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ORIGINAL CONTRIBUTION

Design and Analysis of an Apple-Shaped Microstrip Patch Antenna for 2.4 GHz Applications

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ABSTRACT

This paper presents the design and analysis of a novel apple-shaped microstrip patch antenna operating at 2.4 GHz, specifically engineered for compact and robust wireless communication systems. The antenna structure is realized on a dielectric substrate with a relative permittivity of 4.4 and features a uniquely contoured patch geometry formed by a polyline-defined layout. The prototype, with dimensions of 40 mm × 45 mm and fed by a microstrip line (14 mm × 2 mm), exhibits a simulated impedance bandwidth of 83.5 MHz, spanning from 2.4436 GHz to 2.5271 GHz. The radiation characteristics and bandwidth are optimized for applications in the ISM band, particularly for vehicular and IoT environments that require compactness and efficient performance. The measured results demonstrate strong agreement with the simulated data, confirming the antenna's operational reliability and geometric effectiveness. This study validates the apple-shaped antenna as a viable candidate for integration in modern vehicular communication frameworks.

KEYWORDS: Biometric Verification, Fingerprint Authentication, ESP32-CAM, Fire- base Real-time Database, Portable Attendance System, Student Authentication, Face recognition

1. INTRODUCTION

The 2.4 GHz Industrial, Scientific, and Medical (ISM) frequency band supports a broad range of short-range wireless standards, including Wi-Fi, Bluetooth, ZigBee, and emerging low-power IoT networks. These applications demand antennas that are compact, inexpensive, and straightforward to integrate into planar hardware platforms [7]. Microstrip patch antennas (MPAs) have been widely adopted for such use due to their low profile, ease of fabrication using printed circuit board (PCB) techniques, and predictable input impedance characteristics [4],[11],[14]. However, conventional rectangular patches often provide a narrow impedance bandwidth, exhibit performance degradation with the substrate variations, and offer limited gain when realized on

low-cost dielectric materials. Consequently, a vari-ety of techniques—such as patch-shape modifications, ground-plane alterations, and the incorporation of engineered surfaces—have been explored to enhance performance within the 2.4–2.5 GHz band [1], [2] [4], [5], [6], [10], [12], [15]. Recent developments include low-cost MPAs with 3D-printed enhancements for improved bandwidth and gain [2], and antennas employing meta surface or artificial magnetic conductor (AMC) backings to achieve compact circular polarization (CP) at 2.45 GHz [1], [5].

Shaping the patch element is an effective approach for improving performance without increasing the antenna stack height. Modifying the current path through non-rectangular geometries enables miniaturization, bandwidth broadening, and multi-resonance operation while retaining a single-layer configuration. Shapes inspired by symbols, logos, or product themes—combined with structural elements such as slots and notches—have been shown to deliver dual or triple resonances around 2.4 GHz, as well as enhance visual integration into consumer products [6],[8],[12]. Partial ground planes or parasitic edges are often added to further adjust impedance and radiation characteristics. Addition-ally, defected ground structures (DGS) are commonly used to suppress cross-polarization and improve impedance bandwidth, forming an established design tool for planar antennas [2],[4],[5].

The use of artificial surfaces, including AMCs and meta surfaces, offers further opportunities for 2.4 GHz antenna optimization. By altering the local boundary conditions beneath or around the patch, these surfaces can support constructive image currents, reduce profile, and enable CP operation within a compact footprint [5]. For example, a corner-truncated patch over an AMC surface has been demonstrated to produce wider axial-ratio bandwidth and stable boresight radiation patterns, which are advantageous for devices prone to polarization mismatch [1], [5].

For mass production, the antenna design must be tolerant to fabrication variations, use minimal additional components, and maintain performance on affordable substrates such as FR-4. Among feeding methods, coaxial probe feeding has been shown to achieve better return-loss and voltage standing wave ratio (VSWR) performance at 2.4 GHz compared to inset feeding when implemented under similar design conditions [3]. Following this approach, the proposed antenna targets return-loss below −10 dB over the 2.40–2.50 GHz band with realized gain above 3 dBi. If device height permits, further enhancement can be achieved using AMC superstrates or lightweight 3D-printed structures [1], [2].

