

An Ultrawideband Magnetolectric Dipole Antenna With Gain Improvement and Its Application in Array Design for Sub-6G Intelligent IoT Communication

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Abstract—An ultrawideband magnetolectric (ME) dipole antenna with stable gain is proposed for sub-6G Internet of Things (IoT) communication systems. While several structures can effectively achieve a wide impedance bandwidth, a critical limitation is that an excessively wide beamwidth often results in gain deterioration over the corresponding frequency range. To address this issue, vertically placed metal plate (VPMP) are introduced to generate out of phase currents and narrow the beamwidth, while folded metal branch (FMB) provide additional vertical radiation, thereby improving gain stability. Consequently, the proposed ME dipole antenna exhibits a 108% impedance bandwidth (1.2–4 GHz) with a measured gain of 7.2 ± 1.9 dBi across the band. Furthermore, based on the proposed antenna element, vertical shorting post (VSP) are employed to introduce out of phase currents for mutual coupling suppression, enabling a 100% operating bandwidth (1.26–3.85 GHz) for the array. In addition, a one-dimensional array prototype is fabricated to validate the proposed design strategy. It demonstrates a scanning range of up to $\pm 45^\circ$ across 1.26–2 GHz and $\pm 30^\circ$ across 2–3.85 GHz. Covering most of the L- and S-bands while maintaining stable radiation characteristics, the proposed antenna is a promising candidate for multi-service IoT communication systems including smart home devices, agricultural monitoring, and industrial manufacturing.

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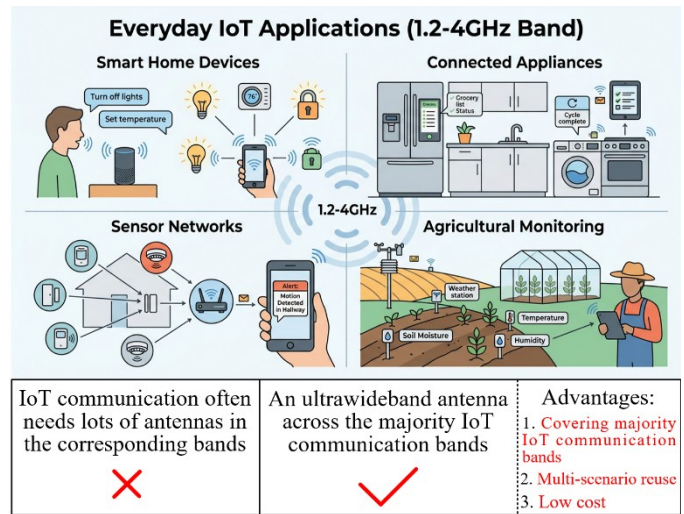


Fig. 1. Intelligent IoT communication applications in everyday life.

Index Terms—Sub-6G IoT applications, ultrawideband antenna, magnetolectric dipole antenna, gain improvement.

I. INTRODUCTION

WITH the rapid development of 5G and smart connected technologies, the Internet of Things (IoT) has been widely adopted in numerous application scenarios, including indoor smart home devices [1]–[2], sensor networks [3], connected applications [4]–[5], agricultural monitoring [6], industrial manufacturing [7], healthcare, and smart cities [8]–[9]. To meet the demands of rapidly evolving wireless communication systems, antennas, as key front-end components in wireless devices, are increasingly required to support broad operating bandwidths to cater to the surging demand for higher data transmission rates [10]–[12]. In recent years, deploying multiple antennas to cover different frequency bands significantly increases the required footprint. Consequently, minimizing the number of antennas needed to cover diverse frequency bands has emerged as a pressing challenge. While a single ultrawideband (UWB) antenna can mitigate the reliance on multiple discrete antennas, such antennas are also expected to provide multiple desirable features, including ultrawide bandwidth, stable gain,

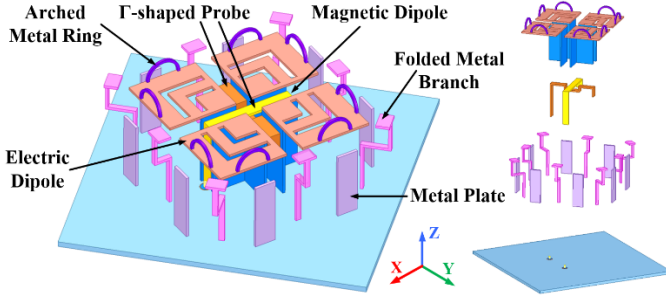


Fig. 2. Perspective view of the proposed antenna.

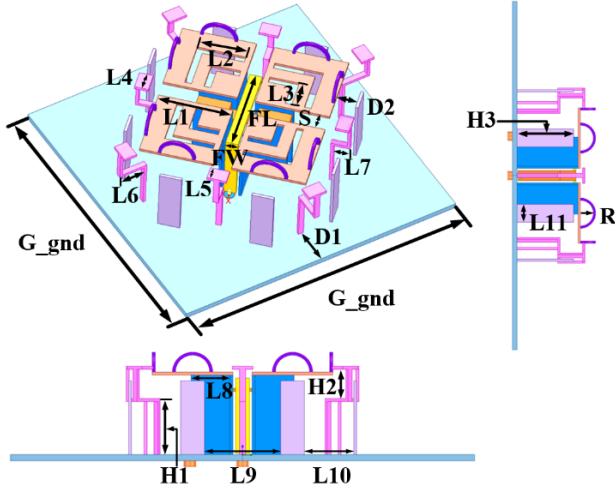


Fig. 3. Configuration of the proposed antenna.

and dual polarization. As a well-established wideband antenna configuration, the magnetoelectric (ME) dipole antenna has been intensively studied owing to its notable merits, broadband operation, stable radiation characteristics, and low cross-polarization levels over the entire operational frequency spectrum. A linearly polarized ME dipole antenna was initially proposed in [10], followed by the introduction of a dual-polarized variant in [11]. Subsequent efforts have yielded a diverse range of wideband ME dipole antenna designs.

