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Miniaturized Notch-Loaded Patch Antenna for Highly Efficient Ku-Band Communication Systems

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Abstract: - This paper presents a comprehensive investigation of an extremely small rectangular patch antenna loaded with a notch, designed for Ku-band satellite communication applications. The antenna is implemented on an FR-4 substrate (εr = 4.4) with compact dimensions, ensuring low cost and mechanical stability. HFSS simulations validate the antenna's performance, demonstrating dual operating bands of 15.73–16.40 GHz and 17.73–18.10 GHz, with resonant frequencies at 16.05 GHz and 17.71 GHz. The design achieves return losses of -18.86 dB and -46 dB, respectively, while maintaining VSWR values below 2, confirming excellent impedance matching. The proposed antenna exhibits peak gains of 7.04 dB and 4.80 dB across the two bands, with radiation efficiency of 69.40% and 49.47%. Radiation patterns show omnidirectional distribution across the azimuth plane, ensuring suitability for robust Ku-band communication. A comparative analysis with recent literature highlights the superior compactness and multiband performance of the proposed design, making it a strong candidate for next-generation aerospace and satellite communication systems.

Keywords: Return Loss, VSWR, Radiation Pattern, Radiation Efficiency, Gain, Ku-Band

1. Introduction

The rapid advancement of satellite-based services, radar systems, wireless broadcasting, and high-speed communication networks has significantly increased the demand for antennas operating at higher microwave and millimeter-wave frequencies. Among these, the Ku-band (12–18 GHz) has attracted particular attention due to its extensive use in direct-to-home (DTH) broadcasting, very small aperture terminals (VSAT), aeronautical communication, and meteorological applications [1-2]. The Ku-band spectrum provides an excellent balance between bandwidth availability, link reliability, and atmospheric attenuation, making it one of the most commercially viable ranges for modern satellite communication systems.

In order to meet the requirements of Ku-band systems, antenna researchers have focused on designing solutions that ensure compact size, multiband coverage, wide impedance bandwidth, stable radiation characteristics, and sufficient gain**.** Microstrip patch antennas (MPAs) are considered highly promising for this purpose because of their planar structure, lightweight profile, ease of fabrication, and integration capability with RF and microwave circuits [10-11] [12]. Despite these advantages, conventional MPAs suffer from limitations including narrow

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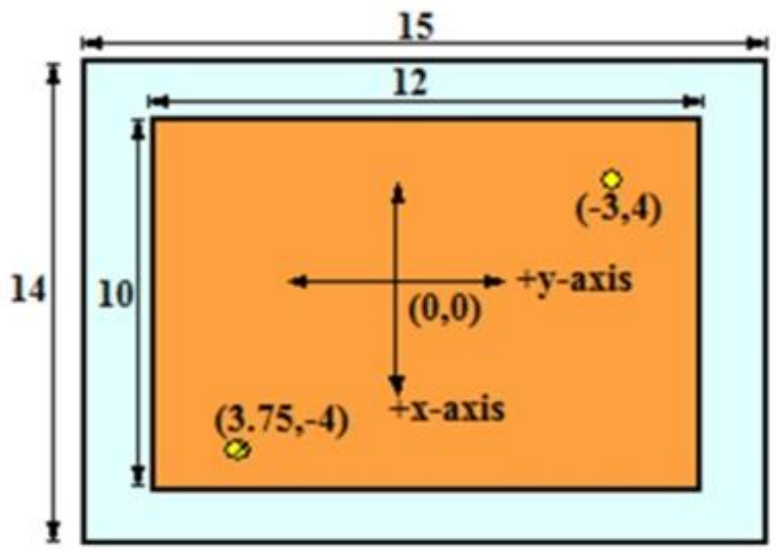
bandwidth, relatively low efficiency, surface-wave excitation, and poor performance when implemented on lossy substrates such as FR-4 [24]. These issues become more critical at Ku-band frequencies, where dielectric and conductor losses significantly degrade antenna performance.