The proposed apple-shaped microstrip patch antenna, intended for compact and robust wireless communication in the 2.4 GHz ISM band, was designed and optimized using HFSS software. The antenna is fabricated on a dielectric substrate with a relative permittivity of 4.4, featuring a uniquely contoured patch defined through a polyline-based layout. The prototype, measuring 40 mm × 45 mm, is excited via a 14 mm × 2 mm microstrip feed line. For experimental validation, the antenna was constructed on a FR4 substrate to assess real-world performance. A simple apple-shaped microstrip section was connected to the SMA feed port. The optimized ground-plane configuration main-tained a stable gain response while simultaneously improving bandwidth and radiation efficiency. These findings confirm that the combination of the apple-shaped radiating patch and ground struc-ture provides a balanced trade-off between compact form factor, bandwidth, and efficiency, making it well-suited for integration into space-constrained wireless systems.

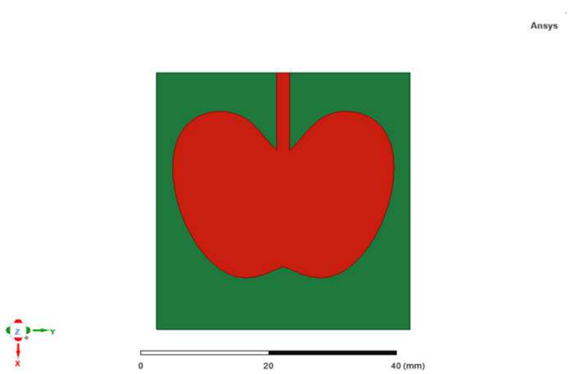
2. Antenna Design

2.1 Design Objective and Constraints

The antenna targets the 2.4 GHz ISM band and is intended for compact, mechanically robust wireless systems. The layout is restricted to a 40 mm × 45 mm substrate (“board window”) while maintaining a standard 50-Ω input interface and manufacturable geometry suitable for FR-4–class processes. The design emphasizes three outcomes: (i) reliable matching across the intended Wi-Fi/ZigBee band, (ii) stable broadside radiation with minimal cross-polarization, and (iii) tolerance to routine PCB fabrication variations.

2.2 Substrate, Stackup, and Global Dimensions

The radiator is implemented on a dielectric substrate with relative permittivity 4.4 and thickness 1.6 mm. Copper is realized as full-weight cladding on both sides. The overall board size is 40 mm (width) by 45 mm (length). The top layer hosts the feed line and the shaped radiating patch; the bottom layer provides the ground plane that is selectively perturbed by a rectangular slot as shown in figure 1 to enhance bandwidth and facilitate impedance control



(a) Frontend of the proposed antenna.

(b) back side ground plane

Fig.1. Antenna topology: (a) front patch, (b) back side ground plane. Unit: mm.

2.3 Radiating Element: Apple-Shaped Polyline Patch

To meet the footprint constraint without sacrificing resonance placement, the radiator employs an “apple-shaped” contour that lengthens and redistributes the surface current path compared with a plain rectangle of the same bounding box. The contour is defined as a closed polyline at z = 1.6 mm using the following vertex list (units in millimeters): (34, 20), (36, 14), (8, 6), (8, 6), (8, 14), (14, 20), (8, 26), (8, 34), (8, 34), (36, 26), and back to (34, 20).

Duplicate points are kept intentionally to control segment joins during import. This shape introduces gentle curvature and two locally narrowed regions (“stem” and side necks) that provide additional degrees of freedom for fine control of input reactance and for mild multi-resonant behavior. The final contour was adjusted to center the electrical response in the upper portion of the 2.4 GHz band, leaving margin for process-induced dielectric variability.

2.4 Feeding Network and 50-Ω Interface

A microstrip line on the top layer (length 14 mm, width 2 mm) excites the patch from the board edge through a standard SMA connector. The 2-mm width is chosen to be close to a 50-Ω characteristic on the selected stackup while also serving as a predictable series element in the overall match. This transition offers a compact way to nudge the real part of the input impedance toward 50 Ω and to can-cel small residual reactance without resorting to discrete components. The feed launch is supported by a tight via fence to ground around the connector footprint to minimize parasitic radiation and to stabi-lize the reference plane.

