

Design and Experimental Validation of a Low-Profile Metasurface Array for Gain Enhancement of a 3.57 GHz Microstrip Patch Antenna

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ARTICLE INFORMATION

Received 12 May 2026

Revised 20 May 2026

Accepted 27 July 2026

Keywords:

5G Antenna

Fabry-Perot cavity

Gain Enhancement

Metasurface

Microstrip Patch Antenna

Sub-6 GHz

ABSTRACT

This paper presents the design, fabrication, and experimental validation of a low-profile metasurface-superstrate antenna to enhance the gain of a 3.57 GHz microstrip patch antenna (MPA) for sub-6 GHz 5G applications. Unlike conventional metasurface-superstrate antennas, this work systematically investigates the influence of metasurface array size and spacing, showing that a compact dual-resonator metasurface can achieve high gain while maintaining structural simplicity and a low profile. The antenna system consists of a rectangular MPA integrated with 1×1, 3×3, and 5×5 metasurface arrays fabricated on an RO4003 substrate ($\epsilon_r = 3.55$, thickness = 0.51 mm). The metasurface enhances radiation directivity through constructive electromagnetic reradiation and Fabry-Perot-like cavity resonance. We perform a parametric study to determine the optimum separation distance between the MPA and metasurface. Both simulations and measurements show significant performance improvement without appreciable resonance-frequency shift. The measured gain increases from 4.5 dBi for the standalone MPA to 5.6, 8.2, and 8.6 dBi for the 1×1, 3×3, and 5×5 metasurface arrays, respectively. The 3×3 configuration provides the best trade-off between gain enhancement, radiation stability, and structural simplicity, while maintaining good agreement between simulation and experimental results, demonstrating its suitability for compact high-gain sub-6 GHz 5G antenna systems.

1. Introduction

The rapid expansion of wireless communication services is expected to drive a substantial increase in network traffic during the coming years. Growth in smartphone adoption, mobile subscribers, internet accessibility, higher connection speeds, and intensive multimedia usage are projected to raise overall data demand by nearly seven times within the next five-year period (Azim, 2021). Among traffic sources, video-based applications are the dominant contributor, accounting for almost 80% of mobile network traffic and placing significant pressure on communication infrastructure (Ahmad, 2022; Al Gburi, 2022).

To accommodate these escalating requirements, beyond-5G (B5G) communication systems must satisfy increasingly demanding performance targets, including ultra-high throughput approaching 10 Gbps, latency on the millisecond scale, extremely dense connectivity reaching approximately 10^6 devices/km², and reliable operation under mobility conditions as high as 500 km/h (Kovacevic, 2022). In addition, B5G radio access architectures are anticipated to maintain simultaneous multi-user connectivity across diverse operating frequency bands (Ali, 2022).

According to the spectrum classification established by the United States Federal Communications Commission (FCC), wireless frequencies are categorized into three principal regions: low band frequencies below 1 GHz, mid-band allocations centered around 3.5 GHz and generally below 6 GHz, and high-band millimeter-wave (mmWave) frequencies (Al Gburi, 2021). Each region offers distinct operational advantages. While mmWave bands provide extremely large bandwidth resources capable of supporting multi-gigabit-per-second transmission, low-frequency bands offer broader coverage characteristics, with mid-band frequencies providing a practical compromise between capacity and propagation performance. Consequently, exploiting the

mmWave spectrum is essential to realizing the ultra-high data-rate ambitions of 5G systems. Nevertheless, several technical barriers continue to hinder large-scale deployment of mmWave cellular technology. As a transitional and practical solution, sub-6 GHz technology is expected to play a major role in early and near-term 5G implementations before mmWave communications fully mature (Hu, 2022).

Sub-6 GHz transmission systems can deliver high-capacity communication over long distances, making them suitable for both densely populated metropolitan areas and sparsely populated rural regions (An, 2020). In Indonesia, the regulatory authority formerly known as the Ministry of Communication and Informatics, currently the Ministry of Communication and Digital, has designated the 410 MHz–7.125 GHz spectrum as the sub-6 GHz frequency range, corresponding to Frequency Range-1 (FR1) operation (Kominfo, 2022).

Despite the considerable progress in metasurface-assisted antenna design, several challenges remain. Most reported studies primarily focus on maximizing gain using a single metasurface configuration, while the influence of metasurface array size and antenna–metasurface spacing on overall antenna performance has received relatively limited attention. In addition, experimentally validated low-profile metasurface-superstrate designs that simultaneously achieve high gain, compactness, and structural simplicity are still scarce. To address these issues, this work proposes a compact dual-resonator metasurface integrated with a 3.57 GHz microstrip patch antenna.

