

An Ultrawideband and Low-Profile Phased Array Design for Satellite-assisted Internet of Things Vehicular Communication

Liangliang Zhao, Hailiang Zhu, Aidong Li, Lehu Wen, *Senior Member, IEEE*,
Shi-Tong Wang, Kai-Cheng Wang, Huiling Zhao, and Chufeng Hu

Abstract—This article presents a low-profile dual-polarized phased array antenna featuring an improved feed structure and a multi-resonant wide-angle impedance matching (WAIM) layer for satellite-assisted Internet-of-Things (SATA-IoT) vehicular communications across the L-, S-, C-, and X-bands. First, an improved feed structure based on a double-sided multi-notch balun (DMB) is developed to provide stable impedance transformation and tailored field distribution, thereby enhancing impedance matching in the low- and mid-frequency bands. Second, a planar nonuniform metasurface (PNM)-based multi-resonant WAIM layer is introduced. By properly engineering its effective permittivity and permeability, two desired resonances together with inductive coupling are achieved, enabling wide-angle scanning performance in the high-frequency band. These two key techniques jointly allow the proposed array to realize ultrawide bandwidth, wide-angle scanning capability, and a low-profile configuration. To validate the design, a 5×5 prototype was fabricated and measured. The measured results show a 9:1 impedance bandwidth from 1.4 to 12.6 GHz. In particular, both array configurations exhibit an active VSWR below 3 at broadside, and maintain active VSWR below 3.3 for scan angles up to $\pm 70^\circ$ across the entire operating band. The overall profile is only $0.075 \lambda_{\text{low}}$. These results demonstrate that the proposed array is a promising candidate for SATA-IoT and related vehicular IoT communication systems.

Index Terms—Satellite-assisted Internet of Things (SATA-IoT) vehicle communication, ultrawideband, phased array.

This work was supported in part by the National Natural Science Foundation of China Grant 62371396 and in part by the National Natural Science Foundation of China Grant 62271407. (Liangliang Zhao and Hailiang Zhu, joint first authors, contributed equally to this work.) (Corresponding author: Hailiang Zhu)

Liangliang Zhao is with the School of Electronics and Information, Northwestern Polytechnical University, Xi'an 710129, China, and also with the State Key Laboratory of Terahertz and Millimeter Waves, Department of Electrical Engineering, City University of Hong Kong, Hong Kong, China. (e-mail: zll18@mail.nwpu.edu.cn).

Hailiang Zhu, Aidong Li, and Huiling Zhao are with the School of Electronics and Information, Northwestern Polytechnical University, Xi'an 710129, China (e-mail: zhuhl@nwpu.edu.cn; Liad@mail.nwpu.edu.cn; zhhl@nwpu.edu.cn).

Lehu Wen is with the Department of Electronic and Electrical Engineering, Brunel University London, UB8 3PH London, U.K. (e-mail: LehuWen@ieee.org).

Shi-Tong Wang and Kai-Cheng Wang are with the State Key Laboratory of Terahertz and Millimeter Waves, Department of Electrical Engineering, City University of Hong Kong, Hong Kong, China. (e-mail: stwang@cityu.edu.hk; kaicwang2-c@my.cityu.edu.hk).

Chufeng Hu is with the Science and Technology on UAV Laboratory, Northwestern Polytechnical University, Xi'an 710129, China (huchufeng@nwpu.edu.cn).



Fig. 1. Various scenarios of SATA-IoT vehicular communications.

I. INTRODUCTION

In recent years, the rapid advancement of the industrial Internet of Things (IoT) has facilitated its widespread adoption in smart homes, autonomous driving, smart cities, industrial manufacturing, and significantly enhancing daily-life convenience [1-10]. However, the massive volume of data transmission inevitably imposes burdens on communication platforms. To mitigate this challenge, ultra-wideband (UWB) technology has been integrated to enable high-speed data transmission and multifunctional communication for IoT systems. Additionally, constrained by harsh or special environments such as forest, oceans, and aerospace, satellite-assisted (SATA) communication has emerged as a viable solution and gained extensive application. Nevertheless, as illustrated in Fig. 1, to cover the multi-band operations (including GPS, GSM, WLAN, 5G, V2X, C, and X bands) and large scanning range (exceeding $\pm 60^\circ$), future SATA-enabled IoT (SATA-IoT) systems, catering to diverse application

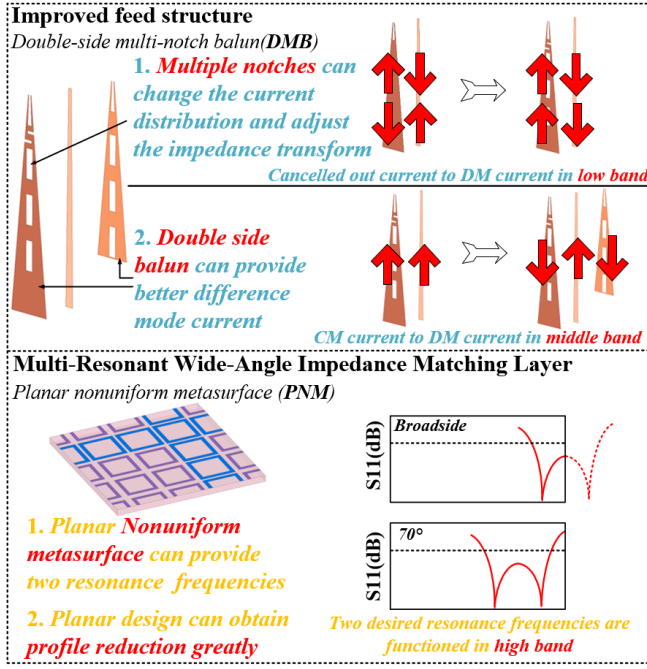


Fig. 2. Two key contributions of the proposed array.

scenarios, require multi-antenna configurations with extremely wide bandwidths and large-angle scanning capabilities. This inevitably gives rise to cross-band interference, increased installation space requirements, and elevated costs.

Inspired by the concept of current sheet arrays from wheeler, the tightly coupled dipole array (TCDA) inherently satisfies the concurrent requirements of UWB performance and compact size [11]-[22]. The ultrawideband characteristics of TCDA relies on a mechanism of intentionally intensified capacitive coupling between adjacent elements, which effectively counters the inductive effects caused by the ground plane [12]. Consequently, TCDAs are distinguished by their superior ultrawideband and wide-angle scanning capabilities, making them a rapidly emerging and highly attractive research topic for multi-IoT applications.

Several studies have demonstrated advanced TCDA designs with extended performance through improved feed structure and wide-angle impedance matching layer. For instance, a one-dimensional wideband TCDA employing a coplanar waveguide ground feeding network achieves a 2.7:1 bandwidth, with two rows of parasitic strips enabling a scanning range of $\pm 45^\circ$ [16]. Similarly, a millimeter-wave TCDA for vehicular communications incorporates a comb-structured Marchand balun, achieving a 7.6:1 bandwidth and a scanning capability of $\pm 45^\circ$ [17]. Additionally, a multi-layer wide-angle conjugate impedance matching superstrate extends the bandwidth beyond 5:1 and supports a scanning range of $\pm 70^\circ$. However, this comes at the expense of a high profile of $1.01 \lambda_{\text{high}}$ [18]. While these designs exhibit favorable radiation performance and broaden the applicability of TCDA, they are constrained by

single-polarization operation and a relatively restricted scanning range.

