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The Study on the Spectral Analysis of Fiber Bragg Grating (FBG) as a Strain Sensor

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Abstract: By adjusting the grating length and refractive index change, parameters of the Fibre Bragg grating which are the effective refractive index, Bragg wavelength, grating period, and strain-optic constant are provided and discussed, along with the characterization of the grating, including strain, Bragg wavelength shift, spectral response, and bandwidth. The coupled mode equations form the basis for data analysis and acquisition. This research uses a high-level computer language, such as GNU Octave software, to simulate FBG spectral responses.
Keywords: Bragg wavelength, Effective refractive index, Electro–optic effect, Fiber Bragg gratings, Thermo-optic effect

I. INTRODUCTION

Fibre Bragg Grating (FBG) have shown over the past ten years [1] a great potential advantage in biomedical application 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. Fibre Bragg Grating was used as a photoacoustic (PA)detection method to detect the existence of tumours because it has the ability to transform the absorbed energy totally into heat without producing PA signals brought on by scattering particles[4]. The photoacoustic approach stands out because it blends light contrast with ultrasonic resolution[5]. Given the benefits of being non-invasive, having a high detection sensitivity, and this method is used in the diagnosis of tumours since it can identify small element sizes[6],[7].

A sensor can be made out of specifically created optical fibre. In a tiny portion of the fibre, the optical fiber's core refractive index differs from the standard fibre core and cladding refractive index for sensor applications [8]. Usually, a periodic structure is introduced in that little area of the optical fibre core. Due to its ability to reflect light of a specific wavelength, this region of the fibre core is referred to as the Fibre Bragg Gratings (FBG). When a dielectric waveguide's properties are periodically changed, this causes periodic variations in the waveguide's effective refractive index [9],[10]. Alternatively, DBR can be created by stacking several, alternative layers of materials with different refractive indices on top of each other.

The sensitivity of FBG-based sensors is based on the Bragg wavelength shift of the Fibre Bragg Gratings. The FBG is a periodic adjustment of the refractive index on a wavelength scale that is stored in the fibre core segment. Bragg gratings reflect light that meets the Bragg condition at a particular wavelength. This reflection in a grating occurs when forward and back propagation modes at a specific wavelength pair [11]. The coupling coefficient of the modes is at its highest when the specific criteria, such as the Bragg condition between the light wave vectors and the grating's vector number, is satisfied:

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

The grating period, core's actual refractive index, effective light wavelength (sometimes called Bragg wavelength), and diffraction order m. The workings of the fibre Bragg grating are shown in Figure 1.

For a single FBG, there are theoretically an infinite number of Bragg wavelengths. Equation (1) makes clear that for different values of m, the diffraction order Bragg wavelength varies. Only one or perhaps two of the Bragg resonance wavelengths are actually employed in practise since there is a large spectral gap between them. For instance, the second Bragg wavelength will be twice as short, at 750 nm, if the grating's first Bragg wavelength, m=1, is 1550 nm. While the spectral range of sources utilised for fibre is normally limited to 100 nm. Additional Bragg peaks could show up if the modulation of the refractive index in FBG is not sinusoidal, which is frequently the case. For instance, a rectangular grating's Fourier spectrum contains a large number of modulation frequencies, which can result in numerous Bragg peaks. Despite the fact that the index modulation of the vast majority of fiber-based gratings is essentially sinusoidal. There are several FBG structures; however, in this work, an experiment and analysis were conducted using a uniform FBG to determine how well an FBG performs as a sensor.

II. FIBER BRAGG GRATING SENSING PRINCIPLE

The Fibre Bragg Grating (FBG) is a single mode fibre with periodic refractive index, n modulation along its core, as seen in figure 1. When a single mode optical fibre is exposed to intense UV radiation, which raises the fibre core's reflective index, the result is a fixed index modulation known as a grating[9]. Since the period of the grating area is roughly half that of the wavelength of the input light, as shown in equation (2) [1][3][8], the wavelength that is reflected when the FBG is exposed to a particular wavelength is the Bragg's wavelength, which is the wavelength with the maximum reflectivity.

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

Where neff is the fibre core's effective refractive index, is the FBG period, and B is the input light's Bragg grating wavelength in free space that will be back-reflected from the FBG. The other part of the light is likewise transmitted by the fibre.

