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Mode Patterns, S-parameters and Dispersion Analysis of a Circular Waveguide

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Abstract: A circular waveguide is a metallic hollow tubular structure that transmits high-frequency electromagnetic waves with negligible losses. This paper presents the design, simulation, and analysis of a circular waveguide in CST Studio's waveguide template using frequency domain solver. The study focuses on mode patterns (focusing TE_{11}, TE_{21}, TE_{01}), S-parameters (reflection and transmission), group delay, phase variation, and phase constant. In this paper, the waveguide is designed to operate in the X-band, functioning as a high-pass filter (HPF) that allows wave propagation above certain threshold frequency. Simulations reveal the field distributions for different modes, highlighting the dominant propagation characteristics. The S-parameter analysis indicates reflectionand transmission characteristics. Additionally, the group delay and phase constant analysis provide insights into dispersion and integrity of signal. These findings contribute to a better understanding of wave propagation in circular waveguides, aiding in their effective implementation in microwave and RF applications.

Index Terms: Waveguides, Circular Waveguides, CST, Mode Patterns, S-parameters, TE, TM, Phase Constant, Group Delay, Phase variation, Dispersion.

I. INTRODUCTION

Waveguides are crucial components in microwave and RF communication systems, enabling efficient transmission of high-frequency electromagnetic waves with minimal loss of power. Circular waveguides, in particular, are widely utilized due to their ability to support multiple propagation modes, high power-handling capacity, and reduced dispersion compared to rectangular counterparts. Every waveguide has a particular cut-off frequency for each mode. If the signal's frequency surpasses the cut-off frequency value of the selected mode, then the electromagnetic energy is transmitted efficiently for that particular mode with no attenuation, else the electromagnetic energy is attenuated to minimal value [1].For designing most of theoptical and microwave devices, such as antennas, couplers and filters, waveguide modes are fundamental.They describe the various ways of propagation of electromagnetic waves within the waveguide, having distinct magnetic and electric field distributions. Circular waveguide basically has two modes of distribution, they are TE (Transverse electric) and TM (Transverse magnetic) modes, theseare described using indices 'm' and 'n' which represents the variation of field in radial and axial direction respectively[2]. In TE modes, the electric field has no component along the direction of propagation i.e., along the Z axis in general, meaning the electric field is entirely in transverse to the direction of propagation, with TE_{11} being the dominant mode due to its lowest cut-off frequency and minimal propagation loss. TE_{11} mode is most preferred due to its almost plane wave like structure of the fields around the centre of the waveguide. In TM modes, the magnetic field has no component along the direction of propagation, meaning the magnetic field is entirely in transverse to the direction of propagation.TM_{01} mode is less desirable due to minimum intensity pattern on the axis [3].S-Parameters or scattering parameters, are a way todescribe the relation between the incident and the reflected waves at the network's ports [2]. In this paper, we focus on two main parameters reflection coefficient (S11) and transmission coefficient (S21), where reflection coefficient is the ratio of reflected component to the incident component and transmission coefficient is the ratio of transmitted component to the incident component. Analysing the S-parameters in the circular waveguide helps in understanding signal transmission, reflection and impedance matching, crucial for designing and optimizing the microwave and RF systems.In waveguides, group and phase velocity of the signal components vary with frequency. The signal as it goes through the waveguide, would undergo distortion, more likely dispersion. The analysis of group delay, phase variation and phase constant help in the analysis of signal dispersion [4]. Group Delay (τ_g) represents the time delay of a signal envelope as it propagates through the medium. It is essential for understanding signal distortion and dispersion in communication systems. Phase Variation (ϕ) indicates how the phase of a signal changes with frequency.

It helps in determining phase shifts and ensuring proper signal synchronization. Phase Constant (β) defines the propagation characteristics of a wave through a medium. It directly affects the wavelength and phase velocity of the signal.

The experimental study on these parameters is conducted by Seyed Mohammadreza Razavizadeh [5].To build the foundation for this paper mode patterns in rectangular waveguides are studied, highlighting how different modal distributions affect field behaviour by V. Prakasam and P. Sandeep [6]. The study laid the foundation for understanding of the electromagnetic propagation and fundamental theoretical insights into microwave waveguides, explaining the principles behind wave propagation, cut-off frequencies, and dispersion characteristics, which is extended in the present studyof circular waveguides. By building on these prior studies, this paper presents a comprehensive simulation-based study of a circular waveguide, analysing its behaviour across multiple modes. The waveguide is designed to operate as a high-pass filter (HPF), effectively transmitting signals above its cut-off frequency while attenuating lower-frequency components. To understand the propagation characteristics of circular waveguides, this study employs CST Studio suite to simulate and analyse different modes of propagation, investigating parameters such as mode patterns, S-parameters, phase variation, phase constant, and group delay. By examining these parameters, the goal is to gain insights into optimizing waveguide designs for efficient electromagnetic wave transmission for various applications such as radar, satellite communications, and high-power microwave systems.

