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The Study on the Fundamental of Fiber Bragg Grating (FBG) Sensing Principle

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Abstract: A single mode fibre core is laterally exposed to a periodic pattern of powerful UV laser light to create an optical sensor called an FBG. The exposure results in a long-lasting rise in the fiber's core's refractive index (n_{core}), producing fixed index modulation known as grating (Λ). A specific wavelength of input light, known as the Bragg wavelength or Bragg related to grating period, must be reflected by the grating inside the fibre optic core while transmitting all other wavelengths. FBG operates as intended by using the regular variations in the single mode fibre core's refractive index, a Bragg reflector can be constructed on an optical fibre. A specific wavelength of light will be reflected and all others will be transmitted as it passes through the FBG. A shift in the wavelength of the light reflected when the temperature or strain surrounding the grating changes is seen.

Keywords: Bragg wavelength, Effective refractive index, Electro–optic effect , Fiber Bragg gratings, Thermo-optic effect

I. INTRODUCTION

Due to their prominent characteristics, such as 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 structure of the object under investigation[2][3], Fibre Bragg Grating (FBG) have demonstrated a great potential advantage in biomedical application over the past ten years [1].Due to its capability of converting the absorbed energy completely into heat without creating PA signals brought on by scattering particles, Fibre Bragg Grating was employed as a photoacoustic (PA)detection tool to identify the presence of tumors[4]. The photoacoustic technique is distinct because it combines ultrasonic resolution with light contrast[5]. Due to its advantages of being noninvasive, having a high detection sensitivity, and being able to detect small element size, this approach is employed in the detection of tumors[6],[7].

Optical fibre that has been specially developed can be used as a sensor. The core refractive index of the Optical Fibre for sensor applications is different from the typical fibre core and cladding refractive index in a small area of the fibre [8]. Normally, that small section of the Optical Fibre core is where a periodic structure is introduced. This area of the fibre core is known as Fibre Bragg Gratings (FBG) because it reflects light of a particular wavelength. Where DBR is a structure made of numerous, alternate layers of materials with varying refractive indices, or by periodically changing a dielectric waveguide's characteristics and leading to periodic changes in the guide's effective refractive index [9],[10]. FBG-based sensors are those whose sensitivity is determined by the Bragg wavelength shift of Fibre Bragg Gratings. The FBG is a periodic wavelength scale modification of the refractive index that is encoded in the fibre core segment. The light at a specific wavelength that satisfies the Bragg condition is reflected by Bragg gratings. When forward and back propagation modes at a particular wavelength couple, this reflection in a grating happens [11]. When the particular requirement e.g Bragg condition between the light wave vectors and the grating's vector number is met, the coupling coefficient of the modes is at its maximum:

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

the grating period, the effective refractive index of the core, the effective wavelength of light known as the Bragg wavelength, and the diffraction order m. Figure 1 depicts the fibre Bragg grating's operating principle.

Theoretically, there are an infinite number of Bragg wavelengths for a single FBG. It is derived from equation (1) that the diffraction order Bragg wavelength varies for different values of m. Since there is a significant spectral gap between both Bragg wavelengths, only one sometimes two Bragg resonance wavelength are actually used in practise. For instance, if the grating's initial Bragg wavelength , m=1 is 1550 nm, the second one will be twice as short, at 750 nm. While the sources used for fibre typically have a spectral range of no more than 100 nm. If the modulation of the refractive index in FBG is not sinusoidal which is typically the case, additional Bragg peaks may appear. For instance, the Fourier spectrum of a rectangular grating includes many modulation frequencies, which can lead to a number of Bragg peaks. Despite the fact that the majority of fiber-based gratings have essentially sinusoidal index modulation. There are several FBG structures; however, in this study, a uniform FBG was used for the experiment and analysis to examine how well an FBG functions as a sensor.

II. THE FUNDAMENTALS OF FBG SENSING PRINCIPLE

According to figure 1, the Fibre Bragg Grating (FBG) is a single mode fibre with a periodic refractive index , n modulation along its core. A fixed index modulation known as a grating is produced when a single mode optical fibre is exposed to strong UV radiation, which increases the reflective index of the fibre core[9]. The Bragg's wavelength which is the maximum reflectivity is the wavelength that is reflected when the FBG is exposed to a specific wavelength since the grating area's period is roughly half that of the input light's wavelength, as indicated in equation (2) [1][3][8].

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

Where n_{eff} is the effective refractive index of the fibre core, Λ is the FBG period, and λ_B is the Bragg grating wavelength in the free-space centre wavelength of the input light that will be back-reflected from the FBG. The fibre also transmits the other portion of the light.