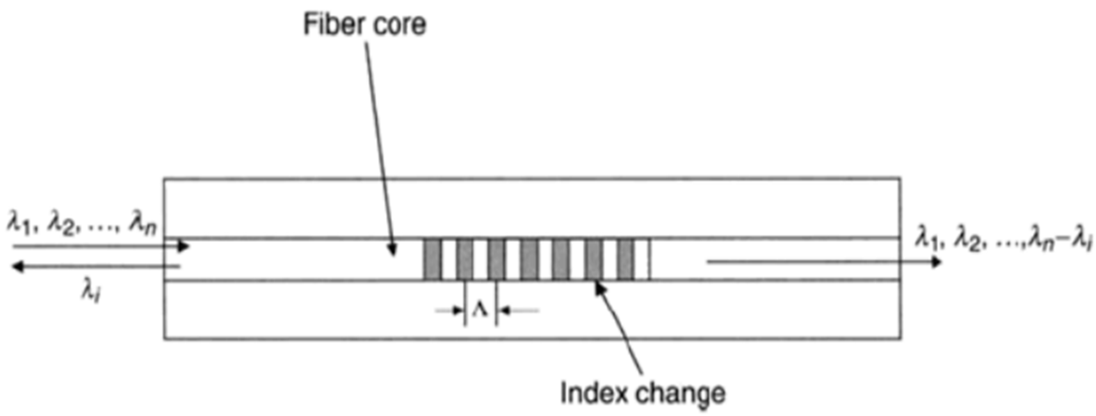

Figure 1: Schematic diagram of a fiber Bragg grating. [14]

Temperature and strain are two parameters in (1) that are subject to changes in the environment. These parameters are the effective index of the core, neff, and grating period. The effective index changes as a result of the thermo-optic effect when a temperature changes, while the period changes as a result of the glass's thermal expansion. When strain is applied, the elasto-optic effect causes changes in effective index, while the elasticity of the glass causes changes in period. Both of these changes are explained by Hooke's law. As a result of the effective index and period of the grating moving due to strain and temperature changes, the overall Bragg wavelength will change by B.[14] The Bragg condition will then result in equation (3):

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

The final component of the formula can be disregarded because it simply multiplies two little quantities. After taking into account (1), we will arrive at the formula for the change in Bragg wavelength:

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

If any of the aforementioned characteristics changes, the Bragg wavelength will also vary. 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 shown in Figure 2, the fibre core's refractive index varies over a period of time. the part of the spectrum of light whose wavelength matches that of the fibre When a light source with a broad spectrum is discharged into one end of the fibre, Bragg grating will be reflected back to the input end while the remaining light will flow through to the other end. This reflection occurrence is illustrated in the following diagram.

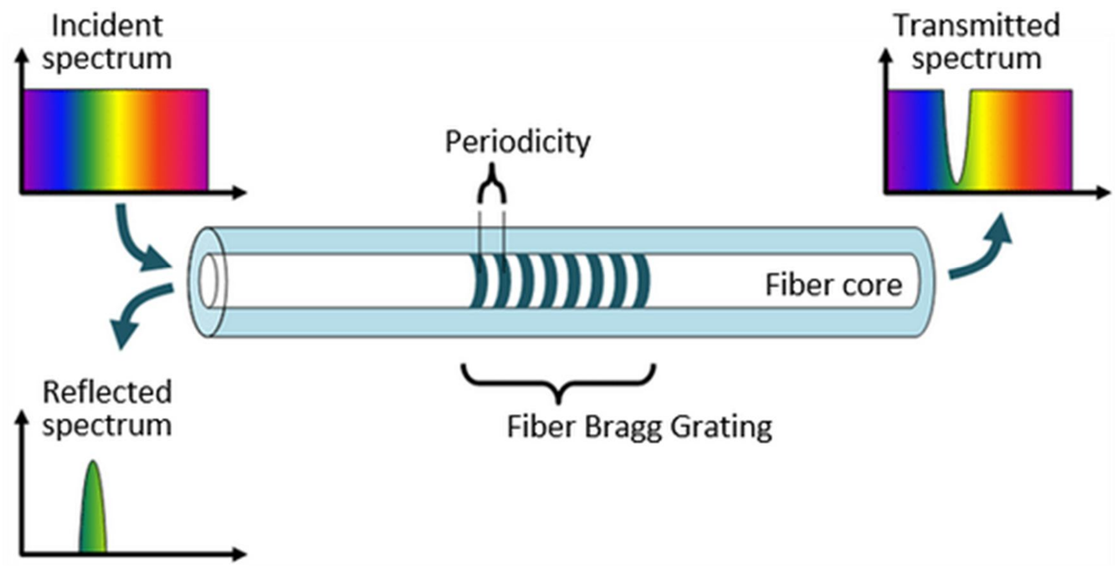

Figure 2 : The reflection and Transmission Spectrum of an FBG. [15]