This study systematically investigates three metasurface array configurations (1×1 , 3×3 , and 5×5) and their optimal separation distances through full-wave simulations and experimental measurements. The results demonstrate that the proposed 3×3 metasurface provides the best trade-off between gain enhancement, radiation stability, and implementation simplicity, thereby offering an effective and practical solution for compact sub-6 GHz 5G antenna systems

2. Literature review

Considerable research attention has focused on advancing antenna technologies for fifth-generation and beyond-fifth-generation wireless systems. The primary objective is to realize antenna structures that simultaneously satisfy compactness, cost efficiency, and enhanced electromagnetic performance, making them suitable for modern base-station implementations. Researchers have therefore investigated various enhancement approaches, including high-index reflective materials (Wu, 2021) and hybridized metallic–dielectric architectures (Deng, 2015).

Huang (2020) introduced a sub-6 GHz hybrid radiating structure that integrated a slotted rectangular patch, a dipole excitation mechanism, and a balun to excite multiple resonant modes concurrently. Through the interaction of these modes, the antenna achieved a broad operating bandwidth of 56.87% and an average gain close to 8 dBi over the 3–5 GHz spectrum. Despite these promising characteristics, the overall feeding arrangement involves substantial structural complexity. In another study, (Ishfaq, 2019) investigated a compact phased-array solution employing a four-element planar inverted-E configuration operating between 5.7 and 6.4 GHz. The design incorporated three different techniques to suppress mutual coupling effects. Although the antenna showed favorable beam-steering performance up to 70° and a realized gain of 8.36 dBi, elevated cross-polarized radiation remained unresolved.

Previous investigations (Park, 2019; Ikram, 2020) highlighted slot antennas as attractive candidates because of their simple geometry, small footprint, and satisfactory operational behavior. These attributes support miniaturization and improve communication hardware efficiency. Nevertheless, while wide impedance matching can be achieved, the attainable gain level is generally insufficient for demanding applications. Jash (2019) examined a circularly polarized miniaturized microstrip configuration employing C-shaped slot loading on a 7×7 reactive impedance surface. The antenna exhibited a fractional bandwidth of 46.52% spanning 3.743–5.976 GHz; however, its radiation enhancement capability remained moderate, producing only 6.8 dBi gain.

In (Fang, 2018), a broadband monopole antenna fed through a coplanar waveguide was developed using a Y-shaped slotted radiator combined with meandered slot features. The coexistence of multiple structural elements—including the meandered sections, modified Y-shaped geometry, and trident-inspired feed configuration—generated several resonant responses that expanded the operating range. Based on this concept, we further realized a four-element compact array with $\lambda/4$ inter-element spacing. Although the antenna achieved a 41.8% bandwidth, it still exhibited limited gain of about 2 dBi and noticeable cross-polarization degradation.

For sub-6 GHz 5G platforms, (Rahman, 2019) proposed a defected-ground antenna topology incorporating a stub-slot arrangement. Dual-band operation was achieved through a modified patch structure using a simple slot-stub combination, while bandwidth improvement was supported by introducing an electromagnetic bandgap mechanism. The reported impedance bandwidth values reached 12.49% around 3.532 GHz and 4.49% near 6.835 GHz. Nonetheless, the design still exhibited shortcomings, including low radiation gain (approximately 3.5 dBi) and significant backward radiation.

Overall, previous studies have demonstrated that high-gain sub-6 GHz antennas can be achieved using hybrid radiators, phased arrays, slot antennas, defected-ground structures, or metasurface-assisted designs. Nevertheless, each approach exhibits inherent limitations. Hybrid antennas and phased arrays generally require complex feeding networks and sophisticated fabrication, while slot and defected-ground antennas often provide insufficient gain for practical base-station applications. Although metasurface-superstrate techniques have shown considerable promise for gain enhancement, most reported designs focus on a single metasurface configuration, with limited attention to how metasurface array size and antenna–metasurface spacing affect antenna performance. Moreover, experimentally validated low-profile metasurface designs that simultaneously achieve high gain, compact implementation, and structural simplicity remain relatively limited.

To address these challenges, this work proposes a compact dual-resonator metasurface integrated with a 3.57 GHz microstrip patch antenna. This work systematically investigates three metasurface array configurations (1×1 , 3×3 , and 5×5) and determines the optimum antenna–metasurface separation distance for each configuration through parametric analysis. Unlike previous studies that primarily maximize antenna gain, the proposed approach identifies the optimum compromise between gain enhancement, radiation stability, and structural simplicity through comprehensive full-wave simulations and experimental validation.

3. Method

The design used in this observation is a microstrip patch antenna (MPA) with rectangular dimensions $L \times W$ illuminating a metasurface (MS) structure consisting of two resonators as illustrated in Figure 1. The antenna system operates at 3.57 GHz in the Sub-6 GHz 5G band, and the structure is modeled and fabricated on a RO4003 substrate with $\epsilon_r = 3.55$ and a thickness of $h = 0.51$ mm.

