iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 7 Issue: VII Month of publication: July 2019

DOI: http://doi.org/10.22214/ijraset.2019.7191

A 2-D Photonic Crystal Polyatomic Structure for Sensing of Different Bio-Analytes

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Abstract: In this paper a two dimensional (2D) photonic crystal cavity (PCC) has been proposed for the sensing of bio-analytes. The 2D photonic crystal (PhC) has additional holes in between the holes of the central row which is to create a polyatomic structure. The additional holes are smaller in size compared to the other holes in the PhC. Parabolic tapering of the bigger and additional smaller holes in the central row has been done to create the cavity nature in the PhC. The quality factor of the structure is obtained to be ~3500. Further, to improve the quality factor of the cavity a slot has been introduced along the central row of holes. The quality factor improved to ~7200. The modified proposed PCC has been utilized for the sensing of bio-analytes such as cytop, blood plasma etc. It has been found that the sensing of the bio-analytes can be done very easily by the proposed modified sensor. The sensitivity of it has been found to be 250 nm/RIU. Therefore, the proposed modified PCC can be realized for the application of bio-analytes sensing.
Keywords: Slotted Photonic crystal, Bio-analytes, FDTD, Sensitivity, Di-electric constant

I. INTRODUCTION

Biochemical sensor based on optical communication recently utilized in forensic science, blood components detection, observation of agents causing diseases is a device capable for transformation of biotic details to perceptible optical signals [1], [2], [3] . It offers greater flexibility and reliability as compared to its electronics aspects. Optical sensing mainly dependent on cavity formed in the structure. Cavity is confinement of light comprises of electron-photon interaction. Photonic crystal cavity used to provide different sensors that offer different benefits compared to traditional sensing systems like high sensitivity with simultaneous high Q-factor. Photonic bandgap plays vital role in addressing the different properties of photonic crystal. A range of frequencies for which light can't propagate through the structure in any direction is Photonic bandgap and because of it many sensing devices are build using photonic crystal waveguides [4].

In most of 2D photonic crystal W1 waveguide is formed by removing the holes of central row to create cavity for the attainment of high Quality factor which attained with low sensitivity [5], [6]. So there is need of the structure with simultaneous high Quality factor and sensitivity. Mohammed Arif Iftekhar [6] analyzed two dimensional Photonic crystal waveguide for biochemical sensing, small wavelength shifting is done by modifying radii and lattice constant of holes. Min Qui [7] have designed channel drop filter with Quality factor of about 1500 using two waveguides with diatomic structure. Jamilah Husna [8] designed 1D photonic crystal tapered structure with Quality factor of 4300.

Quality factor further improved by optimizing the radii of holes in 2D photonic Crystal. Daobin Wang[9] have introduced optical biochemical sensor by using polyatomic structure in which there is small shift in resonant wavelength of 12.5nm and 28.2nm with the change of 0.347 and 0.737 respectively in refractive index which means low sensitivity.

For the analysis of Bio-Analytes in blood there is need to achieve optical behavior of blood under conditions like osmolality [10], [11] which is very difficult and conventional method based on Double Integrating Sphere technique with Inverse Monte Carlo Simulation method is also used for analysis but this conventional method needs time of approximately 12 to 72 hours. So Poonam Sharma [12] analyzed Bio-Analytes in blood with 2D photonic Crystal sensor using Quality factor and Output Transmittance Power. This analysis can be further enhanced using sensitivity and shift in resonant wavelength. With this motive the paper introduces a 2D photonic Crystal Cavity based Sensor having bigger holes and between them additional smaller holes parabolically tapered with a slot along the holes for high confinement of light by which simultaneous high Quality Factor to be ~7200 and high sensitivity of 250nm/RIU is obtained which is higher than most of above stated articles.

II. DESIGN OF THE PROPOSED SLOTTED 2D CRYSTAL PHOTONIC CAVITY

Design of slotted 2D photonic crystal have described in subsequent three subparts. An outline of structure is discussed in the first subsequent subpart. While the other subsection comprises of calculation of Quality factor and sensitivity.

