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Design and Analysis of Antenna Triplexer using SIW

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Abstract: A low-profile antenna-triplexer is realized using a substrate integrated waveguide (SIW) technology for radio altimeter/ WLAN/ISM band applications. The antenna is composed of two SIW cavity resonators where a smaller cavity is nested inside the larger one. The larger cavity is excited by using two distinct microstrip feedlines, while the smaller one by a coax probe. The antenna produces three distinct resonances around 4.18, 5.2, and 5.8 GHz simultaneously employing one annular slot and two transverse slots. By exciting cavity modes (TE110/TE120) and the patch mode (TM10) simultaneously, an average isolation of better than 23 dB is accomplished among three input ports. As compared to the conventional counterparts, the proposed geometry is simple to realize in a compact space. To validate the proposed idea, the design is experimentally tested, and the measured responses show a good agreement with the simulations. Moreover, the antenna shows a front-to-back ratio better than 19 dB and measured gain values of 6.56, 4.2, and 5.85 dBi at three resonances. The proposed design is compact, easy to fabricate, and capable to integrate with planar circuits.
Index Terms: Antenna-triplexer, isolation, multiband antenna, substrate integrated waveguide (SIW).

I. INTRODUCTION

IN RECENT years, with the excessive growth of modern wireless communication systems, the planar low-cost multiband antennas are in high demand. The compact mobile handheld devices are equipped with multiple transceivers to operate for different applications [1]. Therefore, to avoid interference between transmitting and receiving channels, a high intrinsic isolation among the input ports is extremely important. To achieve a high isolation, decoupling networks are used at the input ports of resonating circuits, which leads to an increase in the circuitry size and makes it complicated to use in compact portable devices [2]. Recently antenna diplexer/triplexer has drawn special attention of researchers, as it avoids the requirement of decoupling network and makes an RF front-end system more compact and simple [3]. In previous literature, different antenna-diplexers are designed by using several techniques such as using a defectiveground plane [4], multilayered patch [5], and spiral defected microstrip resonators [6]. The above-mentioned techniques are complex and multilayered structures that are difficult to integrate with planar circuits. However, in the present scenario, there is a demand for triple-frequency band circuits. An antennatriplexer is presented in [7], integrated into a small space using a double-layered structure, but the radiation characteristics are not satisfactory due to the multimode excitation.

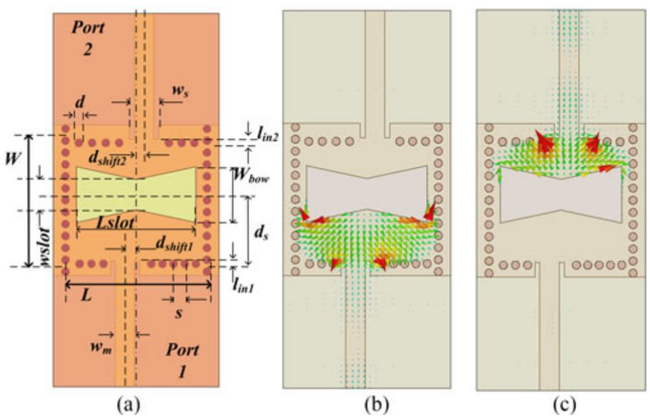
Recently, a substrate integrated waveguide (SIW) has been developed as a mature technology in realizing cavity-backing antennas in a planar circuit [8]. It offers the combined features of slot antennas such as low profile and cavity features of the unidirectional radiation pattern with high gain. Most recently, similar works based on the SIW self-diplexing/triplexing antennas have been introduced in [9]–[11]. In [10], the reported work shows a good in-band band performance, but it covers a relatively larger space than the proposed antenna. In [11], the antenna radiates through a T-shaped slot that produces three resonances in a compact structure, but it shows higher cross-polar level and relatively lower gain than the proposed geometry. This letter presents a simple SIW cavity-backed slot antennatriplexer for radio altimeter (4.2 GHz), WLAN (5.2 GHz), and ISM band (5.8 GHz) applications. An integrated antennatriplexer is designed by nesting a smaller SIW cavity inside the larger one. Three radiating slots produce three distinct resonant frequencies when they are excited by three separate feedlines.