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

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

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

The underlying principle behind fibre Bragg grating (FBG) operation is fresnel reflection. when two mediums with different refractive indices are in contact and allow light to reflect and refract.The fibre Bragg grating typically displays a sinusoidal refractive index fluctuation over a set length. The bandwidth, or the distance between the initial minima in wavelengths, is calculated using the formula: where n0 is the change in refractive index (n3-n2), and is the percentage of power in the core.

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

IV. WORKING PRINCIPLE OF FIBER BRAGG GRATING

An optical sensor known as an FBG is produced by laterally exposing a single mode fibre core to a regular pattern of strong UV laser light. The exposure causes a steady increase in the refractive index of the fiber's core (), resulting in fixed index modulation, or grating (). As seen in the illustration below, the grating inside the fibre optic core must transmit all other light while reflecting a particular wavelength of input light known as the Bragg wavelength (Bragg related to grating period). The Bragg wavelength is given by Equation.

$$\lambda_{Bragg} = 2\ \eta\ \Lambda \quad (7)$$

An interrogating unit, as shown in the above figure, is used to detect the shift in the reflected Bragg wavelength when a change in physical characteristics occurs and is determined by equation.

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

When T is the change in temperature, induced strain, thermal expansion coefficient, and thermo-optic coefficient are all present, pe is the strain-optic coefficient. The above equation indicates that strain and temperature both have an impact on Bragg shift. For silica fibre, Pe = 0.22 and a number of coefficients are known.

V. FBG EQUATIONS FOR STRAIN MEASUREMENT

A sensor length changes from its initial length, or strain, L, when stress is applied to it. The ratio of the fiber's corresponding strain to an applied stress is L/L. Temperature correction is required because, as a result of thermal expansion, temperature affects the physical dimensions. To estimate strain alone with an FBG sensor, the influence of temperature on calculating wavelength shift must be taken out. To mitigate the effect of local temperature on the FBG, this can be achieved by including a temperature sensor for the FBG along it. We have consequently subtracted equation (3) from equation (2) to arrive at equation (5) below, which quantifies strain.

The wavelength shift according to the applied strain is given by equation.

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

$$\Delta\lambda_{Bragg} = \lambda_{Bragg}(1 - p_e)\times\varepsilon_z \tag{10}$$

where ε is the applied axial strain and p_e is the effective strain-optic constant.

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

where p_{11} and p_{12} are components of the strain-optic sensor and v is the Poisson's ratio. For a germanosilicate optical fibre, P_{11} = 0.113, P_{12} = 0.252, V = 0.16, and N = 1.482. p thus has a value of 0.22.

Bragg wavelength sensitivity to strain,

$$\frac{\Delta\lambda}{\Delta\varepsilon} \tag{12}$$

VI. PARAMETERS SETUP

Parameters	Symbols	Values
Effective Refractive Index	n_{eff}	1.46
Bragg Wavelength	λ_B	1550 nm
Grating Period	Λ	530 nm
Strain-optic Constant	ρ_e	0.22

Table 1: The main parameters of Fiber Bragg Grating FBG.

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VII. RESULTS AND DISCUSSION

Simulation Tool: The length of fiber used in this study is L = 40 mm with increment of 0.050 mm. In this study, the ΔL used is in the increment of 0.050 mm ranges from (0.000 to 0.500) mm. In the simulation, the values of grating length, L studied are (L = 1,3,5,7,9 mm) under the influence of different refractive index (Δn = 0.0003, 0.0005, 0.0008, 0.0012, 0.0015, 0.0020). All the formulas from equation 1 to 4 have to be inserted into the Octave software for further mathematical operation and related data and graphs will be initiated by Octave with additional implementation of software, SRS1 Spline to fit the curves.