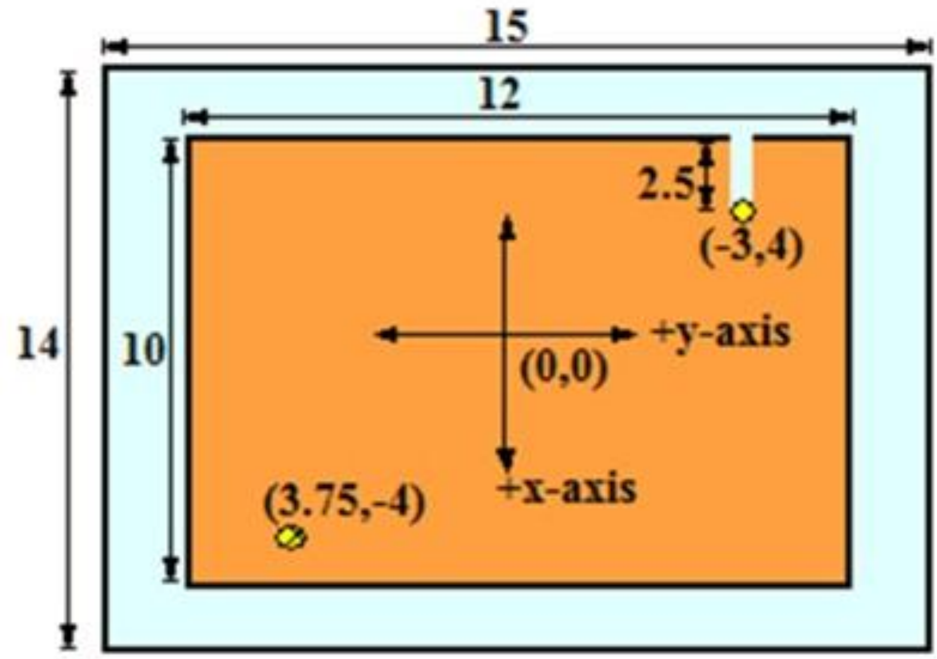
To overcome these shortcomings, researchers have explored several advanced techniques in Ku-band antenna design. Kumar and Singh [1] introduced a compact tri-band patch antenna for Ku-band applications, while Kandwal et al. [2] designed a dual-band elliptical antenna suitable for Ku/Ka satellite links. Kandwal, Pongpaibool, and Siwamogsatham [3] proposed an electromagnetic band-gap (EBG) integrated antenna that exhibited improved impedance matching, and Kumar and Kumar [4] realized a wideband EBG antenna using frequency selective surfaces (FSS) for Ku-band operation. In addition, Ahmadian et al. [5] investigated EBG array structures to suppress mutual coupling, thereby improving radiation performance. Further, Harane and Ammor [6] reported a compact dual-band elliptical antenna for Ku/K bands, while Prasad and Chattoraj [7] presented a compact Ku-band antenna for satellite communication systems. Rahim et al. [8] proposed a high-gain wideband EBG resonator antenna, demonstrating the efficiency of periodic structures. Alongside these works, the theoretical foundations of microstrip antenna design and miniaturization were systematically established by Volakis et al. [9], Balanis [10], Garg et al. [11], and Wong [12], which continue to guide compact and broadband antenna research. Various structural modifications have been explored to achieve improved Ku-band operation. Mishra et al. [13] presented slot-loaded stacked patch antennas with dual and wideband behavior, inspiring the use of slots and notches for performance enhancement. Kumar and Singh [14] developed a Ku-band antenna using slots and defected ground structure (DGS), while Kumar et al. [15] introduced a notch-loaded rectangular patch with improved bandwidth. Ho et al. [16] proposed dual-band and wideband slot antennas, and Chen and Chia [17] discussed design strategies for broadband planar antennas. Similarly, Yang and Mittra [18] demonstrated wideband notched antennas using DGS, whereas Pattnaik et al. [19] reported a U-shaped DGS-loaded compact Ku-band antenna. Miniaturization techniques have also been widely applied. Karimian et al. [20] employed slot loading for antenna size reduction, while Kumar and Kumar [21] integrated EBG structures to achieve gain enhancement. Abdelrahman et al. [22] developed wideband EBG resonator antennas for satellite applications, and Shah et al. [23] optimized compact Ku-band patches with DGS. Best [24] provided a fundamental study of small antenna properties and trade-offs, and Mandal et al. [25] designed extremely small monopole antennas for wideband systems. Extending such approaches to higher frequencies, Kumar et al. [26] demonstrated ultra-compact THz MIMO antennas using DGS. Similarly, Kumar, Kanaujia, and Gautam [27] proposed bandwidth enhancement and cross-polarization suppression techniques in microstrip antennas using DGS. Bhattacharjee and Sarkar [28] presented a tri-band antenna covering C, X, and Ku bands, while Ullah et al. [29] developed a compact Ku-band antenna for satellite TV reception. Majhi and Mandal [30] reported a slot-loaded notch antenna with deep return loss performance in Ku-band. Guha [31] analyzed shorting-pin loaded probe-fed antennas for miniaturization, while Oraizi and Jam [32] explored innovative substrate modifications. Antoniades and Eleftheriades [33] demonstrated a multiband monopole antenna using defected ground planes, and Lee and Nam [34] presented a Ku-band patch array for satellite terminals with high gain. Comprehensive reviews of EBG-based antennas were provided by Iqbal et al. [35], while Yang and Rahmat-Samii [36] proposed low mutual coupling EBG-integrated arrays**.** Kumar and Gupta [37] designed a U-slot Ku-band patch antenna on FR-4, Liu et al. [38] implemented wideband Ku-band antennas with dual-notch slots**,** and Singh and Singh [39] reported dual-band compact DGS-loaded antennas. Recently, Mather [40] introduced a notch-loaded Ku-band patch with promising dual-band behavior. From these studies, it is evident that a variety of techniques such as EBG integration [3] [4] [5] [21] [22] [35] [36]**,** DGS [14] [18] [19] [23] [27] [37] [39]**,** slot and notch loading [13] [15] [18] [30] [40]**,** and shorting pins [31] have been successfully employed to enhance Ku-band antenna performance. While these approaches improve return loss, bandwidth, and gain, several limitations persist. Many reported designs occupy relatively large footprints (>20×20 mm²) [2] [21] [34] [37], which restricts integration into compact devices. Others rely on expensive substrates such as Rogers [1] [4] [6] [22], making them unsuitable for low-cost applications. Moreover, EBG and metamaterial-based designs [3] [5] [21] [22] [35] [36] often involve multilayer periodic structures that increase fabrication complexity. Finally, antennas designed on FR-4 [14] [15] [19] [30] [37] [39] face efficiency trade-offs due to higher dielectric losses at Ku-band frequencies. These challenges highlight the need for compact, cost-effective, and high-performance Ku-band antennas**.** The present work addresses this gap by proposing an extremely compact rectangular patch antenna (12×10 mm²) on FR-4 substrate with notch and shorting pin loading**,** achieving dual-band operation with strong return loss and acceptable gain.

