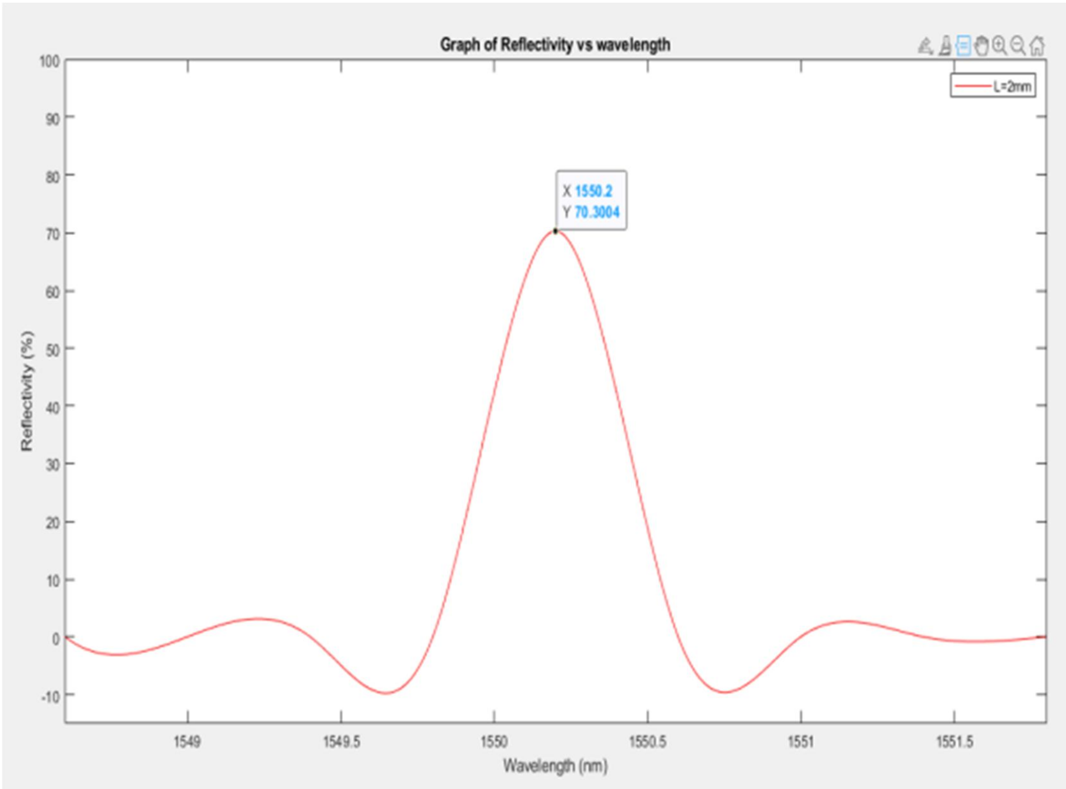

Figure 6: The Fiber Bragg reflection spectrum grating having a peak reflectivity of R = 70.31% and a grating length of L = 2 mm at a refractive index variation of Δn = 0.0003.

