Enhancing Gain for UWB Applications Using 2×1, 2×2 MIMO Microstrip Patch Antennas

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***Abstract*—In this work, a rectangular ultra-wideband (UWB) patch antenna based on an FR-4 substrate (relative permittivity 4.4, dielectric loss tangent 0.024) with dimensions of $35 \times 30 \times 1.6$ mm^3 and a 50Ω microstrip feed is extended into several multi-antenna (MIMO) configurations. Specifically, we propose 2×1 ($35\times62\times1.6$ mm^3), 2×2 loop ($65\times65\times1.6$ mm^3), and 2×2 mirrored ($70\times62\times1.6$ mm^3) MIMO designs to investigate gain improvements across the UWB frequency range. Simulation results indicate that, when compared to the single-antenna design, the gain increases by $0.28-1.28$ dB for the 2×1 configuration, $1.03-1.66$ dB for the 2×2 mirrored design, and $1.11-1.84$ dB for the 2×2 loop arrangement. Notably, the 2×2 loop design provides the highest overall gain but exhibits a mismatch over a portion of its operational bandwidth. The Voltage Standing Wave Ratio (VSWR) and radiation patterns confirm that all proposed MIMO antennas can serve various UWB applications such as WLAN, WiMAX, and satellite communications-without requiring additional transmitter power.**

***Index Terms*—Ultra-wideband, multiple-input multiple-output, return loss, released gain, radiation pattern.**

I. Introduction

ULTRA-wideband (UWB) technology, operating in the $3.1-10.6$ GHz frequency spectrum, offers several advantages for short-range wireless communication, including high data rates, low power consumption, resilience to multipath interference, and precise ranging capabilities [1], [2]. Applications range from radar systems and medical imaging to wireless sensor networks, the Internet of Things (IoT), and next-generation (5G) communication standards.

Microstrip patch antennas have emerged as highly suitable for UWB systems due to their compact size, low profile, straightforward fabrication, and compatibility with planar circuit integration [2]. Research in this area often targets two primary objectives: broadening the operational bandwidth and mitigating interference from coexisting narrowband services such as WLAN (5.2 GHz, 5.8 GHz), WiMAX (3.5 GHz, 5.5 GHz), and X-band satellite links (7.25–8.4 GHz). Designers frequently incorporate strategically placed slots in the patch, feed line, or ground plane to enhance bandwidth and reject undesired signals.

Another critical factor for UWB antennas is multiple-input multiple-output (MIMO) technology, which significantly increases channel capacity, data throughput, and link reliability [3], [4], [5], [6], [7], [8], [9]. However, implementing MIMO in UWB systems introduces mutual coupling concerns between closely spaced elements. High mutual coupling degrades antenna efficiency, radiation patterns, and overall system performance. Solutions include orthogonal or diagonal antenna placement, polarization diversity, decoupling networks, and the integration of metamaterials to reduce coupling [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20].

Beyond bandwidth optimization and interference avoidance, gain improvement is another key focus in UWB antenna design. High-gain antennas extend communication range and improve reliability, especially in challenging environments. MIMO configurations often achieve higher gain than single elements by employing spatial multiplexing and beamforming [21], [22], [23]. Additional gain-enhancement methods include adding shorting vias or optimizing feed-line dimensions [24], [25], [26], [27], [28], [29].

This paper investigates gain enhancement for UWB systems by transforming a rectangular patch antenna into several MIMO configurations. The goal is to evaluate whether these approaches can achieve higher gain while maintaining broadband coverage. Performance metrics include return loss, VSWR, gain, bandwidth, and radiation patterns. We specifically emphasize whether these MIMO designs can provide appreciable gains without the need to increase transmitter power.

II. Antenna Design

This section details the design methodology for a microstrip patch antenna intended for UWB systems. We first adopted a rectangular patch structure (Figure 1a), following the general design in [9]. The antenna initially achieved full UWB operation, but further refinements were introduced to enhance performance:

1) **Rectangular Slots:** Small rectangular slots were added to the patch's lower corners (Figure 1b).
2) **Elliptical Slot:** An elliptical slot was added to the top edge of the patch (Figure 1c), optimized to broaden operating bandwidth and improve gain.

(a) (b) (c) (d)

Fig. 1. Evolution of the antenna design: (a) original design, (b) first modification with rectangular slots, (c) final design with an elliptical slot, and (d) partial ground plane.

A partial ground plane is implemented for additional bandwidth tuning (Figure 1d). Figure 2 and Table I summarize the final structure, including front, back, and side views with annotated dimensions. FR-4 epoxy serves as the substrate

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($\epsilon r = 4.4, \tan\delta = 0.024$), while the feed line provides 50Ω impedance matching.

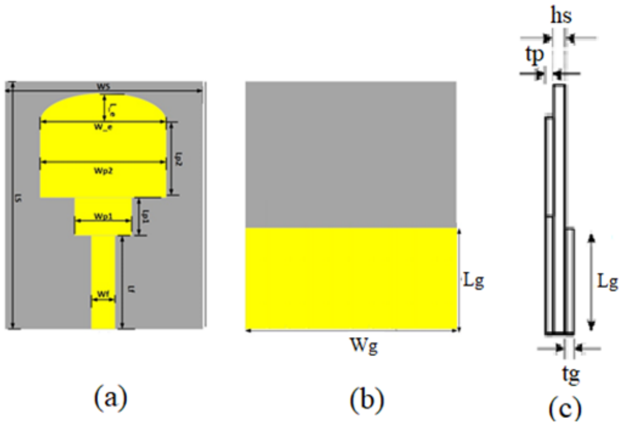
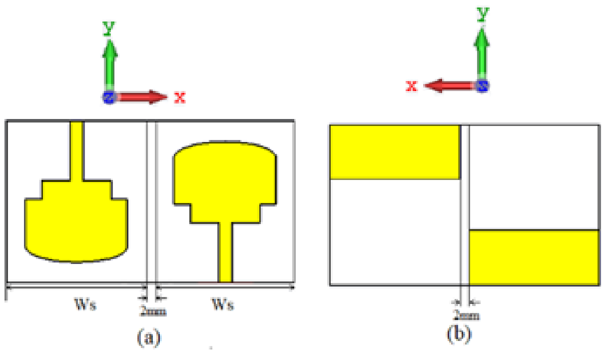