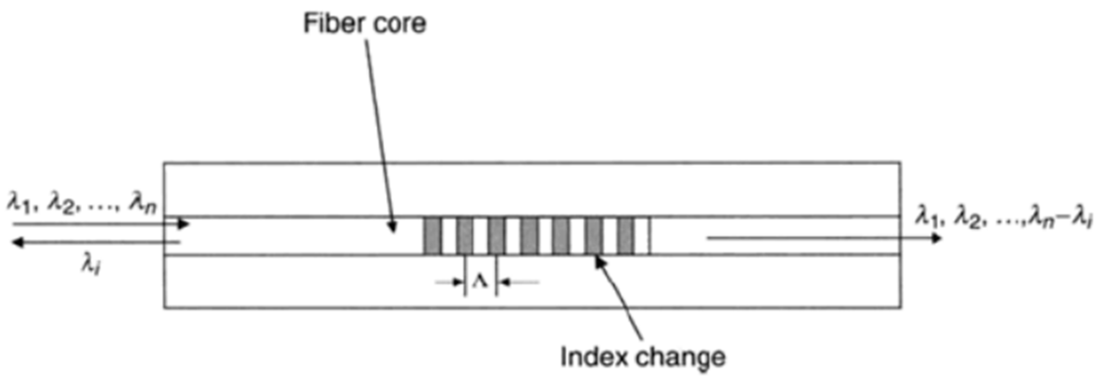

Figure 1: Schematic diagram of a fiber Bragg grating. [14]

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's 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):

$$\begin{aligned}\lambda_B + \Delta\lambda_B &= 2\cdot(n_{eff} + \Delta n_{eff})\cdot(\Lambda + \Delta\Lambda) \\ &= 2(n_{eff}\cdot\Lambda + n_{eff}\cdot\Delta\Lambda + \Lambda\cdot\Delta n_{eff} + \Delta n_{eff}\cdot\Delta\Lambda) \qquad (3)\end{aligned}$$

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):

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

The Bragg wavelength will change if any of the aforementioned parameters changes. One can detect the change by comparing the associated Bragg wavelength shift with the reference.

III. REFLECTION AND TRANSMISSION OF LIGHT IN FIBER BRAGG GRATING.

The refractive index of the fibre core is varied with a period of as seen in the above figure. The portion of light whose wavelength matches the wavelength of the fibre Bragg grating will be reflected back to the input end when a light source with a broad spectrum is fired into one end of the fibre, while the remaining light will flow through to the other end. The following diagram explains this reflection phenomenon.

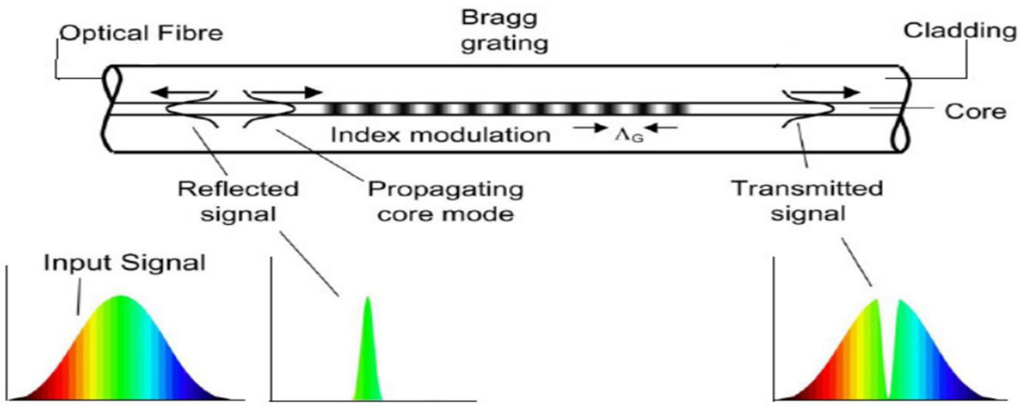

Figure 2 : The reflection and Transmission Spectrum of an FBG. [15]

The following equation can be derived from the Bragg grating condition's requirement for momentum conservation:

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

where λ_B is the wavelength of the light reflected by the Bragg grating and neff is the effective refractive index of the fibre core. Fresnel reflection is the fundamental idea that drives fibre Bragg grating (FBG) operation. When light can reflect and refract at the interface of two media with different refractive indices. Over a predetermined length, the fibre Bragg grating will normally exhibit a sinusoidal refractive index fluctuation. As illustrated in Figure 3, the bandwidth, or the distance in wavelengths between the initial minima, is determined by $\Delta\lambda$ where δn_0 is the variation in the refractive index (n_3-n_2), and η is the fraction of power in the core.