An ME dipole antenna with wide bandwidth and broad beamwidth, incorporating six metallic columns, achieves an impedance bandwidth of 81.1% [13]. However, its dimensions of $1.04 \lambda_{\text{high}} \times 1.04 \lambda_{\text{high}} \times 0.42 \lambda_{\text{high}}$ render it unsuitable for phased array design. Another ME dipole antenna, which integrates a pair of vertically oriented folded shorted patches, exhibits a fractional impedance bandwidth of 43.6% alongside low-profile characteristics [14]. Despite its profile of $0.116 \lambda_{\text{center}}$ is competitive, its operating bandwidth remains insufficient to meet the escalating demands of data growth and user requirements. An ME dipole antenna integrating an ME dipole director delivers an operational bandwidth of 29.21% [15]. The emphasis of this work lies in mounting the ME-dipole director atop a conventional cavity-backed ME-dipole antenna, which enhances the maximum gain to 13.5 dBi. Although these studies improved beamwidth, profile, or gain, many of them focus on single-polarized designs or do not simultaneously achieve ultrawide bandwidth, stable gain, and low-profile.

TABLE I
DIMENSIONS OF THE PROPOSED ANTENNA.

Parameter	G_gnd	D1	D2	S	R	Fw	FL
Value(mm)	110	14	7	6.5	5.75	4.5	34
Parameter	H1	H2	H3	L1	L2	L3	L4
Value(mm)	19	10	25	27	17.75	10.75	7
Parameter	L5	L6	L7	L8	L9	L10	L11
Value(mm)	5	10	6	13	25.5	16.5	8

In this work, several design techniques are applied to an ME dipole antenna to achieve enhanced wideband performance (covering multiple IoT communication bands: Zigbee, NB-IoT, and C-V2X). First, an ME dipole antenna with ultrawide bandwidth and stable gain is developed through several structural modifications. Moreover, out of phase currents play a key role in suppressing mutual coupling within the antenna array. Overall, the key contributions of this work are summarized as follows.

1) In the design of the antenna element,

First, a slotted electric dipole and several L-shaped parasitic branches (LPB) are introduced as key components to realize ultrawideband operation. Then, vertically placed metallic plates (VPMP), which introduce out-of-phase currents to narrow the beamwidth, and folded metallic branches (FMB), which enhance the broadside radiation, are employed to modulate the field distribution and mitigate the gain degradation caused by an excessively broad beamwidth.

Thus, a compact ultrawideband ME-dipole antenna operating from 1.2 to 4 GHz with relatively stable gain is achieved.

2) In the design of the antenna array,

Vertical shorting posts (VSP), as a key component, introduce supplementary current paths that generate out of phase currents., achieving significant suppression of mutual coupling.

Ultimately, the six-element phased array realizes an operational bandwidth of 100% (1.26–3.85 GHz) and achieves a beam-scanning range of up to $\pm 45^\circ$ across 1.26–2 GHz and $\pm 30^\circ$ across 2–3.85 GHz. These merits make the proposed antenna a competitive candidate for intelligent IoT communication applications in everyday life.

II. ULTRAWIDEBAND ANTENNA DESIGN AND ANALYSIS

A. Antenna Geometry

As depicted in Fig. 2, the proposed wideband dual-polarized ME dipole antenna consists of several components, namely an ME-dipole with several slots and an arched metal ring, one pair of orthogonally placed Γ -shaped feeding probes, and the ground plane. In addition, parasitic elements including folded metal branches and metal plates are situated outside the radiator. Moreover, the antenna can be manufactured using 3D printing technology. The detailed geometry is shown in Fig. 3, and the corresponding dimensions are summarized in Table I.

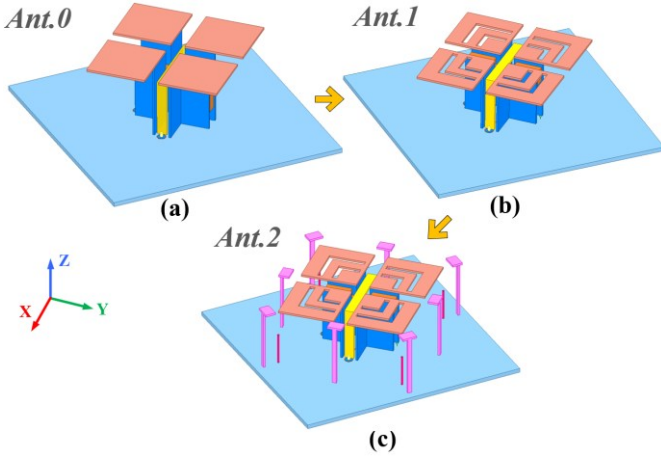


Fig. 4. Evolution of the ME dipole antenna for broadening bandwidth. (a) Ant. 0. (b) Ant. 1. (c) Ant. 2.

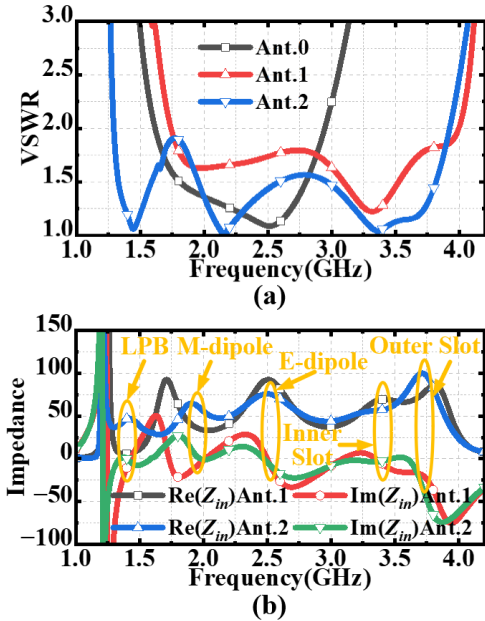


Fig. 5. Performances of (a) VSWR and (b) input impedance.

