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In-Band Radar Cross Section Reduction and Enhancement of Gain for a Patch Antenna Array by Using a 1-D Periodic Metasurface Reflector

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Abstract: Based on far-field cancellation, a low-profile metasurface (MS) for both x- and y-polarizations is created. This concept uses a 1-D MS instead of a typical MS with a low RCS that uses checkerboard architecture. The proposed MS can be integrated more freely in various applications because it does not require periodicity in two dimensions. A patch antenna array is proposed based on the proposed MS. Under normal incidence, full-wave calculations and measurements demonstrate that integrating the proposed MS reduces the scattering of the antenna array by more than 5 dB over the antenna working frequency band of 10.7 to 12 GHz (11.45 percent). Moreover, when the array radiates, parasitic radiation from the slots of the MS can be activated, increasing the array's boresight gain.
Keywords: Antenna array, periodic metamaterials, gain enhancement, RCS reduction.

I. INTRODUCTION

Although antennas contribute so much to a platform's overall radar cross section (RCS), many approaches for achieving low-RCS antenna designs have been proposed, including bending the antenna [1]–[3] and using materials that absorb EM waves [4]–[6]. Backscattering is decreased by redesigning the antenna so that EM waves are dispersed away from the direction of incidence. Absorbing materials absorb electromagnetic waves and convert them to heat. An antenna, on the other hand, is supposed to send and receive EM waves successfully. As a result, using absorbing materials on antennas to reduce RCS without compromising radiation performance necessitates careful planning. A partially reflecting antenna [7], [8] was built with a low-scattering reflector on top of a Fabry–Perot resonance cavity, resulting in antenna gain augmentation and in-band RCS reduction. However, the antenna had to meet a thickness constraint, and different components of the construction were used to provide in-band RCS reduction and gain increase.

A checkerboard structure made from an artificial magnetic conductor (AMC) [9] is another way to reduce RCS. Each fragment's contribution balances out in the distant field in the backward direction when the AMC provides in-phase dispersion, and a perfect electric conductor (PEC) provides out-of-phase dispersion. A MS can be simply built to be in the same plane as the object, unlike approaches based on absorbing materials. Two types of AMCs are employed to produce the needed phase difference in a considerably broader frequency spectrum to broaden the frequency band of a low-RCS MS [10]–[13]. Low-RCS reflectors like this can be incorporated into antennas to reduce scattering [14]. The in-band RCS of an antenna array is more difficult in this type of application since the out-of-band RCS may be addressed by a well-designed frequency selection surface [15]–[19] without impacting the antennas' in-band performance. In [20] and [21], in-band RCS reduction and gain augmentation were achieved simultaneously throughout the full operating frequency range by incorporating polarization-dependent AMCs into single antennas.

However, applying these 2-D MSs to an antenna array for RCS reduction is difficult due to significant coupling between the MSs and array elements in the antenna operating band.

In antenna arrays, many methods have been devised to reduce RCS. With a modest RCS bandwidth of around 3%, the RCS of the antenna array was decreased by 6 dB by the MS reflector [22]. To lower the array's RCS, a polarization rotation reflective surface superstrate was proposed [23]. The impedance bandwidth was also found to be increased to 14.2 percent. The total scattered fields are distributed over a large angular region in this fashion, resulting in a low backscattering RCS [3]. This method, however, usually necessitates a high level of design complexity, requiring several antenna elements, a sophisticated optimization procedure, and a complex network. Optimization has been widely employed to design the pattern of ultrawideband low-RCS MSs based on the far-field cancellation technique [25]–[32] since Cui et al. [24] established the notion of coding metamaterials.

