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A Review of RF Antenna Integrated with Solar Array for Spacecraft Application

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Abstract: The objective of this effort was to develop and demonstrate an integrated high-gain RF antenna and solar array technology for spacecraft application. By combining the antenna and solar panels, thus eliminating one support structure, Significant mass and launch vehicle stowage volume savings can be achieved. The goal of this research effort was to breadboard and test a half-meter-diameter aperture.

I. INTRODUCTION

There is a critical need for enabling technologies that will reduce the mass, physical size and cost of major spacecraft components. Virtually all spacecraft include at least one large-aperture telecommunications antenna and a large-aperture solar array. Combining these large apertures will achieve critical goal of reducing spacecraft mass, stowage volume, cost, and deployed surface area, without significantly affecting the performance of either the antenna or solar array [l]. This will also facilitate spacecraft maneuvers and attitude control, and increase the field of view of scientific instruments. The performance of the RF antenna and solar array both vary with the cosine of the angle from their broadside directions. This would allow significant mission flexibility and the potential to optimize the integrated array pointing-angle between the Sun and the Earth to obtain the proper combination of electrical power and RF gain. Most deep space missions have Sun/Earth subtended angles of less than 40'. If an integrated array were pointed half-way between the Sun and the Earth with a 40' subtended angle, then this would represent only a 0.5 dB loss for the antenna and only a 6% reduction in solar array output. The objective of this research effort was to develop and demonstrate an integrated high-gain RF antenna and solar array technology for spacecraft application. The RF antenna technology selected was a printed microstrip reflect array, which uses a large number of thin crossed dipoles as the radiating elements.

II. MICROSTRIP REFLECT ARRAY – EXISTING ANTENNA

A microstrip reflect array is a flat reflector antenna that can be mounted conformally onto a spacecraft's outside structure without consuming a significant amount of spacecraft volume and mass. For large apertures (2 m or larger), the antenna's reflecting surface, being flat, can be more easily and reliably deployed than a curved parabolic reflector.Its efficiency and bandwidth characteristics are analyzed. Numerous advantages of this antenna system are discussed. Three new concepts using this microstrip reflect array are also proposed. A microstrip reflect array has the capability of integration with a solar array for the following reasons:

1) The reflect array consists of many array elements printed on a flat panel, which is illuminated by a feed horn and does not require a power division network.
2) The electrical characteristics of a reflect array are similar to those of a conventional curved parabolic reflector, but since its aperture is physically flat and its elements function without power division network, it is amenable to integration with a flat solar panel; and,
3) The microstrip dipoles that are used as array elements are physically very thin, and will not significantly reduce blockage of sunlight to the solar cells situated below the RF elements. Although both the microstrip reflect array and the solar array are very thin in profile and low in mass, they separately require massive and large support panels to maintain their required aperture flatness. By combining the antenna and solar panels, thus eliminating one support structure, significant mass and launch vehicle stowage volume savings can be achieved. The goal of this research effort was to breadboard and test a half-meter diameter aperture that was populated by both X-band reflect array crossed-dipole elements and silicon solar cells.

The bandwidth performance of a microstrip reflect array can be limited by four factors: (1) the microstrip patch element, (2) the array element spacing, (3) the feed antenna bandwidth, and (4) the differential spatial phase delay. Due to its thin cavity, the microstrip patch element can generally achieve a bandwidth of only 3 percent. To achieve a bandwidth larger than 3 percent, techniques such as the stacked dual patch or the patch with a thicker substrate can be employed. Ten- to fifteen-percent bandwidths for microstrip antennas have been reported. The array element spacing limits the reflect array performance such that, as frequency is decreased, the electrical element spacing becomes small, and excessive mutual coupling effects start to degrade the array performance. As the frequency is increased, the electrical element spacing becomes large, and undesirable grating lobes begin to appear. Fortunately, previous calculations and experiences have shown that the element spacing effect will not be detrimental until the frequency variation is more than 30 percent (ß15 percent around center frequency). The third bandwidth limiting factor is the feed antenna, which can be designed to operate over a bandwidth of at least 10 percent while maintaining a relatively constant beam shape and input impedance. Waveguide horns and cavity-backed dipoles are good candidates. If desired, an Archimedean spiral can be used to achieve more than 100 percent of bandwidth. The first antenna / solar array integration presented here uses a low-gain UHF crossed-slot microstrip radiator fix future Mars rover application. The second integration uses a high-gain microstrip reflectarray at X-band [3,4] for future deep-space telecom application.