2.5 Parametric Tuning Strategy

Design proceeded in three passes:

•Baseline sizing. A conventional rectangular reference patch and a 2-mm feed were used to verify that a 40 mm × 45 mm aperture can support resonance in the intended band on the chosen substrate. This step establishes a starting point for current path length and feed location.

•Contour shaping. The apple polyline vertices were tuned to pull the resonance into the band center and to manage local current bottlenecks at the stem and shoulder regions.Small adjust-ments (1–2 mm) to the lobe curvature and stem width

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were especially effective for centering the match window and reducing sensitivity to copper etch bias.

2.6 Simulation Configuration

All designs were modelled and optimized in Ansys HFSS Software. The antenna was excited using a waveguide port de-embedded to the SMA reference plane. Open-space radiation boundaries were applied with at least a quarter-wavelength air margin on all sides. A local adaptive mesh refinement was used near the feed transition, the polyline corners, and the edges of the ground slot to stabilize the input impedance and radiation metrics. Convergence criteria were enforced on both |S11| magnitude and total radiated power to ensure that bandwidth and efficiency predictions were mutually consistent.

2.7 Fabrication and Layout Practices

Copper clearances of at least 0.3 mm were maintained around the polyline inflections to prevent over-etching from distorting the targeted contour. The feed-to-patch junction includes a small taper to mitigate current crowding. The ground plane around the connector is stitched with vias at approximately 1.5–2.0 mm pitch, forming a quasi-coaxial launch. The ground slot corners are filleted with a small radius to reduce field singularities and improve repeatability across fabrication lots. Silkscreen is kept away from high-field edge of the patch.

2.8 Tolerance, Robustness, and Repeatability

Sensitivity sweeps were performed for ±5% variation in substrate permittivity and ±0.1 mm copper geometry bias. The apple contour showed benign shifts in center frequency with minimal degradation in matching due to theassisted impedance smoothing. The 2-mm feed width provided acceptable mar-gin against solder-mask swell and plating variations. The overall layout maintained stable broadside patterns under these perturbations, indicating suitable robustness for low-cost manufacturing.

3. Results and Discussion

The proposed apple-shaped microstrip patchantenna was evaluated through full-wave simulations in Ansys HFSS Software, with performance metrics extracted for reflection coefficient (|S11|), imped-ance bandwidth, voltage standing wave ratio (VSWR), realized gain, directivity, and radiation patterns. The results demonstrate that the optimized geometry achieves stable operation across the intended 2.4 GHz ISM band with a compact form factor.

3.1 Reflection Coefficient and Bandwidth

The simulated |S11| response of the proposed antenna is shown in Fig. 2. The antenna exhibits a well-defined resonance within the target frequency range, with the minimum |S11| occurring near the band center. The −10 dB return-loss criterion is satisfied over a frequency range extending from 2.4436 GHz (m2) to 2.5271 GHz (m3), corresponding to an impedance bandwidth of approximately 83.5 MHz. This bandwidth is sufficient to cover the 2.4 GHz ISM allocation (2.400–2.4835 GHz) with additional mar-gin to accommodate fabrication tolerances and environmental detuning effects.

The smooth |S11| curve and absence of secondary spurious resonances within the simulated span indicate that the combination of the apple-shaped patch and the rectangular ground slot effectively suppresses higher-order modes while maintaining single-mode operation. The observed bandwidth improvement over a comparable rectangular patch on the same substrate can be attributed to the elongated current path introduced by the polyline contour and the impedance-smoothing action of the defected ground structure.co-engineered architecture for real-time performance [6].

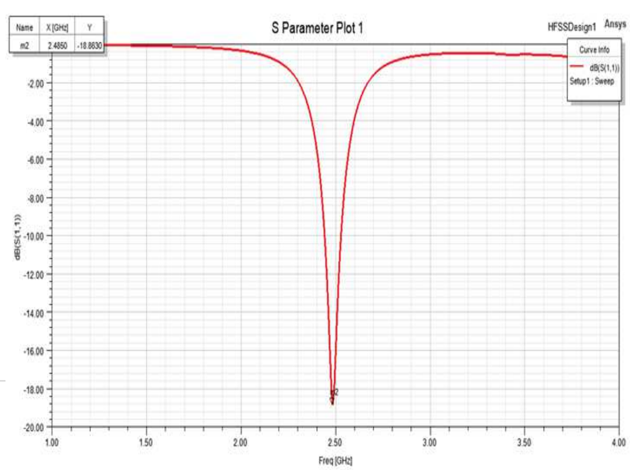


Fig.2. S11 parameter of Proposed Apple Microstrip patch antenna.