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Because of their huge sizes, such MSs are frequently surrounded rather than placed into antenna array elements when integrated into antenna arrays [33], [34]. The antenna array causes a flaw in the low-scattering MS in such a setup. The antenna array's size is thus restricted. On the other hand, there have been occasions when the AMC blocks have been designed in conjunction with the antenna elements, and the cancellation has been achieved using the metallic composition of the antenna element. [14] used a mushroom-like EBG structure to lower the RCS of a patch antenna array with a 2 dB directivity loss. MS bars were added between the rows of a waveguide slot antenna array in [35] to reduce in-band RCS while keeping the antenna gain. To minimise mutual interaction between the slot antenna and the MS, metallic side walls for the MS bars were used in this design. At boresight, the gain after loading the MS was 0.27 dB lower than the gain of the reference antenna. The MS for each slot antenna element was surrounded with [36], resulting in a high-gain low-RCS antenna array. The methods in [35] and [36] are, however, optimised for waveguide slot antennas and may not be immediately applied to any sort of antenna array for the following reason. The primary scattering part of the antennas in [35] and [36] is essentially a metallic surface with a 180-degree reflection phase, which can be paired with the MS to provide far-field field cancellation. The reflected wave from the substrate, whose reflection phase is never 180, should not be neglected for a patch antenna array. As a result, all the reflected waves must be considered when designing a patch antenna array. As a result, establishing the MS's dimension and reflection phase in order to produce a far-field cancellation is significantly more difficult.

The design parameters for a 1-D MS are synthesised in this communication. Furthermore, when the space efficient MS is integrated in the antenna array, slots are introduced. As a result, the 1-D MS can be made smaller, and parasitic radiation occurs, resulting in a gain boost. The experimental results demonstrate that under normal incidence, the antenna array achieves an in-band RCS reduction of more than 5 dB and a directed gain improvement of 1.5 dB over the whole operational frequency band of 10.7 to 12 GHz (11.45 percent). The proposed construction is low-cost, simple to fabricate, and easily scaled up to a larger antenna array.

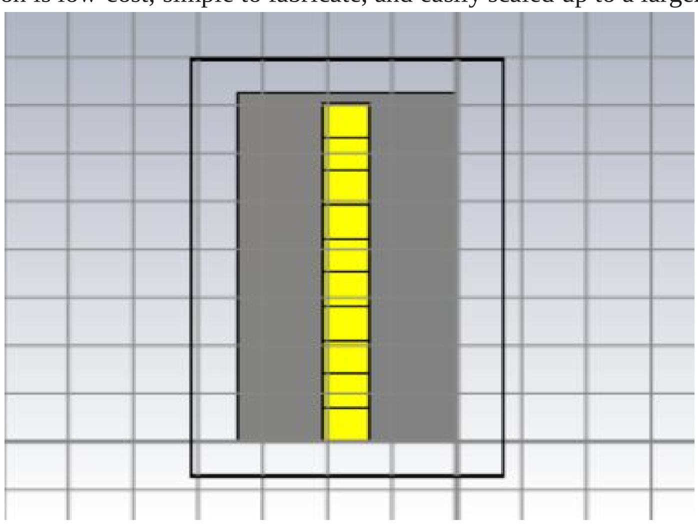

Fig 1. (a) Illustration of 1 Dimensional Metasurface

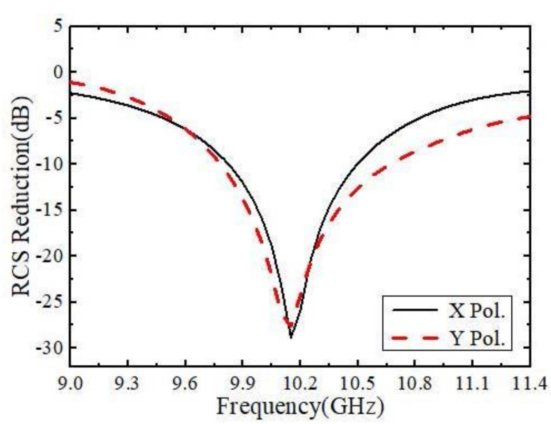

Fig 1. (b) Reduction of Radar Cross Section relative to the RCS of a metal ground.

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II. DESIGN AND ANALYSIS

A. Low RCS 1-D MS Reflector

The ground on which is the 1-D MS is built is a PEC board and in which the substrate of F4B-2 is placed with a relative dielectric constant of 2.2, as shown in Fig. 1(a) (loss tangent: 0.0005). L_{sub} = 34 mm, W_{sub} = 72.45 mm, and h = 2 mm are the length, width, and thickness of the substrate, respectively. The unit cell measures L0 = 7.3 mm, W0 = 7.05 mm, and g = 1 mm, 9 of these patches are placed on top of each other on the substrate.