III. UHF LOW-GAIN ANTENNA

The objective of this task was to develop low-mass, compact, omnidirectional, UHF antennas for future Mars rover application. The antenna was required to have a wide beamwidth (±60° conical coverage) so that it can communicate with an orbiting satellite that flies by horizon-to-horizon in any orbital track. The antenna should be a single unit operational over both the downlink (401 M H z) and the uplink (437 MHz) frequencies (separated by 8.5% bandwidth) with circular polarization (CP) and a minimum gain of -2 dBi over the +60° angular region. It was required to have a mass less than 0.5 kg and a size compact enough so as not to significantly obscure or reduce the area allocated for the solar panel (50cm x 80cm). It is clear that this antenna task is quite challenging. A broad angular coverage with CP generally calls for a physically tall antenna so that it has adequate aperture size to provide close-to-the-horizon coverage. However, such a tall antenna would shadow the solar cells. On the other hand, a low-profile antenna at UHF would have a large physical aperture (half free-space wavelength is about 35cm), which may take significant area away from that allocated for the solar cells. In addition, the antenna requires either a relatively large bandwidth or a dual-frequency capability, which implies that the electrical size of the antenna could be difficult to miniaturize. After a trade-off study, the crossed-slot microstrip patch [5], shown in Fig. 1, was selected for breadboard development. This is because of its ability to radiate a relatively broad beam, to integrate with the solar array, and to achieve very small mass.

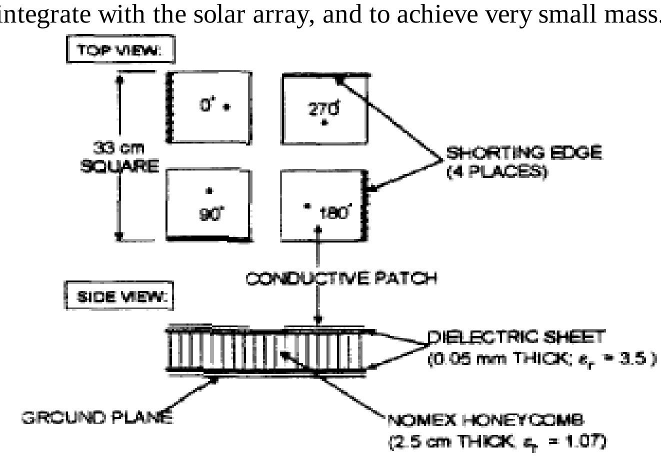

Fig.1 crossed–slot microstrip patch

The crossed-slot patch is a microstrip antenna element that consists of four 1/4-wavelength-long sub-patches. Each sub-patch has a square or slightly rectangular shape. The four sub-patches are shorted to the ground plane at four sequentially located edges. The four sub-patches are sequentially oriented with 0°, 90°, 180°, 270" electrical phase excitations. The four sub-patches are separated from and supported above the ground plane by a 2.5cm thick dielectric honeycomb panel. Since a sub-patch radiates only from its three open edges, foreign low-profile objects (metallic or nonmetallic) can be placed on top of each sub-patch without significantly disturbing the radiation characteristics of the antenna. Consequently, solar cells can be placed on top of the four sub-patches as sketched in Fig. 2.