II. DESIGN AND MODELLING

A. *Waveguide Design Specifications*

The circular waveguide in fig. 1 is designed as a high-pass filter (HPF), ensuring propagation of electromagnetic waves above the cut-off frequency f_c while attenuating frequencies below the cut-off value. The design parameters are written in terms of wavelength (λ_c) as given in table 1, where inner radius is $0.293\lambda_c$,outer radius is $0.326\lambda_c$ and length of the waveguide is $2\lambda_c$.These dimensions ensure optimized mode propagation and allow efficient transmission within the intended frequency range (X band).$\lambda_c$is given by the equation 1:

$$\lambda_c = \frac{c}{f_c} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..(1)$$

Where, c is the speed of the light ($3x10^8$ m/s) and f_c is the cut-off frequency

Table 1. Parameters of circular waveguide

Parameter	Value in terms of λ_c
Inner radius (in mm)	$0.293\lambda_c$
Outer Radius (in mm)	$0.326\lambda_c$
Length (in mm)	$2\lambda_c$

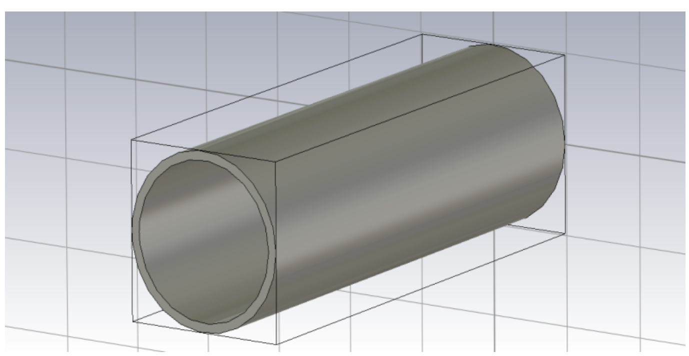

Fig1. Circular waveguidemodel

B. *Cut-off Frequency Calculation*

The cut-off frequency (f_c) determines the lowest frequency at which a specific mode can propagate and is given by equation 2:

$$f_c = \frac{X_{mn}c}{2\pi a} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..(2)$$

Where, $X_{mn}$is root of the Bessel function for the specific mode, c is speed of light (3×10^8 m/s), a is inner radius of the waveguide. This formula is crucial for determining the cut-off frequencyand ensuring the waveguide functions effectively as an HPF.

C. Simulation Setup

The circular waveguideis simulated using the Frequency domain solver in the CST Studio Suite, operating in X band. The circular waveguide constructed is of the material PEC (Perfect Electric Conductor). Open boundary conditions are applied to simulate a realistic wave propagation environment.Two waveguide ports are placed at the open ends to measure wave transmission as shown in fig. 2.

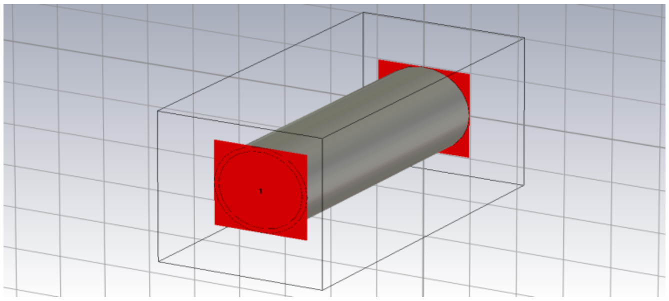

Fig2. Waveguide ports at ends

III. SIMULATION RESULTS

A. S-Parameters

The S-parameter simulation results for the circular waveguide reveal distinct behaviours for the reflection coefficient (S_{11}) and transmission coefficient (S_{21}) across the frequency spectrum as shown in fig. 3 and 4 respectively.