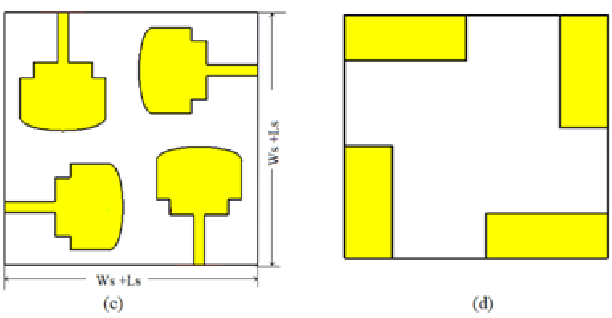
Fig. 2. Investigated antenna dimensions, (a) front, (b) back, and (c) side

Finally, to achieve higher gain and diversity, three distinct MIMO designs were created (Figure 3):

- 2×1 MIMO: Two side-by-side antennas on a common substrate.
- 2×2 Loop MIMO: A loop configuration of four antenna elements placed in a square arrangement.
- 2×2 Mirrored MIMO: A symmetrical arrangement of four elements, mirrored to reduce mismatch and coupling.

Each arrangement aims to exploit spatial or pattern diversity to increase gain and reduce mutual coupling.





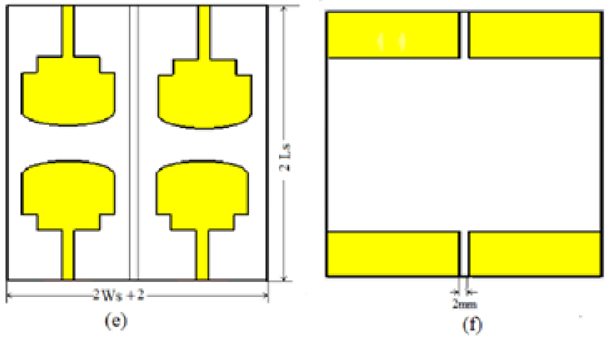


Fig. 3. Proposed MIMO antennas front view 2×1 (a), (c) 2×2 loop, and (e) 2×2 mirrored, back view 2×1 (b), (d) 2×2 loop, and (f) 2×2 mirrored.

III. SIMULATION AND RESULTS

Simulations were performed using CST Studio Suite 2018. This section first discusses the single-antenna design, followed by MIMO extensions.

1) Single Antenna Evaluation:
   - **Return Loss (S11)** Figure 4 shows the return loss, demonstrating an operational bandwidth of approximately 3.11–11 GHz, fully covering the UWB spectrum.
   - **VSWR** Figure 5 indicates that the VSWR remains below 2 across this range, confirming good impedance matching.
   - **Gain** Figure 6 shows the maximum realized gain of about 5.2 dB near the upper band edge (around 10–11 GHz), indicating reasonable radiation efficiency.

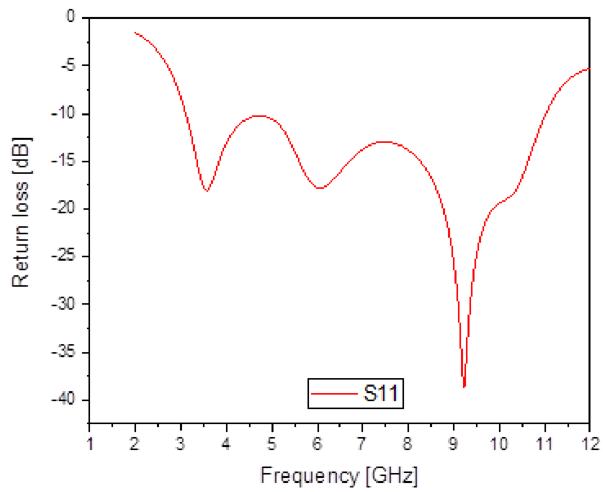


Fig. 4. The simulated S11 for singla antenna.

2) 2×1 MIMO Antenna
   To form the 2×1 design, the substrate was widened to $35 \times 62 \times 1.6$ mm^3, accommodating two antenna elements with partial ground-plane separation 3 (a-b).
   - **Return Loss and Coupling** Figures 7 and 8show S11/S22 and S12/S21, respectively. Both elements maintain UWB coverage, and the coupling metrics (S12, S21) suggest acceptable isolation.
   - **VSWR** Figure 9 confirms that VSWR remains below 2.

TABLE I
ANTENNA DIMENSIONS AND MATERIAL USED.