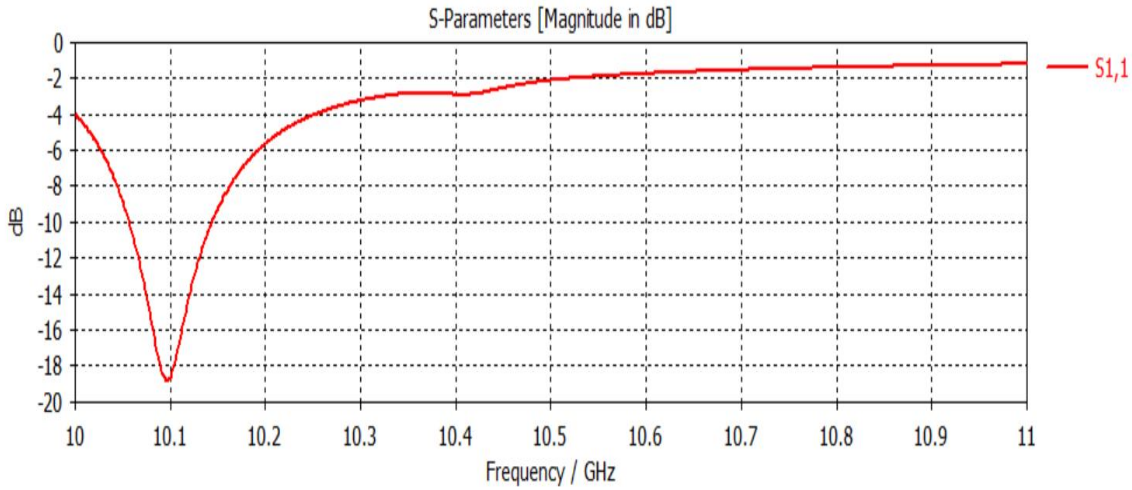

Fig 2. S-parameters of the designed model of 1-D MS.

The full-wave EM simulation software CST Microwave Studio is used to numerically study the models in this communication. 1-D MS model is shown in fig 1.(a) and it's RCS is simulated, and the RCS decrease is presented in Fig. 1 (b). At 10.15 GHz, it can be shown that both polarizations achieve a peak RCS reduction of 28 dB. At 10.15 GHz, distinct modes are excited in the MS for different polarizations, as illustrated in Fig. 2, with strong currents excited primarily parallel to the incidence polarisation. The direction of the current on top of the MS and on the ground is opposite for both polarizations. These two currents in opposite directions cancel each other out in the far field, similar to how the chessboard layout works. Hence, the dispersed energy is diverted from its original path. As a result, under normal incidence, both polarizations can achieve a low RCS. Figure 3 illustrates a 3-D plot of the scattering patterns for both polarisation incidences at the operating frequency. The reflected energy is distributed out of the normal direction, as can be observed intuitively.

B. Parametric Analysis of the Low-RCS 1-D MS Reflector

More numerical experiments are carried out to explore how the characteristics of the 1-D MS reflector affect the scattering performance in order to acquire a better knowledge of the 1-D MS. For production purposes, the substrate's thickness and dielectric constant are unchanged. In 1-D MS, the number "n" of the unit cells is altered first ,"n" has effects on the scattering performance of the 1-D MS until "n" is greater than 5. Second, simulations demonstrates that the extra substrate margins in the vertical dimension (outside the MS units) Y somewhat downgrades the reflector's scattering performance. Or you can say, 1-D MS with Y = 0 shows the best RCS reduction under normal incidence.