The intrinsic isolation is achieved below −23 dB at each operating frequency, which helps to realize triplexing functionality. The proposed antenna shows unidirectional radiation pattern at three operating frequencies due to a cavity-backed structure. The proposed design is a single-layered geometry containing a simple feeding network.

II. DESIGN OF SELF-DIPLEXING SIW

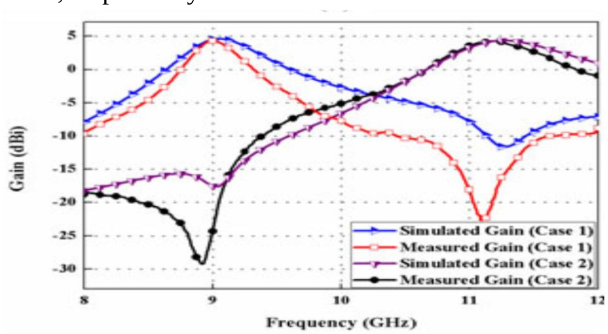
A. *Cavity-Backed Slot Antenna*

A novel design of compact planar SIW cavitybacked self-diplexing antenna using bowtie-shaped slot while maintaining high isolation between input ports is presented. The proposed antenna uses, very simple feeding network consisting of two different feedlines to excite two resonant modes in the SIW cavity, which helps to excite the bowtie slot to radiate into free space. The excitation of perturbed cavity modes is analyzed with the help of half-mode theory. The SIW cavity backing helps to generate high gain and high FTBR of the antenna while maintaining its planar form, which makes it attractive for practical applications, e.g., radio navigation, radar and satellite communication,
etc., in *X*-band (8–12 GHz).



(a) Top view of the proposed design. (b) Surface current distribution at 9 GHz (when port 1 is ON). (c) Surface current distribution at 11.2 GHz (when port 2 is ON). (L = 18.8 mm, W = 17mm, d = 1mm, s = 1.6 mm, $Lslot$ = 15mm, $wslot$ = 3.8 mm, Wbow = 7mm, ds = 9.2 mm, $l$in1 = 0.8 mm, $l$in2 = 0.6 mm, $d$shift1 = 1.4 mm, $d$shift2 = 1mm,wm = 2.42 mm, ws = 4.8 mm.)

By properly optimizing the antenna dimensions, a high isolation of better than 25 dB between two input ports is achieved, which helps to introduce self-diplexing phenomenon in the proposed design. The behavior of the individual cavitymodes at two resonant frequencies is explained using half-mode theory. The proposed antenna resonates at 9 and 11.2 GHz with unidirectional radiation pattern and a high gain of 4.3 and 4.2 dBi, respectively.



III. PROPOSED DESIGN OF SIW CAVITY-BACKED SLOT ANTENNA TRIPLEXER

The proposed SIW cavity-backed antenna-triplexer configuration is displayed in Fig. 1. It is composed of two rectangular SIW cavities (i.e., *Cav1 and Cav2*) and three radiating slots. These cavities are formed by embedding themetallic posts in the dielectric substrate, which forms the lateral conducting walls. In order to avoid energy leakage from the shorting metallic posts, the diameter and pitch of metallic posts are carefully chosen based on the guidelines suggested in [8]. The dimensions of the rectangular SIW cavities are calculated from the empirical equations defined in [12]. Two transverse slots designated
as *Slot1* and *Slot2* are placed on the top surface of the *Cav1*, which are excited with the help of two microstrip-feed