$\Delta\ell\ (\pm\ 0.05\ mm)$	Strain ($\mu\varepsilon$)	Bragg Wavelength Shift, $\Delta\lambda_B\ (\pm\ 0.10nm)$
0.000	0	0.00
0.050	1 250	1.51
0.100	2 500	3.02
0.150	3 750	4.53
0.200	5 000	6.05
0.250	6 250	7.56
0.300	7 500	9.07
0.350	8 750	10.58
0.400	10 000	12.09
0.450	11 250	13.60
0.500	12 500	15.11

Table 2: Changes in Fibre Length Caused by applied Strain

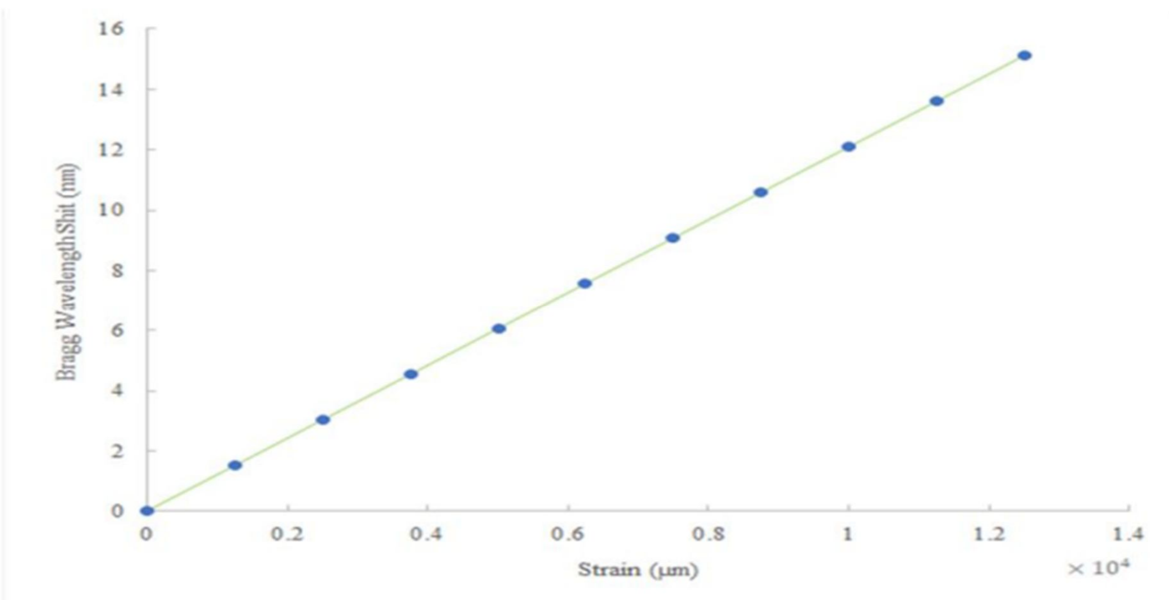

Figure 1: Bragg Wavelength Shift Graph Compared to Applied Strain

Grating Length, L (mm)	Δn = 0.0003	Δn = 0.0005	Δn = 0.0008	Δn = 0.0012	Δn = 0.0015	Δn = 0.0020
	Reflectivity (%)					
1.0	29.46	58.86	85.53	96.96	99.09	99.98
3.0	90.11	99.09	99.98	100.00	100.00	100.00
5.0	99.09	99.98	100.00	100.00	100.00	100.00
7.0	99.92	100.00	100.00	100.00	100.00	100.00
9.0	99.99	100.00	100.00	100.00	100.00	100.00

Table 3: Dependence of Bragg Wavelength Shift on Grating Length and Refractive Index Variations in Spectral Reflectivity

