

A Bandwidth- and Gain-Enhanced Microstrip Patch Antenna Using TM_{30} -Like Mode and $\lambda_g/4$ Resonator Feeding

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Abstract—This paper presents a bandwidth- and gain-enhanced microstrip patch antenna operating at 3.5 GHz for 5G applications. The proposed design integrates a $\lambda_g/4$ resonator-based feeding structure with TM_{30} -like mode operation, enabling a dual-resonance mechanism that improves impedance bandwidth without increasing structural complexity. This approach provides a simple single-layer solution for achieving high gain and low sidelobe levels. Simulated results show a bandwidth of 4.0% (3.41–3.55 GHz) and a peak realized gain of 12.8 dBi at 3.52 GHz. Reflection-coefficient measurements confirm the impedance behavior, yielding a bandwidth of 3.7% (3.41–3.54 GHz).

Keywords—5G communications, Bandwidth enhancement, Gain enhancement, Microstrip patch antenna, TM_{30} mode.

I. INTRODUCTION

Transmission system optimization is a key enabler for meeting the increasing demands of next-generation wireless communications, particularly in 5G networks [1], [2]. In this context, advancements in RF and microwave components are essential to enhance data rates and channel capacity, with antennas playing a central role [3], [4].

Among the available antenna technologies, microstrip patch antennas (MPAs) are particularly attractive for sub-6 GHz 5G applications due to their low profile, lightweight structure, low fabrication cost, and compatibility with planar and integrated circuits. These features make them well suited for compact and conformal platforms in modern wireless systems [5], [6]. However, conventional MPAs exhibit inherent performance limitations. In their classical configurations, they typically provide narrow impedance bandwidth (BW), on the order of 1% to 3% of the resonant frequency (f_0), due to their high quality factor (Q) [5]. In addition, their realized gain is inherently limited, as it is constrained by the electrically small effective radiating aperture associated with fundamental-mode operation.

To overcome these limitations, several techniques have been proposed, focusing on bandwidth enhancement [7], gain improvement [8], or the simultaneous optimization of both

parameters [9], [10]. Methods such as aperture coupling [11], proximity coupling [12], and multilayer configurations [13] provide significant bandwidth improvement, but at the cost of increased structural complexity and fabrication effort.

Alternatively, single-layer feeding techniques based on dual-resonance mechanisms have attracted considerable attention [14]. By introducing an additional resonance coupled to the patch mode, these approaches enable bandwidth enhancement without requiring multilayer structures. For instance, the $\lambda_g/4$ resonator-based feeding technique in [14] achieved a 2.7-fold bandwidth improvement compared to a conventional design, while maintaining stable radiation characteristics.

On the other hand, gain enhancement in MPAs can be achieved through higher-order mode operation, which increases the effective radiating aperture. However, this approach typically leads to high sidelobe levels (SLL), limiting its applicability in directive radiation systems. To address this issue, techniques such as current perturbation, slot loading, and parasitic elements have been investigated [15], [16]. In [16], a combination of central slits, slots, and parasitic patches enabled SLL reduction from -3 dB to -28 dB while achieving a gain of 11.7 dBi. Nevertheless, the design exhibits narrow bandwidth, which limits its use in sub-6 GHz 5G bands.

Achieving simultaneous bandwidth enhancement and high gain in single-layer MPAs, particularly under higher-order mode operation, remains a challenging problem. To address this issue, this work proposes a 3.5 GHz MPA based on TM_{30} -like mode excitation combined with a $\lambda_g/4$ resonator-based feeding structure, enabling a dual-resonance mechanism that enhances bandwidth while preserving high gain and low sidelobe levels in a simple configuration. The proposed antenna achieves a simulated bandwidth of 4.0% (3.41–3.55 GHz) and a peak realized gain of 12.8 dBi at 3.52 GHz, with sidelobe levels below -20 dB. Experimental results show good agreement, with a measured bandwidth of 3.7% (3.41–3.54 GHz), confirming the predicted impedance behavior.

For completeness, the remainder of this paper is organized as follows. Section II describes the antenna geometry and operating principle. Section III presents the experimental results and discussion. Finally, Section IV concludes the paper.