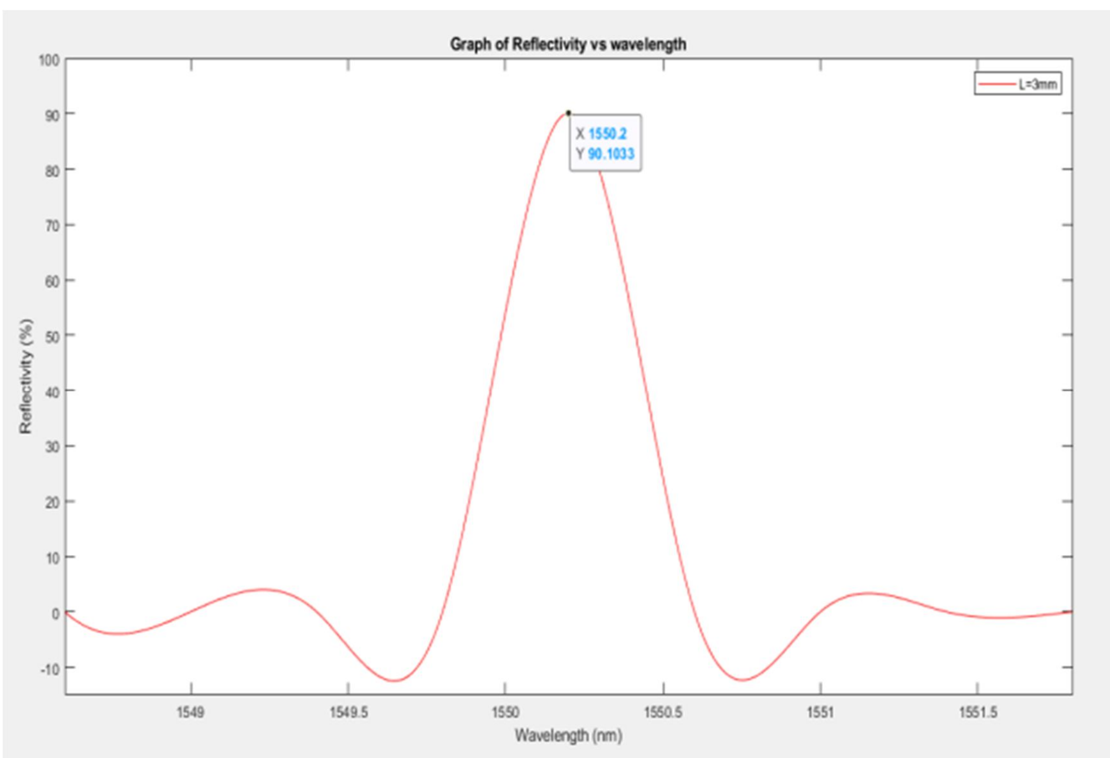

Figure 7: The Fiber Bragg reflection spectrum grating with a peak reflectivity of R = 90.10 percent and a grating length of L = 3 mm at a refractive index variation of Δn = 0.0003.

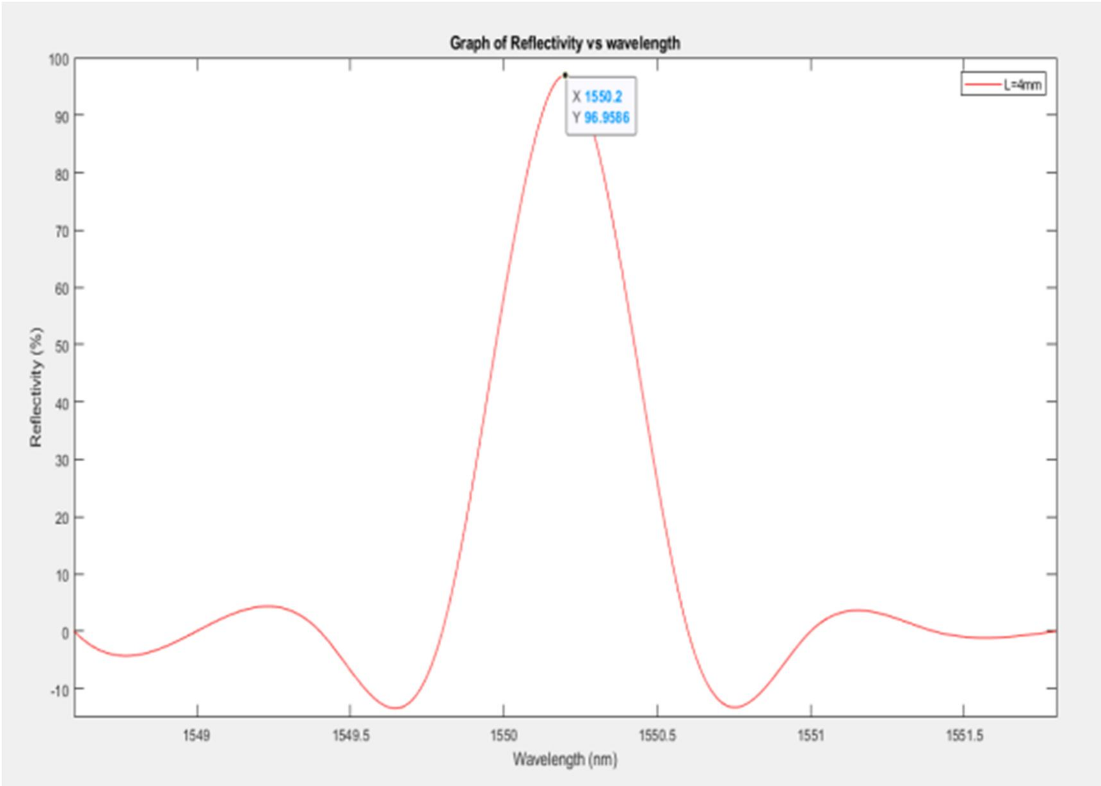

Figure 8: The reflection spectrum of Fiber Bragg Grating with grating length, L = 4mm at refractive index change of $\Delta n = 0.0003$ with peak reflectivity, R = 96.96%