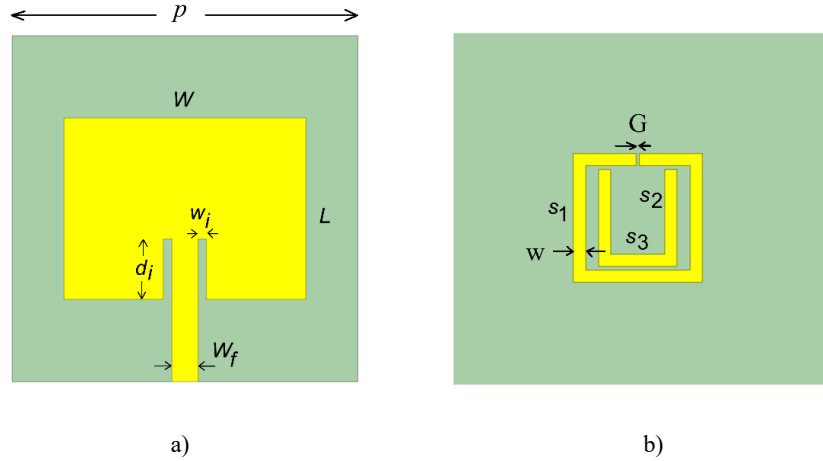


Figure 1. Detailed geometry of a) the microstrip patch antenna (MPA), and b) metasurface unit-cell (1x1 MS).

3.1. Microstrip Patch Antenna

In designing of MPA, there are some guidelines to get an appropriate functional radiating structure (Balanis, 2016), such as

- the width of MPA

$$W = \frac{c}{2f_0} \sqrt{\frac{2}{\epsilon_r + 1}} \approx 27.8 \text{ mm} \quad 1)$$

- the length of MPA

$$L = \frac{c}{2f_0 \sqrt{\epsilon_{r,eff}}} - \Delta \approx 22.2 \text{ mm} \quad 2)$$

- the feedline width for 50 ohm is $W_f \approx 1.1 \text{ mm}$.

The values above can serve as an initial reference for a low-reflection antenna ($S_{11} < -10 \text{ dB}$) at 3.57 GHz. If the minimum of the reflection coefficient is not at 3.57 GHz, we can increase or decrease L .

Adding two insets at the feed point can improve the reflection characteristics of the microstrip patch antenna. The optimal values for the insets are $W_i = 0.25 \text{ mm}$ and $d_i = 8.4 \text{ mm}$.

3.2. Metasurface Structure

A dual-resonator metasurface, as shown in Figure 1b, is designed as an electromagnetic lens. This structure should focus the electromagnetic wave radiated upward from the microstrip patch antenna. The aim of using the metasurface in this research is to increase the antenna gain.

The open rectangular resonator has the overall length of

$$L_{or} \approx \frac{c}{2f_0} \approx 42 \text{ mm} \quad 3)$$

To account for fringing effects, the effective length is shorter than the above value, so a side length of $s_1 = 10 \text{ mm}$ is chosen. The resonator width and gap are 1 mm and 0.5 mm, respectively. The U-shaped resonator dimensions are $s_2 = 7 \text{ mm}$ and $s_3 = 6 \text{ mm}$.

A metasurface structure above a microstrip patch antenna (Figure 2a) enhances gain through the interaction between the antenna's radiated field and the metasurface superstrate's resonant electromagnetic

response (Wang, 2021). The region between the patch antenna and the metasurface behaves similarly to a partially open Fabry–Perot cavity. The patch acts approximately as a primary source and partially reflecting surface, while the metasurface acts as a partially transmitting and partially reflecting superstrate. Multiple reflections occur between these two structures. Constructive and destructive interference occur due to the wave superposition.