II. DESIGN AND ANALYSIS

A. Design Geometry

The evolution of the proposed MPA is illustrated in Fig. 1, with the corresponding optimized dimensions provided in the

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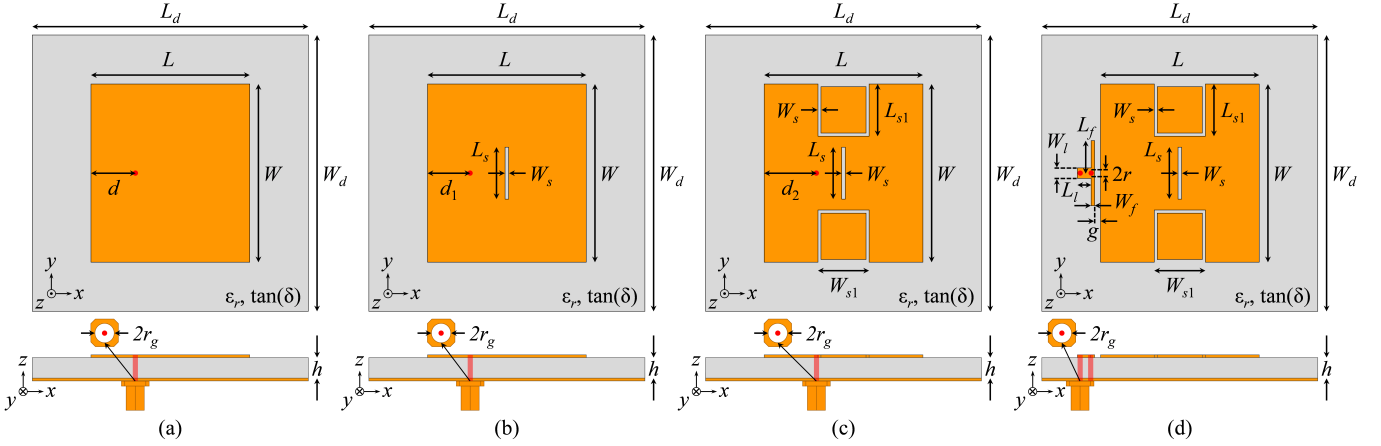


Fig. 1: Configuration of the proposed microstrip patch antenna. Dimensions (in mm): $L = 75.4$, $W = 84.6$, $L_d = 130$, $W_d = 130$, $L_s = 25$, $W_s = 1$, $L_{s1} = 24.4$, $W_{s1} = 24.2$, $d = 21.2$, $d_1 = 20.2$, $d_2 = 24.7$, $L_f = 15.4$, $W_f = 1$, $L_l = 7.3$, $W_l = 4$, $g = 1.5$, $r = 0.6$, and $r_g = 2$. (a) Antenna 1. (b) Antenna 2. (c) Antenna 3. (d) Antenna 4.

caption. All configurations are centered at $(0,0)$ in the xy -plane and were designed using the finite element method in Ansys Electronics Desktop. A $50\ \Omega$ coaxial probe feed is employed in all cases, resulting in linear polarization. The antenna is implemented on an RT/duroid 5880 substrate, characterized by a relative permittivity of $\epsilon_r = 2.20 \pm 0.02$, loss tangent $\tan(\delta) = 0.0009$, and thickness $h = 1.575$ mm.

Antenna 1 (Fig. 1(a)) consists of a rectangular patch of dimensions $L \times W$ printed on a ground plane of size $L_d \times W_d$. Antenna 2 (Fig. 1(b)) introduces a central slot ($L_s \times W_s$), which perturbs the surface current distribution. Antenna 3 (Fig. 1(c)), adapted from [16] for operation at 3.5 GHz, incorporates two symmetric edge slots ($L_{s1} \times W_{s1}$) and parasitic patches separated by W_s , enabling additional current control and radiation shaping.

The feed locations, defined by distances d , d_1 , and d_2 from the patch center, are selected to ensure proper impedance matching [5]. The radius of the ground-plane hole for the SMA connector is set to $r_g = 2$ mm, providing a suitable balance between inductive and capacitive effects and improving matching around the operating frequency.

Antenna 4 (Fig. 1(d)) extends Antenna 3 by incorporating a $\lambda_g/4$ resonator-based feeding network. The resonator pair is positioned along the feedline in proximity to the patch, enabling capacitive coupling through an optimized gap g and introducing an additional degree of freedom for impedance and bandwidth control.