On the other hand, scattering performance is sensitive to the lateral dimension of the substrate Lsub [Fig. 1(a)], dimensions of the patch of the MS (L0, W0) on the surface plays an important role in finding the frequency of the 1-D MetaSurface. To find the relationship of these dimensional parameters with the operating frequency, further simulations are performed. Sixteen frequency points considering the frequency band from 3 to 17 GHz are taken as the target sampling points, along with incident normal plane wave. Some changes were made for optimization, 16 designs of low-scattering MSs are taken for the 16 sampling points satisfying the threshold of 15 dB in the RCS reduction both for the x- and y-polarizations under normal incidence. Dimensional parameters of these 1-D Metasurfaces and the frequencies for the peak RCS reductions are taken as input parameters for curve fitting, yielding the following relation. The dimension is in meters and the frequency is in GHz:

$$L0 = 0.09581/f - 0.00211 \quad (1)$$

$$W0 = 0.08892/f - 0.00166 \quad (2)$$

$$Lsub = 0.3688/f - 0.00237. \quad (3)$$

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The fit values R2 are 0.9997, 0.9982, and 0. The High accuracy in the curve fitting demonstrates a strong relationship. The above curve fitting formulations can provide a convenient guideline for designing such a 1-D MS and shows the applicability for such an Metasurface in a broadband from 3 to 17 GHz, which covers the most of S, C, X, and Ku bands.

C. 1-D Low-RCS Reflector Based on a Slotted MS

As shown in Fig. 3(a), two pairs of parallel slots are kept on the rectangular metallic patch of the Metasurface. The slots result in a large electrical path, having a more compact design. The dimensions of the slotted MS unit cell is L0 = 6.3 mm, W0 = 5.25 mm, slot_l1 = 3.8 mm, slot_w1 = 1.4 mm, slot_d1 = 0.6 mm, slot_l2 = 3.5 mm, slot_w2 = 1 mm, slot_d2 = 4 mm, and g = 1.4 mm. The same PEC-backed F4B-2 substrate is used with designed dimensions of Lsub = 30.5 mm and Wsub = 59.85 mm with a thickness of 2 mm. Comparing it with the RCS of a metallic plate of the same size, an RCS reduction over 18 dB is calculated in the simulations for both polarizations under normal incidence at 11.2 GHz, as plotted in Fig. 3(b).

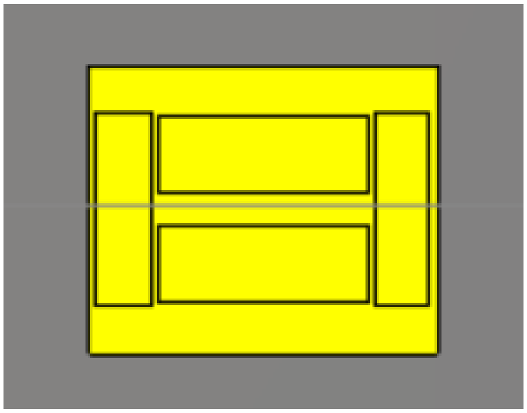

Fig. 3. (a) Unit cell of the slotted MS.

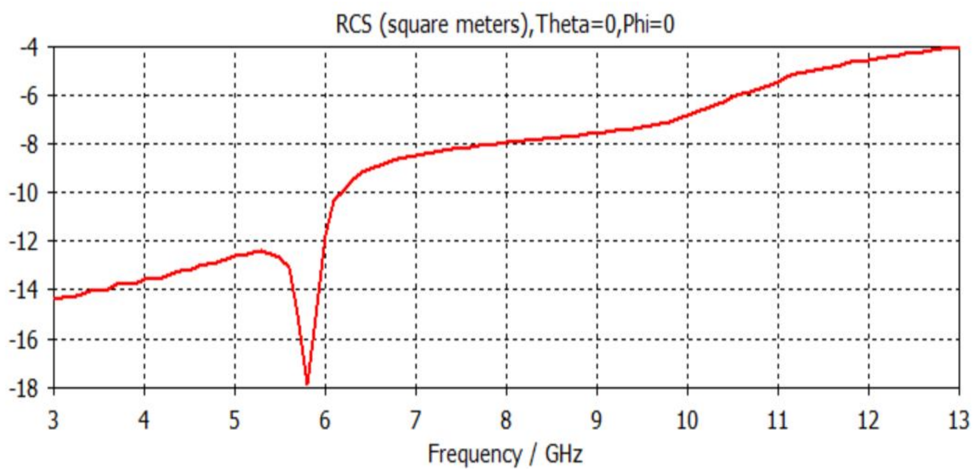

Fig 3 (b). RCS reduction referenced by a metal ground of the same size for the x- and y-polarizations

Above result shows that the enhancement in gain is attached to the radiation from the y-directional slots of the MS. The decremented sidelobe level is related with incremnted directive gain. The sidelobe level is comparably high in the Ø = 0 degree plane. This is a compromise since as a multifunctional antenna, the horizontal distance optimization takes into consideration the low RCS.

