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Compact and Wideband U-Slotted Microstrip Antenna for Modern IoT Devices at ISM Band

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Abstract: This paper presents the design and analysis of a compact U-slotted microstrip patch antenna with a truncated feed, optimized for IoT applications. The antenna is realized on an FR4 substrate with a thickness of 1.6 mm, offering a low-cost and mechanically stable platform. The proposed design achieves a wide operational bandwidth ranging from 1.8 GHz to 3.2 GHz, corresponding to a fractional bandwidth of up to 40%, making it suitable for multiple wireless standards such as Wi-Fi, Zigbee, and Bluetooth. Detailed simulations are performed to evaluate the antenna's performance, including reflection coefficient (S11), voltage standing wave ratio (VSWR), input impedance, radiation pattern, and gain. Results demonstrate efficient impedance matching, stable omnidirectional radiation, and satisfactory gain across the operating band. The integration of the U-slot with the truncated feed enhances multi-resonant behavior while maintaining a compact footprint, making the antenna suitable for smart home devices, wearable sensors, and industrial IoT systems. The proposed antenna design provides a reliable, wideband, and low-profile solution, addressing the size and performance constraints inherent in IoT device integration.
Keywords: Microstrip patch Antenna, U Slot, Wideband antenna, IoT, ISM Band

I. INTRODUCTION

The Internet of Things (IoT) is revolutionizing modern life by enabling seamless connectivity among devices, systems, and environments. In smart homes, IoT facilitates automated lighting, security, and energy management. In industrial automation, interconnected sensors and machinery optimize production, maintenance, and logistics. In healthcare, wearable devices and remote monitoring systems improve patient care and enable timely interventions. These applications rely on reliable wireless communication, making antennas a critical component in IoT networks. Antennas serve as the interface between devices and the wireless medium, directly impacting connectivity, range, and data throughput [1]. The performance of an antenna affects link reliability, coverage, and system efficiency, especially in dense IoT environments with multiple devices and potential interference. Designing antennas that deliver high gain, stable radiation patterns, and sufficient bandwidth while fitting within compact devices is essential for IoT applications. Microstrip patch antennas have emerged as a preferred choice for IoT due to their planar, lightweight, and low-profile structure, which allows easy integration into printed circuit boards and conformal mounting on curved surfaces [2]. They are also cost-effective, simple to fabricate, and compatible with standard PCB processes, making them ideal for both consumer and industrial IoT devices. Despite their advantages, IoT antennas face significant design challenges. Devices often have strict size constraints, and multi-band operation is required to support standards such as Wi-Fi, Zigbee, and Bluetooth. Achieving efficient radiation, wide bandwidth, and stable performance within a small footprint is difficult. Environmental factors such as metallic enclosures or human proximity can further degrade performance [3]. This study aims to design a compact, efficient microstrip antenna optimized for IoT communication, balancing size, bandwidth, and radiation efficiency. The proposed design explores suitable patch geometries, substrate materials, and feeding techniques to ensure reliable connectivity, high data throughput, and adaptability for diverse IoT applications [4].

II. LITERATURE REVIEW

Recent research in the field of microstrip antennas has increasingly focused on addressing the specific demands of Internet of Things (IoT) applications, which require compact, low-cost, and efficient antenna designs capable of operating across narrow and wide frequency bands while maintaining acceptable radiation performance. In ref [5] investigated a rectangular microstrip patch antenna operating at 2.4 GHz using FR4 substrate, achieving a gain of 5.6 dBi with a bandwidth of 80 MHz, highlighting the simplicity and compactness of the rectangular patch while noting the substrate's higher dielectric losses.