B. Working principle

Antenna 1 is a rectangular MPA operating in a higher-order TM_{30} mode, characterized by three half-wavelength variations of the surface current density J along the patch, as illustrated in Fig. 2(a). This configuration provides high gain due to the increased electrical aperture, but also produces pronounced sidelobes in the xz -plane because of the out-of-phase current region at the center of the patch. The corresponding reflection coefficient, realized gain, and radiation patterns are presented in Fig. 3. The antenna exhibits a narrow bandwidth of 1.3%

(3.88–3.93 GHz), a peak realized gain of $G_R = 11.6$ dBi, and sidelobe levels of approximately -3.0 dB in the xz -plane, while sidelobes in the yz -plane remain negligible due to the nearly uniform current distribution along this plane.

Antenna 2 introduces a central slot, resulting in a TM_{30} -like mode. As reported in [16], the slot introduces a capacitive loading effect that shifts the resonance frequency downward to $f_0 = 3.59$ GHz. From a physical standpoint, the slot perturbs the central current half-cycle, which is originally out of phase, enforcing a more symmetric current distribution with respect to the y -axis, as shown by the surface current density in Fig. 2(b). This reduces the contribution of out-of-phase currents to radiation, leading to partial sidelobe cancellation. The corresponding reflection coefficient, realized gain, and radiation patterns are presented in Fig. 3. As a result, the antenna achieves improved radiation performance, with a peak realized gain of $G_R = 12.2$ dBi, sidelobe levels of approximately -10.0 dB in the xz -plane, and a bandwidth of 1.1% (3.57–3.61 GHz), while maintaining negligible sidelobes in the yz -plane.

Antenna 3 further enhances this mechanism by introducing symmetric edge slots and embedded parasitic patches. The slots suppress out-of-phase current components, whereas the parasitic elements support in-phase currents that reinforce broadside radiation, as illustrated by the surface current distribution in Fig. 2(c). This combined effect leads to a significant reduction in sidelobe levels while preserving high gain. The corresponding reflection coefficient, realized gain, and radiation patterns are presented in Fig. 3. For the optimized design, the antenna resonates at 3.51 GHz, achieving a peak realized gain of $G_R = 12.9$ dBi, sidelobe levels of approximately -20.8 dB in the xz -plane, and an increased bandwidth of 2% (3.47–3.54 GHz).

Antenna 4 extends this concept by incorporating a $\lambda_g/4$ resonator-based feeding structure, adapted from [14] to excite a TM_{30} -like mode. The feeding network consists of a microstrip line coupled to a pair of non-radiating resonators through a capacitive gap g , while a short-circuit pin introduces

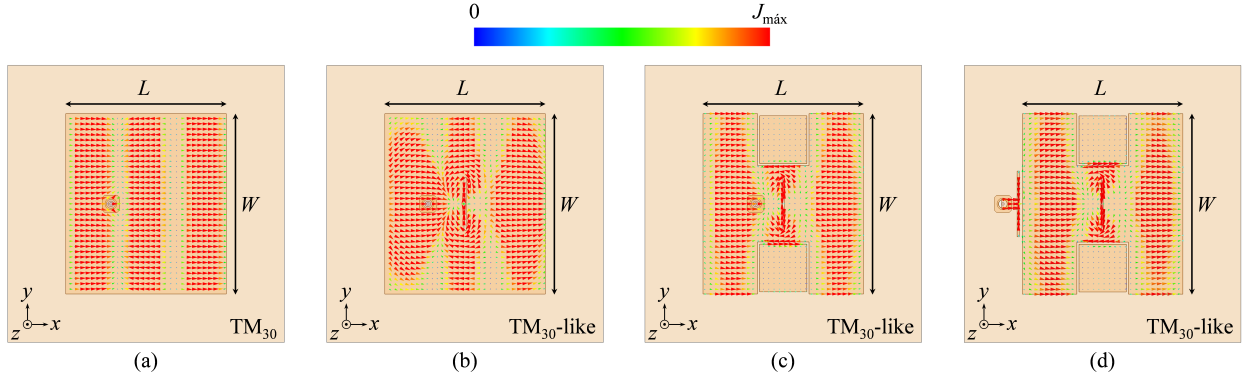


Fig. 2: Surface current density distribution of the proposed microstrip patch antenna. (a) Antenna 1 at $f_0 = 3.9$ GHz. (b) Antenna 2 at $f_0 = 3.59$ GHz. (c) Antenna 3 at $f_0 = 3.51$ GHz. (d) Antenna 4 at $f_0 = 3.52$ GHz.