2. Proposed Antenna Configuration

The proposed antenna is designed as an extremely compact rectangular microstrip patch integrated with a rectangular notch and a shorting pin to achieve dual-band operation in the Ku-band. The antenna is fabricated on a commercially available FR-4 substrate with a relative dielectric constant (εr) of 4.4, substrate thickness of 1.6 mm, and overall board dimensions of 15 mm × 14 mm. The radiating patch has dimensions of 12 mm × 10 mm, which ensures a highly compact footprint compared to most reported Ku-band designs.



(a)



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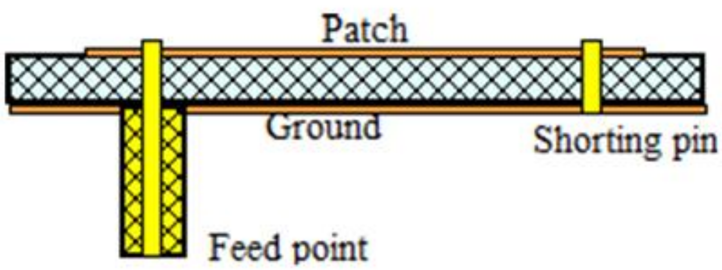

(c)

Fig. 1: (a) Geometry of the reference antenna, (b) geometry of the proposed rectangular patch antenna with notch and shorting pin, and (c) top and side views illustrating the overall configuration.

To introduce dual resonance behavior, a rectangular notch of 2.5 mm × 0.75 mm is embedded within the patch. The notch perturbs the surface current distribution and alters the effective electrical length of the radiator, thereby generating the second resonance within the desired frequency band. A coaxial probe feed is employed to excite the antenna, positioned at coordinates (3.75, –4) mm relative to the patch center, providing impedance matching and efficient power transfer. In addition, a shorting pin is placed at (–3, 4) mm, which not only aids in further miniaturization but also helps in tuning the input impedance to achieve better matching across both resonances.