B. Impedance Improvement for Broadening Bandwidth

To clarify the operating mechanism of the proposed wideband ME dipole antenna, a detailed analysis is presented in this section. As shown in Fig. 4(a), the initial ME dipole antenna, denoted as Ant. 0, exhibits a limited impedance bandwidth of 58.2% from 1.62 to 2.95 GHz [10], [11], which cannot fully cover the N77 and N78 bands in the sub-6G spectrum. To address this limitation, two pairs of slots, including inner and outer slots, are etched on each electric dipole to tailor the current distribution, as illustrated in Fig. 5. For Ant. 1, the introduced slot pairs effectively lengthen the current path and improve the impedance bandwidth, particularly in the upper frequency range [19]–[20]. To further extend the lower edge of the operating band, several L-shaped parasitic branches (LPBs) are introduced to generate an additional LC resonance, as shown in Fig. 4(c) [21]. Compared with Ant. 1, Ant. 2 with the added LPBs exhibits an increased effective radiating area and a further broadened impedance bandwidth. As shown in Fig. 5(b), five resonant

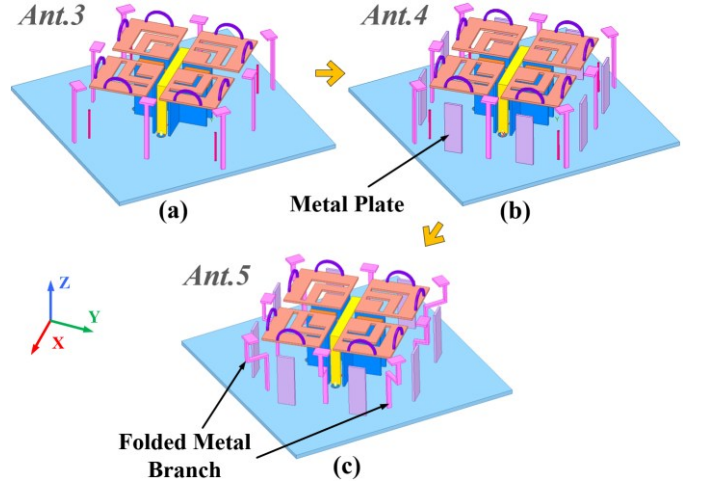


Fig. 6. Evolution of the ME dipole antenna for improving gain. (a) Ant. 3. (b) Ant. 4. (c) Ant. 5.

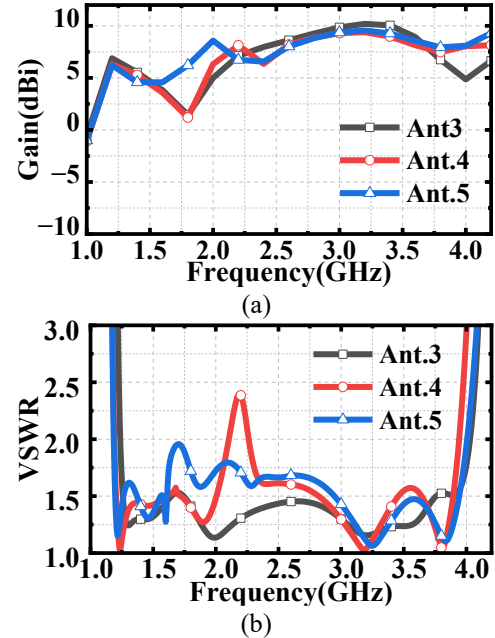


Fig. 7. Performances of (a) Gain and (b) VSWR for Ant. 3 to Ant. 5.

modes are observed within the operating band [22]. Consequently, Ant. 2 achieves a significantly enhanced operating bandwidth of 1.29–3.85 GHz.

As a further modification, four metallic posts are introduced beneath the edges of the electric dipoles in Ant. 2 to lengthen the current path while maintaining effective radiation. As a result, the upper edge of the operating band is extended to approximately 3.9 GHz. Nevertheless, this bandwidth is still insufficient to fully cover the N77 band. To further broaden the operating band, an arched metallic ring is integrated above the electric dipoles, providing an additional current path. With this modification, Ant. 3 achieves a VSWR lower than 1.5 from 1.24 to 4.03 GHz, corresponding to a fractional bandwidth of 106%. Therefore, Ant. 3 covers a large portion of the sub-6-GHz spectrum, including the N78 band and most of the N77 band.

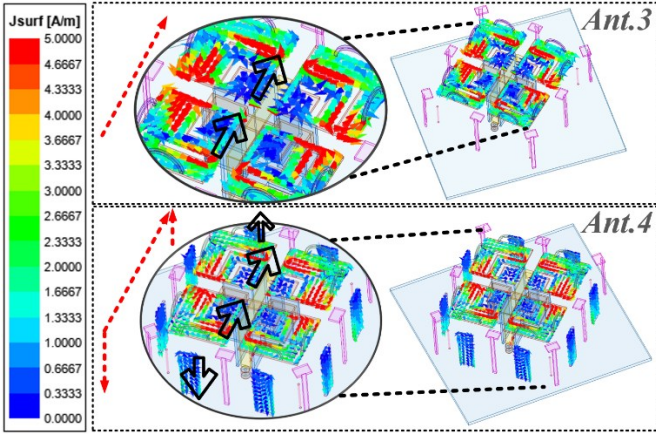


Fig. 8. Surface current distributions for Ant. 3 and Ant. 4 at 3.95 GHz.

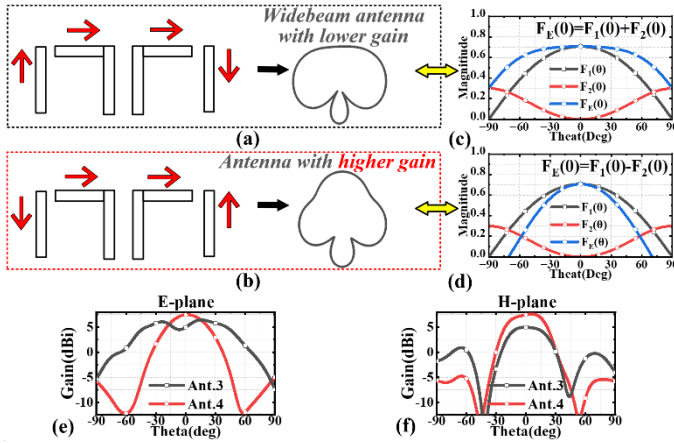


Fig. 9. The principle of widebeam antenna (a) and (c). The principle of Ant. 4 (b) and (d). The gain comparison of Ant. 3 and Ant. 4 in E (e) and H (f) planes.