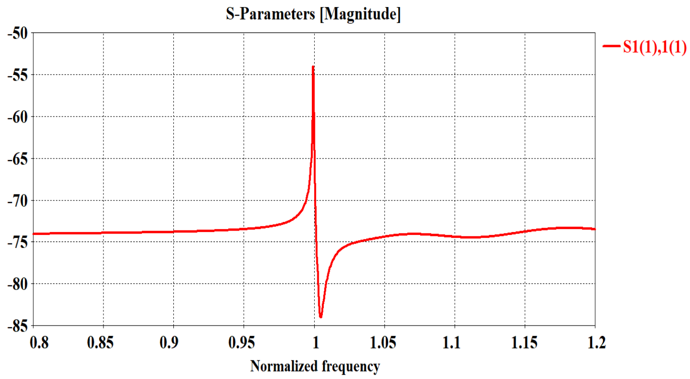

Fig3. Reflection co-efficient

The initial low value of a high-pass waveguide is due to the fact that at very low frequencies, most of the energy is not reflected but rather dissipated, meaning it does not propagate effectively. When the signal is below the cut-off frequency, the incident wave is mostly absorbed or attenuated instead of being reflected back, leading to a low Reflection Coefficient. Around cut-off value, S_{11} exhibits a sharp rise, indicating increased reflection. This behaviour may correspond to mode transitions or resonance within the waveguide structure. Following the peak, S_{11} rapidly decreases, suggesting a return to better impedance matching conditions. However, it then gradually increases back to around -75 dB and stabilizes, indicating consistent reflection characteristics at higher frequencies.

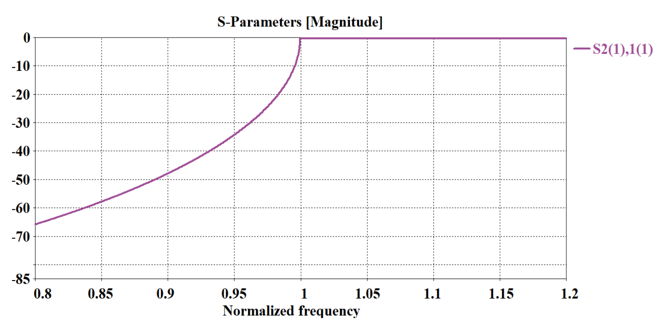

Fig4. Transmission co-efficient

The S_{21} parameter starts at a low value at lower frequencies, indicating minimal transmission due to the cut-off frequencies of the waveguide modes. As the frequency approaches cut-off value, S_{21} gradually increases, signifying enhanced transmission as more modes propagate. Beyond cut-off value, S_{21} stabilizes near 0 dB, suggesting efficient transmission with minimal losses.

The observed S-parameter behaviours can be attributed to the waveguide's modal characteristics and impedance matching: The initial low S_{21} values correspond to frequencies below the cut-off for dominant modes. As the frequency increases, additional modes propagate, enhancing transmission. The S_{21} parameter shows that signal transmission improves gradually and stabilizes at a low value, indicating that most of the energy is transferred efficiently beyond a certain frequency. This is beneficial in applications like RF filters and amplifiers, where selective frequency transmission is required for effective signal processing.The variations in S_{11} reflect changes in impedance matching due to mode transitions or structural resonances within the waveguide. The S_{11} parameter exhibits a strong dip at a specific frequency, representing minimal reflection at that point, which is ideal for impedance-matched systems. This characteristic is critical in designing antennas, wireless communication devices, and microwave circuits, where reduced reflection enhances overall efficiency.

B. Mode patterns Analysis

The mode patterns at port areanalysed for different modes:

TE_{11} mode(fig. 5) exhibits a dominant circularly symmetric field pattern with a single maximum along the radial direction, ensures minimal attenuation and serves as the primary propagating mode due to its lowest cut-off frequency. The field vectors of this mode shows uniform distribution with a slight phase variation across the waveguide cross-section.

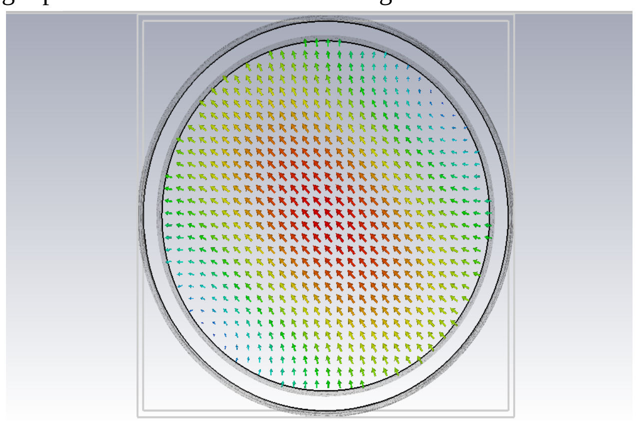

Fig5. TE_{11} mode (E_1 - fundamental mode)

TE_{21} Mode(fig. 6) displays two field lobes along one axis and a single variation along the other. This mode introduces additional propagation paths, leading to different phase velocities and requires a higher frequency for propagation, contributing to mode dispersion effects.

