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Multilayer Slotted LTCC Antenna for S-Band Applications

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ABSTRACT: This paper presents the design and implementation of a novel S-band antenna utilizing low-temperature co-fired ceramic (LTCC) technology. LTCC enables low losses, efficient radiation performance, and robust packaging. The antenna operates at 2.4 GHz with a size of 40 mm × 26 mm and offers a gain of 5 dB. It features a −10 dB impedance bandwidth of 20 MHz within the frequency range of 2.39 GHz to 2.41 GHz with efficiency of 94%. This design highlights the adaptability of LTCC technology in producing antennas that excel in several application while maintaining a desirable balance of size and efficiency.

1. INTRODUCTION

S-band Low-Temperature Co-fired Ceramic (LTCC) chip antenna is an essential component in modern wireless communication systems [1]. Generally, S-band antenna is in demand for applications requiring compact size, high efficiency, and reliable performance within this frequency range [2]. The use of LTCC technology offers several advantages, including miniaturization, multi-layer integration, and enhanced durability [3]. These characteristics make LTCC chip antennas well suited for integration into a wide range of devices across consumer, industrial, and medical sectors [4–6].

One of the primary applications of the 2.4 GHz LTCC chip antenna is in wireless local area networks (WLANs), particularly in devices operating under the IEEE 802.11b/g/n standards [7]. Such antennas are integral to wireless routers, access points, laptops, and other consumer electronics that require high-performance connectivity in compact form factors [8]. Bluetooth-enabled devices also rely on 2.4 GHz antennas for short-range wireless communication [9]. In addition to consumer applications, LTCC antennas play a significant role in Zigbee-based networks [10]. These networks are commonly employed in smart home and industrial Internet of Things (IoT) systems [11], where low power consumption and reliable short-range communication are essential [12].

Moreover, the antenna's compactness and efficiency are particularly beneficial in wearable technology, such as fitness trackers and smartwatches, where space is at a premium [13]. Similar requirements exist in the industrial IoT (IIoT) sector, where wireless sensor networks (WSNs) utilize these antennas for equipment monitoring and data transmission in factory settings [14]. Beyond the consumer and industrial domains, the medical field has also adopted 2.4 GHz antennas in wireless patient monitoring and telemedicine applications, where reliable telemetry systems are critical [15].

Consequently, it has become the preferred choice for engineers and product designers aiming to optimize both space and functionality in wireless communication systems. In this work, the design and characterization of the 2.4 GHz LTCC antenna are reported. This antenna demonstrates exceptional performance compared to previously reported LTCC antennas operating at the same frequency.

2. ANTENNA DESIGN

The structure of the proposed antenna is depicted in Fig. 1. The design is fabricated using LTCC technology [16], incorporating sixteen layers of DuPont Green Tape 9K7, which has a dielectric constant of $\varepsilon_r = 7.1$ and a low loss tangent of $\delta = 0.0010$. The antenna's structure comprises two substrates (a lower and an upper substrate) and a superstrate, with overall dimensions of 40 mm × 26 mm.

The lower substrate is made of 5 layers, and the upper substrate consists of 10 layers, with each LTCC layer having a thickness of 0.254 mm. The superstrate is a single layer with a thickness of 0.125 mm. The design features three conductive layers: a ground plane, a lower patch, and an upper patch, all fabricated from gold with a thickness of 35 μm, chosen for its high performance and low degradation rate. The structure of proposed antenna design is presented in Fig. 1. Detailed design dimensions are provided in Table 1. The design has been simulated and optimized using the CST Microwave

TABLE 1. Design dimensions.

Dimension	Value	Dimension	Value
a_1	36.87 mm	a_9	1.0 mm
a_2	23.57 mm	a_{10}	5.57 mm
a_3	7.0 mm	a_{11}	3.0 mm
a_4	23.06 mm	a_{12}	3.0 mm
a_5	23.07 mm	a_{13}	2.54 mm
a_6	10.0 mm	a_{14}	1.27 mm
a_7	1.0 mm	a_{15}	0.125 mm
a_8	1.0 mm		