For a rectangular waveguide, cut off frequency of arbitrary mode is found by the following formula:

$$f_c = \frac{c}{2\pi}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2} \quad (1)$$

where:
c: speed of light
m, n: mode numbers
a, b: dimensions of the waveguide
For TE_{10} mode, the much-simplified version of this formula is:

$$f_c = \frac{c}{2a} \quad (2)$$

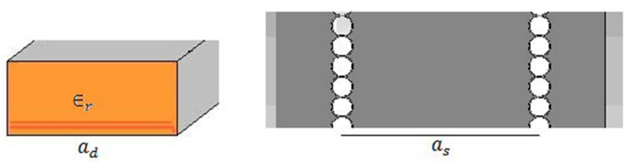
For DFW with same cut off frequency, dimension "$_a$d" is found by:

$$a_d = \frac{a}{\sqrt{\varepsilon_R}} \quad (3)$$

Having determined the dimension "a" for the DFW, we can now pass to the design equations for SIW.

$$a_s = a_d + \frac{d^2}{0.95p} \quad (4)$$

where
d: diameter of the via
p: pitch (distance between the vias)



Dimensions for DFW and SIW

In published articles about SIW design, the following two conditions are required [1]

$$d < \frac{\lambda_g}{5} \quad (5)$$

$$p < 2d \quad (6)$$

$$\lambda_{guide} = \frac{\lambda_{freespace}}{\sqrt{1-\left(\frac{\lambda_{freespace}}{\lambda_{cuttoff}}\right)^2}}$$

$$\lambda_{guide} = \frac{c}{f} \times \frac{1}{\sqrt{1-\left(\frac{c}{2a \cdot f}\right)^2}}$$

$$\lambda_g = \frac{2\pi}{\sqrt{\frac{\varepsilon_R (2\pi f)^2}{c^2} - \left(\frac{\pi}{a}\right)^2}} \quad (7)$$

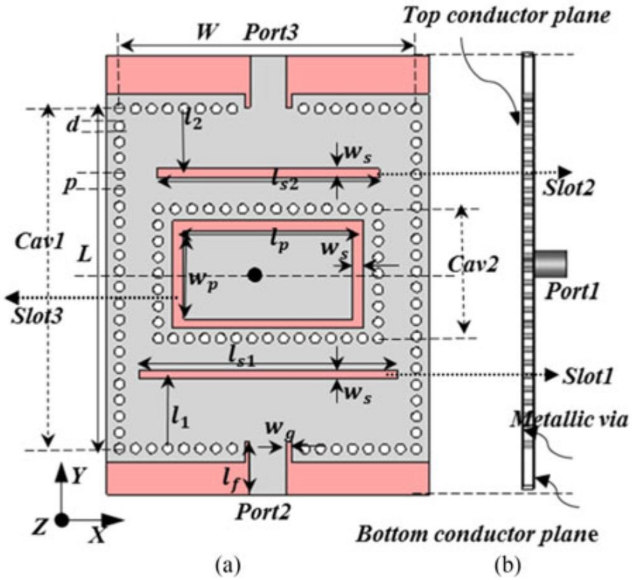


Fig. 1. Schematic diagram of proposed design. (a) Top view. (b) Side view. Dimensions: $W = 40$, $L = 46$, $lp = 23$, $wp = 12$, $l1 = 10.1$, $l2 = 8.8$, $ls1 = 35$, $ls2 = 30$, $ws = 1.2$, $wg = 0.6$, $lf = 7.2$, $w50 = 5$, $p = 1.8$, and $d = 1$(Units: mm).