A design featuring an integrated Marchand balun achieves a 9:1 bandwidth and a $\pm 60^\circ$ scanning capability [20]. However, its profile of $0.102 \lambda_{\text{high}}$ will occupies more space due to the use of a bulky vertical double-layer FSS superstrate. Then, a metasurface-based wide-angle impedance matching (WAIM) superstrate enables the TCDA to obtain a 6.5:1 bandwidth with a reduced profile of $0.455 \lambda_{\text{high}}$ [21]. Moreover, a planar ultra-wideband modular antenna (PUMA) with dual-polarized design and a tapered feed structure employs horizontal dipoles to maintain a low-profile while achieving a 6.1:1 bandwidth [22]. These WAIM configurations, which employ multiple dielectric superstrates, typically increase fabrication complexity. Although these designs prioritize low profile and wide bandwidth, the scanning range remains limited to $\pm 45^\circ$, with additional bandwidth degradation during scanning. Furthermore, a shared-aperture TCDA achieves 23.2:1 bandwidth by combining low- and high-band dipoles, yet its scanning range is restricted to $\pm 30^\circ$ [23]. While these dual-polarized TCDAs achieve significantly enhanced operational bandwidth compared to earlier designs, the limited scanning range presents a substantial challenge. Meanwhile, various SATA-IoT communication modules, including the transmitter, receiver, amplifier, converter, and antenna system, are integrated together, which demonstrates the necessity of the compact design. Consequently, the development of low-profile array antenna that simultaneously maintains ultra-wideband and wide scanning coverage performance has emerged as a pivotal research challenge for TCDA in SATA-IoT vehicular communication.

In this work, a low-profile dual-polarized phased array antenna employing the improved feed structure and multi-resonant WAIM layer is proposed to enhance impedance matching and extend the scanning angle. The whole contributions of this work are summarized as follows,

- 1) The improved feed structure with the double-side multi-notch balun (DMB) can offer great impedance transform and adjust the field distribution, which greatly improves the impedance matching in low and middle bands.
- 2) By investigating and designing the multi-resonant WAIM layer with planar nonuniform metasurface (PNM), it provides two resonance frequencies and inductive coupling in the high band, so the PNM enables the array antenna to realize wide scanning in high band.

Based on these results, the proposed phased array antenna achieves a 9:1 bandwidth even when the array scans up to $\pm 70^\circ$, which also obtains a low-profile of $0.075 \lambda_{\text{low}}$.

This work focuses on the design of an UWB and low-profile phased array targeting SATA-IoT vehicular communication. Section II describes the geometry configuration of the proposed multiband array and the operating principle of this design.

TABLE I
OPTIMIZED DESIGN PARAMETERS SHOWN IN FIG. 2

Parameter	W1	W2	W3	W4	W5	W6	W7	W8	W9	H1
Value (mm)	12	2.44	2.68	6.2	1.92	3.6	2.95	2.5	5.48	13.3
Parameter	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11
Value (mm)	10.3	6.4	13.85	2	11.5	13.3	3.2	3	2.73	2.2

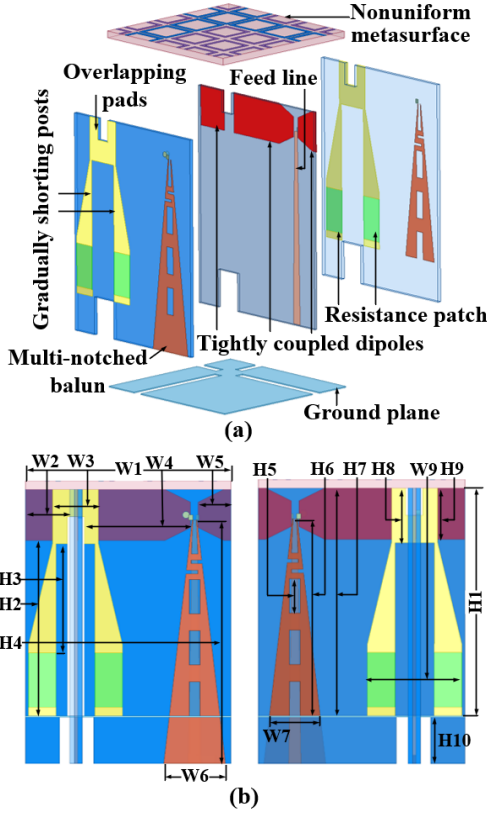


Fig. 3. Configuration of the proposed antenna. (a) Exploded view of the element. (b) Multiple views of the elements.

In section III, the measured array performances are provided and compared. The actual industrial application is introduced in Section IV. Finally, section V concludes this work.

II. ARRAY ELEMENT CONFIGURATION AND OPERATING PRINCIPLE

To provide a clearer description of our work, the key contributions are outlined as shown in Fig. 2. Firstly, the improved feed structure employing DMB adjusts the current distribution and ensures proper impedance transformation in the low and middle bands. Secondly, to achieve wide-angle scanning in the high band, PNM with the nonuniform design introduces two resonance frequencies, thereby improving the scan range at the target high-frequency band. This approach also results in a significant profile reduction with other previously reported TCDA. The detailed design guidelines of the proposed antenna will be discussed in the following section.

A. Antenna Element Configuration

The configuration of the proposed TCDA, incorporating the designs of DMB and PNM, is illustrated in Fig. 3. This model is designed and simulated using periodic boundary conditions. The unit cell is comprised of PNM, overlapping pads, tightly coupled dipoles, DMB, resistance patch, feed structure, and ground plane. Dual polarization is achieved through two orthogonally polarized planes within the antenna element. The structure includes three metal layers supported by two TLY-5 substrates, each with a relative dielectric permittivity $\epsilon_r=2.2$ and thickness $t=0.254$ mm. The overlapping pads and neighboring dipoles form strong capacitive coupling, while the ground reflector beneath the dipoles provides the inductance coupling,

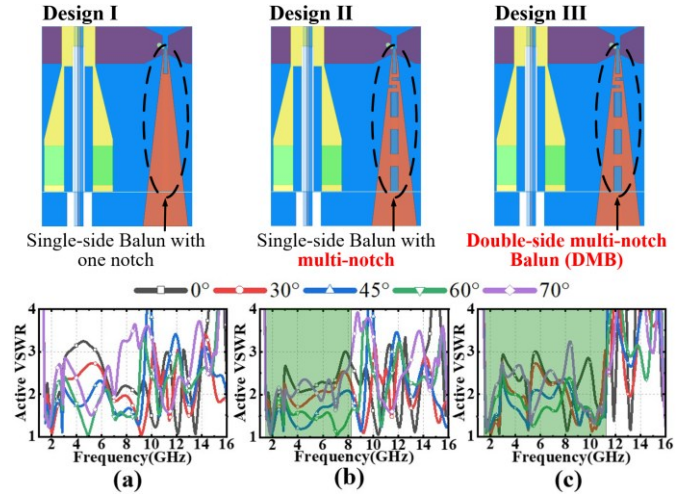


Fig. 4. Active VSWR at different scanning angles of the (a) TCDA with one notched balun, (b) TCDA with multi-notched balun and (c) TCDA with double-side multi-notch balun.

and the UWB characteristics are achieved by balancing the two adjacent parts. The feedline between double-side balun is utilized to excite the entire antenna. Notably, DMB and PNM techniques are employed to suppress the unwanted resonances and improve the scanning range. Additionally, the detailed sizes of the antenna are given in Fig. 3 and TABLE I.