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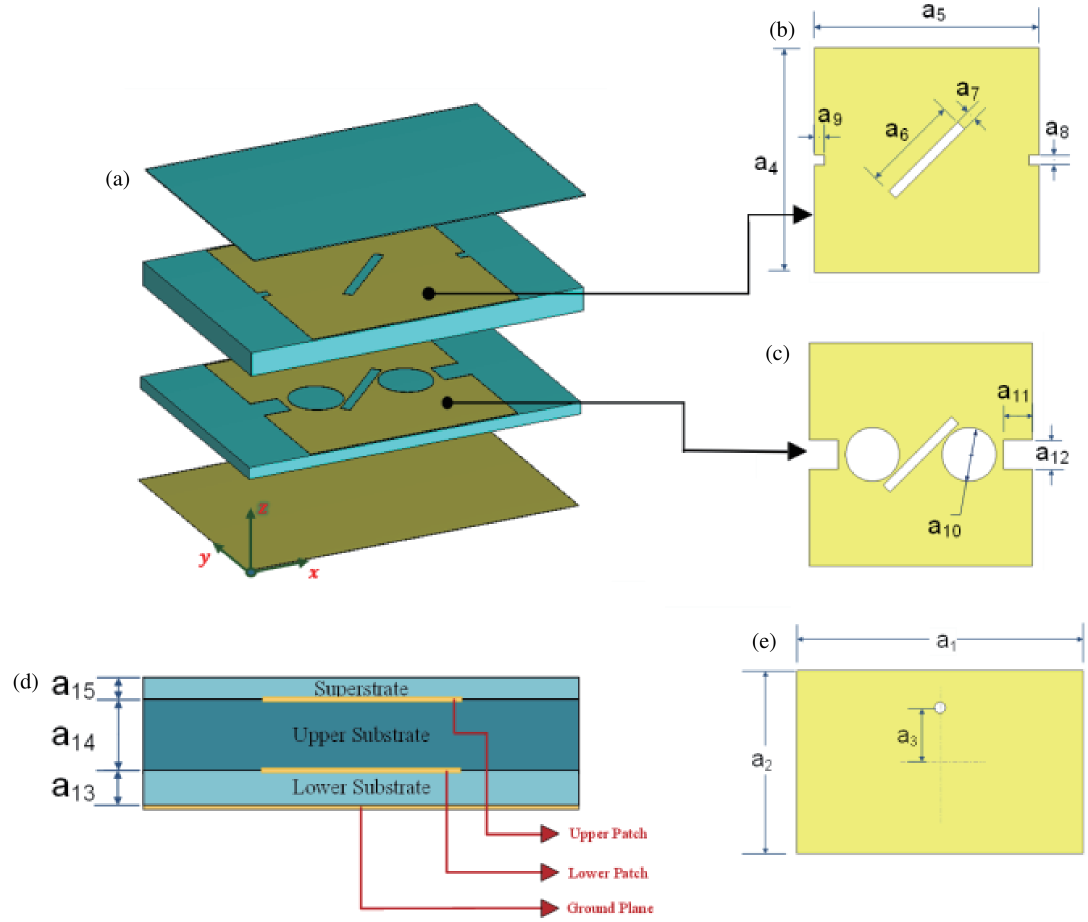

FIGURE 1. Proposed antenna design structure details: (a) 3D assembly view, (b) upper patch, (c) lower patch, (d) side view, and (e) ground plane.

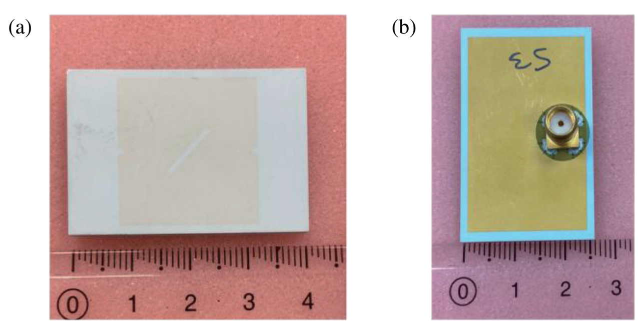

FIGURE 2. Photo of the fabricated prototype: (a) superstate side — frontside. (b) Feeder side — backside.