Following this, Rajeev et al. [6] proposed a circular patch antenna for 2.45 GHz applications using Rogers RT/duroid 5880, demonstrating a gain of 6 dBi and a bandwidth of 90 MHz, which underlines the advantages of low-loss substrates in enhancing efficiency and bandwidth without significantly increasing the antenna size. Liu et al. [7] explored a meandered patch design operating at the sub-GHz IoT band of 868 MHz, employing FR4 and reporting a gain of 3.8 dBi and a bandwidth of 60 MHz, showcasing how meandering techniques enable compact layouts suitable for devices with strict spatial constraints while maintaining acceptable radiation characteristics. Singh and Patel [8] developed a fractal microstrip antenna supporting dual-band operation at 2.4 GHz and 5 GHz using Taconic TLY-5 substrate, achieving gains of 6.2 dBi and 5.8 dBi, respectively, emphasizing the fractal geometry's effectiveness in supporting multi-band operation without enlarging the antenna footprint, though at the cost of slightly increased fabrication complexity. Comparative studies reveal that simple geometries like rectangular and circular patches are preferred for single-band, low-cost IoT devices due to their ease of fabrication and predictable radiation patterns [9], whereas meandered and fractal designs are more suited for applications requiring miniaturization and multi-band functionality [10], highlighting a critical design trade-off between size reduction and operational versatility. Substrate selection plays a pivotal role in antenna performance; FR4 is widely adopted for cost-sensitive IoT devices, offering acceptable dielectric properties but suffering from higher losses at frequencies beyond 2.4 GHz [11], while Rogers RT/duroid and Taconic TLY-5 substrates provide low-loss characteristics that enhance radiation efficiency, gain, and bandwidth [12], making them ideal for performance-critical IoT sensors and wearable devices [13]. Feeding techniques also impact overall performance, with the microstrip line feed being the most popular choice due to its planar nature and ease of integration into printed circuit boards [14]; however, coaxial feeding, though bulkier, offers superior impedance matching and reduced spurious radiation [15], which can be critical in multi-band and high-gain IoT designs. Researchers have consistently observed trade-offs between size reduction, bandwidth enhancement, and radiation efficiency, as miniaturization often leads to narrow bandwidths and decreased gain [16], prompting the development of hybrid feeding mechanisms, slot incorporation, and multi-layer structures to simultaneously improve performance metrics [17]. Recent advancements also focus on optimizing patch shapes using parametric studies, such as altering the length, width, and slot dimensions of rectangular, circular, meandered, and fractal patches, to maximize gain and bandwidth while minimizing antenna area [18]. Despite these innovations, challenges persist, particularly in designing compact antennas capable of multi-band operation with high radiation efficiency, low return loss, and stable performance under environmental variations such as proximity to human body or metallic enclosures. Additionally, achieving impedance matching over multiple frequency bands without resorting to bulky matching networks remains an ongoing research concern, driving investigations into novel geometries like Sierpinski carpets, Koch curves, and hybrid fractal-meandered configurations [4][8][10]. The literature also indicates that integrating IoT-specific antennas into printed circuit boards or wearable platforms often necessitates careful consideration of substrate thickness, patch-to-ground spacing, and encapsulation materials to avoid performance degradation due to dielectric loading or bending [11][12]. Several studies have explored multi-layered and stacked patch configurations to overcome the inherent bandwidth limitations of single-layer microstrip antennas, demonstrating that such approaches can provide up to 50% bandwidth enhancement with moderate complexity [16]. Moreover, research emphasizes the importance of conducting parametric optimization using electromagnetic simulation tools like HFSS and CST Microwave Studio to fine-tune patch dimensions, feed positions, and slot geometries, thereby achieving desired resonant frequencies and gain levels while maintaining a low-profile design [7][9]. A critical gap identified across these studies is the lack of a universally applicable design methodology that balances compactness, multi-band capability, high radiation efficiency, and fabrication simplicity for IoT applications, as most proposed antennas optimize one or two parameters at the expense of others [6][10]. The integration of emerging materials, such as flexible polymers and high-permittivity ceramics, has been investigated to enable conformal or wearable IoT devices while mitigating losses associated with traditional substrates [12][13]. In conclusion, recent literature clearly illustrates that while rectangular and circular microstrip patches provide simple and efficient solutions for single-band IoT applications, meandered and fractal geometries are indispensable for miniaturized and multi-band designs, with substrate selection, feeding techniques, and parametric optimization playing critical roles in performance enhancement. However, the persistent research gap lies in achieving a compact, cost-effective, multi-band microstrip antenna design with high radiation efficiency and stable performance across diverse IoT environments, underscoring the need for continued exploration of innovative geometries, hybrid feeding schemes, low-loss substrates, and advanced fabrication techniques.

III. ANTENNA DESIGN METHODOLOGY

The design of a rectangular microstrip patch antenna begins by determining the desired resonant frequency and selecting an appropriate substrate with a specific dielectric constant and thickness.