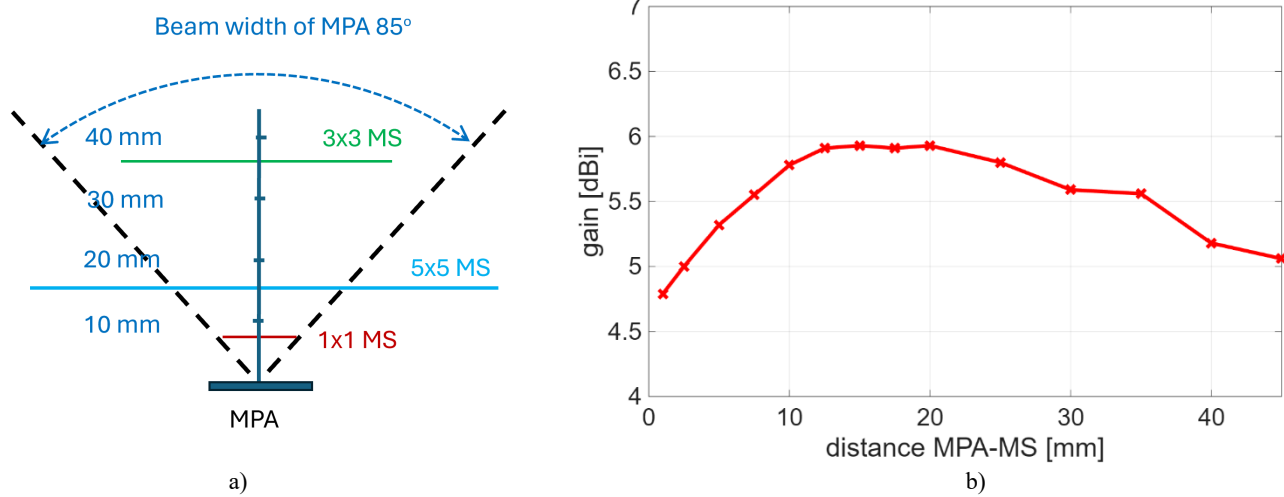


Figure 2. a) Visualization of the radiation of MPA on MSs, b) Calculated gain of single (1x1) metasurface vs distance MPA to MS.

Figure 2b shows the antenna gain as a function of the distance between the MPA and the MS. The gain enhancement of the 1×1 metasurface superstrate mainly arises from near-field electromagnetic coupling and constructive interference between the directly radiated field and the reradiated field from the metasurface resonator. An optimum spacing of approximately 13–20 mm provides the best phase alignment, resulting in maximum broadside gain enhancement. Beyond this distance, weaker coupling and phase mismatch reduce the enhancement.

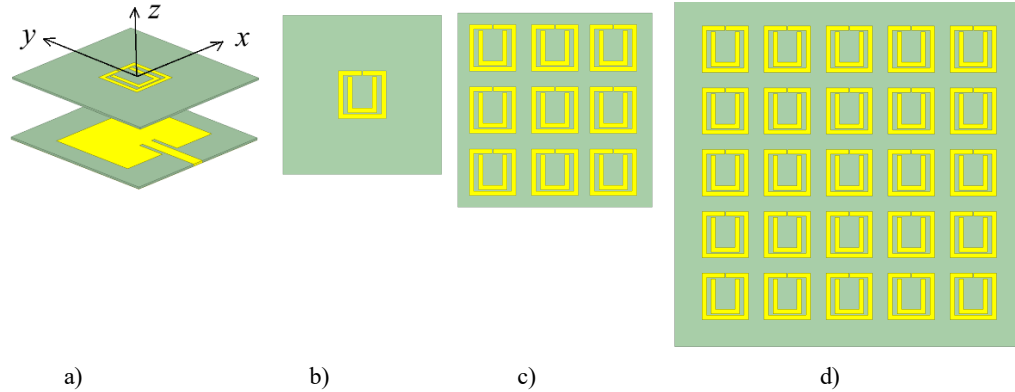


Figure 3. Computer model of developed antennas: a) microstrip patch antenna with single-cell metasurface, b) single (1x1) metasurface, c) 3x3 metasurfaces, d) 5x5 metasurfaces.

The antenna dimensions calculated from the classical microstrip antenna equations were used as initial values. The final dimensions of both the microstrip patch antenna and the dual-resonator metasurface were subsequently optimized using full-wave electromagnetic simulations in ANSYS HFSS. The optimization aimed to achieve resonance at 3.57 GHz while maximizing realized gain and maintaining good impedance matching ($S_{11} < -10$ dB). A parametric analysis was performed on the metasurface unit-cell dimensions, periodicity, and antenna–metasurface separation distance. Table 1 summarizes the optimum geometrical parameters obtained through this iterative process.

Table 1. Optimized geometrical parameters of the proposed antenna and metasurface

Parameter	Value (mm)	Description	Parameter	Value (mm)	Description
L	22.2	Patch length	s ₃	6	U-shaped resonator width
W	27.8	Patch width	G	0.5	Resonator gap
W _f	1.1	Feed width	w	1	Strip width
W _i	0.25	Inset width	p	16	Unit-cell periodicity
d _i	8.4	Inset depth	d ₁	20	MPA–MS spacing (1×1)
s ₁	10	Outer resonator side length	d ₂	10	MPA–MS spacing (3×3)
s ₂	7	U-shaped resonator length	d ₃	7.5	MPA–MS spacing (5×5)

4. Model of Metasurface Antenna and its Fabrication

In this work, a single-element, 3×3-element, and 5×5-element metasurface are designed, as depicted in Figure 3. The resonators are the same as in the single MS and are separated by $p \approx 0.15\lambda \dots 0.3\lambda$ (Bokhari, 2021). As initial separation, a value of $p \approx 15$ mm is chosen.