lines on the opposite sides of the cavity. The lengths of both the slots are longer than half of the guiding wavelength at the corresponding resonant frequency. An annular slot designated as *Slot3* of perimeter slightly longer than one wavelength of the lowest resonant frequency (i.e., 4.2 GHz) is etched inside *Cav2*. This slot is excited with the help of coaxial feed, which is placed at 2 mm away from the center along *x*-axis. The principle of operation to realize the proposed design has been explained *A. SIW Cavities Without the Slots* In the case of *Cav1*, TE110 is chosen as an operating mode and resonates at 3.2 GHz. The corresponding electric field distribution is shown in Fig. 2(a). *Cav2* is nested inside *Cav1*, which shares the total aperture area. After introducing *Cav2*, the electric field is divided into two parts and concentrates on the space between the excited port of *Cav1* and *Cav2*. Hence, both resonances of *Cav1* resonate at the same frequency of 7.2 GHz because *Cav2* perturbs the electric field equally in both the parts of *Cav1*. The modified E-field distribution of the TE110 modes at both the resonant frequencies is displayed in Fig. 2(b) and (c) when the corresponding port is excited.

B. Proposed Geometry

The proposed geometry is realized by inserting *Slot1* and *Slot2* inside *Cav1* and another *Slot3* inside *Cav2* on the top surface of the cavities. To obtain maximum perturbation of the field, the transverse slots are placed about one quarter-wavelength ($\lambda 2/4$) away from the sidewalls of *Cav1*. After placing both the slots, the resonant frequency shifts towards the lower frequencies due to the strong reactive loading of the slots. These phenomena can be better understood with the help of an electric field distribution, exhibited in Fig. 3. When *Slot1* of length (i.e., 35 mm) is excited by *Port2*, it perturbs the field distribution of TE110 mode and radiates the field at 5.2 GHz.

Similarly, when *Slot2* is excited by *Port3*, it perturbsTE120 mode of the cavity and radiates the field at 5.8 GHz. *Slot1* produces a lower resonant frequency ($f2$) because of its longer length ($ls1$). Both slots resonate at two different modes due to the difference in their lengths ($ls1 > ls2$). From Fig. 3(b) and (c), it can be observed that at 5.2 and 5.8 GHz, the electric field concentrates mainly between the corresponding excited port and the adjacent slot,while an insignificant fraction is observed towards the other remaining ports. Also, it shows that both resonating circuits of *Cav1* depict the same polarization in *y*-direction at different resonant frequencies, which is also stated in [9]. On the other side, the lowest resonant frequency ($f1$) is produced by the *Slot3*. This slot separates *Cav2* from the inner conductor and a patch is formed, which is excited by *Port1*. The dimensions of the patch are chosen to operate at 4.2 GHz in TM10 mode, which is evident from the field distribution of Fig. 3(a). To avoid the field coupling between the patch and both resonating parts of *Cav1*, the patch is excited in an orthogonal axis to *Cav1*. Hence, the excited modes in orthogonal axes offer a reasonable isolation (i.e.,<-23 dB) among the three ports. By implementing this configuration, three distinct resonances are found with a good isolation, which helps to attain a triplexing.

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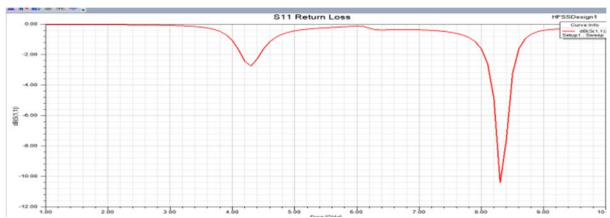
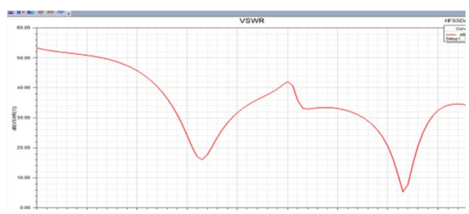
IV. STIMULATION RESULTS

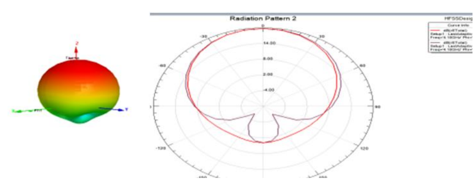
The simulated resonant frequencies are observed at 4.25, 5.15, and 5.83 GHz along with simulated gain of 6.85, 4.5, and 6.1 dBi, respectively. The responses of |*S*|-parameters are measured by exciting the single portwhile the remaining two ports are terminated with the matched loads. The simulated (measured) minimum isolation levels are obtained better than 40 (42), 24.5 (23.7), and 23 (22.5) dB at the resonant frequencies $f1$, $f2$, and $f3$, respectively.