The width of the patch is a critical parameter that influences not only the radiation pattern but also the input impedance and efficiency. It is calculated to balance these factors and can be expressed as:

Parameter / Formula	Expression
Patch Width W	$W = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}}$
Effective Dielectric Constant ε_{eff}	$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+12\frac{h}{W}\right)^{-1/2}$
Effective Patch Length L_{eff}	$L_{eff} = \frac{c}{2f_r\sqrt{\varepsilon_{eff}}}$
Actual Patch Length L	$L = L_{eff} - 2\Delta L$
Length Extension ΔL	$\Delta L = 0.412h\frac{(\varepsilon_{eff}+0.3)(\frac{W}{h}+0.264)}{(\varepsilon_{eff}-0.258)(\frac{W}{h}+0.8)}$

where c is the speed of light, fr is the resonant frequency, and εr is the relative permittivity of the substrate. The patch length, however, is influenced by the phenomenon of fringing fields at the patch edges, which effectively extends the resonant length beyond the physical dimensions. To account for this, the effective dielectric constant is first calculated, capturing the partial presence of the electromagnetic fields in air and in the dielectric. Here, h represents the substrate thickness. With the effective dielectric constant determined, the effective length of the patch, which corresponds to the resonant condition for the fundamental mode. The actual physical length of the patch must then be corrected for the additional extension caused by the fringing effect, which is given by ΔL.Proper impedance matching is essential to ensure maximum power transfer between the antenna and the feed line. For a rectangular patch fed by an inset microstrip line, the input resistance at the feed point varies as a function of its location from the patch edge.

A. *Proposed Design Approach*

Step 1: Patch Width Calculation

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}}$$

$$W = \frac{3\times10^8}{2\times2.4\times10^9}\sqrt{\frac{2}{4.4+1}} \approx 38\ \text{mm}$$

Step 2: Effective Dielectric Constant

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+12\frac{h}{W}\right)^{-1/2} \approx 4.084$$

Step 3: Effective Patch Length

$$L_{eff} = \frac{c}{2f_r\sqrt{\varepsilon_{eff}}} \approx 30.9\ \text{mm}$$

Step 4: Length Extension due to Fringing

$$\Delta L = 0.412h\frac{(\varepsilon_{eff}+0.3)(\frac{W}{h}+0.264)}{(\varepsilon_{eff}-0.258)(\frac{W}{h}+0.8)} \approx 0.738\ \text{mm}$$

Step 5: Actual Patch Length

$$L = L_{eff} - 2\Delta L \approx 29.42 \text{ mm}$$

Step 6: Inset Feed Position (for 50 Ω matching)

$$R_{in}(y_0) = R_{in}(0)\cos^2\left(\frac{\pi y_0}{L}\right)$$

$$y_0 \approx 10.77 \text{ mm}$$

Step 7: Approximate Bandwidth

$$BW \approx \frac{3.77}{\sqrt{\varepsilon_r}}\frac{h}{\lambda_0} \times 100\% \approx 2.3\%$$

Final calculated Parameters: - Width: 38 mm - Length: 29.42 mm - Inset feed position: 10.77 mm - Substrate: FR4, thickness 1.6 mm - Bandwidth: ~2.3% - Resonant frequency: 2.4 GHz. here the target bandwidth is narrower so targeting for widerband performance. For a 2.4 GHz microstrip antenna targeting a wide bandwidth , a conventional single-layer rectangular patch on FR4 (εr=2.2, h=1.6mm) is taken. The design incorporate a truncated-corner rectangular patch or a U-shaped slot to introduce multiple resonances that merge into a wide operational band, effectively achieving upto 40% bandwidth. Key parameters required for this design include the substrate dielectric constant (εr), substrate thickness (h), overall patch dimensions (length L, width W), slot dimensions or corner truncation size, feed technique and location (inset-fed or microstrip line feed for impedance matching), and ground plane size to ensure stable radiation patterns. Additionally, the gap between stacked layers and the top patch dimensions can be tuned to control the impedance bandwidth and resonant frequency. For a 2.4 GHz target, the approximate top patch width would be around 45–50 mm, and the length around 35–40 mm, with the lower patch slightly larger to create coupling, and the feed inset positioned for 50 Ω matching. Using these parameters in a full-wave EM simulator HFSS, one can optimize the patch geometry and slot dimensions to achieve the desired wideband response while maintaining high radiation efficiency and stable gain across the 2.0–2.8 GHz range.