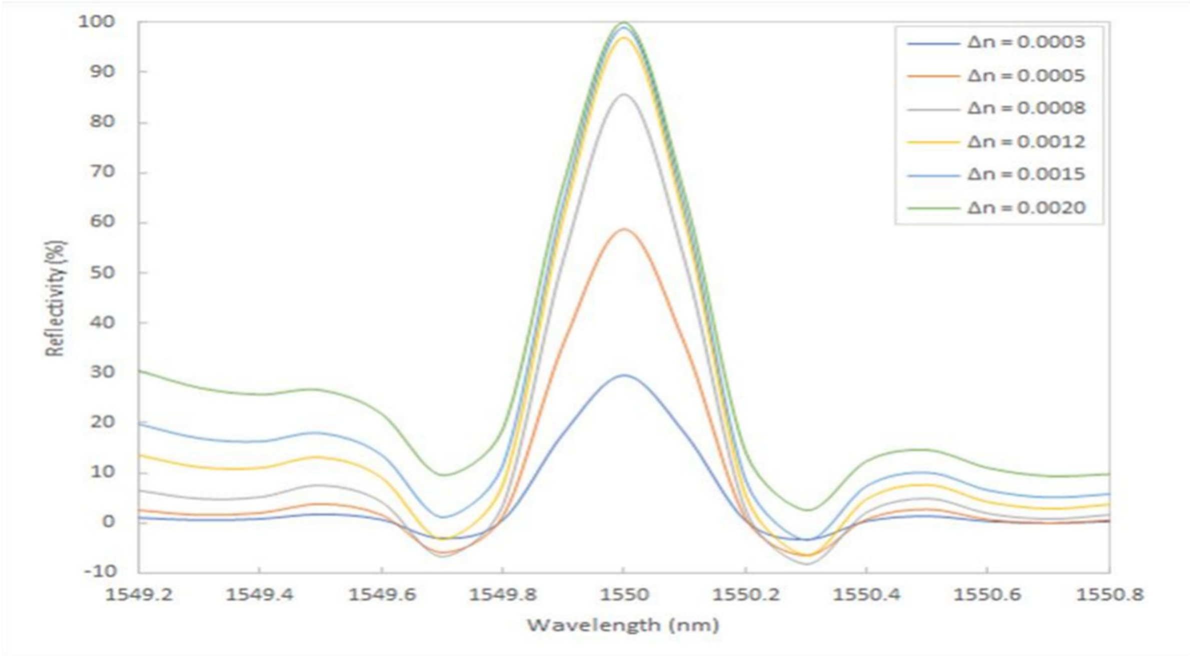

Figure 2: The FBG Reflection Spectrum at Fixed Grating Length, L = 1 mm, with Different Refractive Index Changes.

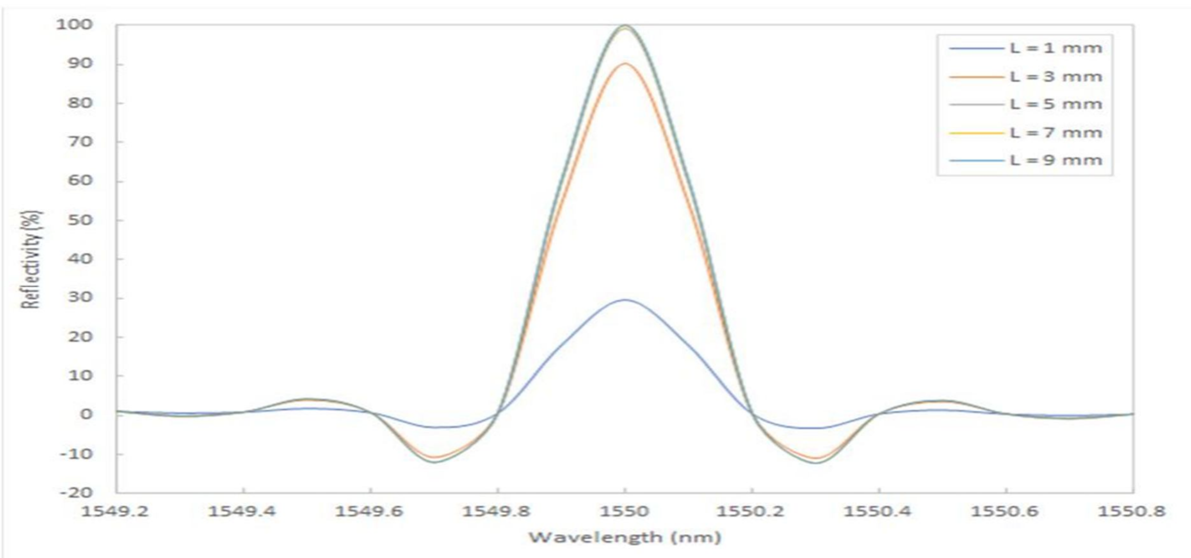

Figure 3: The Reflection Spectrum of FBG for Various Grating Length at Fixed Refractive Index Change, Δn = 0.0003

Grating Length, L (mm)	Δn = 0.0003	Δn = 0.0005	Δn = 0.0008	Δn = 0.0012	Δn = 0.0015	Δn = 0.0020
	Bandwidth (nm)					
1.0	1.68	1.73	1.85	2.08	2.29	2.69
3.0	0.63	0.76	1.01	1.39	1.68	2.19
5.0	0.46	0.63	0.91	1.32	1.63	2.15
7.0	0.40	0.58	0.88	1.30	1.61	2.14
9.0	0.37	0.56	0.87	1.29	1.60	2.13

Table 4: Dependence of Bandwidth on Grating Length and Refractive Index Variations.