C. Adjusting Field Distribution for Enhancing Gain

Although Ant. 3 achieves a broad impedance bandwidth of 106% from 1.24 to 4.03 GHz, covering a large portion of the sub-6-GHz spectrum, its gain deteriorates in both the lower and upper frequency ranges. To alleviate the gain degradation in the upper frequency range, four pairs of vertically placed metallic plates (VPMPs) are introduced in Ant. 4. Fig. 8 compares the surface-current distributions of Ants. 3 and 4. The VPMPs introduce vertical currents that are out of phase with the original currents, thereby enhancing the gain significantly [23].

To further clarify the gain enhancement mechanism, a detailed analysis is given below.

$$F_1(\theta) = \sin\left(\frac{\pi H}{\lambda} \cos\theta\right), F_2(\theta) = A_2 \cos\left(\frac{\pi}{2} \cos\theta\right) \quad (1)$$

$$F_E(\theta) = \sin\left(\frac{\pi}{4} \cos\theta\right) + A_2 \cos\left(\frac{\pi}{2} \cos\theta\right) \quad (2)$$

$$F'_E(\theta) = \sin\left(\frac{\pi}{4} \cos\theta\right) - A_2 \cos\left(\frac{\pi}{2} \cos\theta\right) \quad (3)$$

Where A_2 denotes the amplitude value of coupling from the two current sources of ME dipole and VPMP, and H is the height of VPMP (the size of H is near 0.25λ in this design). In addition, $F_1(\theta)$ is the radiation pattern of the dipole and $F_2(\theta)$

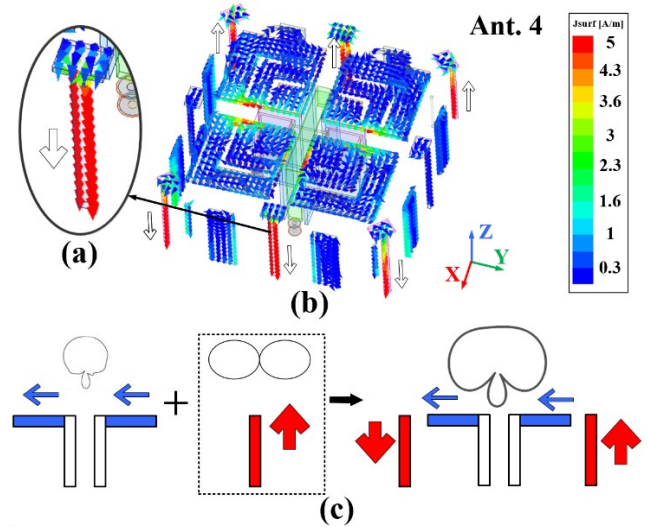


Fig. 10. Surface current distributions of (a) and (b) Ant. 4 at 1.8 GHz. (c) XOZ-plane beam expansion principle at 1.8 GHz.

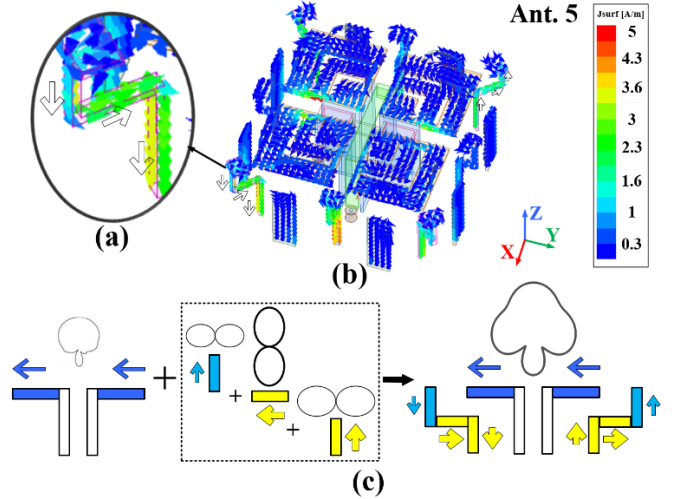


Fig. 11. Surface current distributions of (a) and (b) Ant. 5 at 1.8 GHz. (c) XOZ-plane beam expansion principle at 1.8 GHz.

is the radiation pattern of the VPMP, which is seen as a monopole [24]-[25].

Fig. 9(a) illustrates the radiation mechanism of the widebeam antenna, whose radiation pattern can be approximated by (2). As shown in Figs. 8 and 9(b), the VPMPs introduce oppositely directed currents with respect to the currents on the original radiator. Based on (3), when the radiation pattern associated with the VPMPs is superimposed on the original wide-beam pattern with a magnitude ratio of 0.3, the resulting pattern exhibits a narrower beamwidth. This mechanism accounts for the beamwidth reduction of Ant. 4 [26]-[28].

Therefore, the out-of-phase currents induced on the VPMPs reduce the beamwidth and consequently enhance the gain around 3.95 GHz. As shown in Figs. 9(c)-(f), the good agreement between the approximated and simulated radiation patterns validates the proposed VPMP-based beam-narrowing mechanism. In addition, the gain comparison in Figs. 7(a), 9(e), and 9(f) shows that Ant. 4 achieves a gain improvement from 4.8 to 7.5 dBi compared with Ant. 3, further confirming

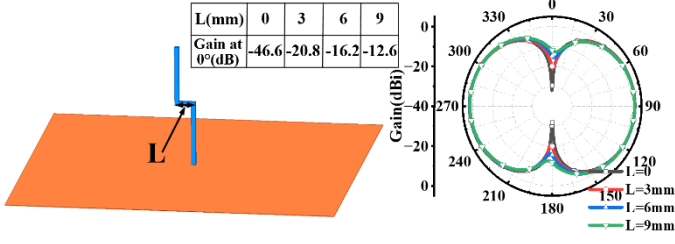


Fig. 12. The simplify model and the gain fluctuation.