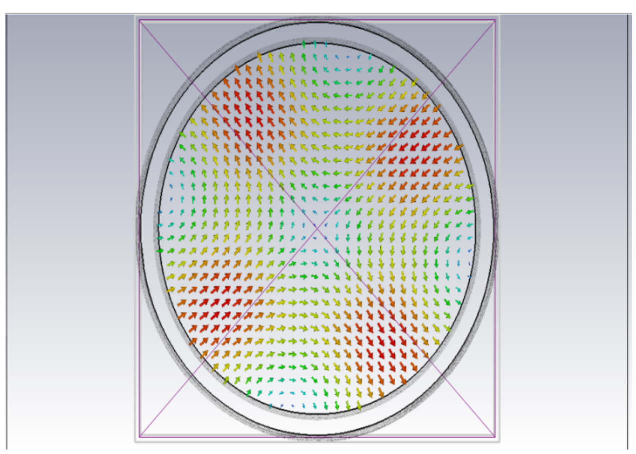

Fig6. TE_{21} mode (E_4 - higher-order mode)

TE_{01} Mode (fig. 7)is characterized by circularly symmetric field variations and supports unique power distribution.Typically, this mode exhibits lower losses compared to asymmetric higher-order modes.

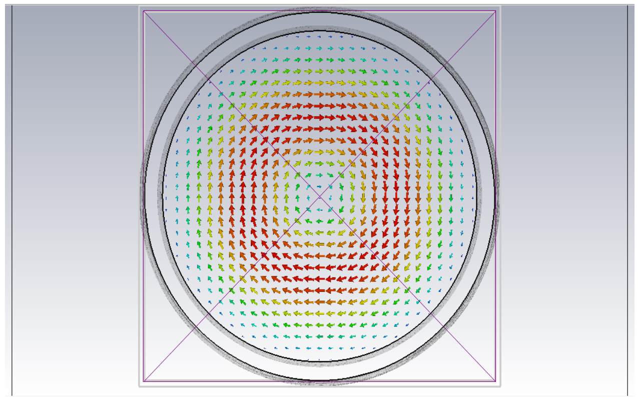

Fig7. TE_{01} mode (E_{10} - non-degenerate mode)

These results align with theoretical mode behaviour in circular waveguides.The observed mode patterns (TE_{11}, TE_{21}, and TE_{01}) demonstrate distinct field distributions, which are critical for optimizing wave propagation in practical applications. TE_{11}, being the dominant mode, is widely used in standard waveguides for microwave transmission, ensuring minimal signal loss. Higher-order modes like TE_{21} and TE_{01} play a role in high-power applications such as particle accelerators and high-frequency antennas, where controlled mode excitation enhances performance. This analysis is essential in designing efficient waveguides for satellite communication, radar systems, and advanced sensing technologies.

C. Group Delay, Phase Variation, and Phase Constant

Understanding the behaviour of electromagnetic waves in waveguides requires analysing key transmission characteristics, including group delay, phase variation, and phase constant. These parameters provide insights into signal integrity, phase distortion, and dispersion, which are crucial in RF and microwave applications.

The group delay is computed using equation 3:

$$\tau_g = -\frac{d\varphi}{d\omega} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..(3)$$

where ϕ is the phase of the S-parameter and ω is the angular frequency.

The simulated group delay characteristics are illustrated in Fig. 8. The response exhibits a sharp peak at the cut-off frequency, followed by a rapid decline and subsequent stabilization. This indicates a significant dispersion near the cut-off, which is expected in waveguide-based transmission lines. The observed behaviour suggests that minimal distortion occurs beyond this point, ensuring stable signal propagation.

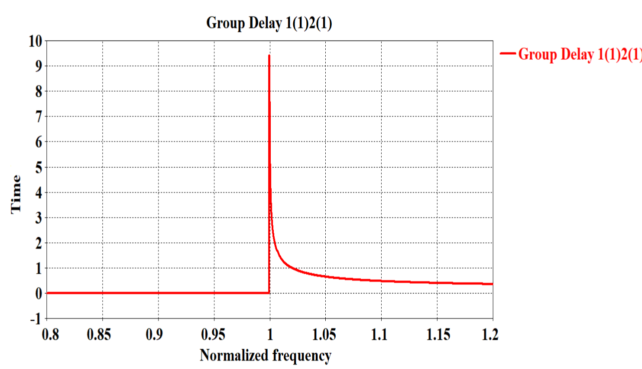

Fig8. Group delay

Phase shift is given by equation 4:

$$\varphi = \beta L \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..(4)$$

where β is the phase constant and L is the propagation length.