B. Improved Feed Structure with DMB

1) Single-side balun with multi-notch for impedance enhancement at low band

To the best of our knowledge, the balun is a critical component for impedance transformation and plays an essential role in achieving impedance matching. Despite its significance, limited prior work has focused on enhancing balun performance to suppress undesired resonances. Therefore, the first contribution of this work lies in the development of an advanced balun design that effectively mitigates these undesired resonant modes. As shown in Fig. 4(a), the initial design as Design I, features a notched balun with poor impedance matching across the entire bandwidth. Inspired by the concept of using modified stripline with perforations for impedance matching in a Wilkinson power divider [24], etching suitable perforations on the balun can optimize the characteristic impedance. Therefore, several notches are added on the single-side balun in Design II to address impedance mismatches. To clearly illustrate the effect of additional perforations, the variations in active VSWR and characteristic impedance are presented in Fig. 5. The impedance mismatch occurs either in the low or middle band, hence the optimized notch design ($W0=0.64$ mm, $H5=2.0$ mm) is naturally selected. In Fig. 4(c), the optimized notched balun enables an impedance transformation from 50Ω to 240Ω , further verifying the effectiveness of the notched balun with selected parameters.

To describe the strategy more intuitively, the comparison of current distribution between different designs are given in Fig. 6. As seen in Fig. 6(a), it is observed that the induced current is canceled out, leading to deterioration in the radiation pattern. To overcome the drawback, introducing appropriate perforations in Design II proves to be an effective approach, as shown in Fig. 6(b), where the reflection current transitions to a normal differential mode (DM) current. Consequently, Design

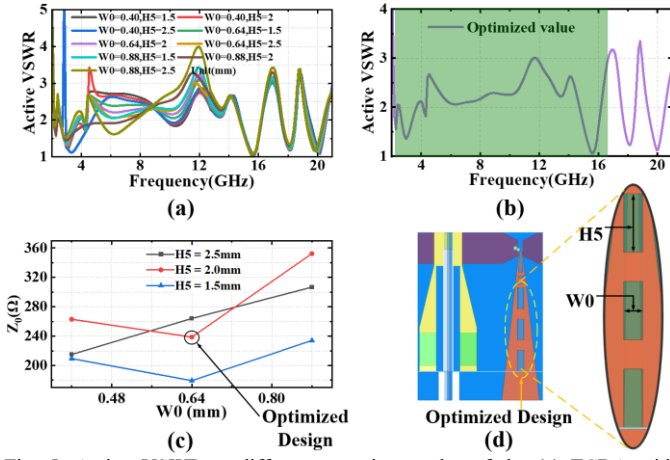


Fig. 5. Active VSWR at different scanning angles of the (a) TCDA with different size of multi-notched balun. (b) TCDA with the optimized multi-notched balun. (c) characteristic impedance of the notched balun. (d) the view of Design II with multi-notch.

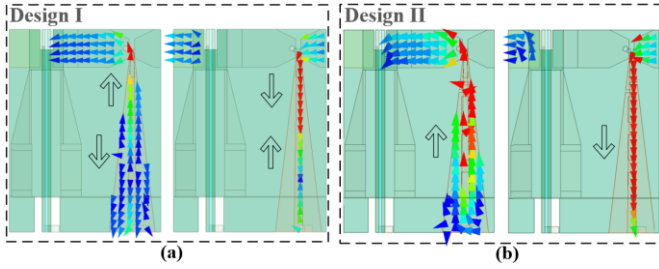


Fig. 6. Current distribution for (a) Design I and (b) Design II at 4 GHz.

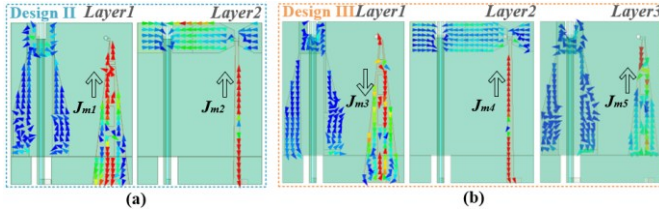


Fig. 7. Current distribution for (a) Design II and (b) Design III when scanning to 45° at 9.8 GHz.

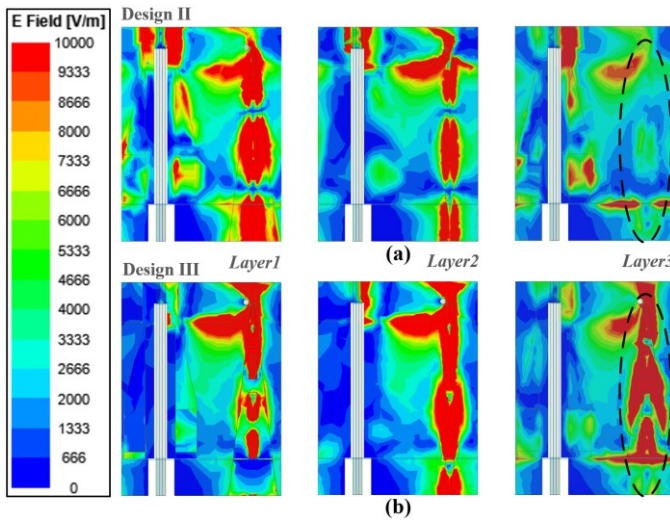


Fig. 8. Field distribution across the array unit cell between (a) Design II and (b) Design III when scanning to 45° at 9.8 GHz.

II loading single-side balun with multi-notch can obtain bandwidth of 5.86:1 (1.4-8.2 GHz) with active VSWR less than 3, indicating the effectiveness of the notched balun.

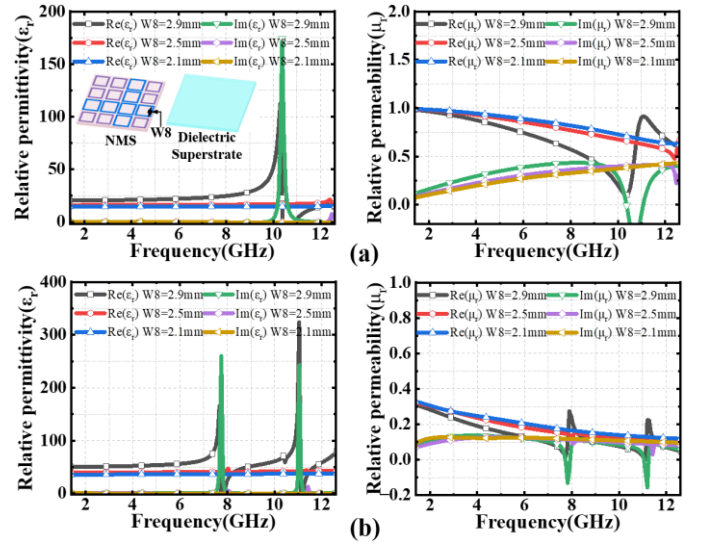


Fig. 9. Relative permittivity and relative permeability of the equivalent metasurface for different sizes ($W8$) at (a) Broadside and (b) 70°.

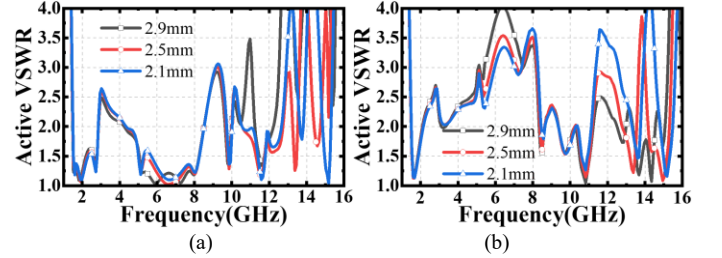


Fig. 10. Active VSWR of TCDA with different sizes ($W8$) of metasurface at (a) Broadside and (b) 70°.