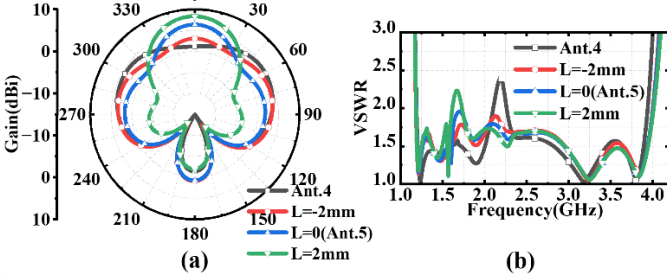


Fig. 13. Performance of Ant. 5. (a) Gain. (b) VSWR (L is the horizontal size of FMB).

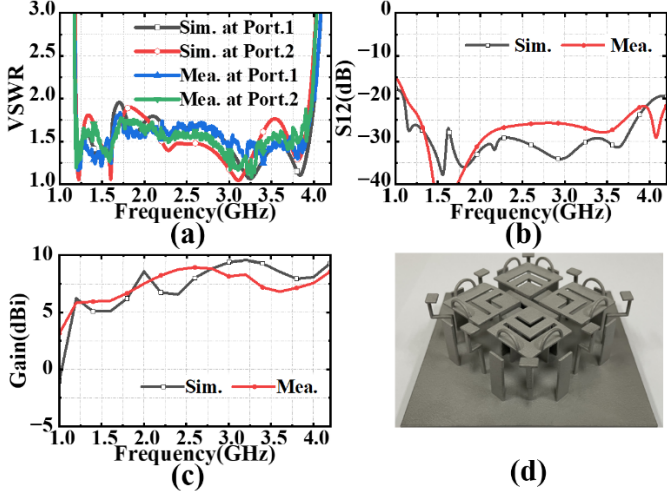


Fig. 14. Simulated and measured performances of the proposed antenna. (a) VSWRs. (b) S12. (c) Gains. (d) Photograph of the antenna prototype.

the effectiveness of the VPMPs in high-frequency gain enhancement.

As shown in Fig. 7(b), Ant. 4 still exhibits gain degradation and impedance mismatch in the lower frequency range. To investigate this issue, the current distributions of Ant. 4 at 1.8 GHz are presented in Figs. 10(a) and 10(b). Strong unidirectional currents are mainly concentrated on the vertical section of the metallic branch, leading to enhanced radiation in the horizontal direction. As illustrated in Fig. 10(c), the radiation components associated with these vertical currents are superimposed, resulting in an excessively broad beamwidth in the xoy-plane [13]. This broadened beamwidth accounts for the gain degradation of Ant. 4 at 1.8 GHz, as shown in Fig. 7(a).

To address these issues, the LPB is folded to form a folded metallic branch (FMB). The horizontal section of the FMB supports in-phase currents, which enhance the broadside radiation and reduce the beamwidth. As shown in Fig. 7(a),

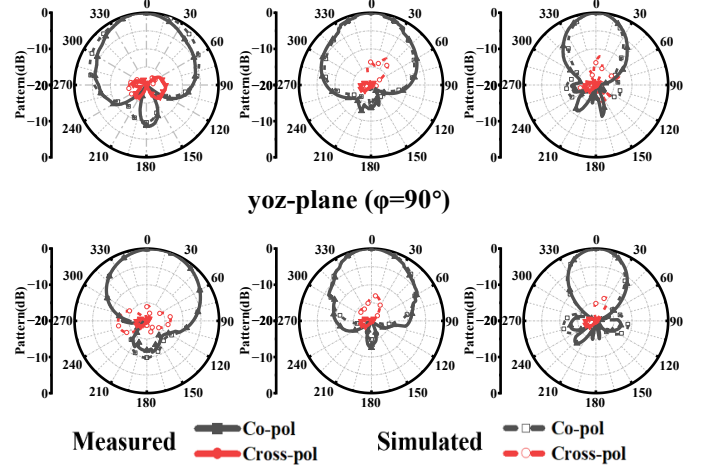


Fig. 15. Measured and simulated radiation patterns of the proposed antenna for port 1 in the xoz- and yoz-planes at 1.6, 2.6, and 3.6 GHz.

Ref	Bandwidth (%)	Gain (dBi)	Size ($\lambda_{\text{center}}^3$)	ISO (dB)
[13]	81.1 (3.3-7.8 GHz)	5.3	$0.74 \times 0.74 \times 0.30$	NG
[17]	78.6 (1.59-3.65 GHz)	10.4	$0.98 \times 0.98 \times 0.27$	>15
[18]	133.3 (1-5 GHz)	9.0	$0.75 \times 0.75 \times 0.55$	>18
[28]	55.3 (3.4-6.0 GHz)	9.2	$1.49 \times 1.49 \times 0.28$	NG
[29]	51 (3.2-5.4 GHz)	6.5	$0.83 \times 0.83 \times 0.18$	>16
Pro	108 (1.2-4 GHz)	9.0	$0.67 \times 0.67 \times 0.30$	>22

ISO: Isolation; NG: Not given.

the additional horizontal currents introduced by the FMB improve the gain at 1.8 GHz, and the corresponding simplified mechanism is illustrated in Fig. 11(c). To further clarify the role of the horizontal section, a simplified FMB model with the same ground-plane size as Ant. 5 is presented in Fig. 12. The broadside gain is observed to increase with the length of the folded section. Fig. 13 further shows the radiation patterns of Ant. 5 for different horizontal-section lengths, denoted as L. As L increases, the gain at 1.8 GHz improves from 1.2 to 6.2 dBi, confirming the effectiveness of the FMB in low-frequency gain enhancement. Considering the tradeoff between gain enhancement and impedance matching, L6=10 mm is selected for Ant. 5. Meanwhile, a wide operating bandwidth of 1.19–4.01 GHz, corresponding to 108.5%, is maintained.