After many calculations using the parameter study approach for fine-tuning, the MPA with three different MSs was fabricated with the ultimate periodicity of $p \approx 16$ mm. Figure 4 shows the antennas. To maintain the gap between the MPA and MS, plastic spacers are used.

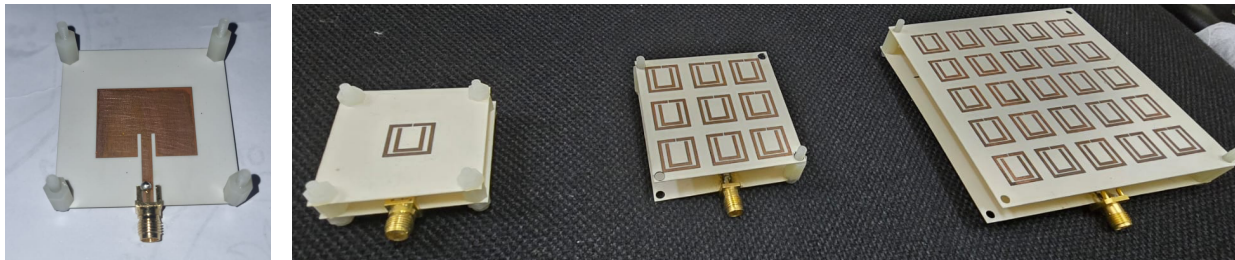


Figure 4. Photograph of fabricated antennas.

Figure 5 gives the measurement setup for obtaining the radiation diagram of each antenna. As the measuring antenna, we used an RS HF907 double-ridge waveguide horn antenna. The antenna under test was placed on a rotating table 85 cm from the horn antenna. The measurement was performed in a semi-anechoic chamber to minimize potential reflections from the surroundings.

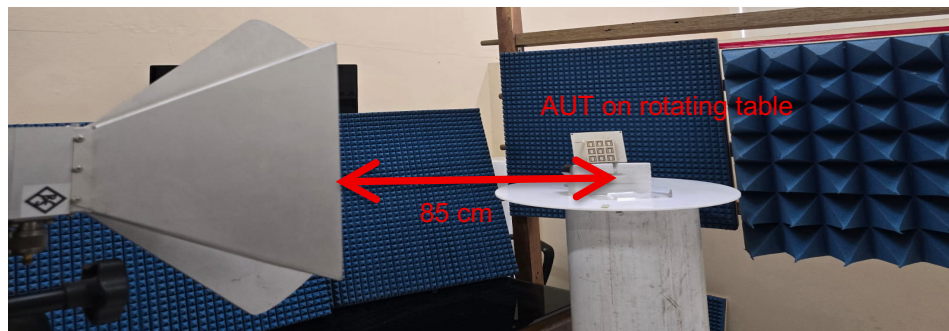


Figure 5. Setup for radiation pattern measurement, antenna under test (AUT) located 85 cm away from transmitting antenna.

5. Result and Discussion

Figure 6 compares the calculated and measured reflection coefficient (S_{11}) of a microstrip patch antenna (MPA), both alone and integrated with metasurface arrays of different sizes. For the standalone MPA, a clear resonance is observed around 3.57 GHz with good impedance matching, though the bandwidth is relatively narrow.

When a single metasurface unit is introduced with a distance MPA-MS of 20 mm, the resonance remains close to the same frequency, but the impedance bandwidth slightly increases, indicating the metasurface begins to improve matching. With a 3×3 metasurface array (distance MPA-MS 10 mm), the effect becomes more pronounced, as both simulation and measurement results show a broader resonance dip and better impedance characteristics compared to the bare patch. Finally, with a 5×5 metasurface array (distance MPA-MS 7.5 mm), the antenna achieves the best performance, maintaining resonance near 3.57 GHz while significantly broadening the bandwidth and deepening the return loss. In all cases, the simulations predict sharper dips than measurements, but the overall trends agree well, with differences mainly due to fabrication tolerances, material losses, and the experimental setup. These results confirm that the metasurface enhances antenna performance by improving impedance matching, suppressing surface-wave effects, and broadening operational bandwidth without shifting the resonance away from the target frequency.