The design rationale is based on creating two closely spaced resonant modes inside the Ku-band by carefully controlling the effective current paths using the notch and the shorting pin.

The incorporation of these elements enables the antenna to maintain a compact structure without compromising impedance performance. To achieve the optimal configuration, extensive parametric sweeps in HFSS were carried out for critical parameters including notch length, feed position, and shorting-pin location. These optimizations ensured significant improvement in return loss, VSWR, and overall radiation performance across both targeted bands.

3. Results and Discussion

The performance evaluation of both the reference antenna and the proposed design has been carried out using HFSS electromagnetic simulation software, which is widely adopted for accurate analysis of high-frequency antennas. The analysis covers the most critical antenna performance parameters, including return loss (S11), voltage standing wave ratio (VSWR), gain, radiation efficiency, and radiation patterns. The obtained results validate the effectiveness of the proposed compact patch antenna with notch and shorting pin in comparison to the reference design.

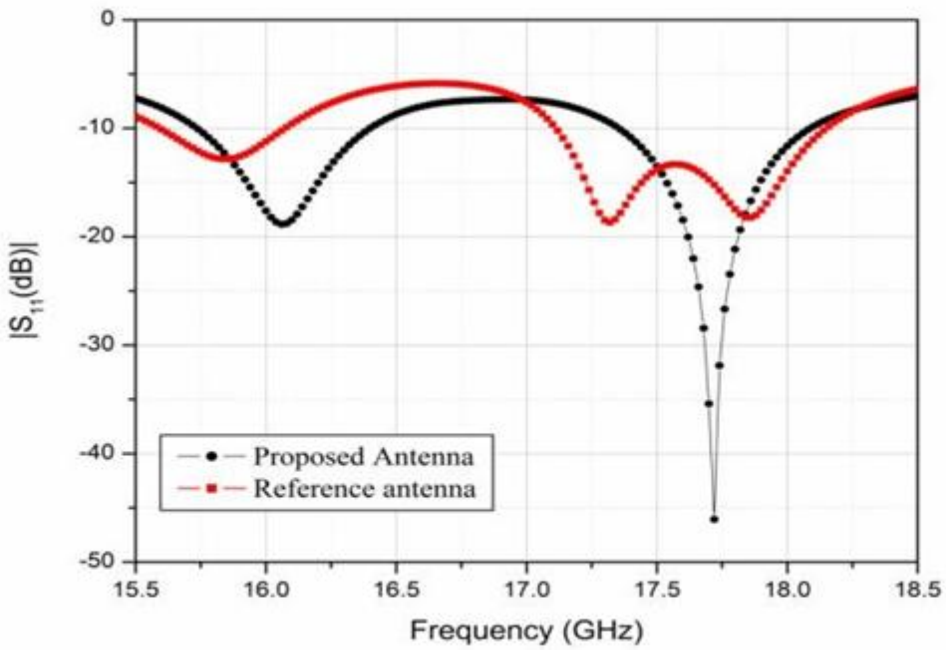

Fig. 2: Simulated return loss (S11) in dB versus frequency (GHz), illustrating the resonant behavior and operating bands of the proposed antenna.

The simulated return loss characteristics of the reference and proposed antennas are illustrated in Figure 2. For the reference antenna, two operating bands are identified: 15.59–16.06 GHz, resonating at 15.84 GHz with a return loss of –12.8 dB, and 17.11–18.15 GHz, exhibiting dual resonances at 17.32 GHz (–18.68 dB) and 17.85 GHz (–18.24 dB). These values reflect moderate impedance matching, but the overall performance remains limited. In contrast, the proposed antenna achieves enhanced impedance characteristics with two well-defined bands of 15.73–16.40 GHz and 17.73–18.10 GHz, resonating at 16.05 GHz (–18.86 dB) and 17.71 GHz (–46 dB), respectively. The significantly deeper resonance of –46 dB indicates excellent impedance matching, leading to minimal reflection, superior power transfer, and highly efficient operation. This demonstrates that the incorporation of the notch and shorting pin effectively improves the impedance response compared to the reference design.