D. Antenna Performance

A prototype of the proposed antenna was fabricated and measured to validate its bandwidth, isolation, and gain performance, as shown in Fig. 14. Fig. 14(a) presents the simulated and measured VSWRs when ports 1 and 2 are

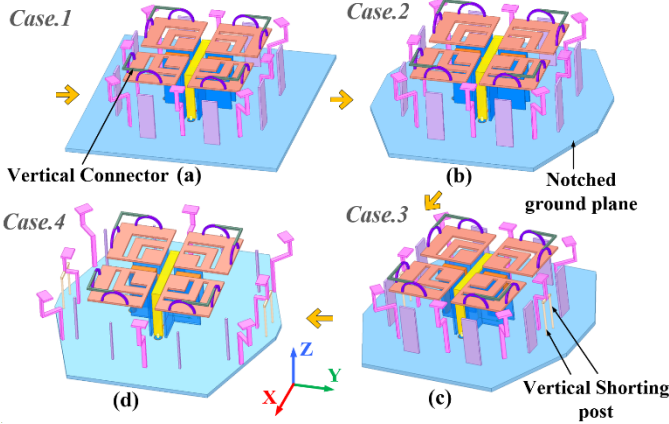


Fig. 16. Evolution of the ME dipole antenna. (a) Case. 1. (b) Case. 2. (c) Case. 3. (d) Case. 4.

excited individually, revealing an impedance bandwidth of 108% (1.2–4 GHz) and thus confirming the wideband design. A slight discrepancy in VSWR between the two ports arises from the differing dimensions of the two Γ -shaped probes. Meanwhile, Fig. 14(b) shows that the measured S12 parameter remains below -21 dB across the entire band, with most values falling beneath -30 dB, indicating excellent isolation. As depicted in Fig. 14(c), the simulated and measured gains remain within 7.2 ± 1.9 dBi across the band, which is consistent with the design objectives.

As illustrated in Fig. 15, the simulated and measured radiation patterns of port 1 at 1.6, 2.6, and 3.6 GHz in the xoz- and yoz-planes exhibit stable radiation and low backward radiation across the entire operating band. The measured cross-polarization levels in both planes are below -15 dB. Since the element is geometrically symmetric, the performance of ports 1 and 2 is expected to be nearly identical. Therefore, the radiation patterns of port 2 are omitted for brevity.

Table II provides a comparison between the proposed antenna and previously reported related designs. While the proposed design does not achieve the wider bandwidth or the higher gain, it provides a favorable tradeoff among bandwidth, gain, profile, and isolation, making it highly promising for multi-service IoT communication systems [36]–[38].

III. SIX-ELEMENT ANTENNA ARRAY

A. Antenna Array Design

As depicted in Fig. 16(a), a model with periodic boundary (PBC) conditions along the y-axis is established for the design of the one-dimensional array [39].

B. Mutual Coupling Suppression

First, mutual coupling between adjacent elements causes impedance mismatch at low frequencies, especially around 1.75 GHz. To mitigate this issue, four vertical connectors are employed to link the arched metal ring positioned on the upper layer of the electric dipole, thereby extending the current path. As a result, the active VSWR of port 1 in Case. 1 remains below 2 across the operating band, while port 2 shows only minor fluctuations at high frequencies.

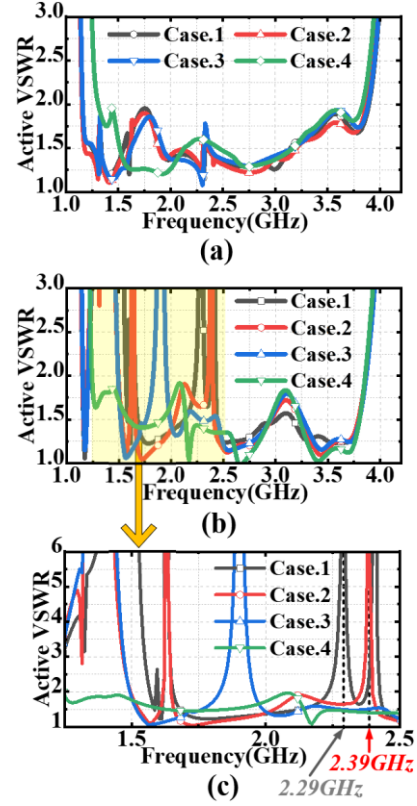


Fig. 17. Active VSWRs for port 1 (a) and port 2 (b), and (c).

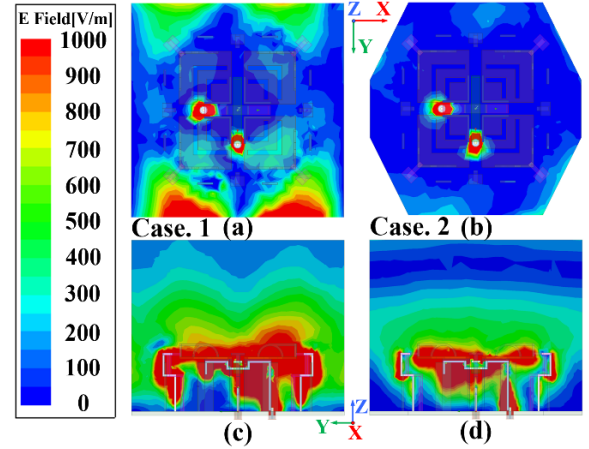


Fig. 18. Electric field distribution on XOY plane (a) and (b) and YOZ-plane (c) and (d) for Case. 1 and Case. 2 at 2.29 GHz.

Since the linear array is arranged along the y-axis, the structural evolution from Case. 1 to Case. 4 mainly affects port 2, while only slightly influencing the impedance matching of port 1, as shown in Fig. 17(a). Therefore, the following discussion focuses on the impedance matching of Port 2. As shown in Figs. 17(c) and 18(a), Case. 1 exhibits an electromagnetic resonance at 2.29 GHz, where mutual coupling significantly degrades impedance performance. To suppress this unwanted resonance, the ground plane is notched along its four edges in Fig. 16(c). Fig. 18(b) confirms that the notched ground plane disrupts the undesired resonance in Case. 2. The efficacy of the notched ground plane design is further validated by Figs. 17(c), 18(b), and 18(d).