Antenna Elements		Dimensions [mm]
Patch		Wp1=15, Wp2=22, Lp1=4, Lp2=10, Le=3.5, tp=0.009
Feed Line		Lf =13, Wf = 2.85
Substrate		Ls = 35 mm, Ws = 30 mm ,2 mm between psub1 & sub2 for MIMO2×1, hs=1.6
The modified patch	Relative permittivity	4.4
is mounted on a	Dielectric tangent loss	0.024
FR4-epoxy substrate	Feed line characteristic impedance	50 Ω

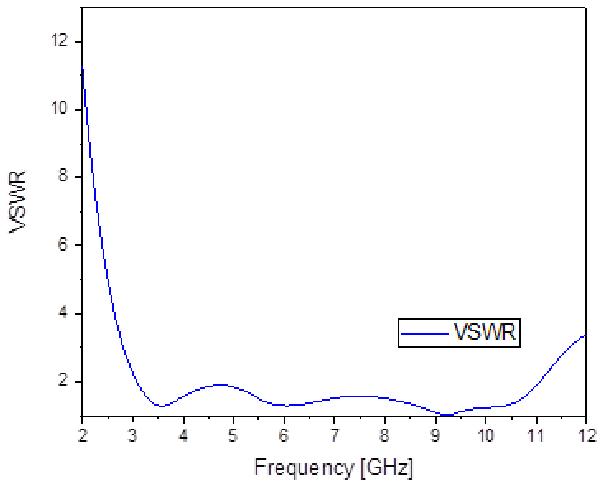


Fig. 5. The simulated voltage standing wave ratio forsingle antenna.

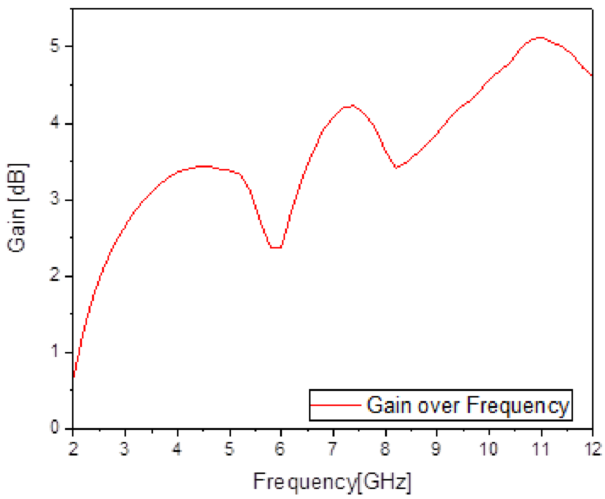


Fig. 6. Single antenna released gain.

- **Gain** Figure 10 shows an increase in gain compared to the single antenna, illustrating how additional elements improve signal strength.

3) 2 × 2 Loop MIMO Antenna
The 2 × 2 loop design rearranges four antenna elements on a 65 × 65 × 1.6 mm^3 substrate (Figures 3c–d).
- **Return Loss and Coupling** Figure 11 and Figure 12 plot S11, S22, S33, S44, and the coupling parameters, respectively. While the antenna covers most of the UWB range, a mismatch is noted between 4.2–4.9 GHz.
- **VSWR** Figure 13 shows that the VSWR is acceptable for most frequencies, but the 4.2–4.9 GHz region

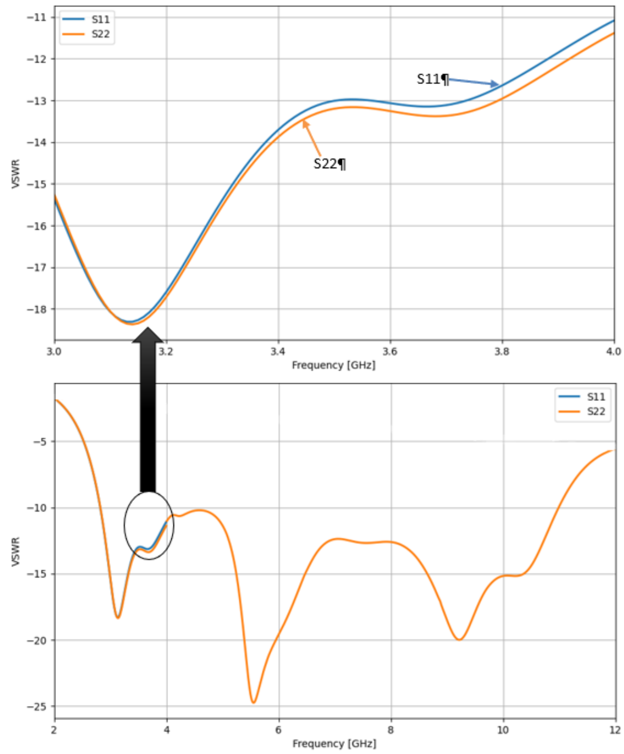


Fig. 7. S11, and S22 for 2×1 MIMO antenna.

indicates a slight mismatch.
- **Gain** As shown in Figure 14, this arrangement yields the highest overall gain among the examined designs—albeit with the stated mismatch.

4) 2 × 2 Mirrored MIMO Antenna
The 2 × 2 mirrored design (70 × 62 × 1.6 mm^3, Figures 3 (e-f)) attempts to reduce the mismatch observed in the loop version:

a) **Return Loss** Figures 15 and 16 show that adjusting the placement and substrate dimensions helps mitigate the mismatch.
b) Figure **Loop vs. Mirrored** 17 compares loop and mirrored configurations directly. The mirrored version exhibits better impedance matching in the problematic band.
c) Figure **VSWR** Figure 18 highlights the improved VSWR profile in the 3.98–4.37 GHz region.
d) Figure **Gain** The gain in 19 remains competitive, approaching that of the loop configuration while improving overall return loss performance.