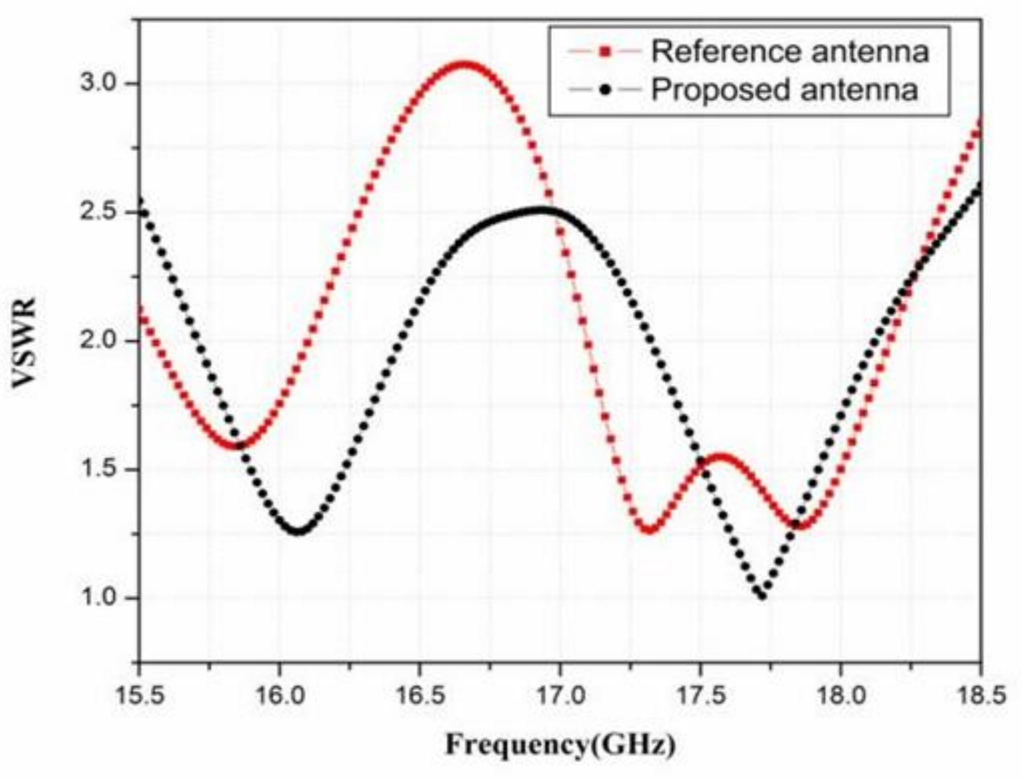

Fig. 3: Simulated Voltage Standing Wave Ratio (VSWR) as a function of frequency (GHz), demonstrating impedance matching and operating bands of the proposed antenna.