B. Proposed Antenna Design

The proposed microstrip antenna is designed with a rectangular radiating patch of overall length L = 28 mm and width W=36 mm, which define the primary resonating area for efficient radiation. The patch is fed using a microstrip line of width Fw =4mm, ensuring proper impedance matching with the source. To enhance the antenna's bandwidth and multi-resonant behavior, a U-shaped slot of length Sl is incorporated into the patch, with the main slot width denoted as Sw1=18mm and a secondary inner slot of width Sw2 = 12mm positioned to optimize current distribution. The antenna structure is supported by a ground plane of length GL=30, providing the necessary reflection and stability for radiation. By carefully selecting the dimensions of these parameters, the antenna can achieve the desired resonance frequency, improved gain, and radiation efficiency suitable for IoT applications.

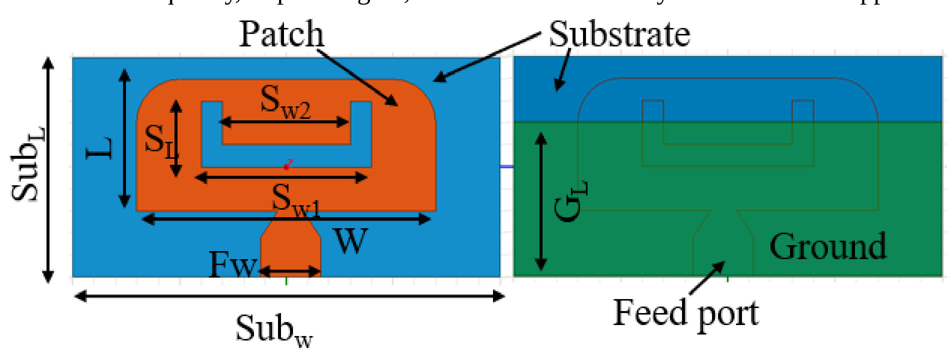

Figure 1: Proposed antenna design top View and Bottom view

IV. RESULTS AND DISCUSSION

The proposed microstrip antenna is designed on an FR4 substrate with a thickness of 1.6 mm, providing a low-cost and widely available material while ensuring mechanical stability. The radiating patch incorporates a U-shaped slot, combined with a truncated feed line, which enhances the impedance matching and enables multi-resonant behavior suitable for modern IoT applications. The antenna was simulated, and the obtained results demonstrate a wide operational bandwidth, covering the frequency range from 1.8 GHz to 3.2 GHz, which is highly suitable for various wireless communication standards. The reflection coefficient (S11) plot, presented in Figure 1, shows that the antenna achieves a return loss well below -10 dB within the desired band, indicating efficient radiation and minimal power reflection. Complementing this, the VSWR plot, shown in Figure 2, remains below 2 across the operating band, confirming that the antenna maintains good impedance matching and efficient energy transfer throughout the intended frequency range. The impedance plot (Figure 3) further supports the design by showing that the real and imaginary components are well-aligned with the expected resonant behavior, ensuring minimal mismatch with standard 50-ohm feed lines. The radiation characteristics, illustrated in Figure 4, indicate that the proposed U-slotted patch antenna produces a stable and omnidirectional pattern in the azimuth plane, while maintaining moderate directivity in the elevation plane, making it suitable for portable and body-centric IoT devices. The gain plot (Figure 5) demonstrates that the antenna achieves a peak gain adequate for short- to medium-range wireless communication, confirming that the U-slot configuration does not significantly compromise radiation efficiency. By integrating the U-slot with the truncated feed, the antenna achieves an effective bandwidth of up to 40%, which supports high data throughput and reduces sensitivity to fabrication tolerances and environmental effects. This wide bandwidth is particularly advantageous for IoT applications, where multiple wireless standards may coexist, and reliable performance across the band is critical. Overall, the simulation results validate the proposed antenna design by demonstrating a well-matched impedance, acceptable VSWR, and satisfactory radiation characteristics over the desired frequency range. The combination of FR4 substrate, U-shaped slot, and truncated feed line not only ensures compactness and cost-effectiveness but also enhances the overall electromagnetic performance of the antenna. The results confirm that the design meets the target specifications for IoT applications, providing a practical solution with enhanced bandwidth and gain, making it suitable for integration into smart home devices, wearable sensors, and industrial wireless systems. The figures collectively illustrate that the proposed design successfully balances physical compactness, bandwidth, and radiation performance, offering a reliable platform for future IoT antenna development.