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

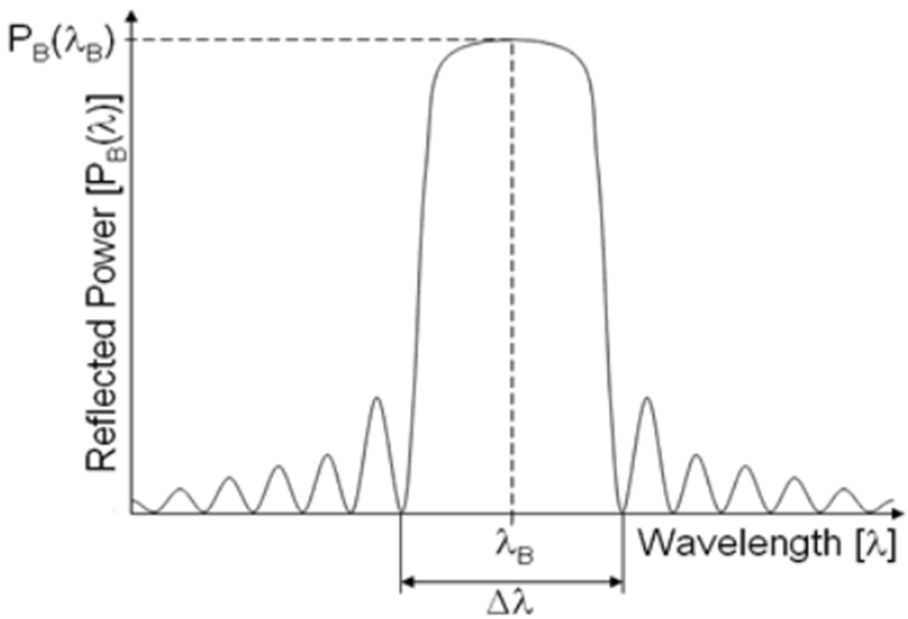

Figure 3: The graph of Reflected Power versus wavelength of a Fiber Bragg Grating. [14]

IV. WORKING PRINCIPLE OF FIBER BRAGG GRATING

A single mode fibre core is laterally exposed to a periodic pattern of powerful UV laser light to create an optical sensor called an FBG. The exposure results in a long-lasting rise in the fiber's core's refractive index (), producing fixed index modulation known as grating (). The grating inside the fibre optic core must transmit all other light, as indicated in the picture below, while reflecting a specific wavelength of input light known as the Bragg wavelength (Bragg related to grating period). Equation provides the Bragg wavelength.

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

When a change in physical qualities takes place and is determined by equation, an interrogation unit, as illustrated in the above figure, is used to detect the shift in the reflected Bragg wavelength.

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

When 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 equation below provides the shift in the peak of the Bragg wavelength.

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

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

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 sensitivity to temperature,

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

VI. FBG EQUATIONS FOR STRAIN MEASUREMENT

When stress is applied to a sensor, the length of the sensor changes from its original length, or strain, L. The corresponding strain over an applied stress to the fibre will be L/L. Due to the fact that temperature influences the physical dimensions due to thermal expansion, temperature correction is necessary. When using an FBG sensor, the effect of temperature on calculating wavelength shift must be eliminated in order to quantify strain alone. This can be accomplished by adding a temperature sensor for the FBG along it to counteract the impact of local temperature on the FBG. To quantify strain, we have therefore taken eq. (10) away from eq. (9) to obtain eq. (5) below.

Equation gives the wavelength shift proportional to the applied strain.

$$\Delta\lambda_{Bragg} = 2\left(\Lambda\frac{\partial\eta_{eff}}{\partial L} + \eta_{eff}\frac{\partial\Lambda}{\partial L}\right)\times\Delta L \tag{14}$$

$$\Delta\lambda_{Bragg} = \lambda_{Bragg}\left(1 - p_e\right)\times\varepsilon_z \tag{15}$$

where p is the effective strain-optic constant, denoted as where e is the applied axial strain.

$$p_e = \frac{\eta^2{}_{eff}}{2}\left[p_{12} - v(p_{11} + p_{12})\right] \tag{16}$$

where v is the Poisson's ratio and p_1 and p_2 are parts of the strain-optic sensor. $P_1 = 0.113$, $P_2= 0.252$, V = 0.16, and N = 1.482 for a germanosilicate optical fibre. As a result, p has the value 0.22.