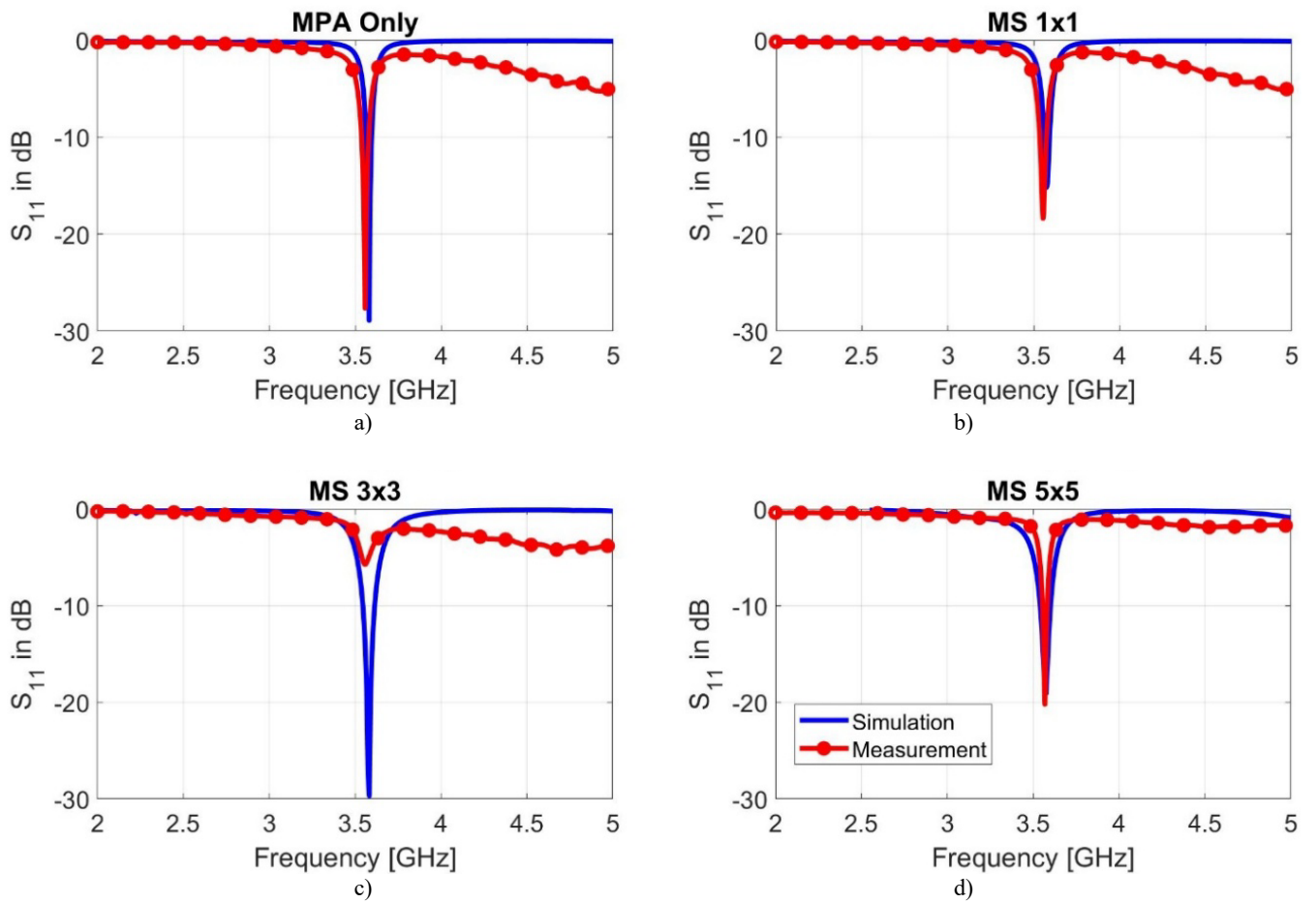


Figure 6. Comparison of calculated and measured reflection coefficients of a) microstrip patch antenna (MPA), b) MPA with 1×1 metasurface (MS), c) MPA with 3×3 MS, and d) MPA with 5×5 MS

The radiation patterns show how the number of metasurface unit cells influences the antenna's directional characteristics. As an initial observation, the distance between the MPA and MS structure for all proposed MS structures was varied, and the impact on the calculated gain was discussed. Figure 7 shows the antenna gain as a function of the separation distance between the MPA and MS for three MS configurations.

The results indicate that metasurface size strongly influences the antenna system's gain-enhancement mechanism. The 1×1 metasurface behaves primarily as a parasitic resonator, resulting in modest but stable gain improvement. The 3×3 metasurface provides the best overall performance because it effectively enlarges the aperture and improves phase coherence in the reradiated fields. In contrast, the 5×5 metasurface shows highly oscillatory behavior due to strong Fabry–Perot cavity resonance and phase nonuniformity across the larger aperture. Although the 5×5 structure achieves the highest peak gain, it also suffers from severe destructive interference at nonoptimal spacings, demonstrating the increased sensitivity of larger metasurface superstrates to cavity distance and phase alignment.