Studio software package [17]. The multilayer structure is displayed in Fig. 1(a). The feed location is optimized to achieve a 50 Ω input impedance, enhancing impedance matching. Both the upper and lower patches are equipped with diagonal rectangular slots to aid in antenna performance enhancement, as shown in Figs. 1(b) and (c). Additionally, the lower patch features two circular slots on either side of the diagonal rectangular slots to further reduce the antenna size. Square notches have also been introduced in both the upper and lower patches to improve impedance matching, as illustrated in Figs. 1(b) and (c). The side view of antenna structures and ground plane layer are presented in Figs. 1(d) and (e), respectively. Fig. 1 shows the ground metallization covering the entire area beneath the substrate. However, in the fabricated prototype, the substrate is made larger than the ground metallization to accommodate the dicing (singulation) process. The ground plate dimensions listed in Table 1 are based on the generated layout. Furthermore, the LTCC fabrication process may cause shrinkage, leading to variations in the metallization dimensions, resulting in either slightly larger or smaller sizes. Fig. 2 shows photos of the fabricated prototype along with a ruler indicating the final device dimensions: the front view of the substrate side and the back view of the feeder side.

3. MEASUREMENTS AND ANALYSIS

3.1. S_{11} Measurements

The performance of the fabricated prototype was characterized in the UAEU RF laboratory. The reflection coefficient (S_{11}) was measured using a Rohde & Schwarz R&S ZVL vector network analyzer. The simulated model resonates at 2.403 GHz with a -10-dB impedance bandwidth of $\sim$ 20 MHz (2.39–2.41 GHz), as shown in Fig. 3.

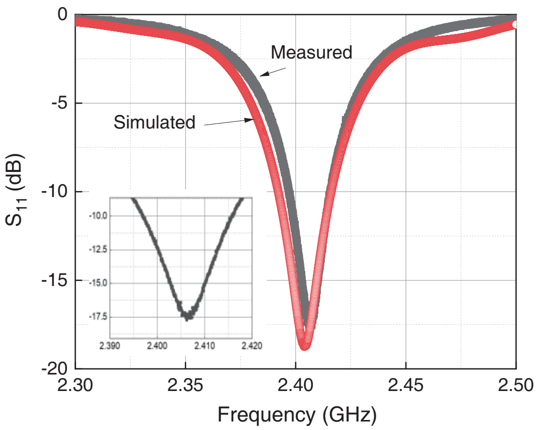

FIGURE 3. Measured and simulated S_{11} for the fabricated antenna, with a magnified view of the measured resonance shown in the inset.

The fabricated model exhibits good impedance matching, with a reflection coefficient of -17 dB around 2.40 GHz indicating that approximately 0.02% of the incident power is reflected back to the source, while the most is radiated or absorbed by the antenna. As shown in Fig. 3, the -10-dB measured bandwidth ranges from 2.39 GHz to 2.41 GHz, providing a bandwidth of $\sim$ 20 MHz. Fig. 3 also includes a magnified view of the measured resonance, as depicted in the inset. It demonstrates that within these frequency ranges, the return loss is less than -10 dB, indicating good antenna performance and acceptable matching.

Figure 4 summarizes the evolution of the antenna design, starting with the initial configuration without any slots. The corresponding performance is depicted in Fig. 4(a), where the structure exhibits poor impedance matching and lacks strong resonance at the desired frequency. To improve impedance matching, a diagonal rectangular slot tilted at an angle of 45° was introduced at the center of the upper and lower patches. As shown in Fig. 4(b), this modification enhanced the impedance matching; however, a secondary undesired resonance appeared around 2.1 GHz. To suppress this undesired resonance, two rectangular notches were added at the ends of the central axis in the upper and lower patches. The resulting performance, shown in Fig. 4(c), confirms good matching around 2.4 GHz and attenuation of the undesired resonance. Finally, two circular slots were introduced on the lower patch to further refine the design and successfully eliminate the undesired resonance, as demonstrated in Fig. 4(d). The size and orientation of each inserted slot were determined through extensive parametric studies to achieve the desired resonance response in the antenna design.

3.2. Radiation Patterns

The gain and radiation pattern for fabricated prototype were measured in RF laboratory using Rohde and Schwarz R&S ZVL VNA vector network analyzer along with a WR-430 standard gain horn antenna from Fairview Microwave (FMWAN430-10SF) as shown in Fig. 5.