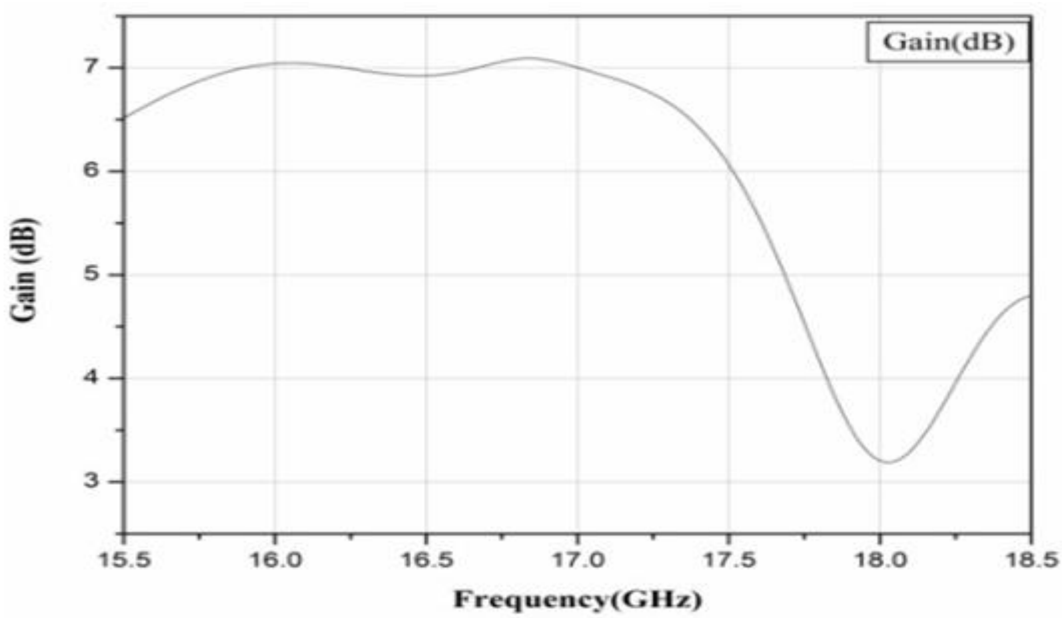

Fig. 4: Simulated gain variation with respect to frequency (GHz), highlighting the peak gain and stable radiation performance of the proposed antenna.

The corresponding VSWR analysis, presented in Figure 3, further validates the return loss results. The proposed antenna maintains VSWR values consistently below 2 across both operating bands, satisfying the standard requirement for efficient antenna systems. Specifically, VSWR values of 1.4 at 16.05 GHz and 1.2 at 17.71 GHz confirm near-ideal impedance matching with the feed line. In comparison, the reference antenna exhibits relatively higher VSWR values, thereby reinforcing the advantage of the proposed modifications. The inclusion of the notch and shorting pin proves instrumental in fine-tuning the input impedance, ultimately leading to superior performance.

The gain response of the proposed antenna is depicted in Figure 4**.** The antenna exhibits peak gains of 7.04 dB at 16.05 GHz and 4.80 dB at 17.71 GHz, while maintaining positive gain across both operational bands. Notably, the gain remains nearly constant within the frequency range of 16.0–17.0 GHz, ensuring stable and reliable performance over a 1 GHz bandwidth. Such gain characteristics are particularly remarkable for a compact FR-4–based structure, since most comparable Ku-band antenna designs reported in the literature typically achieve only 4–6 dB gain [14], [15], [19], [30], [37]. The superior gain performance validates the effectiveness of the proposed antenna for satellite and Ku-band communication applications, highlighting its suitability for practical deployment.

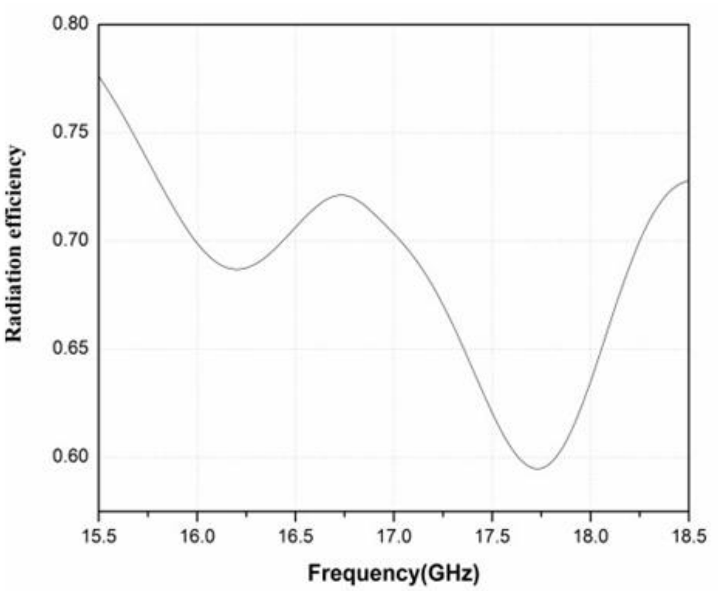

Fig. 4: Simulated gain response of the proposed antenna as a function of frequency (GHz), clearly indicating the resonant bands, maximum gain levels, and overall radiation efficiency.

The simulated radiation efficiency of the proposed antenna, obtained using HFSS, is presented in Figure 5**.** At the resonant frequencies of 16.05 GHz and 17.71 GHz, the antenna achieves efficiencies of 69.40% and 49.47%, respectively. Although the second band exhibits reduced efficiency due to increased dielectric and conductor losses inherent to the FR-4 substrate, both values remain within acceptable limits for practical Ku-band applications. The efficiency approaching 70% in the first band is particularly significant, demonstrating the antenna's ability to effectively mitigate substrate-induced losses despite employing a cost-efficient FR-4 material.