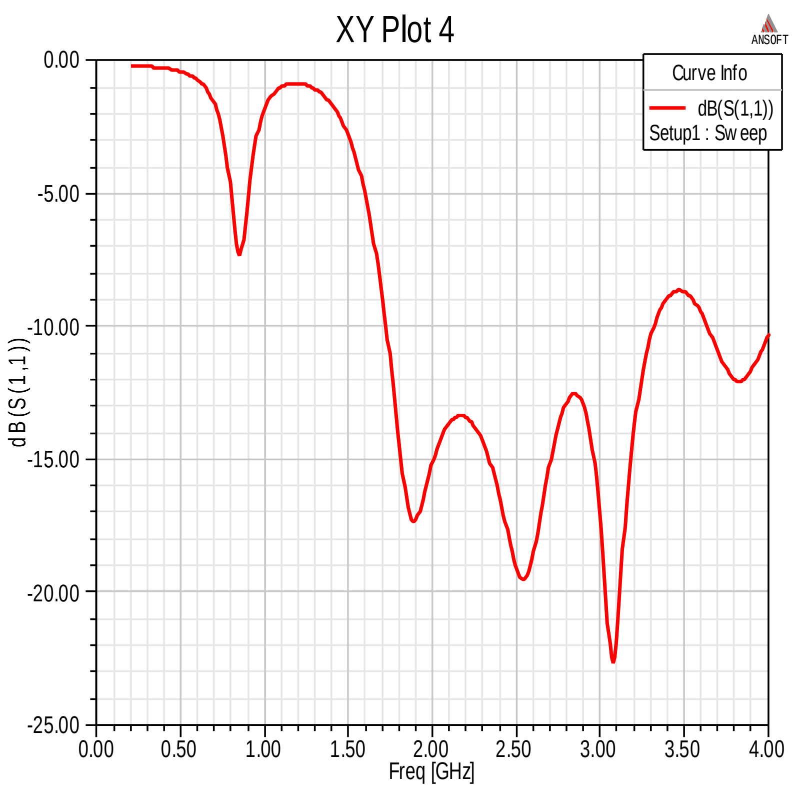

Figure 2: S11 (Return Loss) Plot of the Proposed U-Slotted Patch Antenna

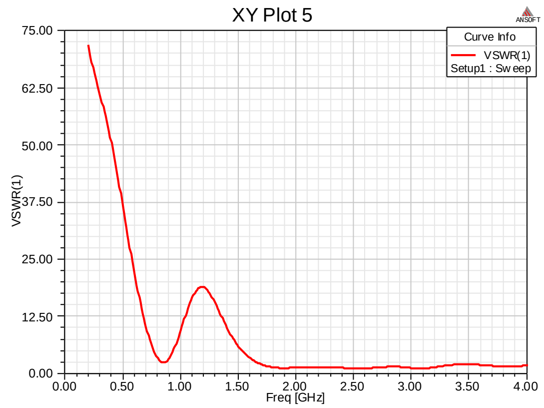

Figure 3: VSWR Plot of the Proposed Antenna

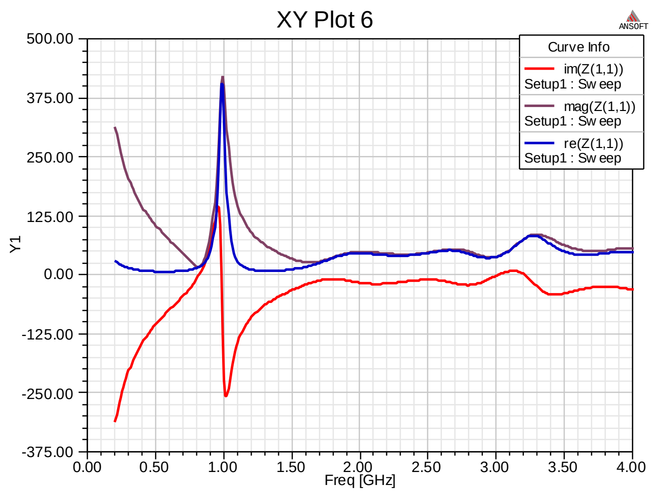

Figure 4: Input Impedance(real, Imag, mag) Plot of the Proposed Antenna

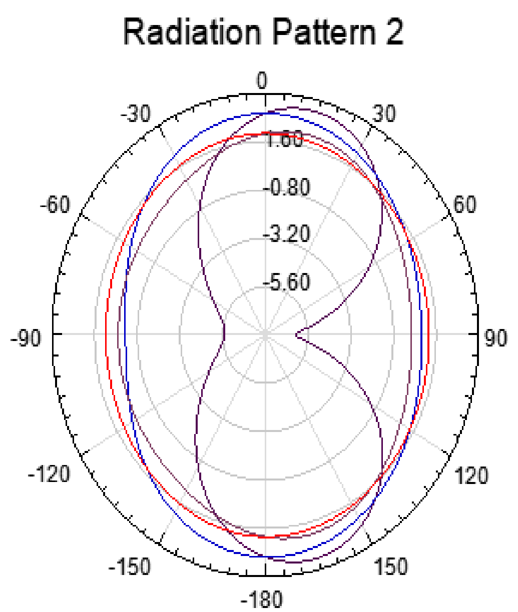

Figure 5:Radiation Pattern Plot of proposed antenna

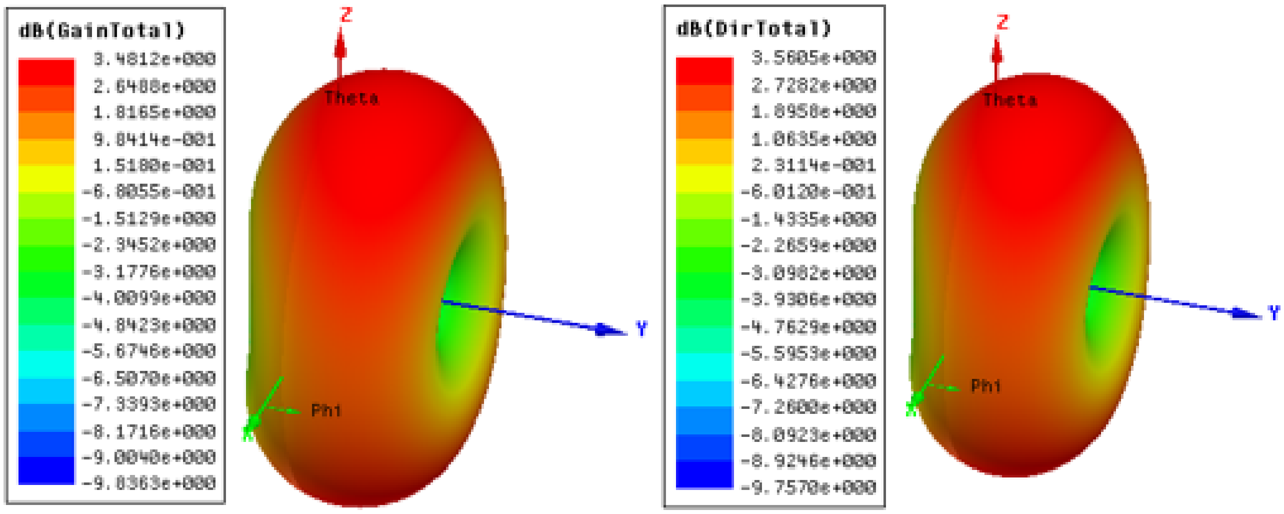

Figure 6:Gain and Directivity Plot of Proposed Antenna

V. CONCLUSION

A compact U-slotted microstrip antenna with a truncated feed has been successfully designed and analyzed on an FR4 substrate of 1.6 mm thickness for IoT applications. The antenna operates efficiently over a wide frequency range of 1.8 GHz to 3.2 GHz, achieving a bandwidth of up to 40%, which demonstrates its capability to support multiple wireless communication standards. Simulation results, including S11, VSWR, impedance, radiation pattern, and gain plots, confirm that the antenna maintains good impedance matching, stable radiation characteristics, and satisfactory gain across the operating band. The U-slot configuration, combined with the truncated feed, enhances the overall performance by providing multi-resonant behavior while maintaining a compact and cost-effective design. Overall, the proposed antenna proves to be a promising solution for integration into IoT devices, offering wide bandwidth, reliable radiation performance, and ease of fabrication.