2) DMB for CM suppression at middle band

Although the single-side balun with multi-notch realizes a broadband, the phenomenon of common mode (CM) resonance at high frequency caused by unbalanced-fed dipole feed still exists, which limits the bandwidth enhancement. In Fig. 7(a), more in-phase currents are observed in Design II due to the presence of CM currents, which adversely affects the radiation performance, particularly on the vertical dipoles. To address the issues arising from CM mode resonance, an additional multi-notch balun is incorporated into layer 3 to form DMB and the DM current is distributed on the DMB. To further highlight the importance of DMB, Fig. 8 compares the field distribution between Design II and Design III at 9.8 GHz. It can be found that a stronger electric-field concentration is observed around the feed structure in Design III after adding DMB [25]. By analyzing the variations in active VSWR, current distribution, and field distribution, Design III is capable of adjusting impedance transformation and controlling the field distribution for impedance enhancement at various scanning angles, hence the value of active VSWR remains less than 3 across the 8:1 (1.4-11.3 GHz) bandwidth as seen in Fig. 4(c).

C. Multi-resonant WAIM layer

1) Investigating characteristics of PNM

Generally, WAIM layer can avoid the scan blindness caused by surface waves and suppress the mutual coupling of adjacent elements [26]-[27]. Nevertheless, traditional WAIM layer has a thick and bulky dielectric. Although metasurface has been employed in TCDA [21], whereas the majority of structures feature simple design and are vertically oriented with a high

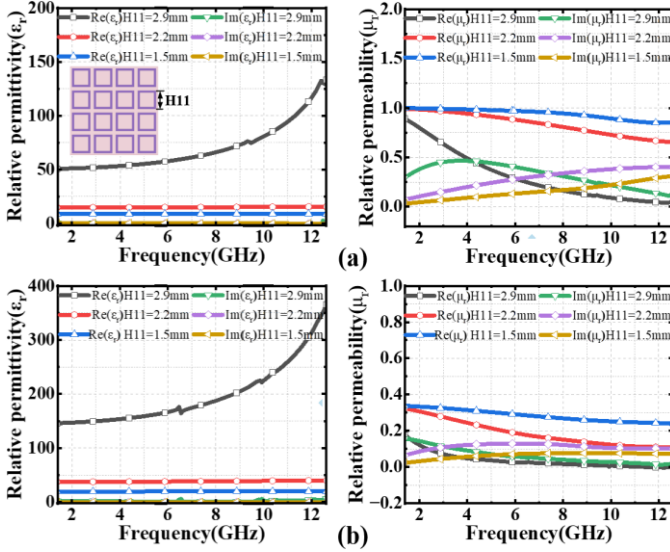


Fig. 11. Relative permittivity and relative permeability of the equivalent metasurface for different sizes (H11) at (a) Broadside and (b) 70°.

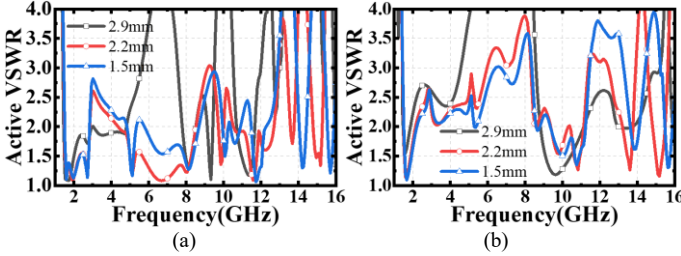


Fig. 12. Active VSWR of TCDA with different sizes (H11) of metasurface at (a) Broadside and (b) 70°.

profile, indicating a lack of extensive research and application of metasurface in TCDA.

To obtain the wide scanning range in higher band, we firstly introduce PNM as WAIM layer in TCDA, offering the merits of multi-resonant frequencies and more stable physical characteristics. Then, the permittivity and permeability of PNM are investigated and compared to elucidate the advantages of the proposed PNM. As seen in Fig. 9, the effect of loop width (W8) on PNM is examined for broadside and 70° scan conditions. It can be found that as the W8 increases, the value of the relative permittivity and permeability exhibit a pronounced fluctuation in the high band at broadside. Moreover, the other value fluctuation in relative permittivity and relative permeability occur at the middle frequency when scanning to 70°.

To further illustrate the aforementioned phenomenon from the perspective of the physical characteristics of PNM, a more detailed analysis is provided. As the scanning angle increases, the resonance frequency shifts to a lower frequency [28]. Consequently, as indicated by formula 1, the relative permittivity ϵ_r increases with the decrease in resonance frequency f [29], explaining why the relative permittivity ϵ_r at 70° is higher than the condition at broadside. These observations align with the variations in relative permittivity ϵ_r and permeability μ_r shown in Fig. 9. Furthermore, the active VSWR of TCDA with the PNM versus size of the loop width (W8) is illustrated in Fig. 10, demonstrating the impact of the PNM in proposed TCDA. It is evident that the active VSWR varies with the loop width (W8) in the high-frequency band. In

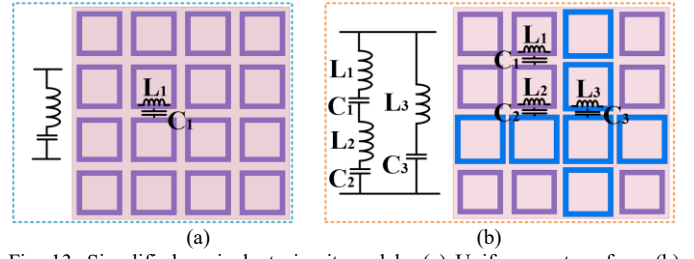


Fig. 13. Simplified equivalent circuit models. (a) Uniform metasurface. (b) PNM.

$$f = f_0 / \sqrt{\frac{1 + \epsilon_r}{2}} \quad (1)$$

summary, based on the study of PNM design and its application in TCDA, the proposed PNM (H11=2.2 mm, W8=2.5 mm) is selected, providing a viable design guideline for achieving a 1.4-12.6 GHz ultrawideband and a $\pm 70^\circ$ wide-angle scanning in this proposed antenna.

Under the same single-layer and fixed-thickness constraint adopted in this work, a uniform rectangular-loop metasurface tends to exhibit a dominant resonance. In Fig. 11(a), as the size of rectangular loop increases, the value of relative permittivity of the equivalent metasurface gradually increases, while the relative permeability of the equivalent metasurface decreases [30]. The simulated data for the relative permittivity and relative permeability of the equivalent metasurface at 70° is provided in Fig. 11(b). The plot indicates that the relative permittivity and relative permeability locus of the metasurface is larger than the broadside condition, consistent with the description of PNM. However, the optimized uniform metasurface design with size of H11 (2.2 mm) fails to achieve good impedance matching (active VSWR < 3) throughout the whole operating frequency band, as shown in Fig. 12. To alleviate these issues from the impedance mismatching at high frequency, the antenna with design of PNM is proposed.

$$Z_1 = Z_L + Z_C = j\omega L_1 + \frac{1}{j\omega C_1}, \omega_1 = \sqrt{\frac{1}{L_1 C_1}} \quad (2)$$

$$Z_2 = \frac{(j\omega L_1 + \frac{1}{j\omega C_1}) + (j\omega L_2 + \frac{1}{j\omega C_2}) \times (j\omega L_3 + \frac{1}{j\omega C_3})}{j\omega L_1 + \frac{1}{j\omega C_1} + j\omega L_2 + \frac{1}{j\omega C_2} + j\omega L_3 + \frac{1}{j\omega C_3}}, \omega_2 = \sqrt{\frac{C_1 + C_2}{C_1 C_2 (L_1 + L_2)}}, \omega_3 = \sqrt{\frac{1}{L_3 C_3}} \quad (3)$$

As shown in Fig. 13, the characteristics for the periodic structure of square loop are further studied from the side of equivalent circuit. The periodic structure of square loop has the characteristics of band-stop and single resonance frequency is generated as ω_1 at high band, as shown in Fig. 13(a) and formula 2. In contrast, for PNM with different resonance characteristics, two resonance frequencies are obtained as ω_2 and ω_3 , as shown in Fig. 13(b) and formula 3. Meanwhile, $\omega_2 < \omega_1$ is obvious, which means that a lower resonance frequency appears. Based on the above investigations, it can be observed that PNM provides two proper resonances by utilizing PNM, which can greatly facilitate the proposed TCDA to improve matching at broadside and while scanning down to $\pm 70^\circ$.