The Antenna Measurement Studio package from Diamond Engineering was utilized for data acquisition and measurement recording. Fig. 6 shows the simulated radiation pattern for the proposed antenna using CST package. The antenna has a measured realized gain of 5 dBi at 2.4 GHz. The measured co-polarized and cross-polarized gains in Z-X plane, Z-Y plane, and X-Y plane of radiation patterns are shown in Figs. 6(a), (b), and (c), respectively. The maximum gain takes place at $\theta = 0°$, and the antenna has a broader radiation pattern with beamwidth of 95° ($\theta = -325°$ to $\theta = 60°$ in Z-Y plane and has a beamwidth of around 130° (from $\theta = -300°$ to $\theta = 70°$ in Z-X plane. The radiation beam has the least radiation gain at $\theta = 100°$ and $\theta = 290°$ which represent radiation nulls in co-polarized Z-Y plane.

The tilt in the radiation patterns shown in Figs. 6(a) and 6(b), despite the antenna's symmetry, arises from fabrication-related factors inherent to LTCC technology. Misalignments during the lamination and sintering processes, along with thermal-induced shrinkage and deformation, disrupt the intended symmetry. These fabrication effects also account for the discrepancies between simulated and measured S-parameters, as variations in dimensions and metallization properties deviate from the ideal simulated model.

4. BENCHMARKING

Interestingly, only a few LTCC antennas have been fabricated and characterized for the 2.4 GHz band. Taoglas' antenna offers a compact, low-profile design with dimensions of $1.6 \times 0.8 \times 0.4\,\text{mm}^3$ and a peak gain of 0.5 dBi with 60% efficiency [18]. Taoglas' antenna exhibits linear polarization and omni-radiation characteristics. In the second study, Dakeya et al. reported a 2.45 GHz antenna with dimensions of $2 \times 2 \times 9.5\,\text{mm}^3$, achieving a gain of -3 dB [19]. This performance was attained by optimizing the mounting conditions on the ground plane, while exhibiting radiation characteristics comparable to those of a dipole antenna. The third work, reported by the Ciais' group from LETI, presents an antenna with dimensions of $2 \times 8 \times 0.5\,\text{mm}^3$ operating at 2.47 GHz [20]. It achieves a minimum radiated efficiency of 50% across this bandwidth, a maximum gain of 0.51 dBi, and features a quasi-omnidirectional radiation pattern. Another antenna was reported by Tang and operates at 2.4 GHz with dimensions of $6 \times 3.8 \times 1.5\,\text{mm}^3$, achieving a gain of approximately 1.3 dBi and exhibiting well-defined omnidirectional radiation patterns [21]. Moreover, Molins-Benlliure et al. reported a miniaturized 2.4 GHz IoT LTCC chip antenna designed for on-ground applications [22]. Positioned on a ground plane, the antenna, measuring $9.3 \times 7 \times 2.45\,\text{mm}^3$, demonstrates a bandwidth with an S_{11} value below -6 dB. Kuang et al. reported a novel antenna-in-package design featuring a double fractal patch structure based on LTCC technology for 2.4 GHz applications [23]. The antenna, with overall dimensions of $43 \times 43\,\text{mm}^2$ including the ground plane, was fabricated using a double air cavity LTCC technique.

The current antenna design demonstrates exceptional performance, particularly in terms of peak gain of 5 dB and an average of 4.7 dB, impedance matching, and bandwidth. In summary, our fabricated design achieved a balance between a compact size and reduced cost by eliminating the air cavity in the manufacturing process.