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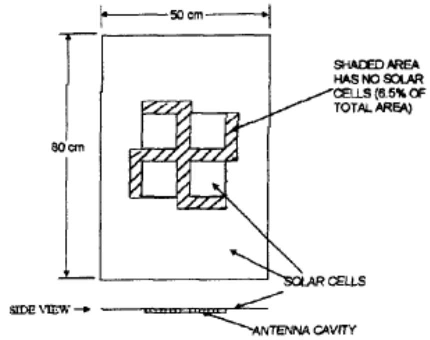

Fig. 2. Sketch of crossed-slot patch

A. Integrated with the Solar Panel

A conceptual drawing of the antenna mounted on a Mars rover is shown in Fig. 3. With this antenna concept, only 6.5% of the total solar-panel area is lost due to the antenna, while the antenna's electrical aperture takes about 25% of the total solar panel area. The input return loss of the antenna, when integrated with the solar panel, was measured to be -10dB or less across the required bandwidth of 40 MHz . The measured radiation patterns in the two principal planes of the integrated array are given in Figs. 4(a) and 4(b). These patterns indicate the achievement of the needed broad beam radiation. The measured peak gain is 4.5 dBic at the two required frequencies.

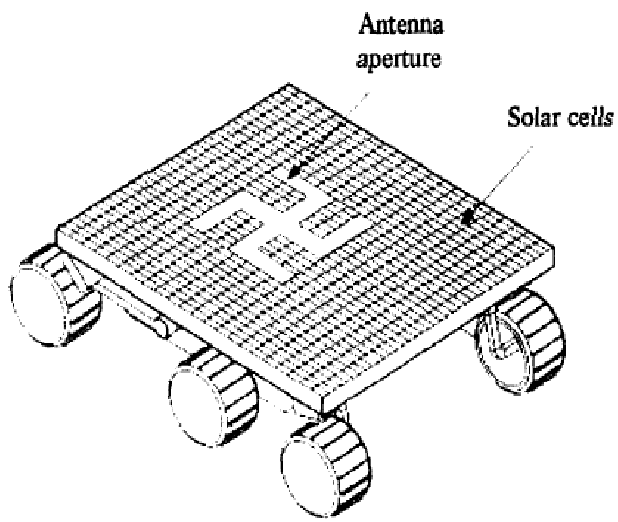

Fig. 3. Antenna integrated with solar panel On Mars rover

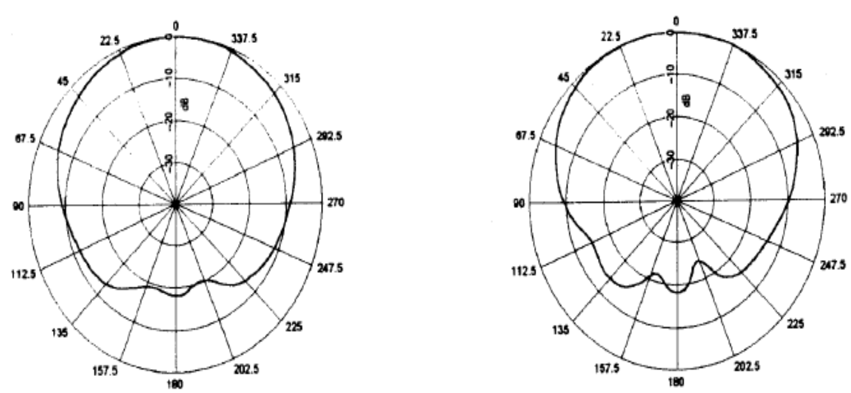

Fig. 4. The measured principal plane patterns of the crossed slot antenna

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B. X-band high-gain Antenna

The objective of this task was to develop a 0.5m high-gain CP X-band antenna

Integra table with a solar array. The antenna selected was a printed microstrip reflect array with crossed- dipoles as the radiating elements. It was selected based on three key reasons: 1) the reflect array elements do not require a power division network, which makes the integration much more feasible than a conventional array antenna; 2) it has a flat aperture which is amenable to integration with a flat solar panel; 3) the crossed- dipoles are physically very thin and do not significantly block the sunlight to the solar cells situated below the RF elements. The reflect array in this design consists of 408 X-band crossed dipole elements. The element spacing is 0.56 free-space wavelengths at 8.4 GHz and was chosen to fit the solar cell size of 2cm x 4cm. This yields an integer number of 2 crossed-dipoles per solar cell. Fig. 5 shows a photograph of the final integrated antenna solar array structure, and Fig. 6 gives the cross-section sketch of the integrated array wrth a top view of a single solar cell.