In terms of scattering, the x- and y-polarized plane waves are normally incident on the proposed antenna arrays, which are both matched and loaded. The simulation results are shown in Fig. 3(b) , for normal incidence, the shown antenna array yields an RCS reduction of greater than 5 dB for both polarizations for the entire antenna operating frequency band. Unless a large-scale MS with many unit cells is used [25]–[32], the low-RCS reflectors design based on the far-field cancellation strategy normally runs with a narrow incident angle. Hence, the sensitivity of the mentioned design to the incident angle is calculated. The backscattering of a flat PEC plate decreases as the incident angle increases.

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As validated on the commercial software CST, the monostatic RCS of a flat PEC board of the same size as that of the proposed antenna array reduces from −3.84 to −9.47 dBsm when the incident angle increases from 0 to 5. Hence, decreasing the RCS of the antenna for cases with normal incidence and small incident angles is a practically possible. Correspondingly, the monostatic RCS reduction at oblique incidence angles (with incident angles below 5 deg) is calculated .Although the RCS reduction can be done for oblique incidence up to an incident angle of 5˚, the RCS reduction generally becomes lesser when the incident angle increases from 0˚ to 5˚. It is as also noticed that the RCS reduction applies to the bistatic RCS (specular) for different incident angles (15˚, 30˚, and 45˚) for perpendicular polarization and parallel polarization in the Ø = 0˚ plane, because the working phenomena of the 1-D MS is similar to the phase cancellation of the chessboard configuration. Conclusion can be obtained for the incidence wave when Ø is not 0˚.

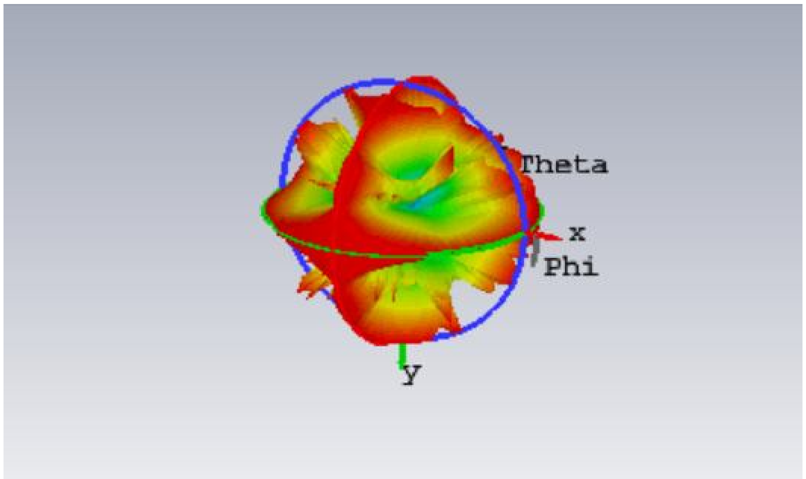

Fig 4. Theta x Phi plot

III. CONCLUSION

In this paper, a low-RCS ,low-profile, 1-D Metasurface based on far-field cancellation is proposed. The design parameters were simulated and experimentally verified. .This 1-D design is space efficient, making it perfectly suitable in many applications as conventional low-scattering MSs normally require sufficient periodicity. For example, the design can be inserted to array antennas to decrease the scattering of the array. Compact and multifunctional features can further be added to the 1-D Metasurface. The simulation and experimental results shows that, incorporated into a patch antenna array, this 1-D Metasurface leads to an RCS reduction of more than 5 dB under normal incident wave for both polarizations in scattering mode and a directive gain enhancement of more than 1.5 dB in radiating mode, throughout the entire operating frequency band (11.45%) of the antenna array. Hence, the proposed Metasurface is only valid for the bistatic RCS and near-normal incidences for the monostatic RCS. The problem of monostatic RCS reduction of array antennas, for an arbitrary angle, is still challenging and could be solved by another novel MS in the future.