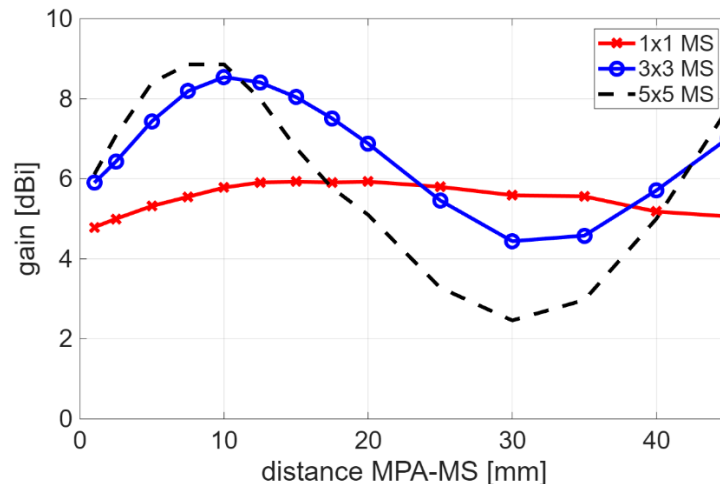


Figure 7. Calculated gain as a function of the separation distance between MPA and MS.

From the calculated gain, we chose the separation distance for the highest gain: 20 mm, 10 mm, and 7.5 mm for 1×1 MS, 3×3 MS, and 5×5 MS, respectively. Figure 8 compares simulation and measurement for all MS structures on the xy plane, as shown in Figure 3a.

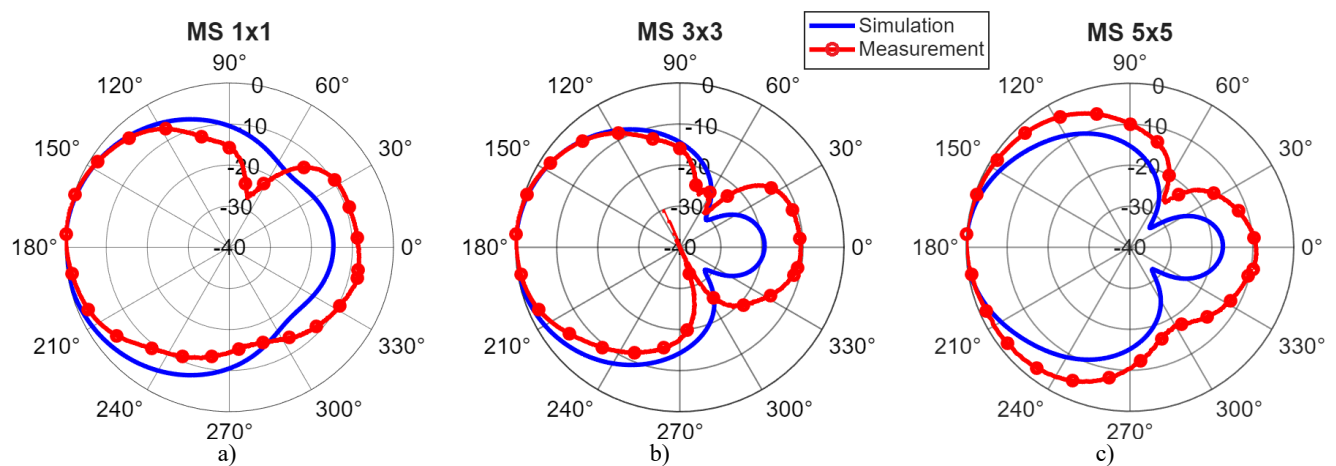


Figure 8. Comparison of calculated and measured radiation patterns on the xy plane according to Figure 3a) of a) microstrip patch antenna (MPA) with 1×1 metasurface (MS), b) MPA with 3×3 MS, and c) MPA with 5×5 MS.

For the microstrip patch antenna (MPA) with a 1×1 metasurface (MS), the radiation pattern is relatively broad with limited directivity, showing moderate agreement between simulation and measurement. As the array size increases to 3×3 MS, the radiation pattern becomes more directional, with reduced sidelobe levels and improved front-to-back ratio, indicating that the metasurface array channels more energy toward the main lobe. Finally, with the 5×5 MS configuration, the antenna achieves the highest directivity and stronger forward radiation, clearly forming a more focused main lobe. The measurements follow the same trend as the simulations, though some discrepancies in sidelobe levels and symmetry appear, which can be attributed to fabrication tolerances, metasurface-layer alignment, and measurement-setup limitations. Overall, the results confirm that increasing the number of metasurface unit cells enhances radiation directivity and improves pattern stability, validating the metasurface's effectiveness in shaping the antenna's radiation characteristics.

Table 2 summarizes the proposed antenna's gain performance for different metasurface configurations. The standalone microstrip patch antenna achieves a simulated gain of 4.62 dBi, which increases to 5.93 dBi, 8.54 dBi, and 8.90 dBi for the 1×1 , 3×3 , and 5×5 metasurface arrays, respectively. The improvement demonstrates that increasing the metasurface aperture enhances radiation directivity and wavefront control. The measured gains closely agree with the simulated results, with only slight reductions due to material losses, fabrication tolerances, connector and cable losses, and measurement uncertainties, thereby validating the proposed metasurface-assisted antenna design.