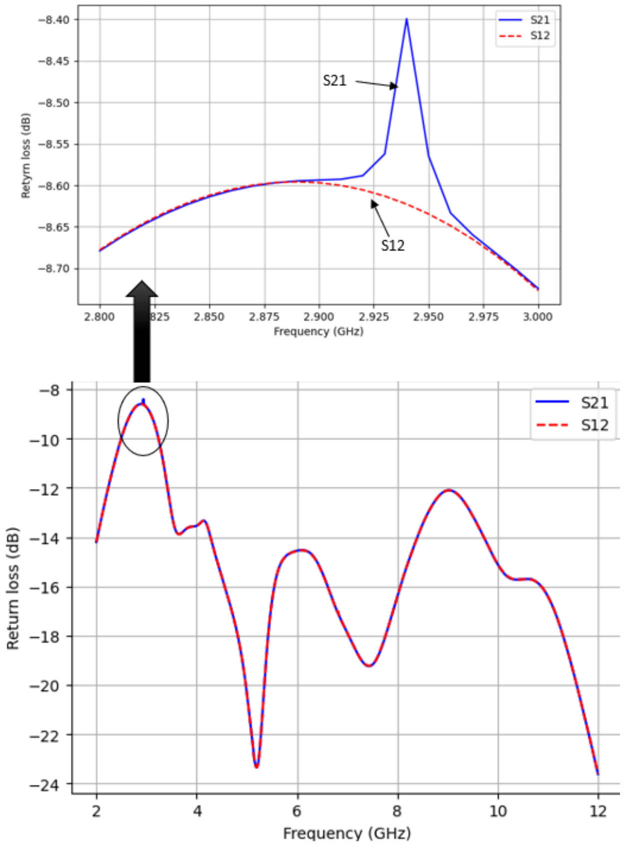


Fig. 8. S12, and S21 for the antennas coupling.

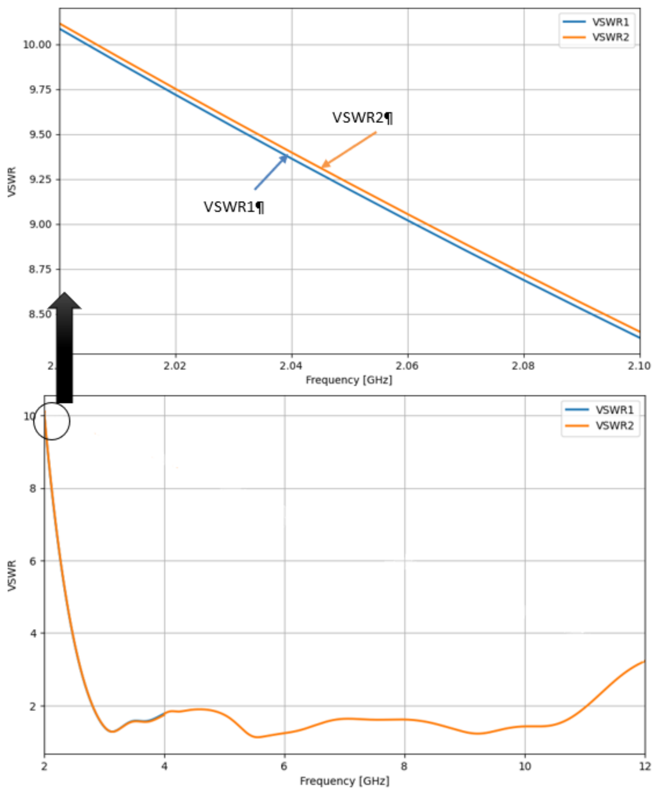


Fig. 9. VSWR for investigated 2 × 1 MIMO antenna.

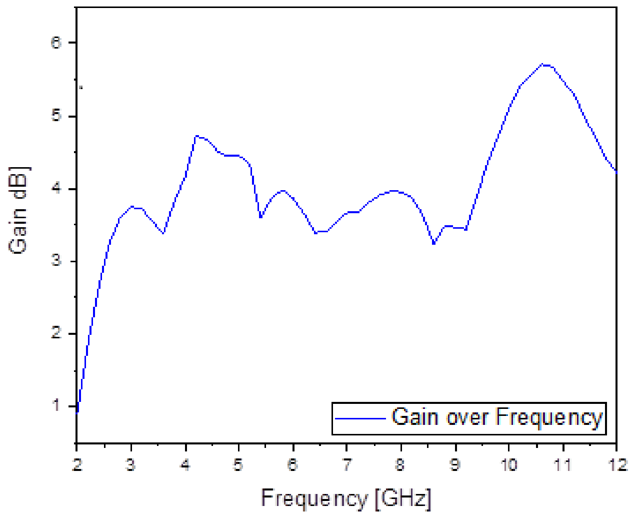


Fig. 10. Released gain for investigated 2 × 1 MIMO antenna.

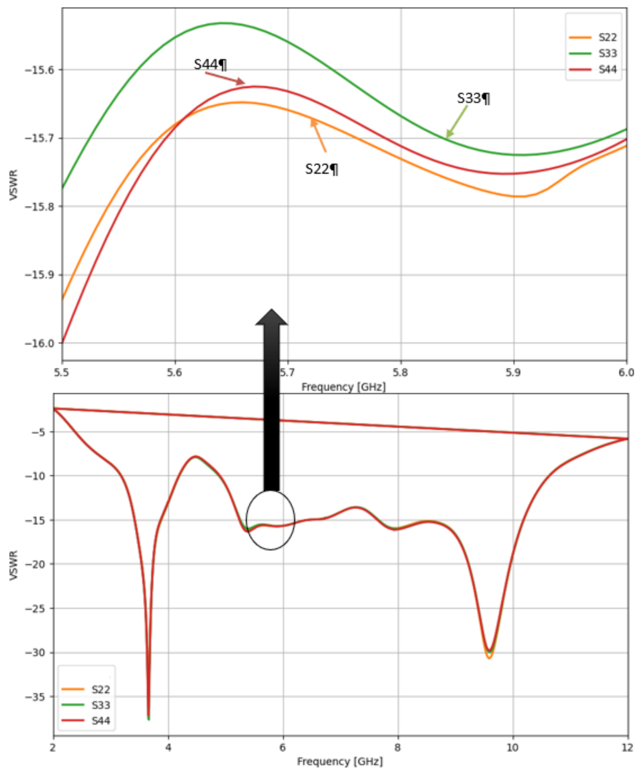


Fig. 11. S11,S22,S33,and S44 ,for 2 × 2 loop MIMO antenna.