A. Outline of the Structure

Schematic diagram of proposed structure of 2D photonic crystal with triangular lattice of periodic air holes shown in Fig. 1. The silicon substrate is used in the designing of Photonic crystal because it offers the significant Photonic Bandgap (PBG) and significant bandgap offers good cavity. The lattice constant for the PhC slab used is 420 nm and thickness taken for PhC slab is 220 nm. Fifteen rows of periodic air holes in triangular lattice is taken in ΓK direction. The radius of periodic holes above and below central row is taken as 0.28a where ‘a’ is lattice constant. Moreover, in the central row, additional smaller air holes in the middle of two bigger air holes is added to create polyatomic structure. On another note radii of bigger air hole in the center of central row taken as 0.23a which forms the resonant cavity. The radii of the bigger air holes parabolically tapered towards the trailing edges of structure. The radii of eight periodic air holes on both sides of cavity is tapered down from 0.23a to 0.22a and radii of additional smaller air holes is tapered down from 0.16a to 0.14a on both sides of hole forming cavity. The tapering in the radii of bigger air holes and additional smaller air holes is computed using the subsequent formula [13]

$$r(i) = r_{cavity} - (i / i_{max})^2 \times (r_{cavity} - r_{outer}) \quad \text{(I)}$$

Where i represents index of periodic air holes and manually inserted air holes moving outwards in both directions. The i_{max} represents number of holes that are tapered in either side of cavity which are 8 here. Radii of the cavity hole and radii of external lowermost sized tapered hole are denoted as r_{cavity} and r_{outer} respectively.

Outermost lowest sized hole offers mirror nature for specific resonating wavelength compared to cavity hole [14]. Due to mirror nature shown by the tapered down holes termed as tapered mirror holes. Tapering down of radii of holes is done parabolically because it is able to obtain the field profile which is like Gaussian that allows to attain narrow line width of resonance due to which high Quality factor is achieved [14], [15]. Mirror nature of optical signal is improved by adding the three non-tapered mirror holes of radii 0.22a and two non-tapered mirror holes of 0.14a on both side of the structure.

B. Quality Factor

Finite difference time-domain method is used to calculate the Quality factor of the structure. Multiple peaks are obtained due tapered hole radii [16]. The peak at fundamental mode obtained at a wavelength of 1440 nm and the quality factor to be ~3500. The transmittance graph is shown in Fig.2 which shows the multiple peaks at different wavelength with different Quality factor. Since there is furthermore scope for enhancement of Quality factor by introducing a slot along tapered holes of central row.

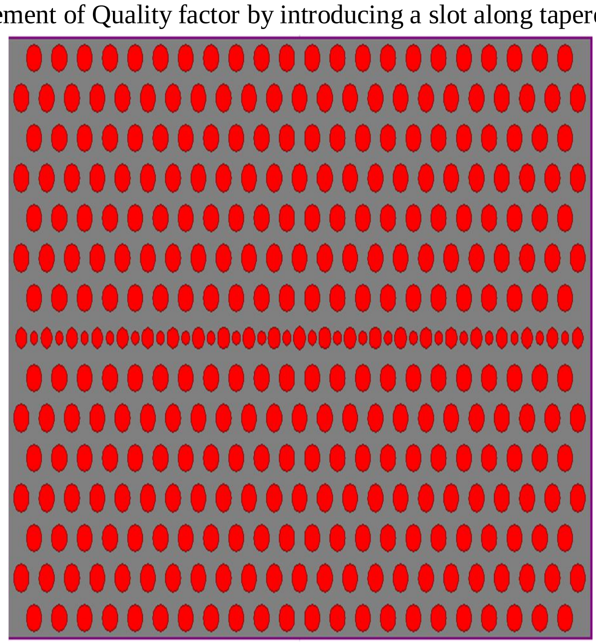

Fig.1 schematic diagram of slotted 2D photonic crystal cavity having the central row holes tapered with slot in the middle. The radius of periodic holes and manually inserted holes parabolically tapered from central hole to both ends of structure with non-tapered mirror holes where lattice constant ‘a’ is constant.