The simulated and measured normalized radiation patterns ($\varphi = 0°$ and $\varphi = 90°$) are plotted at three opearating frequencies in Fig. 9. Each plot shows a unidirectional radiation pattern due to a cavity-backed structure and maximum radiation orients towards the boresight direction. The cross-polar levels in the boresight direction are below −28, −25, and −24.5 dB at the corresponding resonant frequencies. The overall front-toback- ratio is better than 19 dB for each resonant frequency. To highlight the significance of the proposed design, the performance of the proposed antenna-triplexer is compared with other reported works [7]–[11] in Table I. The proposed design shows the higher value of gain and comparable circuitry size with a uniform radiation pattern. Moreover, the proposed antennatriplexer can be scaled for any other desired frequency band by simply altering its dimension below figure are the obtained result for given frequencies

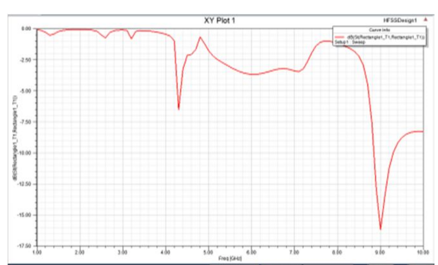
A. 4.18GHZ

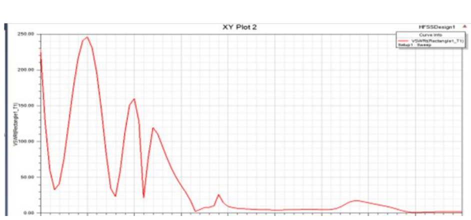


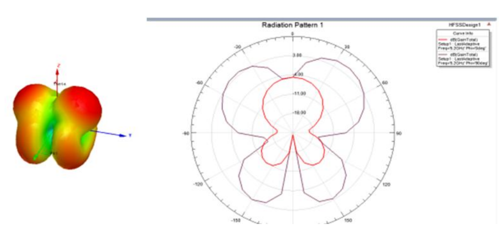




B. 5.2GHZ







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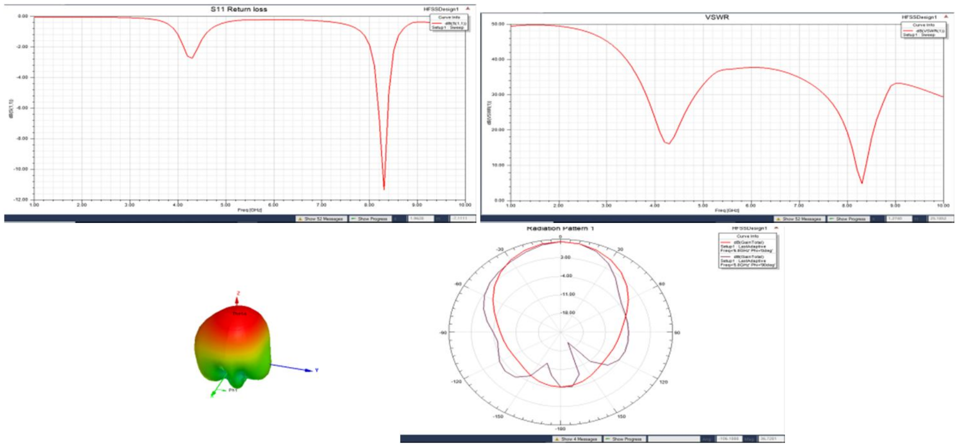
C. 5.8 GHZ