IV. Impact of Substrate Material Variations on Antenna Performance

Substrate material choices have substantial effects on bandwidth and gain. Lower-permittivity materials generally yield broader bandwidth and higher gain but may increase the antenna's physical size.

- **Substrate Comparisons** Simulations using FR-4 ($\varepsilon r = 4.4, \tan\delta = 0.024$), Rogers RT/duroid 5880 ($\varepsilon r = 2.2, \tan\delta = 0.0009$), and Teflon ($\varepsilon r = 2.1, \tan\delta = 0.0002$) were conducted for both 2×1 and 2×2 MIMO configurations. Rogers RT/duroid and Teflon provided bandwidth increases up to $15-20\%$ over FR-4, along with a 1-1.5 dB gain improvement, owing to lower dielectric losses.
- **Practical Considerations** While premium substrates boost performance, they also increase fabrication cost. FR-4 remains viable for cost-conscious applications, despite moderate performance trade-offs.

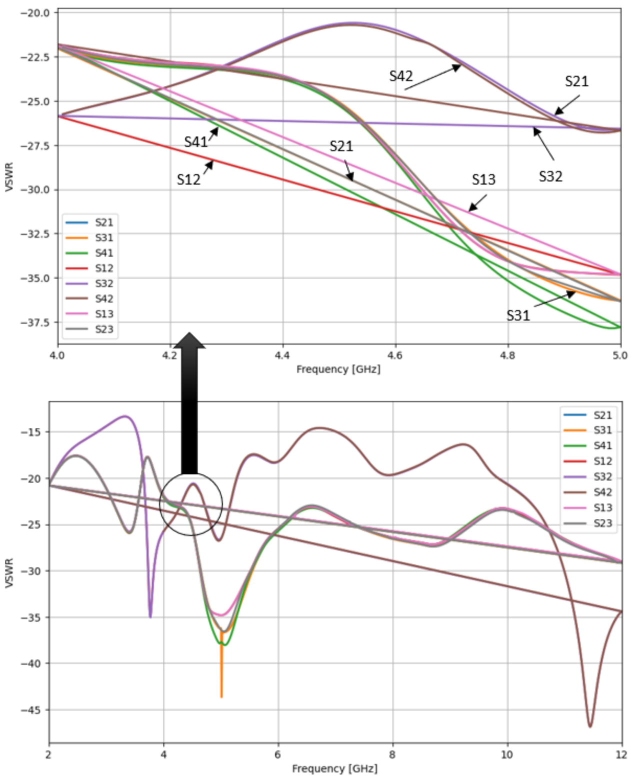


Fig. 12. The simulated return loss for 2×2 loop MIMO antennas coupling.

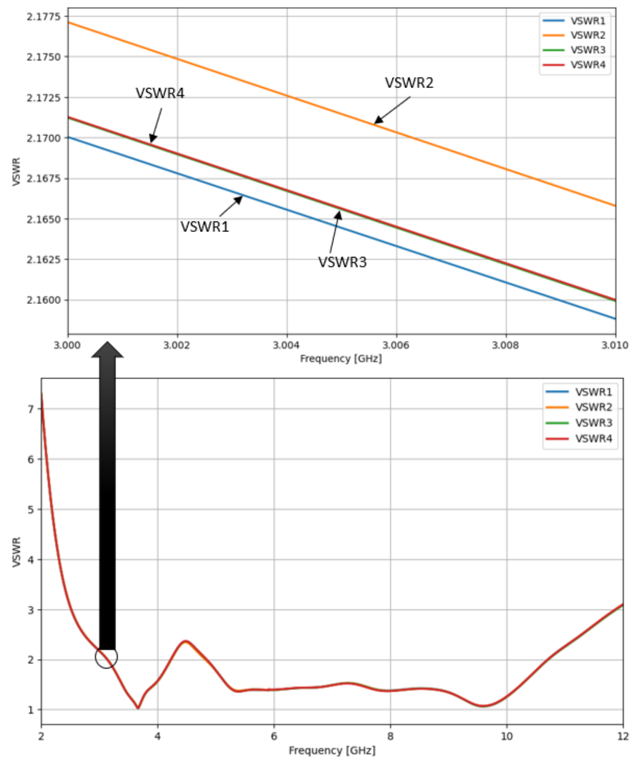


Fig. 13. The simulated VSWR for all four 2 × 2 loop MIMO antennas.

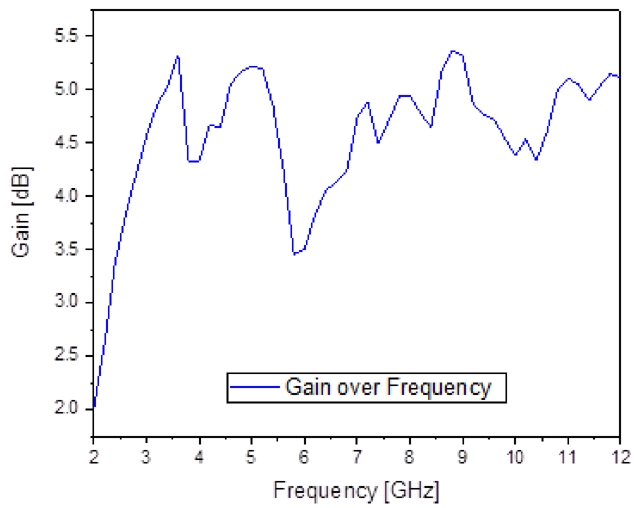


Fig. 14. 2 × 2 loop MIMO antenna gain.