Normalized transmittance graph of 2D photonic crystal cavity is depicted in Fig. 2

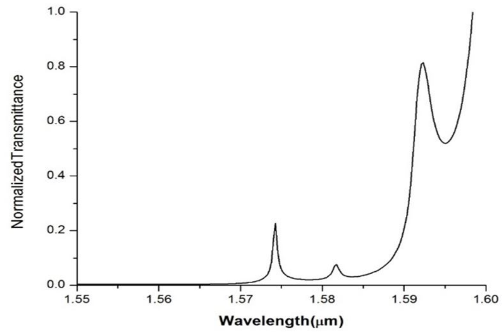

Fig. 2 Normalized transmittance graph of 2D photonic crystal cavity without slot obtained from FDTD simulation

C. Including Another Element Of Control By Introducing Slot Along Tapered Holes

Further modification has been done by introducing a slot along tapered holes in central row of structure. In this revised structure shown in Fig .3, a slot of 50nm is introduced along the central row tapered holes which in turn separates the structure in the two halves. It is used to obtain high Quality Factor with simultaneous high sensitivity due to high confinement of light.

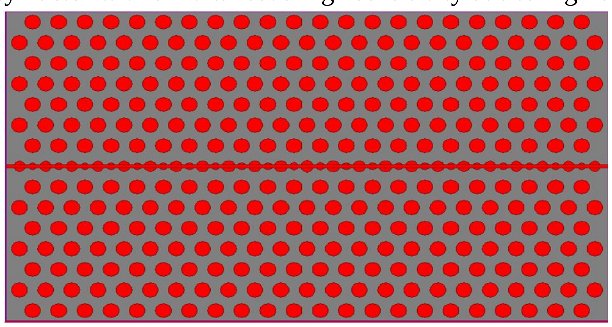

Fig. 3 schematic diagram of slotted 2D photonic crystal cavity having the central row holes tapered with slot in the middle. The radius of periodic holes and manually inserted holes parabolically tapered from central hole to both ends of structure with non-tapered mirror holes where lattice constant 'a' is constant and slot of 50 nm is present in the middle of the row.

Improved Quality factor to be ~7200 with high confinement of light which means high sensitivity in this modified structure. Improvement in Quality Factor and Sensitivity is noted by introducing slot of 50nm compared to structure shown in Fig. 1. A comparison between 2D photonic crystal cavity with slot and without slot is done based on the parameters sensitivity and Quality factor and outcome of that comparison is that Slotted 2D photonic crystal cavity have better Quality factor and Sensitivity compared to 2D photonic crystal cavity without slot because due to slot confinement of light is high which enhance the Quality factor and Sensitivity simultaneously. Hence revised structure shown in Fig. 3 is further utilized for analysis of Bio-Analytes in blood. Normalized transmittance graph of 2D photonic crystal cavity without slot depicted in Fig. 4. The quality factor is obtained at wavelength of 1441 nm to be ~7200.

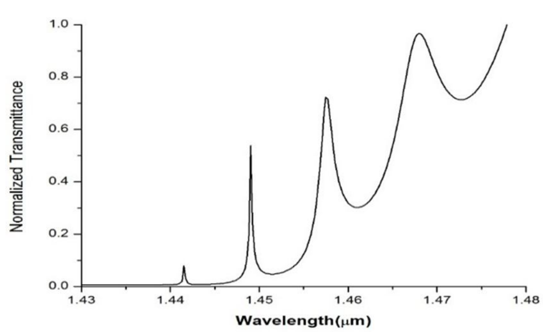

Fig. 4 Normalized transmittance graph of slotted 2D photonic crystal obtained from FDTD simulation

III. ANALYSIS OF QUALITY FACTOR FOR DIFFERENT BIO-ANALYTES BY USING SLOTTED 2D PHOTONIC CRYSTAL CAVITY SENSOR

Sensitivity is factor from which the ability of sensor to sense is decided. Sensitivity of sensor is decided by amount of shifting in the resonant peak with unit change in refractive index of sensing region. So to calculate the sensitivity, the shift in the resonant peaks of the structure is supervised with the change in refractive index of sensing region.