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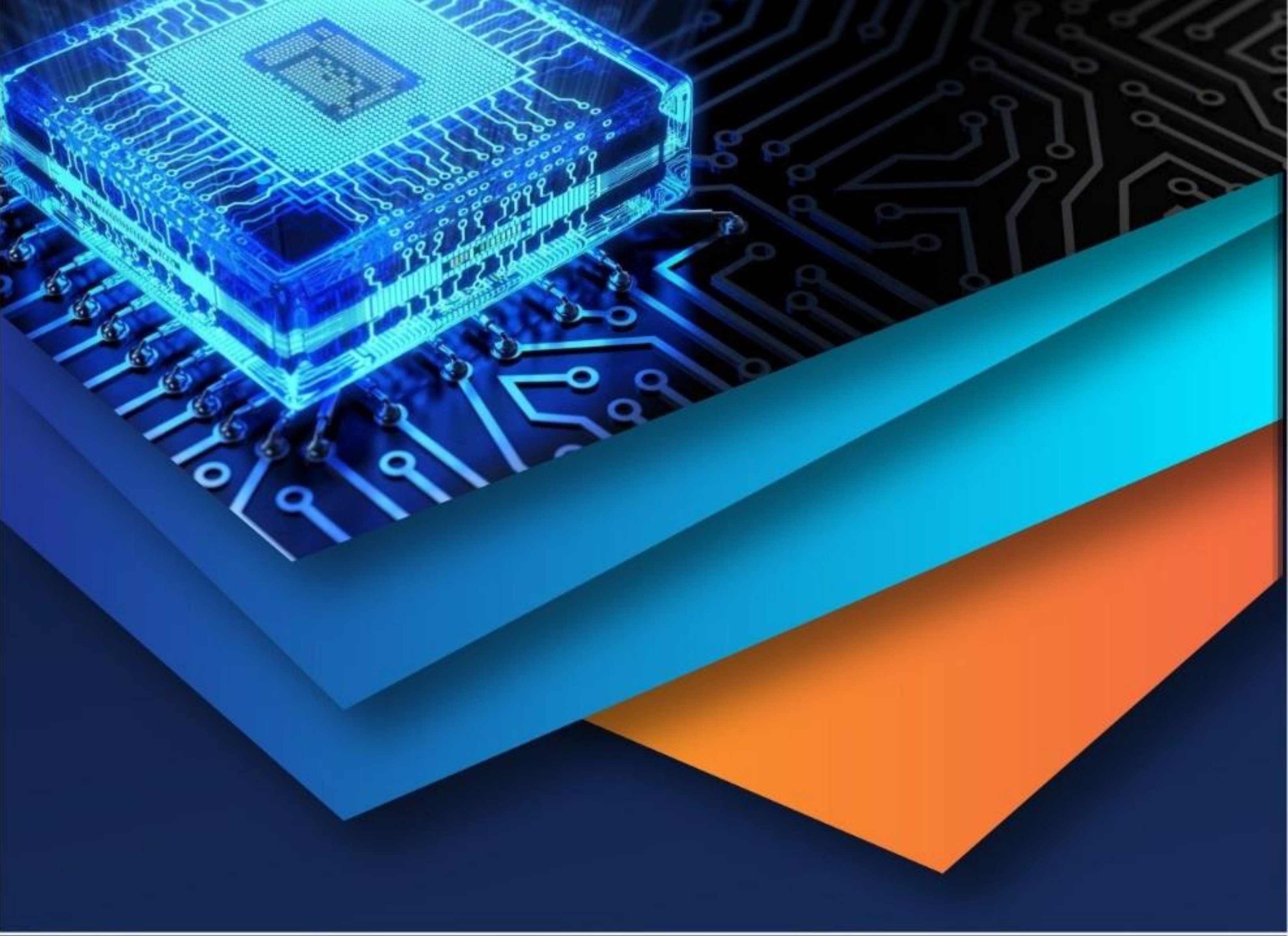

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