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Fig. 9 presents the phase variation across the frequency spectrum. The phase response exhibits a monotonic increase, demonstrating a gradual phase shift with increasing frequency. This behaviour is characteristic of wave propagation through guided structures, confirming proper impedance matching and minimal phase anomalies. The phase stability beyond the cut-off frequency suggests efficient signal transmission without abrupt phase discontinuities.

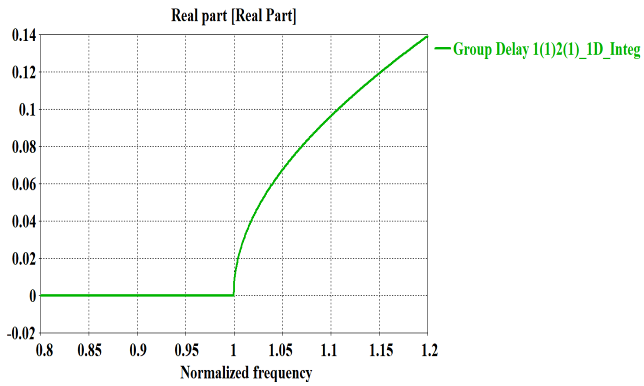

Fig9. Phase variation

The phase constant is given by equation 5:

$$\beta = \frac{2\pi f}{v_p} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

where f is the frequency and v_p is the phase velocity.

The phase constant simulation results are shown in Fig. 10. The curve follows an increasing trend, confirming the expected dispersion relationship. The smooth variation of the phase constant with frequency indicates minimal mode interference, ensuring predictable signal propagation

characteristics. The obtained results align well with the theoretical expectations, reinforcing the accuracy of the designed waveguide structure.

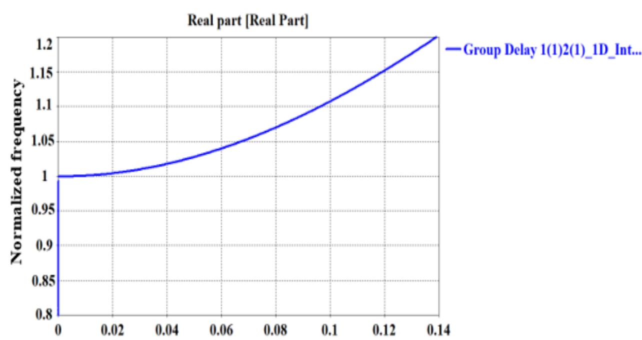

Fig10. Phase constant

The group delay analysis indicates that signal distortion is prominent near the cut-off frequency but stabilizes afterward. This is crucial in high-frequency communication systems, where minimizing signal distortion ensures reliable data transmission in applications such as radar and satellite communication.The phase variation analysis shows a gradual increase in phase shift with frequency, which is essential for maintaining synchronization in phased array antennas and optical communication networks. Proper phase control helps to improve signal integrity and reduces errors in wireless communication systems.The phase constant analysis confirms stable wave propagation beyond the cut-off frequency, making the system suitable for applications like waveguides, RF filters, and microwave circuits. This ensures minimal signal loss and efficient power transmission in wireless networks and radar systems.Overall, the analysis demonstrates that after the cut-off frequency, the system operates efficiently with reduced distortion, making it highly applicable for advanced telecommunication, radar, and high-speed data transmission technologies.

IV. CONCLUSION

The analysis of mode patterns, S-parameters, and wave propagation characteristics in a circular waveguide is essential for practical applications in satellite communication, radar, and high-frequency microwave systems. The mode pattern study reveals how different modes propagate, influencing system efficiency in applications requiring low-loss and high-power transmission. The dominant TE_{11} mode ensures stable propagation, making it ideal for satellite feeds and deep-space communication, while higher-order modes like TE_{21} and TE_{01} play a role in advanced signal processing and high-power applications. The S-parameter analysis confirms the waveguide's high-pass filtering behaviour, where S_{21} shows effective power transmission beyond the cut-off frequency, ensuring minimal loss in practical microwave and RF applications. Meanwhile, the S_{11} response highlights impedance mismatches that can be optimized to improve antenna performance and minimize signal reflection. The group delay analysis demonstrates that after the cut-off frequency, signal distortion stabilizes, which is critical for maintaining data integrity in high-speed communication systems. The phase variation and phase constant results ensure predictable signal behaviour, essential for phased-array antennas and precise frequency control in radar and satellite links. Overall, these analyses validate the circular waveguide's efficiency in supporting multiple propagation modes while maintaining stable transmission, making it a vital component in modern high-frequency communication systems.