Photonic crystal cavity sensors are also termed as optical resonance sensors that can be integrated as a lab-on-a-chip system having high Quality factor and small footprint [17], [18]. Photonic crystal cavity sensors work on a principle of modification in optical characteristics of structure with the change in refractive index. It mainly depends on the amount of change in dielectric constant of Bio-Analytes due to which the propagation velocity [19] of wave changes which can be quantified that is proportionate to amount of Bio-Analytes present on the surface. Hence it can be used as a tool for diagnosis for Bio-Analytes. This is result from the interaction of wave and Bio-Analytes [17], [4]. Photonic Band Gap [PBG] is property of photonic crystal by which propagation of wave for respective range of wavelength is restricted and by introducing defect some leaky wave propagates which is used for sensing. FDTD tool is used for the simulation for the analysis of Quality factor of Bio-Analytes present in the blood. For this analysis structure shown in Fig. 3 of slotted 2D photonic crystal cavity sensor is used and when this sensor device gets immersed in sample of blood then sensing region gets replaced with Bio-Analytes. Analysis is done on basis of interaction of wave with Bio-Analytes due to which there is a variation in velocity of wave which gets sensed.

A. Simulation Results

Different transmittance spectrum obtained for different Analytes. The shift in transmittance peaks is observed for different Analytes having different dielectric constant which are shown in the table below. The Table comprises of Bio-Analytes with their Resonant Wavelength, Sensitivity and input Dielectric Constant.

Table 1. Dielectric constant, Resonant Wavelength and Sensitivity

Bio-Analytes	Dielectric Constant	Resonant Wavelength(nm)	Sensitivity
Cytop	1.7956	1605.9	203 nm/RIU
Blood Plasma	1.8225	1608.2	199 nm/RIU
Ethanol	1.8496	1610.8	196 nm/RIU
Hemoglobin	1.9044	1615.6	189 nm/RIU
Glucose	1.96	1620.3	183 nm/RIU
Biotin-Streptavidin	2.1025	1632.0	170 nm/RIU
Bovine Serum Albumin	2.1609	1638.6	167 nm/RIU

Normalized transmittance graph for cytop depicted in Fig.5. The resonant wavelength of the transmittance peak found is 1605.9 nm.

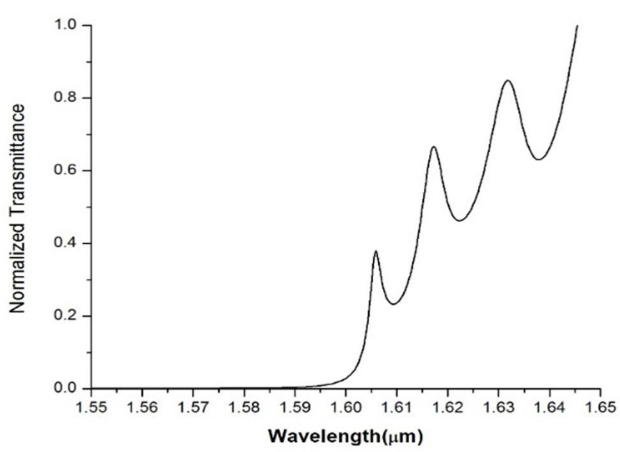

Fig. 5 Normalized Transmittance Graph of Cytop.

Normalized transmittance graph for Blood Plasma depicted in Fig.6. The resonant wavelength of the transmittance peak found is 1608.2 nm.

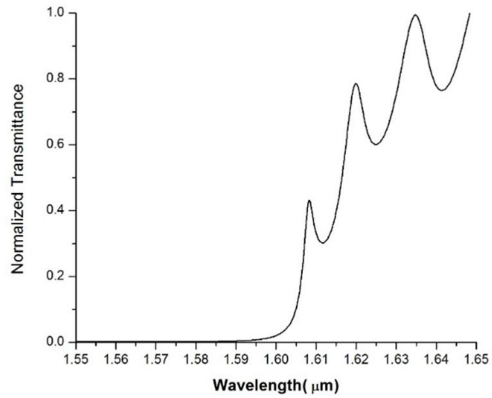

Fig. 6 Normalized Transmittance Graph of Blood Plasma.

Normalized transmittance graph for Ethanol depicted in Fig.7. The resonant wavelength of the transmittance peak found is 1610.8 nm.

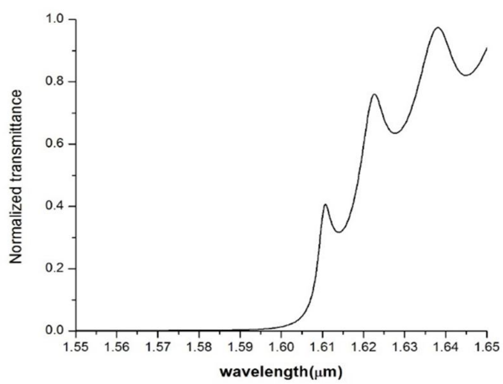

Fig. 7 Normalized Transmittance Graph of Ethanol.