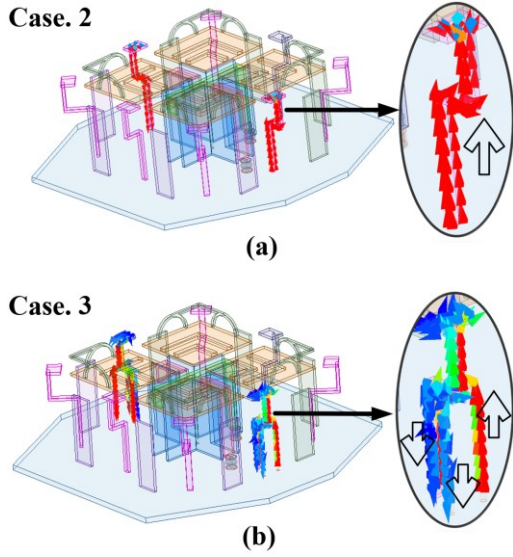
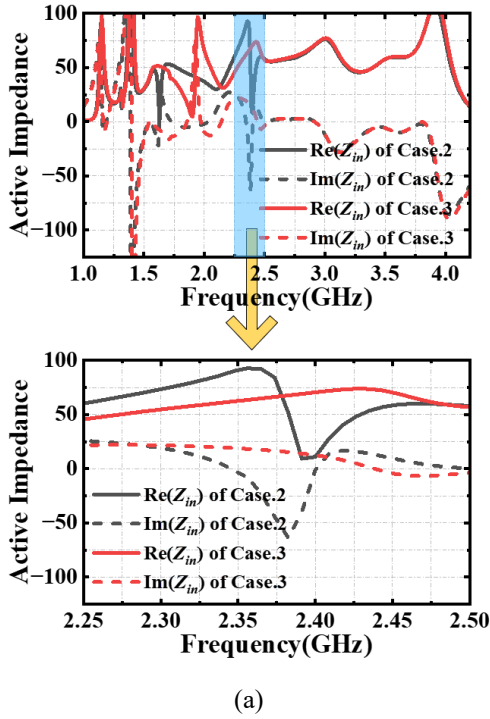
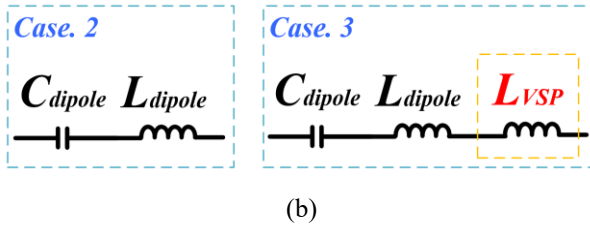


Fig. 19. Surface current distributions on (a) Case. 2 and (b) Case. 3 at 2.39 GHz.



(a)



(b)

Fig. 20. (a) Active input impedance of Case. 2 and Case. 3. (b) simply equivalent circuit between Case. 2 and Case. 3.

While one of the two dominant high frequency resonances in Case. 1 has been successfully suppressed, the unwanted resonance at 2.39 GHz still persists. To address this remaining issue, a pair of VSPs are incorporated exclusively into the folded metal branches (FMB) along the y-axis, as shown in

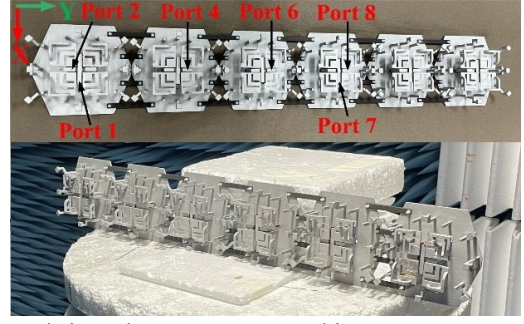


Fig. 21. Fabricated antenna array and its measurement view.

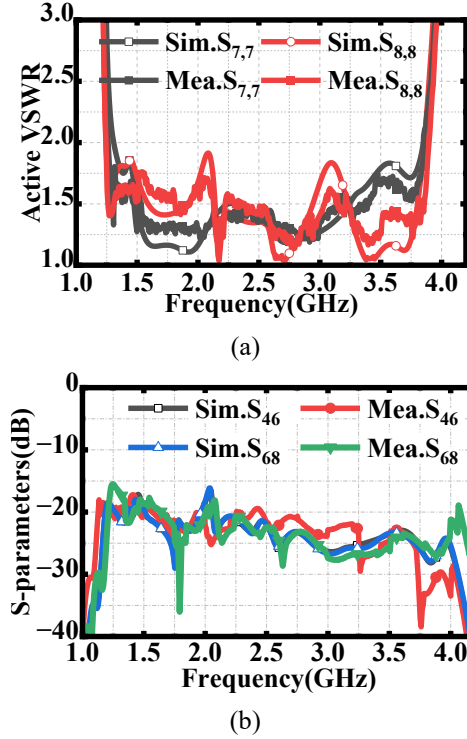


Fig. 22. Measured parameters of the proposed array. (a) Active VSWRs. (b) S-parameters.

Fig. 16(d). Compared with Case. 2, the VSPs in Case. 3 introduce opposing vertical currents, as shown in Fig. 19, reducing horizontal coupling [21]–[22]. To further clarify how the VSP suppresses the 2.39 GHz resonance in Case. 3, Fig. 20(a) compares the real and imaginary components of the active input impedances for the two designs. The VSP design maintains comparable resistance values, but the reactance in Case. 3 is minimized to near zero at 2.29 GHz, which is attributed to the inductance introduced by the VSP at this resonance point as seen in Fig. 20(b). This indicates that the VSP introduce additional inductive effects, which help suppress the resonance [40]–[43].

However, as depicted in Fig. 17(c), the use of only the notched ground plane and VSP is insufficient to fully resolve the resonance issue. Consequently, the dimensions and positions of the parasitic elements were slightly optimized in Case. 4, with this refinement validated by the active VSWR results. Ultimately, the one-dimensional ME dipole array antenna achieves an overlapping impedance bandwidth of 100% (1.27–3.84 GHz).