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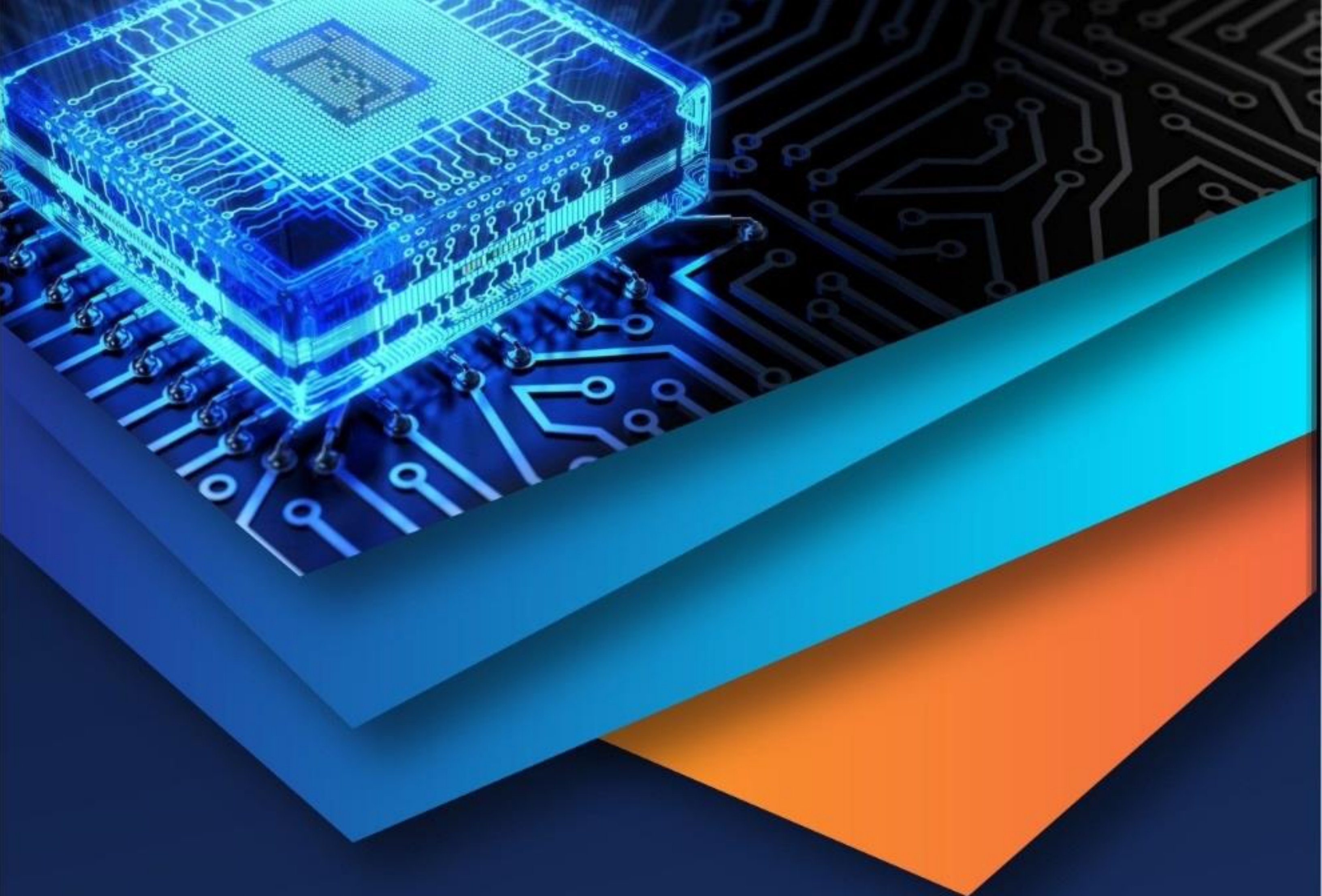

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