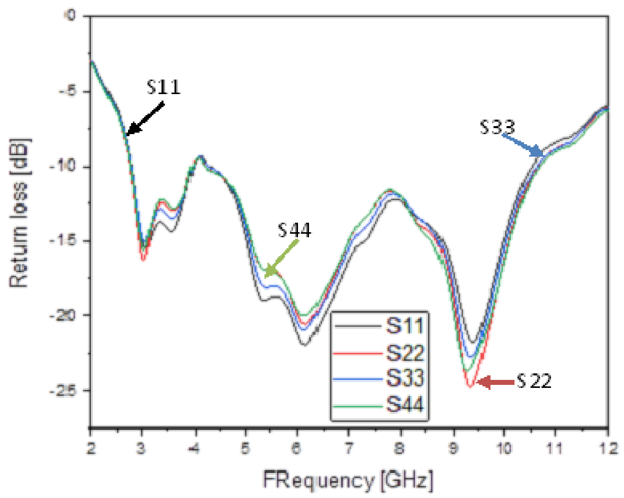


Fig. 15. S11,S22,S33,and S44,for 2 × 2 mirrored MIMO antenna.

V. DISCUSSION OF THE RESULTS

1) **Return loss**
Figure 20 compares the S11 results of the single antenna with the MIMO designs. Table II details operating bandwidth, mismatch ranges, resonant frequencies, and fractional bandwidth. The 2 × 1 antenna achieves the widest bandwidth (2.81–11 GHz) and highest relative bandwidth (approximately 138%), with multiple resonant points.

2) **Released gain**
Figure 21, overlays the gain curves. Compared to the single patch, the MIMO configurations exhibit gain improvements ranging from 0.28 dB up to 1.84 dB, depending on frequency:
- 2 × 1 MIMO: +0.28 − 1.28 dB
- 2 × 2 Mirrored: +1.03 − 1.66 dB
- 2 × 2 Loop: +1.11 − 1.84 dB

Despite minor mismatches, the 2 × 2 loop design provides the largest overall gain boost. However, the 2 × 1 MIMO can deliver comparable gains without the extra complexity or physical size of a 2 × 2 array.

3) **Radiation Patterns**
Figure 22 compares the 2D radiation patterns for the single antenna and the 2 × 2 loop configuration at select resonant frequencies. Patterns are generally omnidirectional at lower frequencies and become more directional at higher frequencies.

4) **Comparison with other reported works**

TABLE II
COMPARISON BETWEEN ORIGINAL AND PROPOSED MIMOS

Antenna	Operating BW (GHz)	Mismatch (GHz)	Resonant frequencies (GHz)	Relative BW (%)
Single antenna	3.08–11.03	non	3.55, 6, 9.22	112.6
2×1 MIMO	2.81–11	non	3.13, 3.7, 5.55, 7.52, 9.22, 10.22	138.1
2×2 loop MIMO	3.18–10.63	4.2 – 4.9	3.67, 5.33, 7.92, 9.6	107.9
2×2 mirrored MIMO	2.81–10.55	3.98 – 4.25	3.07, 3.58, 5.33, 6.15, 9.36	115.9

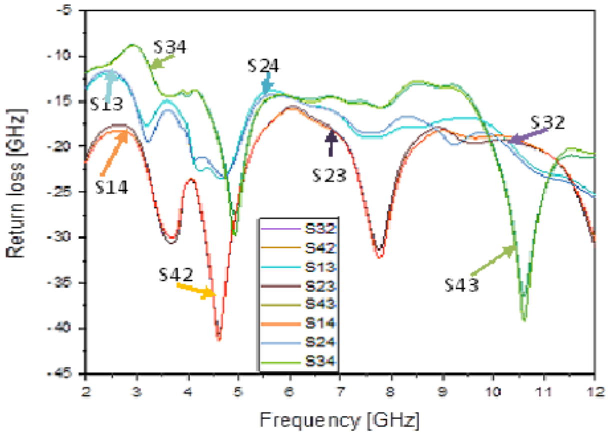


Fig. 16. Coupling return loss for 2 × 2 mirrored MIMO antennas .

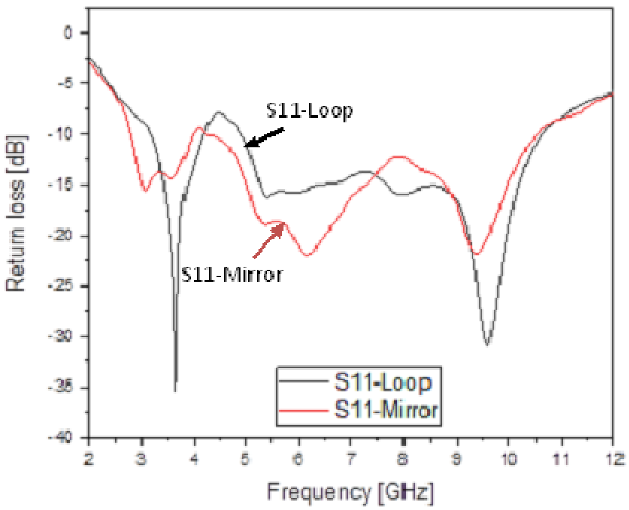


Fig. 17. Comparing 2 × 2 loop and 2 × 2 mirrored MIMO antennas.