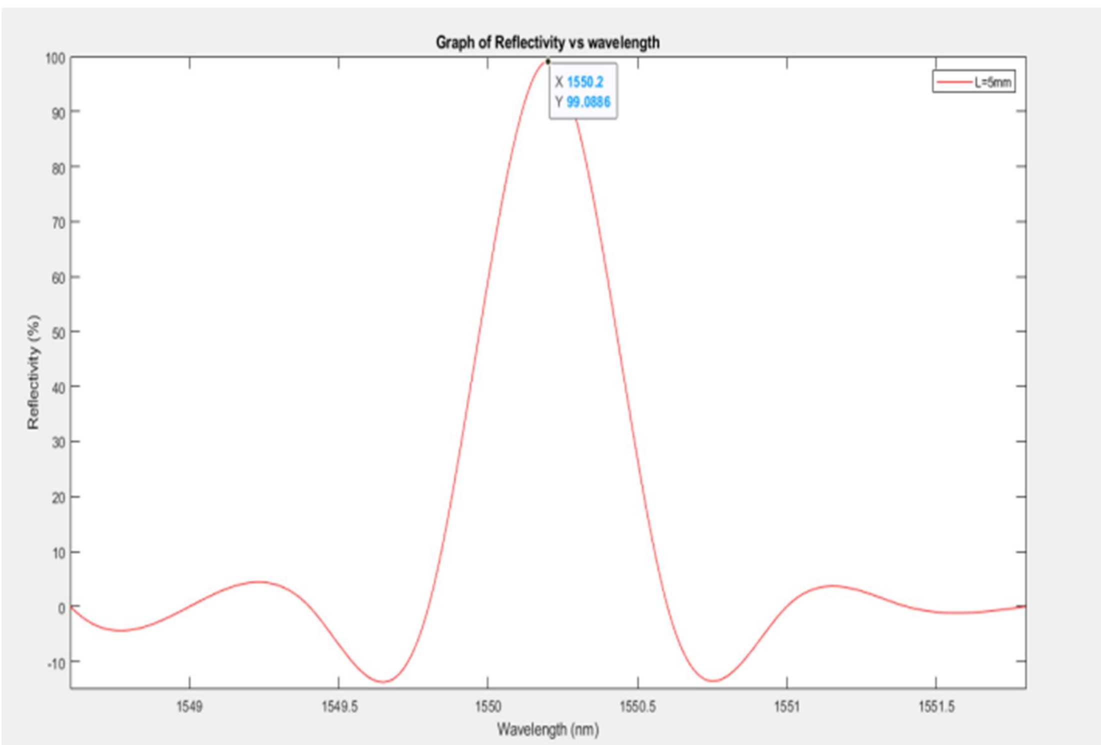

Figure 9: The Fiber Bragg reflection spectrum grating with a peak reflectivity of R = 99.08% and a grating length of L = 5mm at a refractive index change of $\Delta n = 0.0003$.

IX. CONCLUSIONS

In conclusion, all of the objectives of this study have been successfully met. In order to simulate temperature sensors, this study proposed modeling the characteristics and behaviors of fiber bragg gratings. Performance analysis, trait and behavior identification, and the evaluation of the temperature sensor functionality can all be done with this simulation. MATLAB was successfully used to analyze the current work for this simulation-designed model for the temperature sensors in the Fiber Bragg Grating. For this study, MATLAB software was used to simulate the spectral characteristics for temperature sensors of the Fiber Bragg Grating sensing system. The behavior, features, and functionality of Fiber Bragg Gratings can be examined with this simulation. The same for temperature, which in this study is simulated linearly. The temperature will be affected by the Bragg wavelength shift, as the Bragg wavelength shift increases, so does the temperature.

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