The radiation characteristics are shown in Figures 6 and 7. At 16.04 GHz, the E-plane (Φ = 0°) and H-plane (Φ = 90°) patterns indicate broadside radiation, with the main lobe directed at 0° (boresight) and a minimum at approximately –15 dB at the backside (180°). At 17.71 GHz, the antenna preserves a directional pattern, with maximum fields observed at Φ = 90° (0 dB) and Φ = 0° (0 dB at 350°). The back lobes are well suppressed, with minima around –20 dB (Φ = 0°, 165°) and –23 dB (Φ = 90°, 240°), indicating good front-to-back ratio and desirable directivity for communication links.

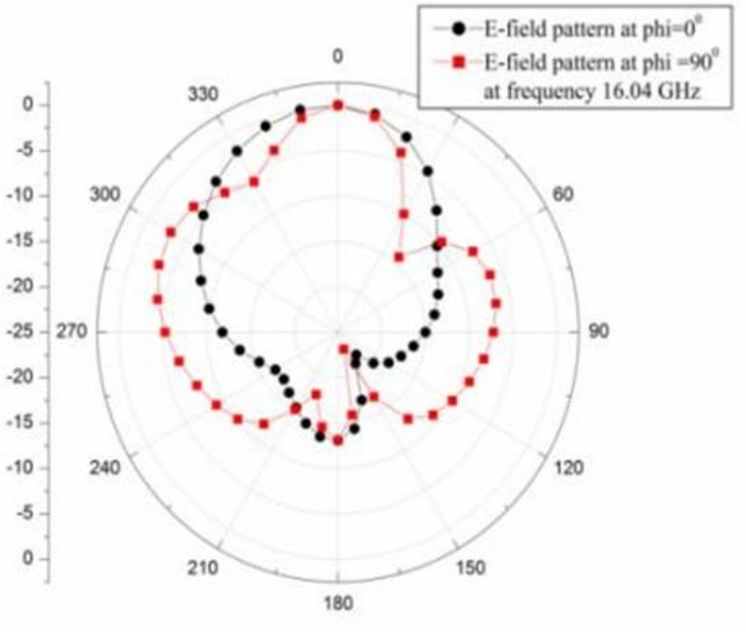

Fig. 6: Simulated radiation patterns of the electric field at 16.04 GHz, illustrating the directional characteristics and field distribution of the proposed antenna.

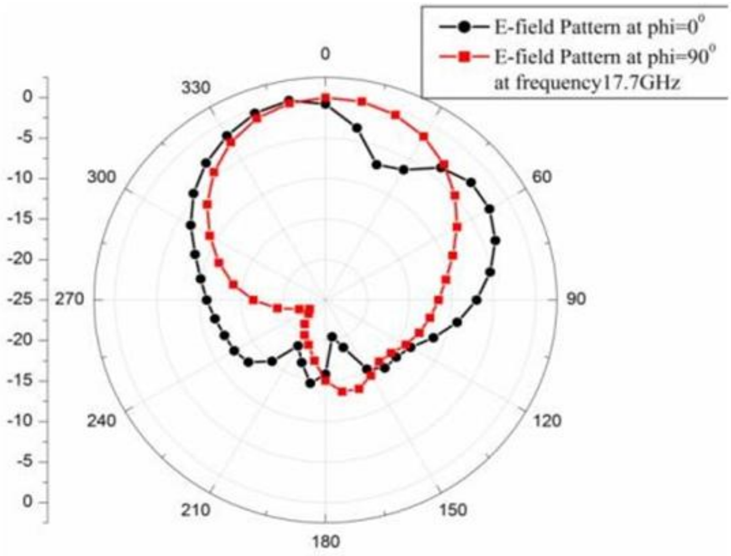

Fig. 7: Simulated radiation patterns of the electric field at 17.7 GHz, highlighting the directional behavior and radiation characteristics of the proposed antenna.

The HFSS-based simulation analysis validates that the proposed antenna successfully achieves dual-band operation with superior return loss, low VSWR, stable positive gain, and satisfactory radiation efficiency. In comparison to the reference antenna, the design exhibits markedly improved impedance matching, enhanced gain performance, and consistent radiation behavior, all while maintaining an extremely compact geometry on a cost-effective FR-4 substrate. These advancements collectively establish the proposed antenna as a highly efficient and practical solution for Ku-band applications, including direct-to-home (DTH) broadcasting, very-small-aperture terminal (VSAT) systems, and aeronautical satellite communication networks.