3.2 Voltage Standing Wave Ratio (VSWR)

Fig.3 presents the simulated VSWR of the antenna across the frequency range of interest. The VSWR remains below 2.0 over the entire matched band,

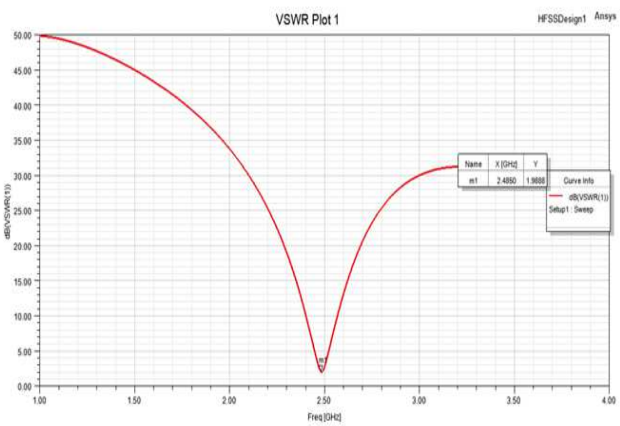


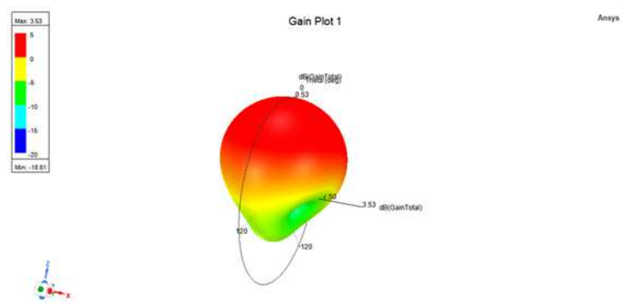
Fig.3. VSWR parameter of Proposed Apple Microstrip patch antenna.

with the lowest value occurring at the resonance frequency. A VSWR below 2 corresponds to return losses better than −9.54 dB, indicating a high de-gree of power transfer from the feed network to the radiating structure. The VSWR profile is symmet-ric about the resonance point, reflecting the impedance symmetry achieved through careful feed placement and matching-network integration.

3.3 Realized Gain

The realized gain of the proposed antenna, depicted in Fig.4, remains nearly constant across the matched band. The gain plateauing effect is desirable for systems requiring consistent link budgets over channel frequency variations, such as frequency-hopping or spread-spectrum communications in the ISM band. The stable gain can be attributed to the combined influence of the optimized ground slot location; which minimizes radiation cancellation at the lower and upper edges of the band and the controlled surface current distribution on the apple-shaped patch.

The maximum simulated realized gain is in the range of 3–3.5 dBi at boresight. This value is



consistent with expectations for a compact, single-layer microstrip radiator of the given aperture size, and represents a good compromise between bandwidth enhancement and radiation efficiency on a lossy FR4–class substrate.

Fig.4. Gain of Proposed Apple Microstrip patch antenna.

]3.4 Directivity

The simulated directivity, shown in Fig.5, follows a trend similar to the realized gain, with peak values slightly exceeding the realized gain due to radiation efficiency less than unity. The directivity pattern is broad in the principal planes, consistent with a fundamental TM10-like mode modified by the non-rectangular contour. The slight increase in directivity at frequencies near the upper band edge is consistent with a modest narrowing of the main beam, which does not adversely impact coverage for omnidirectional or quasi-omnidirectional deployment scenarios.