Table III contrasts the proposed antennas with previously reported MIMO designs in terms of dimensions, bandwidth, and gain. The gains of our antennas are competitive, and in some cases higher, while preserving relatively compact dimensions.

Moreover, additional simulations showed that slightly increasing patch dimensions (by about 5%) improved gain by 1–2 dB across much of the UWB band, though at the cost of minor impedance mismatches. Designers can tune these parameters to balance size, bandwidth, and gain requirements.

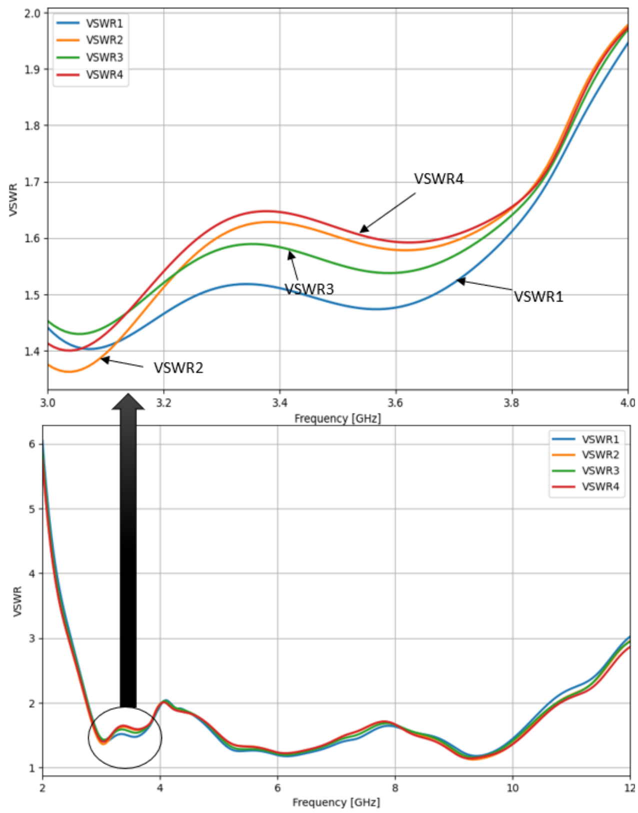


Fig. 18. VSWR for all four 2 × 2 mirrored MIMO antennas.

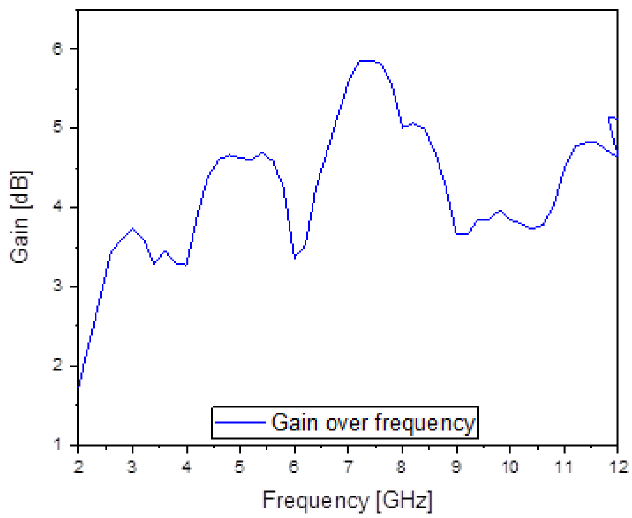


Fig. 19. The gain for 2 × 2 loop MIMO antenna.

VI. CONCLUSION

This paper presents multiple MIMO adaptations—2 × 1, 2 × 2 loop, and 2 × 2 mirrored—of a base UWB patch antenna to enhance gain while maintaining broad operational bandwidth. All proposed configurations surpass the single-antenna design in gain, without requiring extra transmit power. Among them, the 2 × 2 loop design achieves the highest gain increases (up to 1.84 dB), though it experiences a mismatch over part of its bandwidth. The 2 × 2 mirrored

TABLE III
COMPARISONS TO EXISTING WORK

Ref.	Ant. Dimension [mm]	MIMO Antenna	Operating frequency [GHz]	Fractional bandwidth	Released gain [dB] for MIMO Antenna Antenna
[21]	60 × 60	2 × 2	2.65 – 15	139.9	>6
[23]	Inverted 35 × 62	2 × 1	3.28 – 40	169.7	6.51
	Plus-shaped 100x70	2 × 2	3.44 – 14.2	1222	6.16
	Loop 65x65	2 × 2	2.48 – 12.5	133.8	5.6
	Chair-shaped 65x105	2 × 2	3.13 – 13.6	125.1	6.62
[24]	20 × 24	2 × 1	42.0 – 49.0	15.3	> 8
[25]	70 × 70	2 × 2	2 to 4.5	7.7	1.84 – 3.49
[27]	20 × 45	2 × 2	2.97 – 19.62	148.3	3.3 – 8.12
[28]	15 × 10.3	2 × 2	27 – 28.95	7	6.14
[29]	66 × 66	2 × 2	2.2 – 2.7	2.04	6.17
This work	35 × 62	2 × 1	2.81 – 11	138.1	5.8
	loop MIMO 65 x 65	2 × 2	3.18 – 10.63	107.9	5.5
	mirrored MIMO 70 x 62	2 × 2	2.81 – 10.55	115.9	5.8

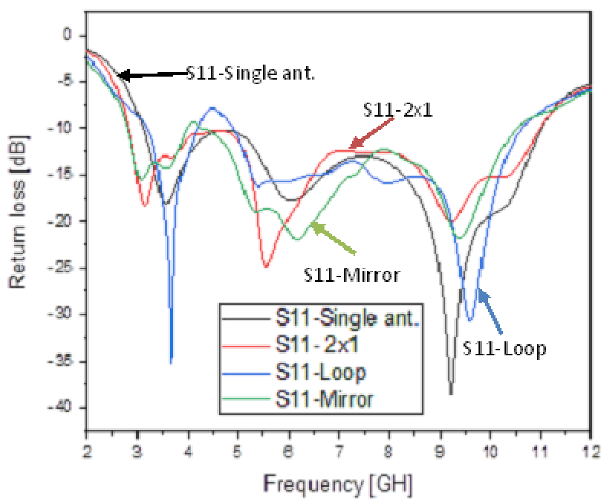


Fig. 20. The simulated S11 for all simulated antennas.