TABLE III
COMPARISON OF THE PROPOSED AND PREVIOUS ARRAYS

Ref	Ant. type	Bandwidth(%)	Scanning range	Side-lobe level (dB)	Profile ($(\lambda_{\text{center}})$)
[18]	ME dipole	133.3 (1-5 GHz)	$\pm 45^\circ$ (1-2GHz)/ $\pm 30^\circ$ (2-5GHz)	-8.6	0.55
[32]	Patch	32 (8-11 GHz)	$\pm 45^\circ$	-13	0.1
[33]	Dipole	26.1(2.0-2.6 GHz)	$\pm 50^\circ$	-8.8	0.05
[34]	Patch	16.1 (3.7-4.4 GHz)	$\pm 45^\circ$	Not Given	0.23
[35]	Dipole	66.7 (2.5-5.0 GHz)	$\pm 45^\circ$	-9.3	0.13
Pro	ME dipole	100 (1.26-3.85 GHz)	$\pm 45^\circ$(1.26-2GHz)/$\pm 30^\circ$(2-3.85GHz)	-9	0.3

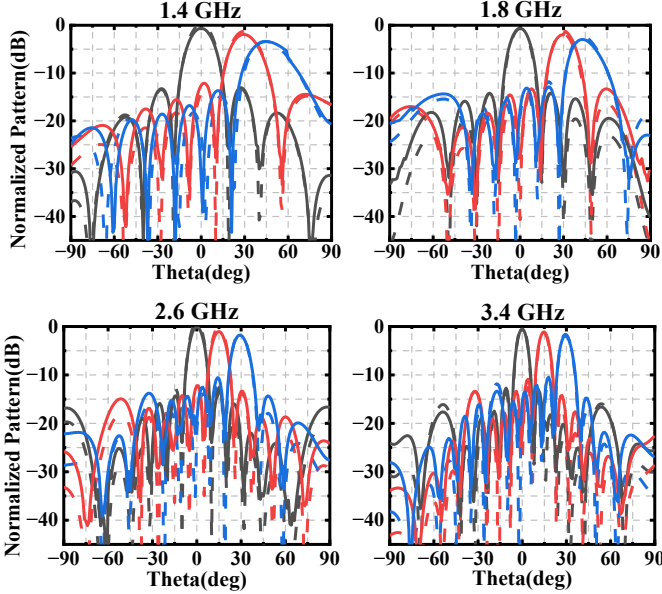


Fig. 23. Measured (solid line) and simulated (dashed line) scanning patterns of the proposed array in yoz-plane at selected frequencies (0° , 30° , and 45° at 1.4 and 1.8 GHz, 0° , 15° , and 30° at 2.6 and 3.4 GHz).

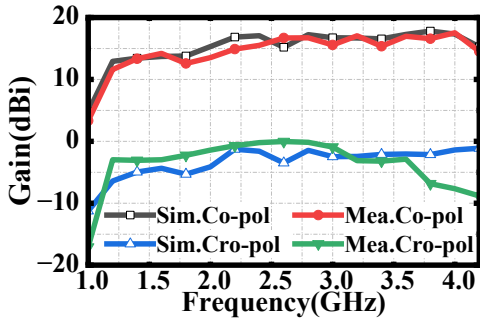


Fig. 24. Measured and simulated boresight gain in co-polarization and cross-polarization.

C. Experimental Verification and Results

Fig. 21 shows the fabricated array and the measurement setup. Fig. 22(a) depicts the simulated and measured active VSWR of center elements for ports 1 and 2 at broadside. Both ports exhibit an impedance bandwidth of 100% with the Active VSWR less than 2. Additionally, Fig. 22(b) shows the S-parameters of two adjacent elements, with measured values below -20 dB for both ports across the majority bandwidth. Similar coupling performance is observed across other

adjacent ports, though these are omitted here for clarity. With some variances, the measured and simulated S-parameters are almost in agreement. This is as a result of some manufacturing flaws in the actual processing. There are errors in the antenna test instruments, such as cables and the surrounding environment cannot achieve an ideal environment during the test.

Measured beam-scanning results at 1.4, 1.8, 2.6, and 3.4 GHz are omitted because of the bandwidth limitation of the available programmable phase shifter. Considering the emergence of grating lobes at higher frequencies, the main beam of the array can be scanned over $\pm 45^\circ$ across 1.26–2 GHz and $\pm 30^\circ$ across 2–3.85 GHz, as illustrated in Fig. 23. Good agreement is observed between the simulated and measured radiation patterns. Minor discrepancies in the side lobes are primarily attributed to port imbalances in the phase shifter and power splitter.

As seen in Fig. 24, the measured and simulated co-polarized gains are almost in agreement. Besides, in the operating band, measured results indicate that the gain changes from 14.5 to 17.5 dBi and the measured cross-polarization level remains at least -20 dB across most of the band, consistent with simulation results. Table III presents a comparison between the proposed array and recently reported wideband arrays, encompassing metrics such as bandwidth, scanning range, gain fluctuation, and side-lobe level (SLL). Notably, the proposed design achieves an ultra-wideband (UWB) response while demonstrating superior performance in fractional bandwidth, gain stability, and low SLL. It is further noteworthy that the proposed array features a lower profile ($0.3 \lambda_{\text{center}}$) than [18] ($0.55 \lambda_{\text{center}}$).

IV. CONCLUSION

A novel ME dipole antenna with stable gain has been presented for broadband IoT communication applications. Several design techniques are employed to improve impedance matching and expand the operating bandwidth. More importantly, the VPMP introduces out of phase currents to narrow the beamwidth, while the FMB provides additional vertical radiation, enabling stable gain across the entire operating bandwidth. Experimental validation demonstrates that the antenna achieves a measured impedance bandwidth of 108% (1.2–4 GHz) with a VSWR below 2, while exhibiting a broadside gain of 7.2 ± 1.9 dBi. Furthermore, VSP, as key component, introduces supplementary current paths that induce opposing currents in array design, effectively suppressing mutual coupling. Based on these merits, a one-

dimensional array antenna is developed. Measured results indicate that the array main beam can scan within $\pm 45^\circ$ across 1.26–2 GHz and $\pm 30^\circ$ across 2–3.85 GHz. These merits make the proposed design a promising candidate for consolidating multiple antenna functions in IoT communication systems.

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