Moreover, the admittances of the fundamental Transverse Electric (TE) and Transverse Magnetic (TM) Floquet modes are listed in formula 4 [25]. Next, the impedance of each transmission line section when scanning in the E- and H-planes is set by combining formula 5.

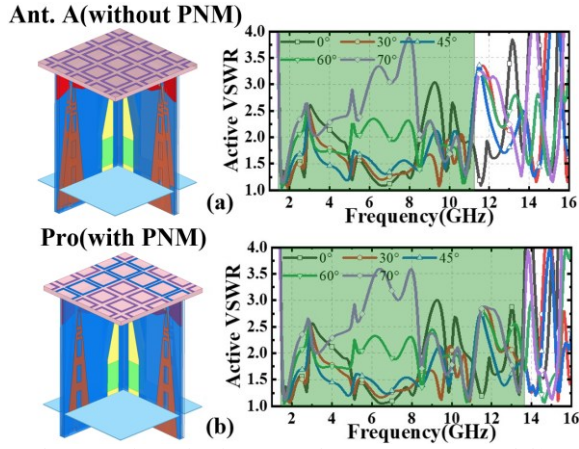


Fig. 14. The comparison of active VSWR between (a) Ant. A and (b) Pro.

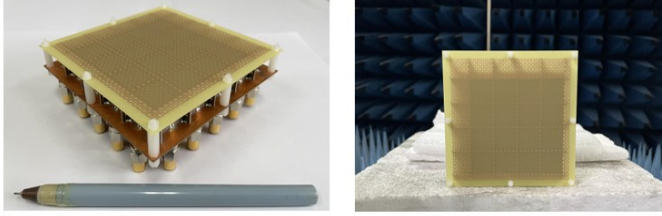


Fig. 15. Fabricated prototype of the 5x5 dual-polarized TCDA and its measurement scenario.

$$Y_{00}^{TE} = \frac{K_{z00}}{\omega\mu_0\mu_r}, Y_{00}^{TM} = \frac{\omega\epsilon_0\epsilon_r}{K_{z00}} \quad (4)$$

$$Z_r^E = \frac{d_E}{d_H} \frac{1}{Y_{00}^{TM}} = \eta \sqrt{\frac{\mu_r}{\epsilon_r}} \frac{d_E}{d_H} \cos\theta_r, Z_r^H = \frac{d_E}{d_H} \frac{1}{Y_{00}^{TE}} = \eta \sqrt{\frac{\mu_r}{\epsilon_r}} \frac{d_E}{d_H} \frac{1}{\cos\theta_r} \quad (5)$$

where K_{z00} denotes the propagation constant in the z -direction, θ represents the beam's scan angle, ϵ_r and μ_r are the relative material properties of each layer (i.e., substrate, superstrate, free space) and η is the characteristic impedance in free space. Furthermore, d_E and d_H are the length of the unit cell.

As shown in Figs. 11 and 12, the value of relative permittivity ϵ_r is increased significantly at each resonance frequency. Meanwhile, the relative permeability μ_r is decreased at the same frequency. The variation of relative permittivity ϵ_r and the relative permeability μ_r can lead to the improved impedance of each transmission line section when scanning in the E- and H-planes, as seen in formula 5. These explanations further validate the effectiveness of PNM, suggesting that the PNM-based WAIM can be a viable option for future ultrawideband phased-array apertures, subject to system-level validation.

2) PNM for bandwidth improvement and low-profile

In addition, the active VSWRs of Ant. A and the proposed design (Pro) are compared in Fig. 14. It is observed that some undesired resonances existing in high band cause impedance mismatch at various scan angles. To solve the issues, PNM with rectangular loop will provide more inductive coupling compared to Ant. A. More obviously, due to the introduction of PNM, the active VSWRs of Pro. are distinctly reduced at higher bands as shown in Fig. 14(b), leading to the bandwidth broadening. Compared to previous TCDA, this design employing the planar PNM not only achieves a wider operating frequency band and a larger scanning range, but also achieves a significantly lower profile.

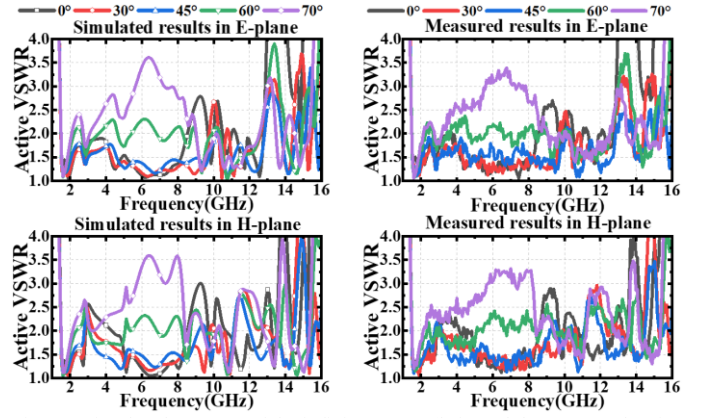


Fig. 16. Simulated VSWRs of the infinite TCDA (left) and the measured active VSWRs of the center element (right).

Generally, the concept of miniaturization consists of reducing phase velocity and ensuring excellent impedance matching, simultaneously [31].

$$v_p = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{\mu\epsilon}}, Z_0 = G\sqrt{\frac{L}{C}} = G\sqrt{\frac{\mu}{\epsilon}} \quad (6)$$

where L is the series inductance per unit length, C is the shunt capacitance per unit length, and G is a geometrical factor.

Material loading is an efficient way to modify the inductance and capacitance with $\epsilon_r > 1$ and $\mu_r > 1$. However, normal material has relatively stable permeability μ_r and permittivity ϵ_r , which is hard to meet the requirements of low phase velocity and great impedance matching. Obviously, PNM with proper permeability and permittivity provides a practical solution toward the realization of low-profile.

Based on the above these analyses, the proposed TCDA shows remarkable advantages in realizing UWB and wide-angle range, and the optimized profile is only $0.075 \lambda_{low}$, showing a huge profile reduction than others TCDA.

III. PROTOTYPE FABRICATION AND MEASUREMENT

A 5x5 prototype was fabricated and experimented to verify the characteristics of the proposed TCDA, as illustrated in Fig. 15. Mutual coupling measurements between the central and designated elements were conducted under matched termination conditions for all remaining ports of identical polarization [32]. Radiation patterns of TCDA are measured following the unit excitation active element pattern (UEAEP) method [33]-[34]. During measurements, each port is either excited via 50 Ω subminiature connectors or directly terminated with 50 Ω loads.