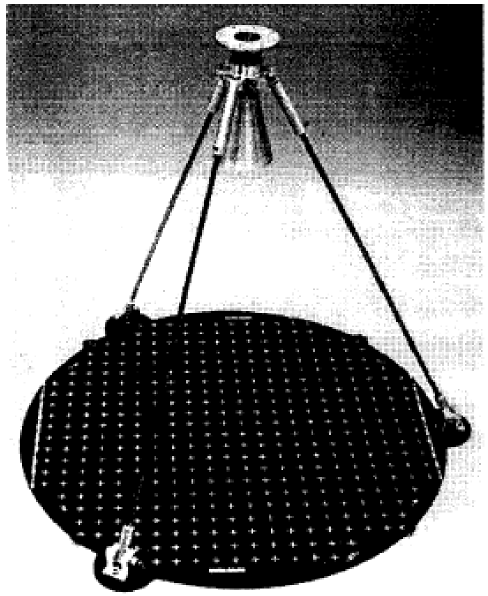

Fig.5 . Photograph of integrated solar arrav with reflect array crossed-dipole elements

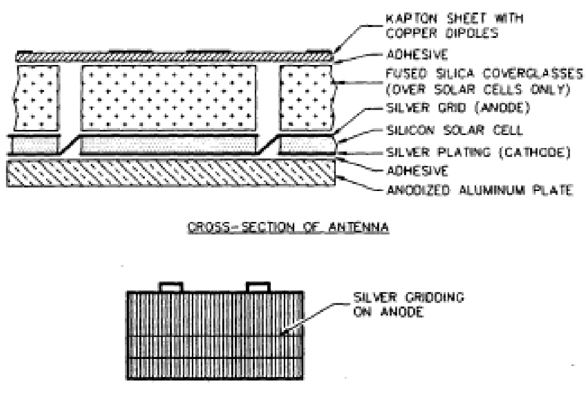

Fig. 6. Cross-section of antenna and top view of solar cell.

A tripod strut assembly was used to hold a circularly-polarized conical feed horn with a 3dB-beamwidth of 390 and a -9dB edge taper to the reflect array aperture. The f/D ratio of the antenna is 0.75. The 204 solar cells were secured onto the anodized aluminum plate with a silicon-based adhesive. A 1 S2mm-thlck cover glass, which serves to protect the solar cell, was bonded to the top of each cell. This cover glass also provides the required vertical separation between the solar cells and the dipoles. The printed crossed-dipoles were etched onto a sheet of 0.05l mm-thick Kapton membrane, and secured to the top of the coverglasses kith a silicon-based adhesive. Even though Kapton does absorb a significant amount of light energy, it was chosen because it was readily available in large quantities with a thin copper coating that is easily etched. Polymers wrth high optical transparency should be used in the future for actual implementation of the integrated array. The measured solar array results were very good. The addition of the dipoles only reduced the electrical output by about 10%. This loss of power could be easily regained by increasing the area of the solar array by 10%, or by increasing the diameter by only 5%. This is a very small amount considering the overall reductions of mass and volume realized by combining the RF and solar arrays. The result for the antenna, while encouraging, was not as good. The measured radiation pattern, shown in Fig. 7, indicates that the reflect array did form a good coherent beam in the h r field; however, the measured aperture efficiency was only about 10% - far from the expected value of 40%.