Normalized transmittance graph for Hemoglobin depicted in Fig.8. The resonant wavelength of the transmittance peak found is 1615.6 nm.

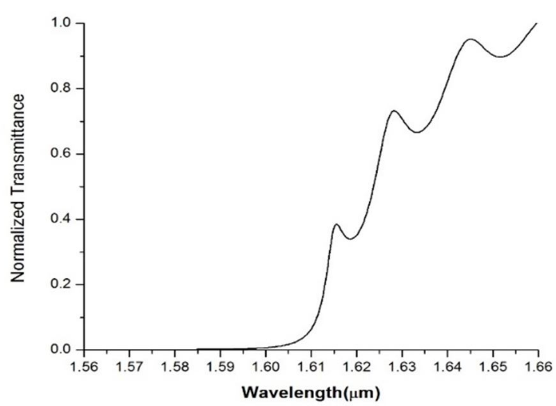

Fig. 8 Normalized Transmittance Graph of Hemoglobin.

Normalized transmittance graph for Glucose depicted in Fig.9. The resonant wavelength of the transmittance peak found is 1620.3 nm.

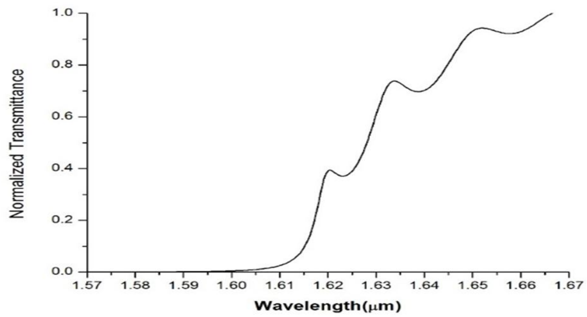

Fig. 9 Normalized Transmittance Graph of Glucose.

Normalized transmittance graph for Biotin-Streptavidin depicted in Fig.10. The resonant wavelength of the transmittance peak found is 1632 nm.

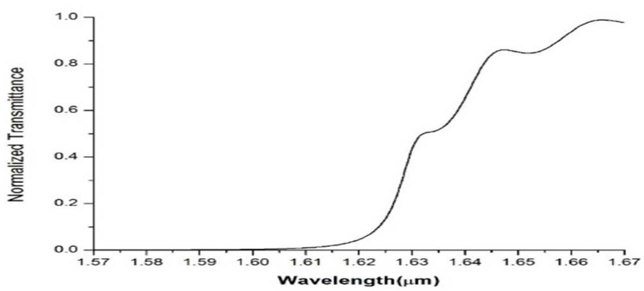

Fig. 10 Normalized Transmittance Graph of Biotin-Streptavidin.

Normalized transmittance graph for Bovine Serum Albumin depicted in Fig.11. The resonant wavelength of the transmittance peak found is 1638.6 nm.

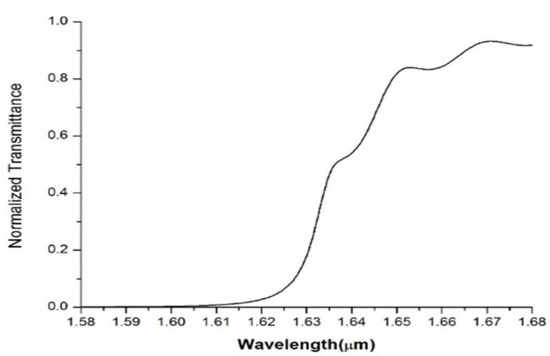

Fig. 11 Normalized Transmittance Graph of Bovine Serum Albumin.

IV. CONCLUSION

In this paper, 2D Photonic crystal is realized and used as biochemical sensor. FDTD simulation is used for analysis, quality factor of ~3500 is obtained in 2D Photonic crystal. The slot of 50 nm is introduced along the tapered hole in central row of structure so that simultaneous improved Quality factor and sensitivity can be obtained. By introducing slot, improved Quality factor to be ~7200 and sensitivity of 250 nm/RIU is obtained in Slotted 2D Photonic crystal. Hence Slotted 2D Photonic crystal is utilized for the detection of different Bio-Analytes in blood. The sensor design utilized for detection of cytop, blood plasma etc. Sensitivity decreases as the dielectric constant of Bio-Analytes increases. As per author best knowledge structure is highly sensitive and such Quality factor have not been obtained in similar structure. Hence it is hoped to be propitious device for sensing applications.