The active VSWRs of the antenna, scanning from broadside to 70°, are calculated, simulated, and plotted in Fig. 16. Measurement data confirm that the active VSWR remains below 3.3 throughout this angular range in both principal planes. Excellent agreement is observed between simulated and measured responses across the E- and H-planes for scanning angles up to 70°. The prototype demonstrates a 9:1 impedance bandwidth (1.4-12.6 GHz) under the VSWR < 3 criterion, once again verifies our design. Due to the small size of the prototype, the reflected electromagnetic wave from the edge of the array will result in multiple reflection in the finite array, hence, causing the slightly deterioration of the impedance matching and beam pointing error.

TABLE II
COMPARISON OF THE PROPOSED AND THE REFERENCE ARRAYS

Antenna	Type	Bandwidth	Profile	Scanning	Element size
[20] ²⁰¹⁹	TCDA	9:1 (2-18 GHz, VSWR<3)	0.102 λ_{low} (0.92 λ_{high})	E-60°/H-30° (VSWR<4)	0.48 λ_{high} ×0.48 λ_{high}
[35] ²⁰²⁵	PUMA	8:1 (1.8-14.6 GHz, VSWR<3)	0.085 λ_{low} (0.68 λ_{high})	E-45°/H-45° (VSWR<3.5)	0.56 λ_{high} ×0.56 λ_{high}
[36] ²⁰²⁵	Planar TCADA	3.72:1 (5.9-22 GHz, VSWR<3.5)	0.100 λ_{low} (0.37 λ_{high})	E-45°/H-45° (VSWR<3.5)	0.52 λ_{high} ×0.52 λ_{high}
[37] ²⁰²⁴	Planar CSA	4:1 (2–8 GHz, VSWR<3)	0.160 λ_{low} (0.64 λ_{high})	E-60°/H-60° (VSWR<3)	0.40 λ_{high} ×0.40 λ_{high}
[38] ²⁰²⁰	Vivaldi	8.15:1 (2.6-21.2 GHz, VSWR<3.2)	0.136 λ_{low} (1.11 λ_{high})	E-45°/H-45° (VSWR<3.8)	0.50 λ_{high} ×0.50 λ_{high}
Pro.	TCDA	9:1 (1.4-12.6 GHz, VSWR<3)	0.075 λ_{low} (0.67 λ_{high})	E-70°/H-70° (VSWR<3.3)	0.50 λ_{high}×0.50 λ_{high}

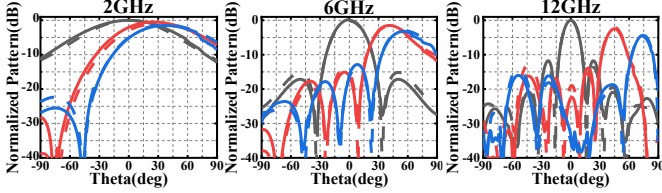


Fig. 17. Simulated (dashed line) and measured (solid line) normalized patterns in E-plane when scanning to 0°, 45°, 70° at 2, 6, and 12 GHz.

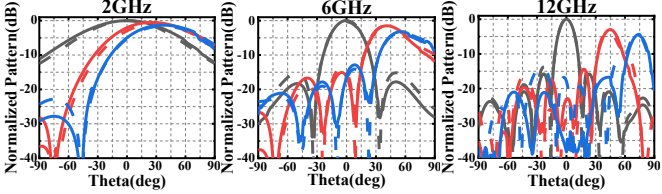


Fig. 18. Simulated (dashed line) and measured (solid line) normalized patterns in H-plane when scanning to 0°, 45°, 70° at 2, 6, and 12 GHz.

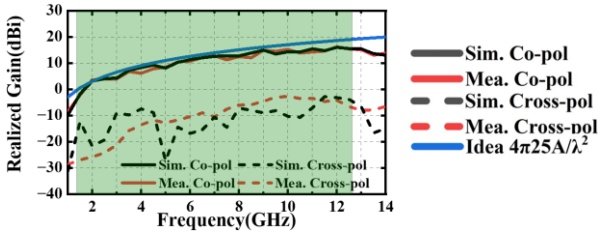


Fig. 19. Simulated and measured broadside realized gains of the proposed TCDA.

Normalized radiation patterns depicted in Figs. 17 and 18 illustrate the array's scanning performance from broadside to 70° in both principal planes. The close alignment between simulated and measured results at select frequencies (2, 6, and 12 GHz) validates the TCDA's consistent beam-steering behavior over a broad bandwidth. Due to the limited aperture of the prototype, the steering range of the beam is located at a smaller angle than the expected one. Note that as the scanning angle increases, the beam pointing error increases slightly, is attributed to beam spreading induced by the small array size. Thus, enlarging the array size can enhance the beam pointing accuracy [14]. Additionally, considering the manufacturing tolerances, transition loss, and measurement errors, the values are acceptable for active beam scanning arrays.

Fig. 19 presents a comparison between simulated and measured co- and cross-polarized gains for an embedded center element at broadside. Excellent agreement is observed across the operational bandwidth, with measured co-polarization maintaining a variation within ± 3 dBi of simulated values. Furthermore, the measured gain characteristics demonstrate close alignment with theoretical aperture gain predictions, confirming the TCDA's conformance to theoretical performance expectations. Moreover, there are some minor discrepancies between the simulated and measured curves,

which are mainly attributed to reflections from the feed cables, edge effects, and the small size of the array. The cross-polarization of H-plane scanning reaches a maximum of -20 dBi over the entire working band. Since the element is designed to be fully symmetrical, the above simulation results of radiation patterns are all in H-plane for brief.

For the proposed low-profile TCDA with DMB and PNM, comparisons among recently reported broadband TCDA are also presented in Table II. We can easily find that the proposed TCDA stands out for its design of DMB and PNM, which is designed to achieve ultra-wide bandwidth, large scanning angle, and low-profile. It is worth mentioning that PNM as the WAIM replaces the usual dielectric slab superstrate [39]-[42], implying much lower profile, lighter weight, simpler fabrication, and wider angular scanning. In addition, planar design can save more space for deploying other devices in wireless communication system. In short, considering the above parameters, the proposed phased array antenna shows a competitive merit compared to existing works in multiple IoT scenes [43]-[49]. Obviously, the proposed phased array featuring wideband coverage (L-band, S-band, C-band, and X-band) and wide-angle scanning ($\pm 70^\circ$) can substantially reduce costs and is well-suited for large-scale deployment in SATA-IoT vehicular communication terminals.

IV. CONCLUSION

To achieve a phased array with the merits of ultrawideband, wide-angle scanning, and low-profile simultaneously, these techniques of DMB and PNM are proposed to design a new antenna element. Firstly, by realizing better impedance transform and controlling field distribution, DMB is introduced to improve the impedance matching characteristics at low and middle bands. Then, by investigating and adjusting the relative permittivity and relative permeability of the equivalent metasurface, PNM introducing the two desired resonance frequencies obtains wider bandwidth and larger scanning range in high band, which is also helpful to achieve a low-profile ($0.075 \lambda_{\text{low}}$). Based on these, a configuration was fabricated and measured to verify the TCDA, which realizes 9:1 bandwidth (covering L, S, C, X bands) with active VSWR less than 3.3 at scan to $\pm 70^\circ$ in both E/H-planes. Future work will focus on system-level beamforming and spectrum-management constraints, which warrants further system-level validation for SATA-IoT and related IoT vehicular communication.