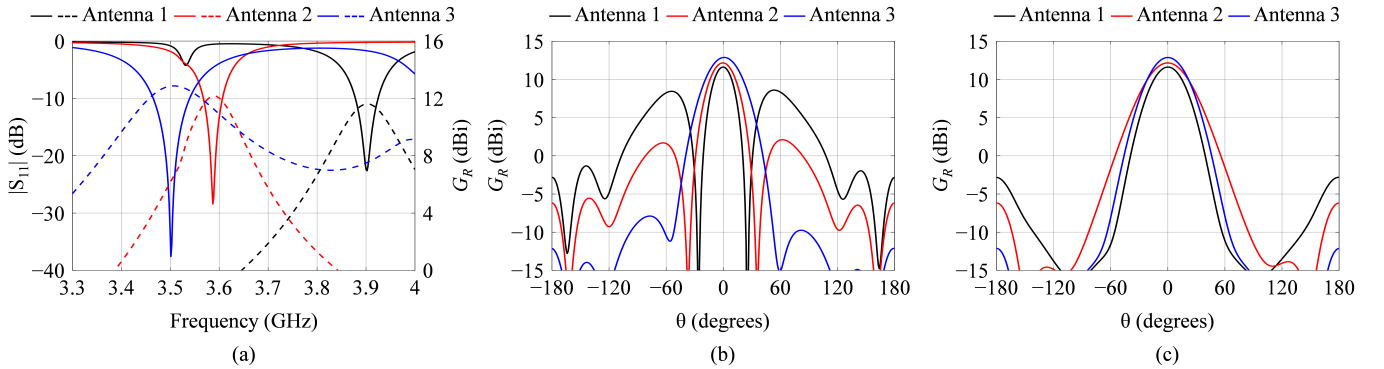


Fig. 3: Performance of Antennas 1–3. (a) Reflection coefficient and realized gain versus frequency. (b) Realized gain radiation patterns in the xz -plane. (c) Realized gain radiation patterns in the yz -plane.

inductive loading. This configuration enables controlled electromagnetic coupling between the resonators and the patch without modifying the radiating structure.

The operating principle is based on the introduction of a second resonance through the feeding structure. When this additional resonance is properly tuned close to that of the patch, their interaction produces a dual-resonance response, leading to bandwidth enhancement. This mechanism can be interpreted as an integrated bandpass filtering effect, in which the resonators shape the impedance response of the antenna.

The design procedure involves three main steps: (i) estimation of the resonator length L_f using the $\lambda_g/4$ condition for the target frequency, (ii) optimization of the resonator–patch spacing g to control the coupling level and the separation between resonances, and (iii) adjustment of the microstrip line length L_l to improve impedance matching and excitation. The parametric analyses shown in Fig. 4 summarize the influence of these parameters on the reflection coefficient. As shown in Fig. 4(a), increasing L_f shifts both resonances toward lower frequencies, confirming its dominant role in resonance positioning. Fig. 4(b) shows that the spacing g directly controls the coupling strength between the resonators and the patch, thereby affecting the resonance separation and the achievable bandwidth. Finally, Fig. 4(c) indicates that variations in L_l mainly influence impedance matching and the relative balance

between the two resonances.

The current distribution of Antenna 4, shown in Fig. 2(d), confirms that the TM_{30} -like modal behavior is preserved after introducing the resonator-based feeding structure. This indicates that the proposed feeding network enhances bandwidth without significantly perturbing the original current distribution of Antenna 3.

III. RESULTS AND DISCUSSIONS

To validate the bandwidth performance of the proposed MPA, a prototype was fabricated and experimentally characterized. The antenna geometry was defined using a PCB-Proto 1S prototyping machine, followed by chemical etching with ferric chloride to remove excess copper. Photographs of the fabricated prototype are presented in Figs. 5(a) and 5(b).

A. S-Parameters and Radiation Performance

Fig. 6(a) shows the simulated reflection coefficient and realized gain of the proposed MPA. The antenna operates from 3.41 to 3.55 GHz for $|S_{11}| \leq -10$ dB, corresponding to a fractional bandwidth of 4.0%. Within this range, the realized gain varies from 11.1 to 12.8 dBi, with a peak at $f_0 = 3.52$ GHz.