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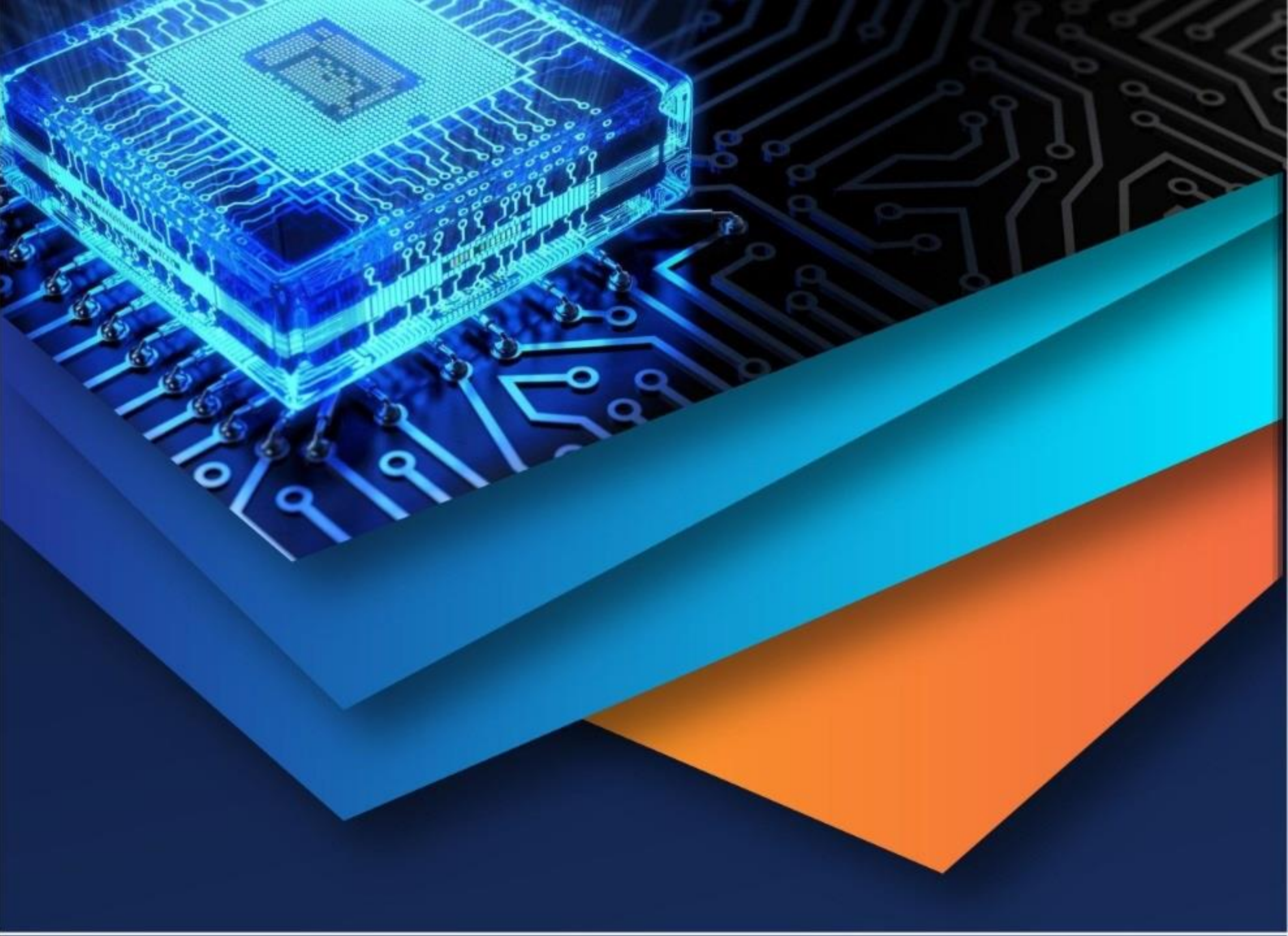

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