REFERENCES

- [1] J. J. Yang, J. Y. Li, S. G. Zhou, D. Li, and G. W. Yang, "A Polarization and Frequency Reconfigurable Microstrip Antenna for Vehicular Communication System Application," *IEEE Trans. Veh. Technol.*, vol. 72, no. 1, pp. 623-621, Jan. 2023.

- [2] R. Xu, S. Gao, J. Y. Li, K. Wei, and Q. Luo, "ARconfigurable Dual-Band Dual-Circularly Polarized Antenna for Vehicle Global Navigation Satellite System Application," *IEEE Trans. Veh. Technol.*, vol. 69, no. 10, pp. 11857-11867, Oct. 2020.
- [3] Z. H. Zhang, S. W. Wong, Y. Q. Wen, S. Q. Zhang, W. T. Li, and Y. J. He, "A Full-Metal Dual-Band Millimeter-Wave Antenna Array With Concomitant Multifold Orthogonal Beamforming for V2V and V2I Communications," *IEEE Trans. Veh. Technol.*, vol. 73, no. 7, pp. 10381-10389, Jul. 2024.
- [4] B. Feng, H. Li, L. Rao, X. Ding, C.-Y.-D. Sim, and K. L. Chung, "An aperture-shared vehicular antenna with large frequency ratio and pattern diversity for future 5G millimeter-wave and DSRC applications," *IEEE Trans. Veh. Technol.*, vol. 73, no. 2, pp. 1942-1956, Feb. 2024.
- [5] Z. Sun, X. Lv, X. Zhu, Z. Liang and Y. Yang, "A Dual-Band Circularly Polarized Antenna With Shared Aperture for Satellite-Assisted Internet of Things Communications," *IEEE Internet Things J.*, vol. 12, no. 7, pp. 8461-8469, Apr. 2025.
- [6] Y. -H. Ke, J. Zhou and J. -X. Chen, "Dual-Band Dual-Polarized Omnidirectional MIMO Antenna With Ultra-Low Profile for Vehicular Communications," *IEEE Trans. Veh. Technol.*, vol. 74, no. 6, pp. 9240-9251, June 2025.
- [7] S.-T. Wang, and L. Zhu, "Single- and dual-beam pattern reconfigurable patch antenna with dual switchable CP for Internet of Vehicles," *IEEE Internet Things J.*, vol. 12, no. 12, pp. 21904-21914, Jun. 2025.
- [8] W. An, X. Zhang, W. Zhao, Y. Luo, M. Li and K. Ma, "A Triple-Band Broadband Antenna for the Internet of Vehicles," *IEEE Trans. Veh. Technol.*, vol. 74, no. 11, pp. 17235-17246, Nov. 2025.
- [9] L. Zhao et al., "Design of Wideband Co-Linearly-Polarized Magnetolectric Dipole Antenna With Stable Gain for Vehicular Sensing and Communications," *IEEE Trans. Veh. Technol.*, doi: 10.1109/TVT.2025.3650047.
- [10] J. -W. Huang, R. -Y. Guo, R. Gao and Q. -Y. Guo, "Design of a High-Gain Duplex Antenna With Multibeam Radiation Based on a Fabry-Pérot Cavity," *IEEE Trans. Veh. Technol.*, vol. 74, no. 6, pp. 8966-8974, June 2025.
- [11] H. Wheeler, "Simple relations derived from a phased array made of an infinite current sheet," in *Proc. Antennas Propag. Soc. Int. Symp.*, vol. 2, pp. 157-160, Sep. 1964.
- [12] J. P. Doane, K. Sertel and J. L. Volakis, "A Wideband, Wide Scanning Tightly Coupled Dipole Array with Integrated Balun (TCDA-IB)," *IEEE Trans Antennas Propag.*, vol. 61, no. 9, pp. 4538-4548, Sept. 2013.
- [13] Y. Wang, L. Zhu, H. Wang, Y. Luo and G. Yang, "A Compact, Scanning Tightly Coupled Dipole Array With Parasitic Strips for Next-Generation Wireless Applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 4, pp. 534-537, Apr. 2018.
- [14] A. O. Bah, P. -Y. Qin, R. W. Ziolkowski, Y. J. Guo and T. S. Bird, "A Wideband Low-Profile Tightly Coupled Antenna Array With a Very High Figure of Merit," *IEEE Trans Antennas Propag.*, vol. 67, no. 4, pp. 2332-2343, Apr. 2019.
- [15] Y. Yang, Y. L. Wu, B. W. Xu, W. S. Chan and S. Y. Zheng, "A Reconfigurable Switched-Beam System With Single/Dual-Lobe and Wide-Beam Radiation Patterns," *IEEE Trans Antennas Propag.*, vol. 73, no. 3, pp. 1585-1596, Mar. 2025.
- [16] J. X. Sun, Y. J. Cheng and Y. Fan, "Planar Ultra-Wideband and Wide-Scanning Dual-Polarized Phased Array With Integrated Coupled-Marchand Balun for High Polarization Isolation and Low Cross-Polarization," *IEEE Trans Antennas Propag.*, vol. 69, no. 11, pp. 7134-7144, Nov. 2021.
- [17] J. Wang, X. Zhao, Y. Ye and S. Liu, "A Millimeter-Wave Ultrawideband Tightly Coupled Dipole Array Antenna for Vehicle Communication," *IEEE Antennas Wireless Propag. Lett.*, vol. 21, no. 10, pp. 2135-2139, Oct. 2022.
- [18] C. H. Hu, B. Z. Wang, G. F. Gao, R. Wang, S. Q. Xiao and X. Ding, "Conjugate Impedance Matching Method for Wideband and Wide-Angle Impedance Matching Layer With 70° Scanning in the H-Plane," *IEEE Antennas Wireless Propag. Lett.*, vol. 20, no. 1, pp. 63-67, Jan. 2021.
- [19] K.-C. Wang, S. Gao and H. Wong, "A Single-Fed Dual-Band Shared-Aperture Endfire Antenna With Independent Band Control," *IEEE Trans Antennas Propag.*, vol. 73, no. 7, pp. 4311-4319, Jul. 2025.
- [20] J. Zhong, A. Johnson, E. A. Alwan and J. L. Volakis, "Dual-Linear Polarized Phased Array With 9:1 Bandwidth and 60° Scanning Off Broadside," *IEEE Trans Antennas Propag.*, vol. 67, no. 3, pp. 1996-2001, Mar. 2019.
- [21] D. M. Sun, Z. C. Hao, C. Y. Ding, R. J. Liu, Z. J. Guo and H. Y. Yin, "A Low-Profile Ultra-Wideband and Wide-Scanning Phased Array for UHF Applications," *IEEE Trans Antennas Propag.*, vol. 71, no. 1, pp. 473-486, Jan. 2023.
- [22] D. M. Sun, Z. C. Hao, H. J. Gang, C. Y. Ding, W. Y. Liu and Z. W. Miao, "A Planar UHF-Band Ultrawideband Modular Antenna Array With Tapered Probes Feed," *IEEE Trans Antennas Propag.*, vol. 72, no. 2, pp. 1483-1496, Feb. 2024.
- [23] S. Zhang, Y. Chen and S. Yang, "An Extremely Wideband Tightly Coupled Dipole Array With Shared-Aperture Configuration," *IEEE Antennas Wireless Propag. Lett.*, vol. 22, no. 6, pp. 1366-1370, Jun. 2023.
- [24] L. L. Zhao, H. L. Zhu, C. Ding, G. Y. Liu, H. L. Zhao, J. C. Mou, and Y. J. Guo., "An Ultrawideband Dual-Polarized Tightly Coupled Dipole Array (TCDA) With Wide Scanning Range," *IEEE Antennas Wireless Propag. Lett.*, vol. 23, no. 7, pp. 1961-1965, Jul. 2024.
- [25] E. Yetisir, N. Ghalichechian and J. L. Volakis, "Ultrawideband Array With 70° Scanning Using FSS Superstrate," *IEEE Trans Antennas Propag.*, vol. 64, no. 10, pp. 4256-4265, Oct. 2016.
- [26] C. Yang, G. -B. Wu, K. F. Chan and C. H. Chan, "Linear-to-Circular Polarization Conversion Metasurface With Broadband Independent Amplitude/Phase Control for Sidelobe Suppression," *IEEE Trans Antennas Propag.*, vol. 71, no. 12, pp. 9944-9949, Dec. 2023.
- [27] L. Zhao et al., "Design of Wideband Dual-polarized ME Dipole Antenna With Parasitic Elements and Improved Feed Structure," *IEEE Antennas Wireless Propag. Lett.*, vol. 22, no. 1, pp. 174-178, Jan. 2023.
- [28] B. A. Munk, *Frequency Selective Surfaces: Theory and Design*. Hoboken, NJ, USA: Wiley, 2000, pp. 125-189.
- [29] T. K. Wu, "Four-band frequency selective surface with double-square-loop patch elements," *IEEE Trans Antennas Propag.*, vol. 42, no. 12, pp. 1659-1663, Dec. 1994.
- [30] X. L. Chen, P. Wang, Y. Shao, and H. Y. Jin, "Gradient Relative Permittivity Superstrate for Decoupling of Two Closely Located Dual-Polarized Slot Antennas," *IEEE Trans Antennas Propag.*, vol. 70, no. 4, pp. 3046-3051, Apr. 2020.
- [31] B. J. Wang, S. W. Yang, Z. Z. Zhang, Y. K. Chen, S. W. Qu, and J. Hu, "A Ferrite-Loaded Ultralow Profile Ultrawideband Tightly Coupled Dipole Array," *IEEE Trans Antennas Propag.*, vol. 70, no. 3, pp. 1965-1975, Mar. 2022.
- [32] N. Liu, S. W. Qu, and S. Yang, "Dual-polarized phased array with ultralow profile for wide-angle scanning application," *IEEE Antennas Wireless Propag. Lett.*, vol. 23, pp. 613-617, 2024.
- [33] D. Pozar, "The active element pattern," *IEEE Trans Antennas Propag.*, vol. 42, no. 8, pp. 1176-1178, Aug. 1994.
- [34] L. L. Zhao, H. Zhu, Y. Di, H. Zhao, J. Mou, and C. Hu, "Design of joinable antenna array with wide-angle scanning," *IEEE Antennas Wireless Propag. Lett.*, vol. 24, no. 2, pp. 479-483, Feb. 2025.
- [35] J. Xu et al., "A Dual-Polarized PUMA Array With 8.1:1 Bandwidth and 45° Scanning Off Broadside Using Dual-Layer