Table 2. Calculated and measured gain of antenna configurations

Configuration	Gain (simulation)	Gain (measurement)
MPA standalone	4.62 dBi	4.5 dBi
1×1 MS	5.93 dBi	5.6 dBi
3×3 MS	8.54 dBi	8.2 dBi
5×5 MS	8.90 dBi	8.6 dBi

Table 3 compares the proposed antenna with recently reported high-gain antennas operating in similar frequency bands. Compact antennas based on DGS, strip-loaded patches, and microstrip modifications generally achieve gains below 7 dBi. In contrast, dielectric resonator antennas provide improved gain at the expense of increased profile and structural complexity. Although the Fabry–Pérot cavity antenna reported by Wang and Zheng achieves a much higher gain (21.6 dBi), it operates at Ku-band frequencies. It requires a significantly larger and more complex cavity structure.

In contrast, the proposed metasurface antenna is specifically designed for the sub-6 GHz 5G band. It achieves a measured gain of 8.9 dBi with an aperture efficiency of 68.1%, outperforming the compared sub-6 GHz designs in gain while maintaining a simple, low-profile configuration. These results show that the proposed metasurface effectively balances gain enhancement, aperture utilization, fabrication simplicity, and suitability for practical sub-6 GHz 5G applications.

Table 3. Comparison of the proposed antenna with recently reported results

Ref.	Operating Frequency (GHz)	Dimension (mm ³)	Gain (dBi)	Aperture eff. (%)	Design Technique
Rahman et al. (2019)	6.835	33.5×33.5×1.52	6.38	-	DGS with 2D-EBG
An and He (2020)	3.0–4.0	40×15×0.8	3.0	-	Microstrip with strips
Al Gburi et al, 2021	3.5–5.0	16×18×0.254	-0.98	27.2	Microstrip with cuts
Ali et al. (2022)	3.57–4.48	50×50 ×26	6.8	-	Rectangular dielectric resonator with DGS
Wang and Zheng (2021)	13.48–16.95	60×97 ×12.1	21.6	-	Fabry–Pérot cavity antenna
This work	3.50–3.62	80×80×7.5	8.9	68.1	Metasurface

6. Conclusion

This paper presented the design, fabrication, and experimental investigation of a low-profile metasurface-superstrate antenna to enhance the gain of a 3.57 GHz microstrip patch antenna for sub-6 GHz 5G applications. The proposed antenna system used dual-resonator metasurface unit cells arranged in 1×1 , 3×3 , and 5×5 arrays above the radiating patch to improve radiation characteristics through constructive electromagnetic reradiation and Fabry–Perot-like cavity resonance.

The study showed that the metasurface significantly influences antenna performance, depending on both array size and the separation distance between the microstrip patch antenna and the metasurface. Parametric analysis showed that each metasurface configuration has an optimum spacing to achieve constructive phase alignment and maximum gain enhancement. Among the investigated structures, the 3×3 metasurface provided the best overall trade-off between gain enhancement, radiation stability, and structural simplicity. Meanwhile, the 5×5 metasurface achieved the highest peak gain but exhibited stronger sensitivity to spacing variations due to increased cavity resonance and phase nonuniformity across the larger aperture.

Simulation and measurement results showed good agreement. The standalone microstrip patch antenna achieved a measured gain of 4.5 dBi, while integrating metasurface arrays increased the measured gain to 5.6 dBi for the 1×1 configuration, 8.2 dBi for the 3×3 configuration, and 8.6 dBi for the 5×5 configuration. In addition to gain improvement, the metasurface structures also enhanced radiation directivity and slightly broadened the impedance bandwidth without significantly shifting the operating frequency from the target 3.57 GHz band.

Overall, the proposed metasurface-superstrate technique provides an effective and relatively simple approach for improving the performance of compact sub-6 GHz antennas. Compared with existing gain-enhancement techniques, it offers a favorable combination of high gain, low-profile implementation, structural simplicity, and experimental validation without requiring complex feeding networks or bulky dielectric resonators. However, this improved gain comes at the expense of a larger antenna aperture for higher-order metasurface arrays, while the operating bandwidth remains relatively narrow. The proposed design is therefore suitable for low-profile 5G wireless communication systems requiring moderate-to-high gain. Future work will focus on bandwidth enhancement, polarization control, beam steering, and reconfigurable metasurface structures for adaptive wireless applications.

7. Acknowledgements

This research was supported by the Directorate of Research and Community Service (DPPM), Ministry of Higher Education, Science, and Technology (Kemdiktisaintek), Republic of Indonesia, under the Penelitian Tesis Magister research grant program No. 0988/LL3/AL.04/2025; 01-1-4/031/SPK-RISSET/VI/2025 for the fiscal year 2025.

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