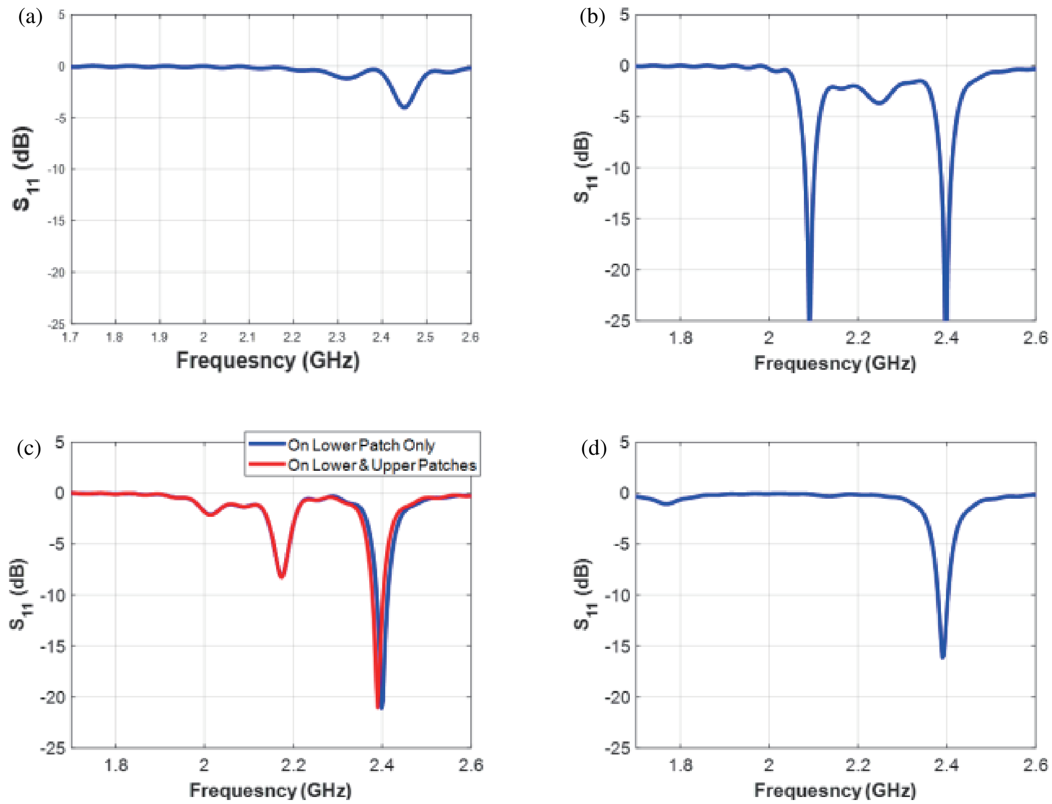

FIGURE 4. Antenna evolution: (a) without slots, (b) with a diagonal slot, (c) with diagonal and rectangular slots, (d) with diagonal, circular, and rectangular slots combined.

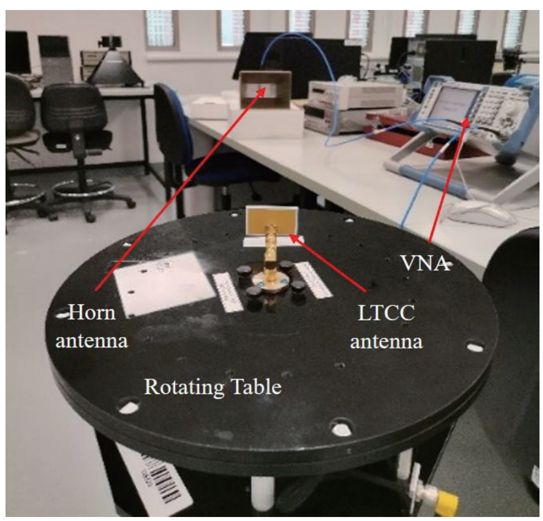

FIGURE 5. Far-field radiation pattern measurements setup.

By utilizing LTCC technology, the antenna benefits from miniaturization, multi-layer integration, and enhanced durability, providing a significant advantage over previously reported designs. Its size, high efficiency, and reliable performance makes it a valuable solution for various applications, including WLANs, Bluetooth-enabled devices, Zigbee networks, wearable technologies, and industrial IoT systems. Furthermore, the successful fabrication and testing of this antenna validate its suitability for a broad range of consumer, industrial, and medical applications. In comparison to other LTCC antennas within the 2.4 GHz band, the proposed design exhibits superior performance, particularly in terms of realized gain and radiation characteristics, highlighting its potential for widespread use in wireless communication systems. The extracted efficiency of this antenna from the measurements is 94%. The antenna efficiency was estimated by calculating the ratio of the maximum measured gain to the average gain at the resonance frequency.