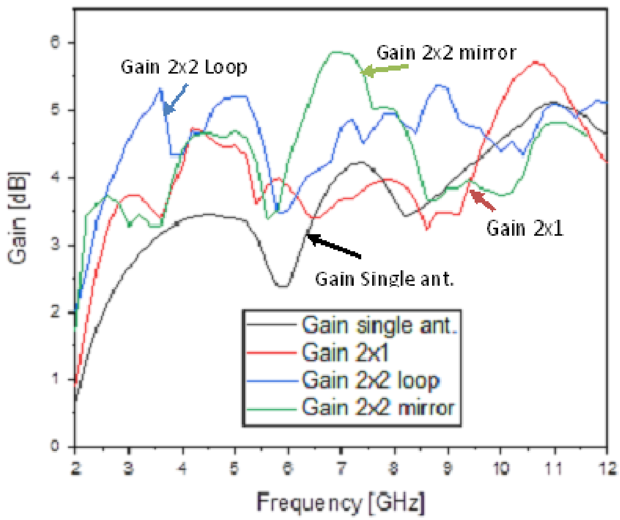


Fig. 21. The simulated released gain for all investigated antennas.

arrangement mitigates that mismatch while retaining gain improvements, and the 2×1 configuration offers a simpler solution with adequate gain enhancement. Radiation patterns, typically omnidirectional at lower frequencies and more directive at higher frequencies, align with standard UWB behavior.

Given their strong performance, these MIMO configurations are suitable for UWB applications such as WLAN, WiMAX, and satellite communications, where higher gain and wide coverage are desired. Future efforts may investigate further decoupling methods, additional array geometries, and alternate substrate materials to optimize performance for specific frequency ranges or physical constraints.

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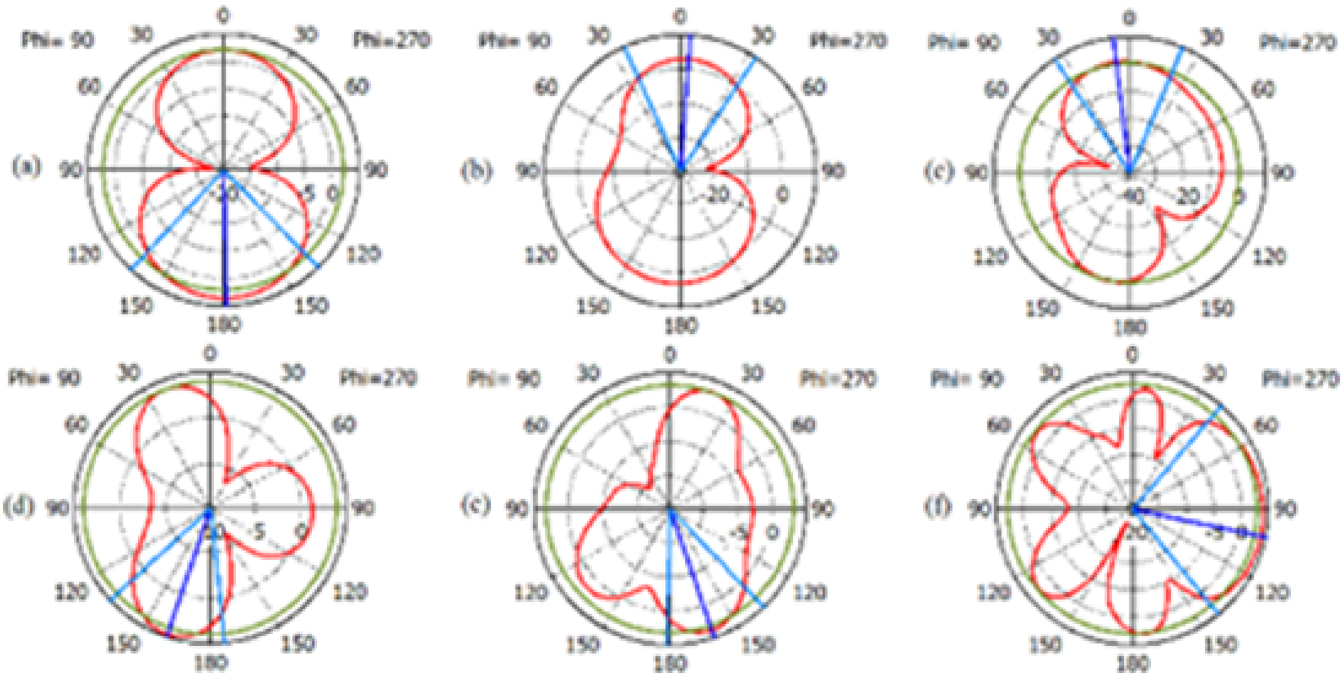

Fig. 22. 2D radiation for original antenna (a) 3.6GHz, (b) 6 GHz, and (c) 9.2 GHz. 2×2 loop MIMO antenna (d) 3.6 GHz, (e) 5.3 GHz, and (f) 9.6 GHz.

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