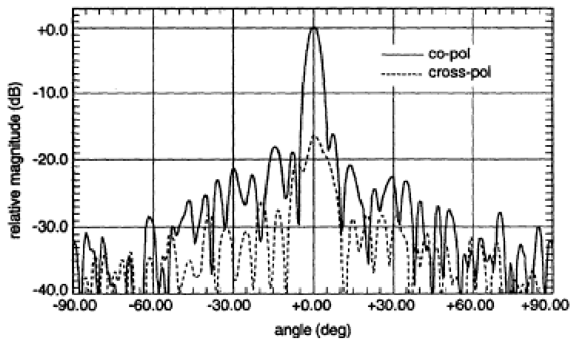

Fig. 7. Measured radiation pattern of the integrated antenna at *8.5GHz*

This relatively low efficiency is likely the result of two main factors. First, the electrical characteristics of the overall dipole substrate and the inhomogeneous ground plane were not well-understood or well considered in the design, mainly because the fine and in homogeneous silver grid on the top surface of the solar cells is difficult to characterize. The second factor has to do with the reflect array element itself. It was felt that elements other than crossed dipoles should be examined in an attempt to find an optimal and more efficient element. Future work to improve the RF efficiency wouId focus on these two areas. Nevertheless, the results of this development indicate that the integration of large antenna and solar array apertures is highly feasible.

IV. ANTENNA DESCRIPTION

The reflect array in this design consists of 408 X-band crossed dipole elements that are etched onto a Kapton substrate, which is then laid on top of a standard solar array. The element spacing on the reflect array was chosen to fit the solar cell size. The integrated solar/RF may consists of four basic components: I) a mechanical support structure; 2) an X-band feed horn; 3) a solar array with 198 silicon solar cells; and, 4) a thin-film polyimide material (Kapton) with 408 printed reflect array crossed dipoles. Fig. 5 shows a photograph of the final antenna, and Fig. 6 shows a sketch of the antenna cross-section with a top view of a single solar cell. Support for both the reflect array and the solar cells is provided by a circular anodized aluminium plate, which is 0.5m in diameter and 6.4" thick. A tripod strut assembly is used to hold a circularly- polarized, conical feed-horn with a 3dB-beamwidth of 39" and a -9dB edge taper to the aperture. The EID ratio of the structure is 0.75. The solar cells are secured directly onto of the anodized aluminum plate with a silicon-based adhesive. A 1.52mm-thick (60mil) coverglass, which serves to protect the solar cell in space, is bonded to the top of each cell. This coverglass also provides the necessary vertical separation between the solar cells and the dipoles. The printed crossed- dipoles are etched onto a sheet of 0.05Imm-thick (2mil) Kapton membrane, and secured to the top of the cover glasses with a silicon-based adhesive. Even though Kapton absorbs a significant amount of light energy in the same spectral region as the solar cells, which reduces the amount of light that reaches the solar cells, it was chosen because it is readily available in large pieces with a thin copper coating that is easily etched. This was a carefully considered trade:. Polymers with higher optical transparency would be favored for future versions of the integrated array. The reflect array was designed using software developed by The University of Massachusetts [2], and used the Moment Method technique. Since the effect of the inhomogeneous nature of the cross-section, particularly the irregular ground plane (see Fig. 6), on the performance of the reflect array was unclear, the strategy adopted was to etch three separate reflect arrays – one designed at the desired center frequency of 8.4GHz, and the other two 53% away.

V. CONCLUSIONS

The solar array results were very good. While the Kapton membrane alone (no dipoles) reduced the power output of the cells by 40.5% (from the reference of using just cover glasses), the addition of the dipoles only reduced the output by about I0%, which would them be the expected overall loss if an optically clear membrane were used. This loss in power could be easily regained by increasing the area of the solar array by I0%, or by increasing the: sides of a square array by only 5%. This is a very small amount considering the overall reductions of mass and volume realized by combining the RF and solar array. The news for the RF portion, while encouraging, was not as good. As can be seen from the radiation patterns in Fig. 7, the reflect array did form a coherent beam in the far field; however, the measured aperture efficiency was only about 10% **-** far from the expected value of 40%.

VI. FUTURE ENHANCEMENTS

Future work to improve the RF performance would focus on two areas. This relatively low efficiency is likely the result of two main factors. First, the electrical characteristics of the overall reflect array substrate, especially the inhomogeneous ground plane, were not well-understood or well-considered in thedesign, mainly because the fine, inhomogeneous silver grid on the top surface of the solar cells is difficult to characterize. The second factor has to do with the reflect array element itself. It was felt that elements other than crossed-dipoles should be examined in an attempt to find an optimal element. Future work to improve the RF performance would focus on these two areas. Nevertheless, the result of this development indicates that the integration of large antenna and solar array apertures is highly feasible.