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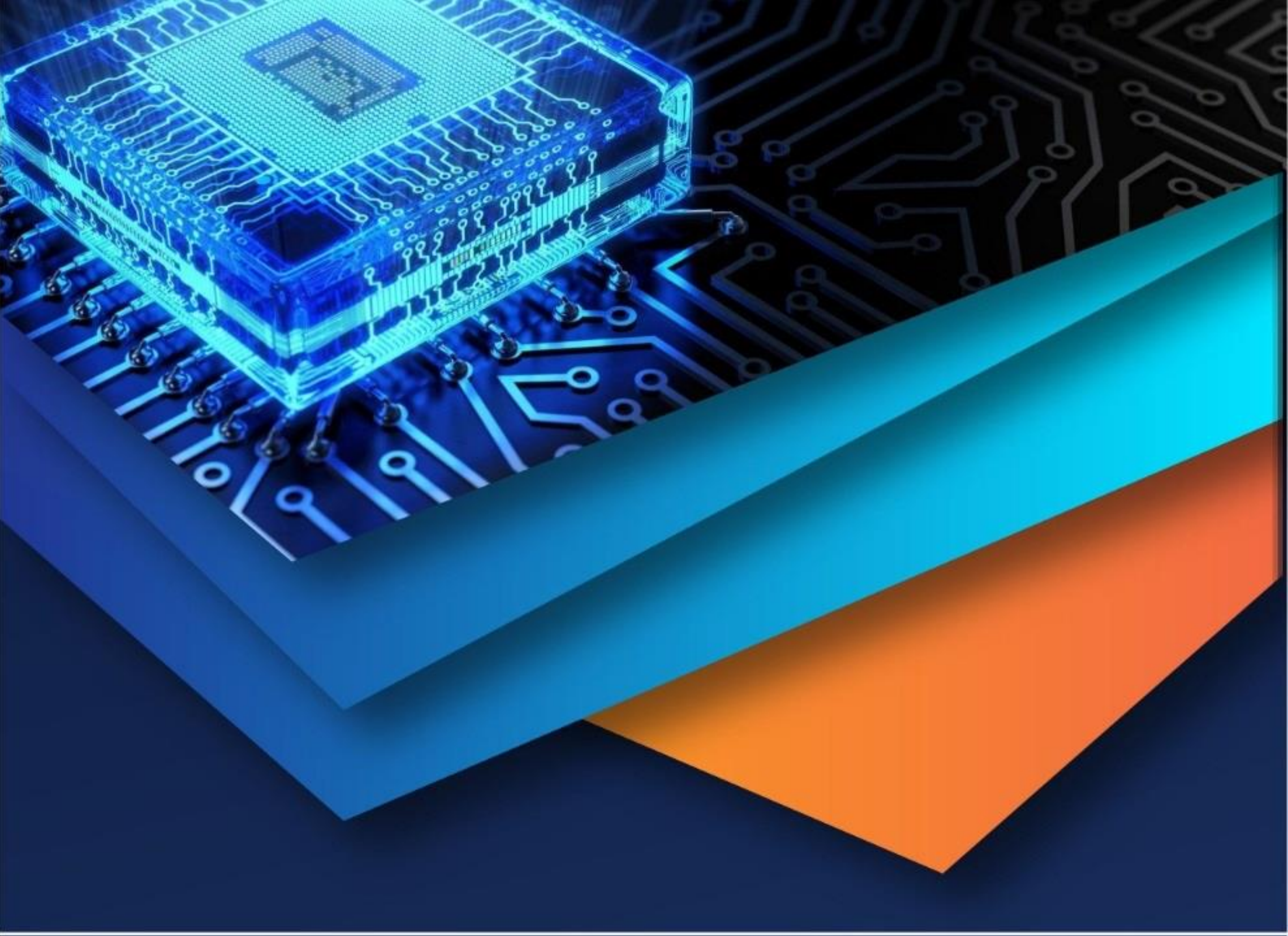

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