- Dipoles," *IEEE Trans Antennas Propag.*, vol. 73, no. 9, pp. 6979-6984, Sept. 2025.
- [36] D. -M. Sun, W. -Y. Liu, Z. -C. Hao and S. Gao, "A 6–21 GHz Dual-Polarized Planar Wide-Scanning Phased Array Antenna for Upper Mid-Band 6G Applications," *IEEE Trans Antennas Propag.*, vol. 73, no. 11, pp. 8475-8489, Nov. 2025.
- [37] R. Ozzola, A. Neto, U. Imberg, and D. Cavallo, "Connected slot array with interchangeable ADL radome for sub-8 GHz 5G applications," *IEEE Trans Antennas Propag.*, vol. 72, no. 1, pp. 992–997, Jan. 2024.
- [38] R. W. Kindt and J. T. Logan, "Dual-Polarized Metal-Flare Sliced Notch Antenna Array," *IEEE Trans Antennas Propag.*, vol. 68, no. 4, pp. 2666-2674, Apr. 2020.
- [39] W. Wang, Q. Cao and Y. Zheng, "Bandstop Frequency-Selective Structures Based on Stepped-Impedance Loop Resonators: Design, Analysis, and Measurement," *IEEE Trans Antennas Propag.*, vol. 67, no. 2, pp. 1053-1064, Feb. 2019.
- [40] W. Wang, S. Yang, Z. Fang, Q. Sun, Y. Chen and Y. Zheng, "Compact Dual-Polarized Wideband Antenna With Dual-/Single-Band Shifting for Microbase Station Applications," *IEEE Trans Antennas Propag.*, vol. 69, no. 11, pp. 7323-7332, Nov. 2021.
- [41] W. Wang and Y. Zheng, "Wideband Gain Enhancement of High-Isolation Fabry–Pérot Antenna Array With Tandem Circular Parasitic Patches and Radial Gradient PRS," *IEEE Trans Antennas Propag.*, vol. 69, no. 11, pp. 7959-7964, Nov. 2021.
- [42] W. Wang et al., "Wideband Gain Enhancement of MIMO Antenna and Its Application in FMCW Radar Sensor Integrated With CMOS-Based Transceiver Chip for Human Respiratory Monitoring," *IEEE Trans Antennas Propag.*, vol. 71, no. 1, pp. 318-329, Jan. 2023.
- [43] Y. F. Wu, G. Zhuang, S. L. Liu, Y. Chai and Y. J. Cheng, "FOWLP-Based THz Quasi-Omnidirectional Antenna-in-Package for Chip-to-Chip Wireless Interconnect in AIoT," *IEEE Internet Things J.*, vol. 13, no. 3, pp. 4964-4974, 1 Feb. 1, 2026.
- [44] Y. F. Wu, Y. J. Cheng, Y. C. Zhong and H. N. Yang, "Substrate Integrated Waveguide Slot Array Antenna to Generate Bessel Beam With High Transverse Linear Polarization Purity," *IEEE Trans Antennas Propag.*, vol. 70, no. 1, pp. 750-755, Jan. 2022.
- [45] S. Shuai, G. Deng, J. Lin, H. Su, H. Huang and X. Y. Zhang, "Ultra-Wideband Omnidirectional Filtering Antenna for Vehicular Communications Based on Coupled Mode Theory and Cross Coupling," *IEEE Trans. Veh. Technol.*, doi: 10.1109/TVT.2025.3645260.
- [46] Y. F. Wu, Q. You, Y. Zhang, Y. Guo and Y. J. Cheng, "Sidelobe Level Reduction for a W-Band SIW Slot Array Antenna by Only Reversing Offset Direction of Partial Slots," *IEEE Trans Antennas Propag.*, vol. 71, no. 10, pp. 8360-8365, Oct. 2023.
- [47] Y. Chen, L. Zhang, Y. He and Z. N. Chen, "A Polarization and Radiation Beam Reconfigurable Integrated Antenna With Broadband and High Gain for mmWave Vehicular Communication," *IEEE Trans. Veh. Technol.*, vol. 74, no. 3, pp. 4526-4538, March 2025.
- [48] W. Wang et al., "Compact Quad-Element Vertically-Polarized High-Isolation Wideband MIMO Antenna for Vehicular Base Station," *IEEE Trans. Veh. Technol.*, vol. 69, no. 9, pp. 10000-10008, Sept. 2020.
- [49] W. Wang and Y. Zheng, "Wideband Gain Enhancement of a Dual-Polarized MIMO Vehicular Antenna," *IEEE Trans. Veh. Technol.*, vol. 70, no. 8, pp. 7897-7907, Aug. 2021.