VIII. CONCLUSION

Changes in fibre length are used to simulate strain based on the outcomes of the simulation. When the strain increases, the Bragg wavelength shift increases. Therefore, grating length also increases which causes the FBG reflectivity to increase. At grating lengths greater than 9.0 mm, the reflectivity of FBG achieves its maximum point, also known as full reflection. As the refractive index change increases, so does FBG reflectivity. When the refractive index change is greater than $\Delta n = 0.0020$, 100% of reflection will occur. Additionally, when the refractive index changes and the grating length increases, the FBG sensor bandwidth decreases.

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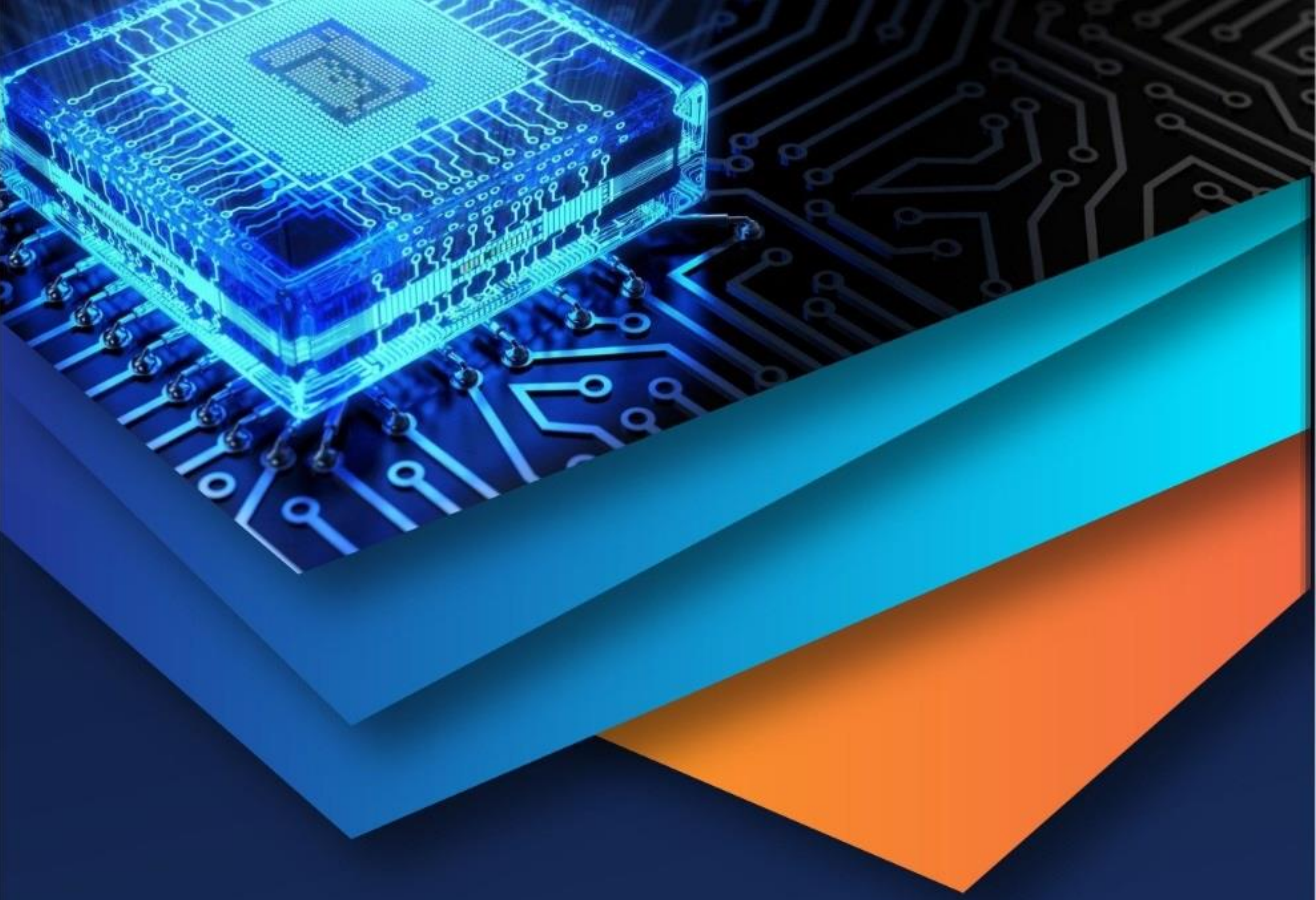

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