The reflection coefficient was measured using a Tektronix TTR506A vector network analyzer, resulting in a bandwidth

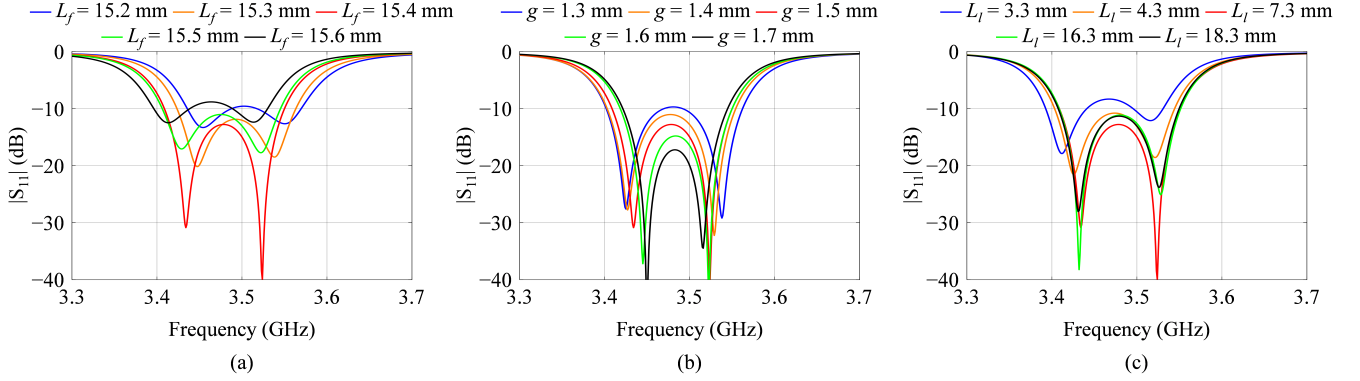


Fig. 4: Effect of the feeding parameters of Antenna 4 on the reflection coefficient. (a) Non-radiating resonator length (L_f). (b) Resonator-patch spacing (g). (c) Microstrip line length (L_l).

of 3.7% (3.41–3.54 GHz). The measured results are in good agreement with simulations, with minor deviations attributed to fabrication tolerances and uncertainties in substrate parameters.

Compared to Antenna 3, the proposed design achieves approximately a twofold increase in simulated bandwidth due to the $\lambda_g/4$ resonator-based feeding structure, with only a slight gain reduction of about 0.1 dB due to the insertion loss introduced by the feeding structure. Relative to [16], the prototype provides nearly a threefold bandwidth enhancement (3.7% versus 1.3%).

Figs. 6(b)–(d) show the simulated radiation patterns at 3.41, 3.52, and 3.55 GHz. Since far-field measurements were not available during characterization, only the reflection coefficient was measured. Simulations indicate stable radiation performance across the operating band, with gains of 11.1 dBi at 3.41 GHz, 12.8 dBi at 3.52 GHz, and 12.3 dBi at 3.55 GHz. The sidelobe level is approximately -20.6 dB in the xz -plane, while sidelobes are negligible in the yz -plane. These results demonstrate that the proposed antenna provides high gain and low sidelobe levels throughout the operating bandwidth.

B. Comparative Study

To further evaluate the proposed antenna, Table I compares its bandwidth, realized gain, and normalized gain-to-area ratio (G_R/A) with representative bandwidth- and gain-enhanced microstrip patch antennas reported in the literature.

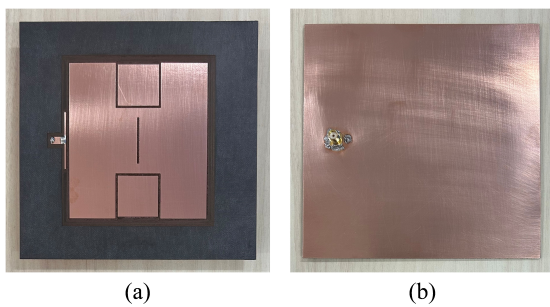


Fig. 5: Fabricated prototype of Antenna 4. (a) Top view. (b) Bottom view.

The design in [9] employs dual higher-order radiative modes (TM_{30}/TM_{50}) to obtain bandwidth enhancement through dual-mode resonance, achieving a bandwidth of 6.1% and a realized gain of 10.7 dBi. The compact antenna in [17] uses modal control techniques to excite a TM_{03} -like mode, resulting in an 8.5% bandwidth and a gain of 10.5 dBi. In [18], a mushroom-type parasitic structure is employed to generate a quasi- TM_{30} mode, achieving a wide bandwidth of approximately 40% with stable gain around 10.5 dBi. However, the design relies on metamaterial-inspired parasitic structures for bandwidth enhancement. Finally, the SIW-fed antenna in [19] achieves a 22% bandwidth but requires a multilayer filtering structure and a complex feeding network.