V. ACKNOWLEDGEMENT

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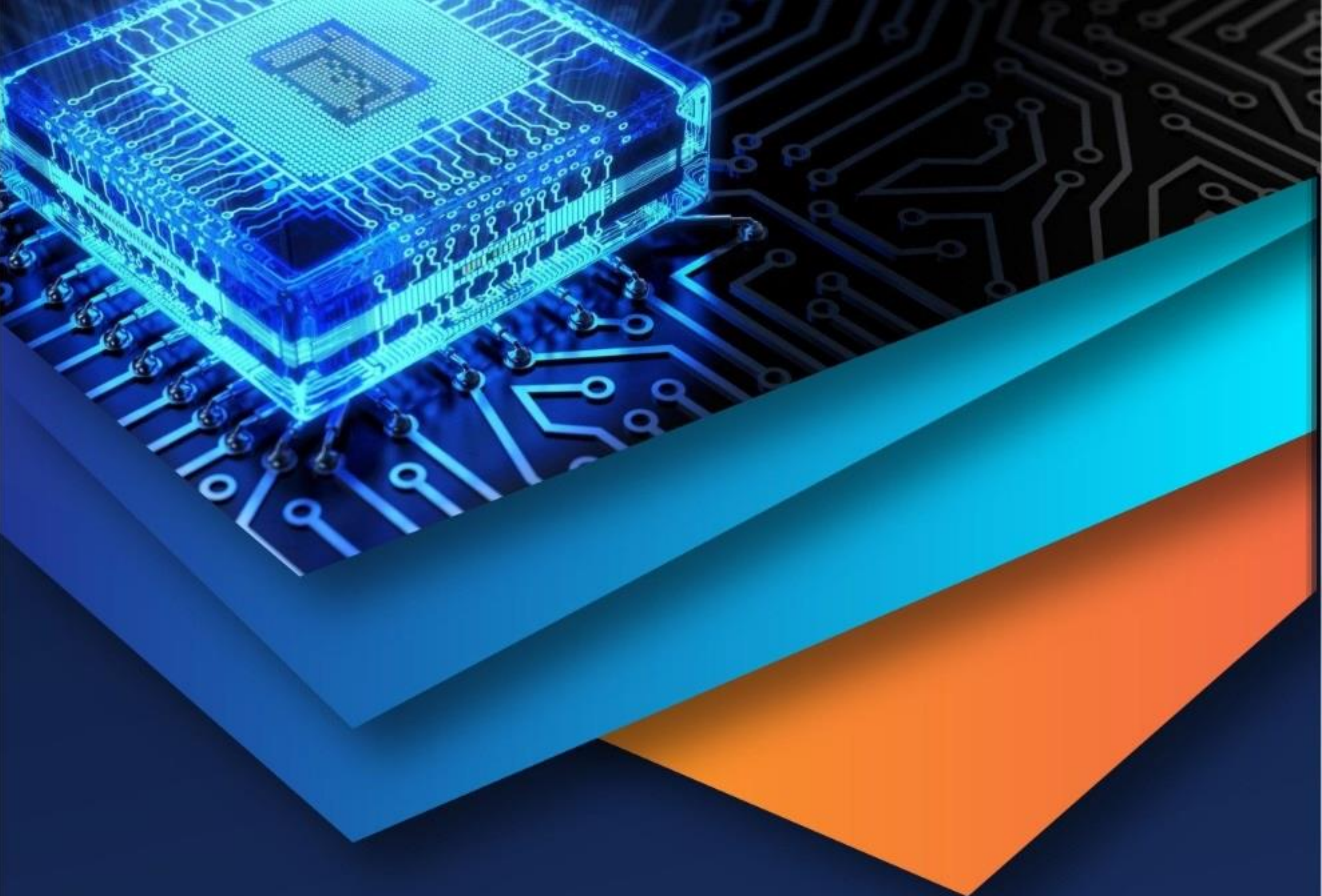

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