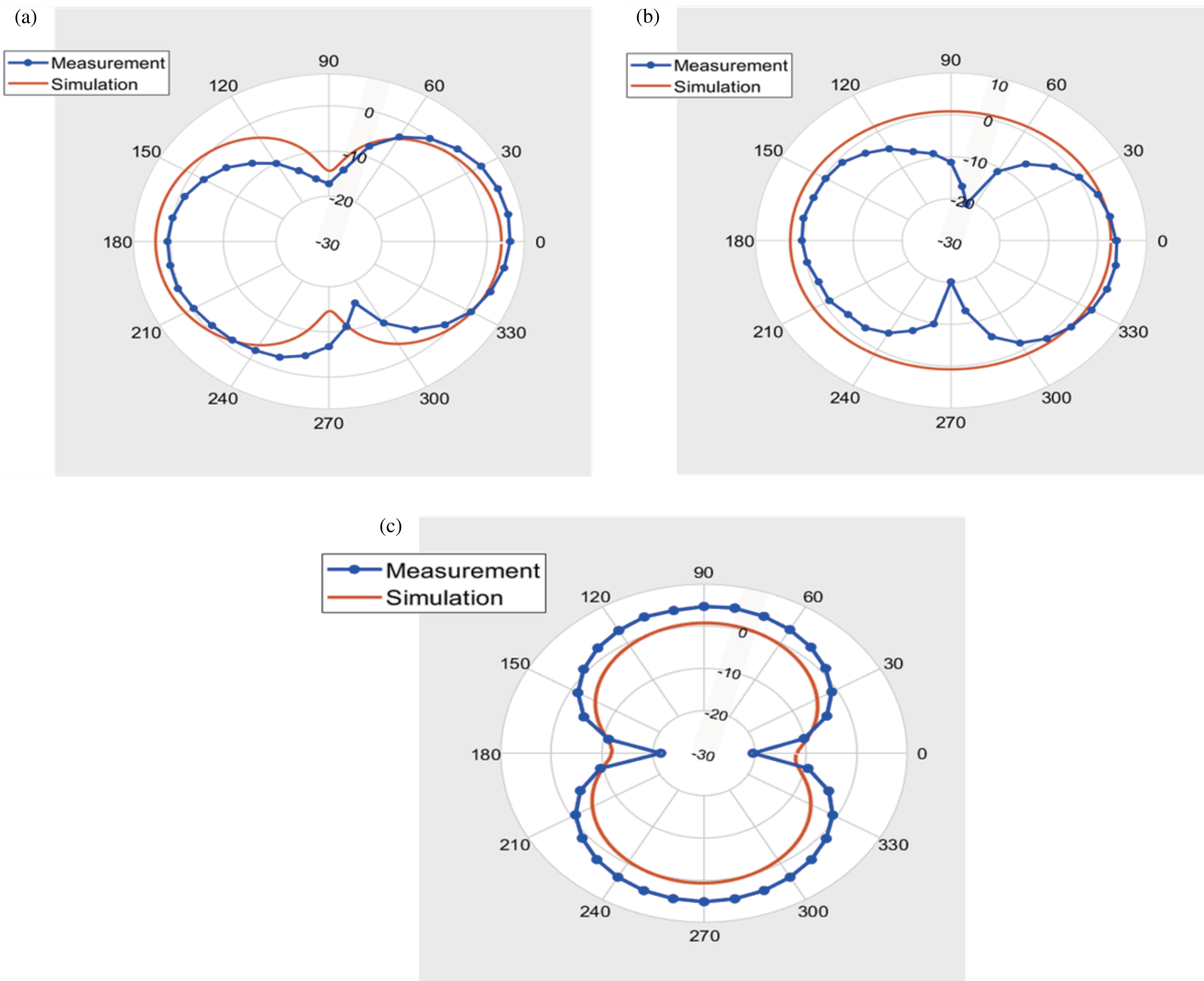

FIGURE 6. Simulated and measured radiation patterns for antenna design1: (a) Z-X plane ($\phi = 0°$), (b) Z-Y plane ($\phi = 90°$) and (c) X-Y plane.

5. CONCLUSIONS

This paper details the design of a optimal S-band antenna for several applications utilizing Low Temperature Co-fired Ceramic (LTCC) technology, which achieves an optimal balance between size and efficiency. The antenna's performance was comprehensively evaluated, with key parameters such as return loss, far-field radiation patterns, and gain thoroughly characterized. Compared to existing designs in the literature, the proposed antenna demonstrates higher gain and superior overall performance.

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