In contrast, the proposed antenna achieves the highest realized gain among the compared designs, reaching 12.8 dBi while maintaining a simple single-layer configuration and low sidelobe levels. In addition, the proposed design exhibits the highest normalized gain-to-area ratio, with $G_R/A = 8.2/\lambda_0^2$, demonstrating an efficient use of the physical aperture for gain enhancement. Although the achieved bandwidth (4.0%) is lower than that of strongly coupled or multilayer multi-resonant structures, the proposed antenna still provides a significant bandwidth improvement over conventional high-gain higher-order patch antennas without increasing structural complexity.

Therefore, the proposed approach offers an attractive trade-off between bandwidth, gain, aperture utilization, sidelobe suppression, and implementation simplicity, making it particularly suitable for compact high-gain sub-6 GHz applications.

TABLE I: Comparison with representative bandwidth- and gain-enhanced microstrip patch antennas.

Reference	f_0 (GHz)	A (λ_0^2)	BW (%)	G_R (dBi)	G_R/A ($1/\lambda_0^2$)
[9]	5.65	1.74	6.1	10.7	6.8
[17]	5.8	1.70	8.5	10.5	6.6
[18]	15.0	1.60	40.0	10.5	7.0
[19]	4.36	2.11	22.0	11.9	7.3
This work	3.52	2.33	4.0	12.8	8.2

A is the overall antenna area $L_d \times W_d$ normalized to λ_0^2 , and G_R is taken in linear scale in the G_R/A ratio, where λ_0 is the free-space wavelength at f_0 .

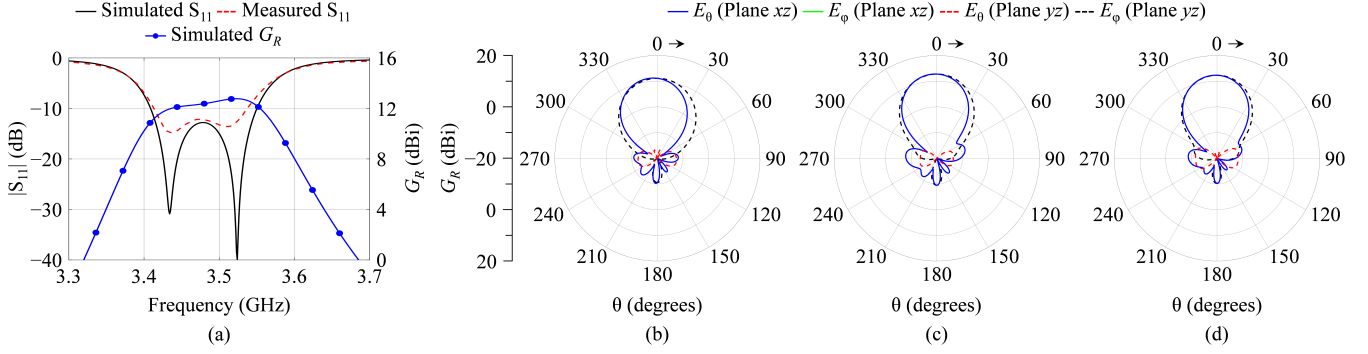


Fig. 6: Performance of Antenna 4. (a) Simulated and measured reflection coefficient, and simulated realized gain versus frequency. (b) Radiation patterns at 3.41 GHz. (c) Radiation patterns at $f_0 = 3.52$ GHz. (d) Radiation patterns at 3.55 GHz.

IV. CONCLUSIONS

This work presented a bandwidth- and gain-enhanced microstrip patch antenna operating at 3.5 GHz for sub-6 GHz 5G applications. The proposed approach combines TM_{30} -like mode operation with a $\lambda_g/4$ resonator-based feeding structure, enabling bandwidth enhancement through a dual-resonance mechanism while preserving higher-order mode radiation characteristics. The fabricated prototype achieved a measured bandwidth of 3.7% (3.41–3.54 GHz). Simulations indicate a peak realized gain of 12.8 dBi and sidelobe levels below -20 dB across the operating band. The proposed antenna achieved the highest realized gain and gain-to-area ratio among the compared designs in a single-layer configuration. Experimental validation was limited to the reflection coefficient. Good agreement between simulations and measurements validates its potential for compact high-gain wireless systems. Future work includes full far-field characterization and array integration for 5G base-station applications.

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