4. Contribution of the Present Work

A detailed comparison of the proposed antenna with recently reported Ku-band designs is presented here. The majority of existing works occupy relatively larger dimensions. For instance, tri-band and dual-band designs such as [1] (20×18 mm²) and [2] (25×20 mm²) cover wide operating bands of 15–18 GHz and 14–18 GHz, respectively, but at the expense of a footprint ranging from 360–500 mm². Similarly, slot- and DGS-based structures like [14] (18×15 mm²), [16] (20×20 mm²), and [19] (22×18 mm²) achieve bandwidths of 2–3 GHz with peak gains between 4.7–5.8 dB, though they still require moderate to large substrate areas.

Table 1: Comparison of proposed antenna with recent Ku-band designs

Ref	Size (mm²)	Technique Used	Operating Band (GHz)	Bandwidth (GHz)	Return Loss (dB)	Peak Gain (dB)
[1]	20×18	Tri-band patch	15–18	3.0	-25	5.2
[2]	25×20	Dual band elliptical	14–18	4.0	-30	6.0
[14]	18×15	Slot and DGS	15–18	3.0	-32	5.8
[15]	15×12	Notch and slot	15–18	3.0	-40	6.1
[16]	20×20	Wideband slot antenna	14.5–17.5	3.0	-20	5.0
[19]	22×18	U-shaped DGS	15.5–17.5	2.0	-25	4.7
[28]	24×20	Notch and DGS	13.2–15.2	2.0	-22	5.5
[30]	18×15	Slot loaded notch	16–18	2.0	-45	5.0
[34]	30×25	Patch array	14–18	4.0	-20	7.5
[37]	20×18	U-slot patch	12–14 / Ku	2.0	-32.9	6.2
Proposed	12×10	Notch and Shorting Pin	15.7–16.4 17.7–18.1	1.2 0.4	-18.86 -46	7.04 4.80

Compact designs such as [15] (15×12 mm²) and [30] (18×15 mm²) utilize notches and slot-loading to achieve return losses up to –40 dB and –45 dB, respectively, with gains around 5–6 dB. While effective, these designs still occupy 180–270 mm², which is considerably larger than the proposed work. Techniques involving notch and DGS combinations [28] (24×20 mm²) or U-slot patches [37] (20×18 mm²) provide reasonable return loss (–22 to –32.9 dB) and moderate gain (5.5–6.2 dB), but again require areas above 350 mm². Patch array configurations such as [34] (30×25 mm²) offer higher gain (7.5 dB) but at the cost of very large area (750 mm²).

In contrast, the proposed antenna demonstrates a remarkable miniaturization, requiring only 12×10 mm² (120 mm²) the smallest among all compared designs. Despite this extremely compact size, it successfully achieves dual-band operation within the Ku-band, resonating at 16.05 GHz and 17.71 GHz with sharp return losses of –18.86 dB and –46 dB, respectively. Furthermore, the antenna maintains positive gain of 7.04 dB and 4.80 dB across the two operating bands, which is comparable to or even superior to several larger counterparts.

This analysis confirms that the proposed design offers a unique balance of compactness, dual-band operation, and competitive gain, while employing only a simple notch and shorting pin, thereby avoiding the need for complex DGS, EBG, or array structures.

5. Conclusion

A compact rectangular patch antenna incorporating a notch and shorting pin has been designed and optimized for Ku-band applications. The antenna achieves dual-band operation with resonances at 16.05 GHz and 17.71 GHz, exhibiting strong return losses of –18.86 dB and –46 dB, and maintaining VSWR values well below 2. The corresponding peak gains of 7.04 dB and 4.80 dB, along with radiation efficiencies of 69.40% and 49.47%, validate the antenna's suitability for reliable high-frequency communication. Radiation pattern analysis further confirms the broadside and directional characteristics, which are highly desirable for stable satellite communication links. In comparison to conventional reference designs, the proposed structure delivers superior impedance matching, enhanced gain, and significant miniaturization, while relying on a low-cost FR-4 substrate, ensuring practicality and cost-effectiveness.Overall, the results highlight the proposed antenna as a promising candidate for modern Ku-band systems, including VSAT terminals, DTH broadcasting, and aeronautical satellite communication, where compact geometry, efficiency, and consistent performance are critical requirements.

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