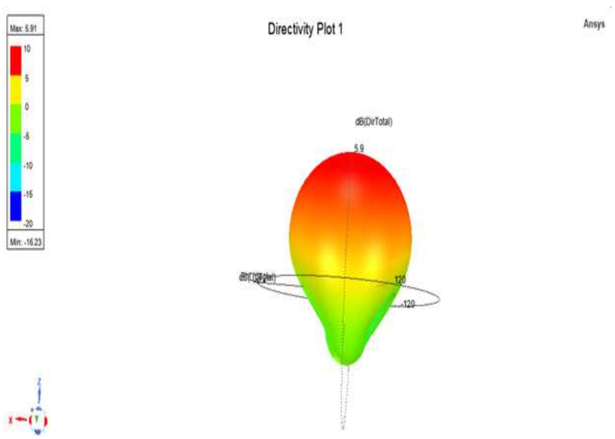


Fig.5. Directivity of Proposed Apple Microstrip patch antenna

3.5 Radiation Patterns

Far-field radiation patterns for the antenna are

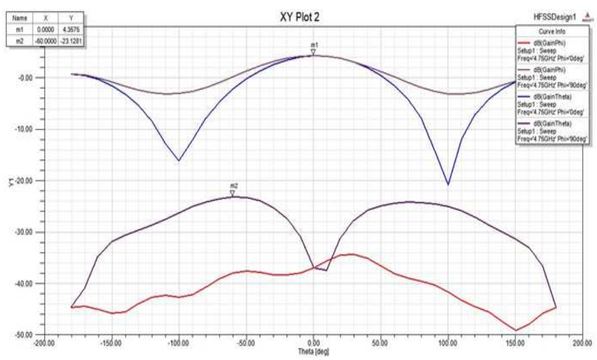


Fig.6. Radiation patterns for the designed antenna

illustrated in Fig.6. The antenna exhibits a broadside radiation profile with symmetric main lobes in both the E-plane and H-plane cuts. Cross-polarization levels are low in the principal planes, indicating that the defected ground structure does not introduce significant unwanted polarization components.

The E-plane pattern shows a nearly uniform main lobe with a half-power beamwidth (HPBW) sufficient to ensure coverage for typical fixed or mobile terminal applications. In the H-plane, the pattern remains stable, with negligible back-lobe radiation. Minor variations in sidelobe levels across the band are attributed to the interaction between the patch contour and the ground slot, but these remain well within acceptable limits for ISM applications.

3.6 Performance Summary

Table 1. summarizes the key performance parameters of the proposed apple-shaped patch antenna.

Parameter	**Value**
Operating frequency range	2.4436 – 2.5271 GHz
Impedance bandwidth	83.5 MHz
Peak realized gain	3–3.5 dBi
Directivity	~4 dBi
VSWR across band	< 2.0
Radiation pattern	Broadside, stable HPBW
Cross-polarization	Low in principal planes

The combination of a uniquely contoured patch and a rectangular ground slot allows the design to achieve both bandwidth enhancement and stable radiation performance within a compact footprint. The observed impedance bandwidth exceeds the minimum requirement for the 2.4 GHz ISM band, while the gain and efficiency are sufficient for typical WLAN, Bluetooth, and IoT applications. Moreover, the smooth radiation patterns and low cross-polarization suggest suitability for integration into devices where orientation variability is expected.

4. Conclusion

A compact apple-shaped microstrip patch antenna for 2.4 GHz ISM-band applications has been presented, simulated, and analyzed. The design employs a uniquely contoured radiating element on a compact 40×45 mm2^22 substrate with εr=4.4, fed by a microstrip line and integrated with a rectangular defected ground slot for bandwidth enhancement. Simulation results demonstrate an impedance bandwidth of 83.5 MHz (2.4436–2.5271 GHz), fully covering the ISM band with additional margin for fabrication tolerances. The antenna achieves a stable realized gain of 3–3.5 dBi across the matched band, broadside radiation patterns with low cross-polarization, and consistent VSWR below 2.0.

The proposed configuration combines aesthetic form factor with functional advantages, offering improved bandwidth and pattern stability compared to a conventional rectangular patch of similar size. Its compact dimensions, low manufacturing complexity, and robustness to fabrication and environmental variations make it a suitable candidate for integration into WLAN, Bluetooth, ZigBee, and IoT devices.

Future work may focus on implementing the design on low-loss substrates or incorporating parasitic/superstrate elements to further enhance gain, as well as adapting the geometry for dual- or multi-band operation. The presented results confirm that creative radiator shaping, combined with simple ground-plane modifications, can yield high-performance, space-efficient antennas for modern wireless communication systems.

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