Bragg wavelength sensitivity to strain,

$$\frac{\Delta\lambda}{\Delta\varepsilon} \tag{17}$$

VII. CONCLUSIONS

A high voltage and high electromagnetic interference environment might cause an electronic sensor to malfunction in the electrical and electronics industries. Under these circumstances, it is almost hard for a standard sensor to measure. The measuring of parameters by an FBG sensor built on an optical fibre is a good solution to this issue. Lightweight, simple to install, and capable of multiplexing, fibre bragg grating (FBG) sensors may sense a variety of characteristics, including temperature, strain, load, pressure, and others, at numerous locations along the same sensor cable. Traditional sensors require electricity to function. Because optical fibre sensors are inert, they can be installed passively for many hundred kilometres on transmission lines, gas pipelines, etc. without a power source.

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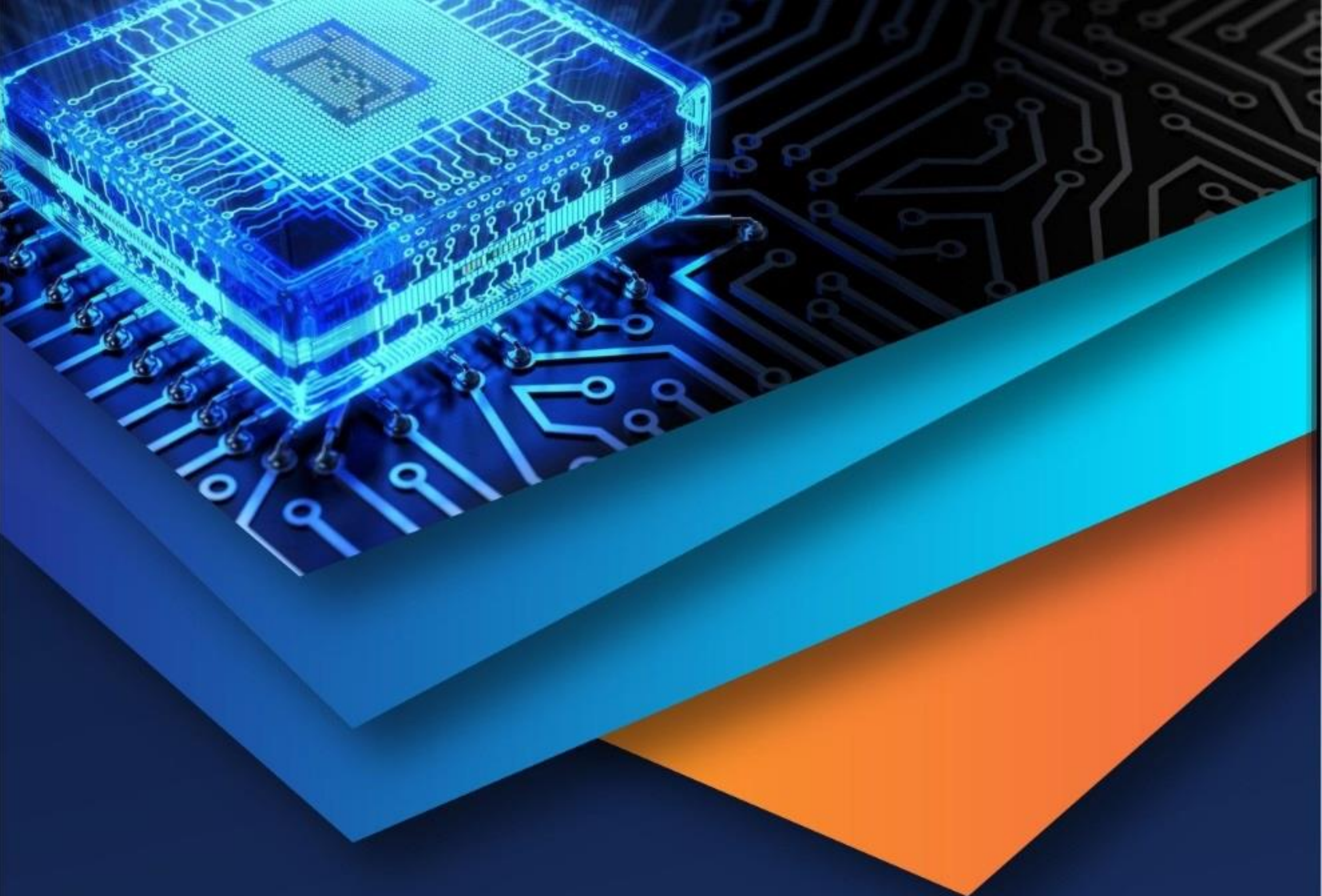

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