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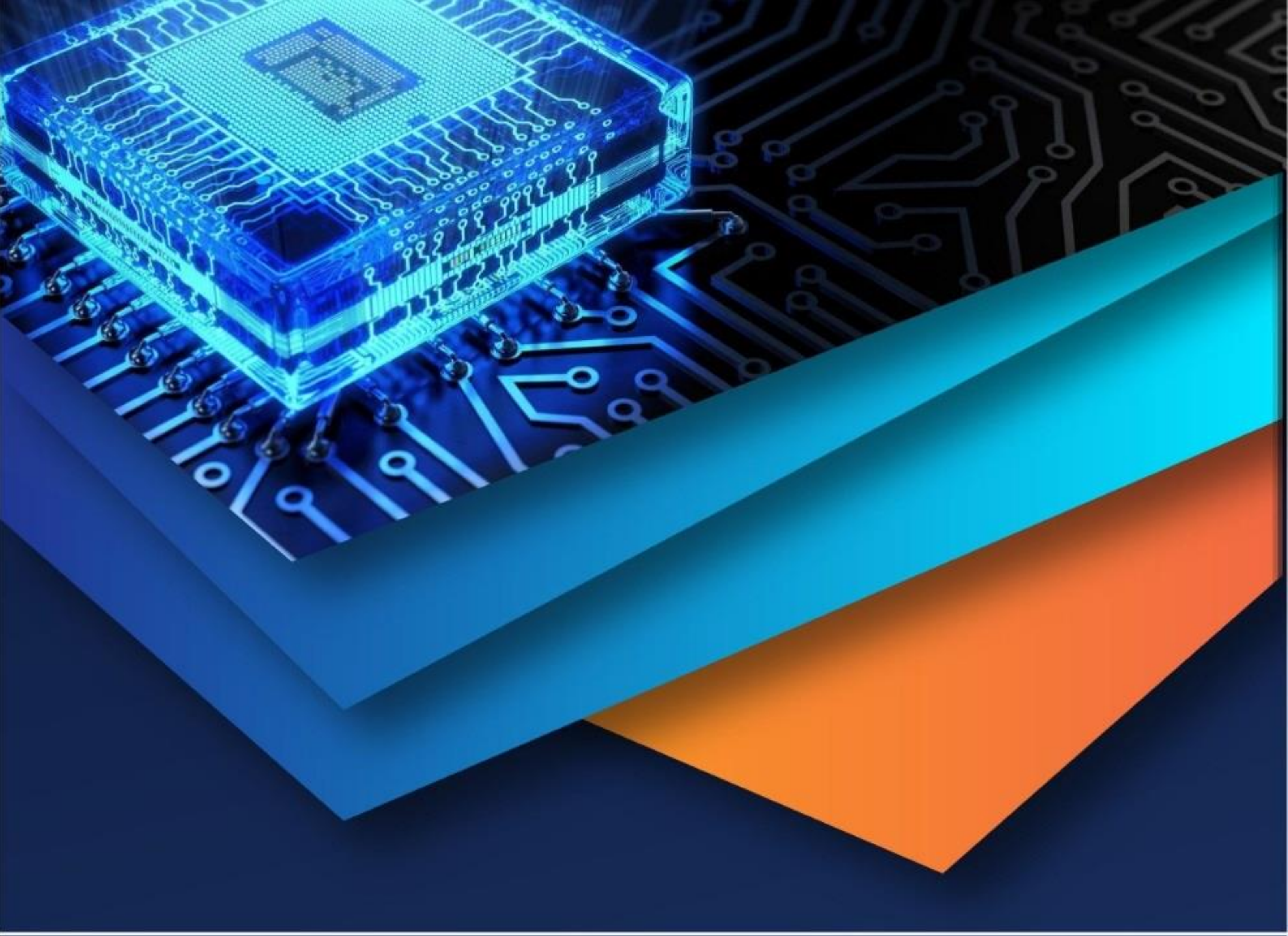

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