

Design and Experiment of a Conformal Antenna with Reconfigurable Multi-Mode Radiation Patterns

Lijing Qin, Yanzhe Wang, Yuxin Gao, Shuai Zou, Chuang Wang*, Wenquan Cao

College of Communication Engineering, Army Engineering University of PLA, Nanjing, 21007, China

Corresponding Author: Chuang Wang (cwang@aeu.edu.cn)

Abstract: To address the application requirements of limited onboard space for unmanned aerial vehicles (UAVs) and the need for full communication coverage across multiple airspace domains, this paper conducts design and experimental research on a conformal antenna with reconfigurable multi-mode radiation patterns. First, based on the phase regulation mechanism of odd and even modes, a low-profile broadband broadside-beam reconfigurable antenna element is designed. By switching between single-port and dual-port in-phase/anti-phase feeding, four radiation beams are achieved: omnidirectional, broadside, left-tilted, and right-tilted. The measured effective bandwidth ranges from 2.23 GHz to 2.60 GHz (relative bandwidth of 15.4%), with a peak gain of 5.80 dBi, enabling wide-range beam coverage in the vertical plane. Second, utilizing PIN diode switching control technology, a broadband end-fire beam pattern reconfigurable antenna element is designed. By switching the device states, four end-fire beams with different orientations in the horizontal plane are obtained. The operating frequency band is 2.26 GHz to 2.83 GHz (relative bandwidth of 23.8%), with a maximum gain of 4.47 dBi in the directional mode. The 3-dB beamwidth for all operating states exceeds 90°, achieving full 360° coverage in the horizontal plane. Finally, the two types of antenna elements are integrated and conformally arranged on the surface of the UAV carrier. Without additional increases in antenna profile or volume, the radiation advantages of wide coverage in the elevation plane and omnidirectional scanning in the horizontal plane are combined, enabling multi-modal beam cooperative reconfiguration. The measured results demonstrate that the integrated conformal antenna offers the advantages of wide bandwidth, multi-beam switching capability, low profile, and carrier conformality. It can significantly expand the UAV communication airspace coverage range and is well-suited for communication conditions in clustered UAV cooperative networking, showing practical value and application potential in the field of airborne wireless communication equipment.

Keywords: Pattern reconfigurable; Multi-mode; Conformal antenna

1. Introduction

communication technology, wireless communication scenarios and functions have become increasingly complex [1]. As the core radio frequency front-end device of UAV communication systems, antennas need to possess comprehensive performance characteristics such as low profile, wide bandwidth, wide beam coverage, and fast beam switching to meet the requirements of

multi-UAV networking communication. Traditional airborne antennas have a single beam direction and limited spatial coverage capability, making it difficult to simultaneously meet the demands for wide-range communication in both the elevation and horizontal planes, and thus unsuitable for dynamic multi-UAV networking application scenarios. Pattern reconfigurable antennas, due to their low cost, high integration, ability to adaptively switch beams, and intelligent radiation control, have become a research hotspot [2-6].

Existing pattern reconfigurable antennas, while capable of dynamic beam switching and offering certain radiation state control, generally suffer from drawbacks such as large profile size, narrow operating bandwidth, and limited beam coverage. For instance, traditional planar reconfigurable antennas [7-9] often rely on multi-layer substrate stacking and complex feed network designs. Narrowband reconfigurable antennas [10-12] can only adapt to a single narrow frequency band, failing to meet the requirements of multi-service communication frequency bands such as telemetry, tracking, and data transmission. Moreover, their beams are mostly designed as directional narrow beams, making it difficult to achieve wide-area coverage over a large airspace. Additionally, UAV platforms have limited payload capacity and extremely high requirements for aerodynamic performance. Traditional antennas occupy onboard space, increase flight resistance, and compromise stealth characteristics. Therefore, conformal design has become an inevitable trend in UAV antenna design. In response to the application scenarios of UAVs with limited payloads and diverse communication needs, research on pattern reconfigurable conformal antennas holds significant engineering value [13-14]. Such antennas can be integrated onto the surface of UAV carriers using low-profile conformal antenna structures, effectively saving onboard installation space and reducing aerodynamic drag. Through dynamic reconfigurable control of beam direction, wide beam coverage can be achieved while expanding the operating bandwidth to satisfy the requirements of UAV networking applications.

This paper conducts design and experimental research on a reconfigurable multi-mode radiation pattern conformal antenna. Specifically, a broadside-beam reconfigurable antenna unit based on odd-even mode phase control and an end-fire-beam reconfigurable antenna unit controlled by PIN diodes are designed. After completing the design of both antenna units, they are conformally integrated onto the surface of a UAV carrier. This approach eliminates the need for additional antenna volume or increased profile height, effectively expands the beam coverage in space, enhances the multi-mode radiation adaptability of the UAV platform in networking applications, and demonstrates promising application prospects in the field of UAV communication.

2. Antenna Design and Analysis

2.1 Antenna Design

The proposed low-profile, full-space beam coverage, multi-mode pattern reconfigurable antenna structure for UAV platforms is shown in Figure 1. The antenna consists of a low-profile broadside-beam pattern reconfigurable antenna element and a low-profile endfire-beam pattern reconfigurable antenna element. The low-profile broadside-beam pattern reconfigurable antenna element can reconfigure four different beam states—omnidirectional, broadside, left oblique, and right oblique—by switching between single-port (P1/P2) excitation and dual-port in-phase or out-of-phase feeding. It achieves wide coverage of the broadside beam, with an antenna size of only $100 \times 80 \times 0.7 \text{ mm}^3$ ($0.8 \times 0.64 \times 0.006 \lambda_0^3$), as shown in Figure 2(a) and Table 1. The low-profile endfire-beam pattern reconfigurable antenna element employs a coaxial feeding method (P3), with its

inner and outer conductors connected to the upper and lower printed square patches, respectively. By controlling the states of the PIN diodes, four end-fire radiation modes with different orientations in the horizontal plane are realized. In all four end-fire radiation modes, the 3-dB beamwidth exceeds 90°, enabling full 360° beam coverage in the horizontal plane. The antenna size is only 65×65×0.781 mm³ (0.52×0.52×0.006λ₀³), as shown in Figure 2(b) and Table 1.

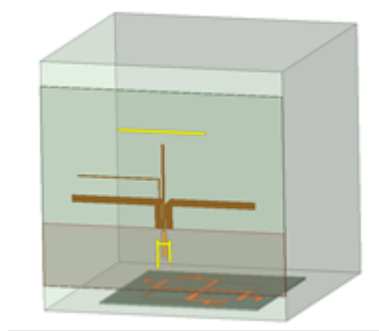


Figure 1: Low-profile Multi-mode Pattern Reconfigurable Antenna with Full-space Beam Coverage.

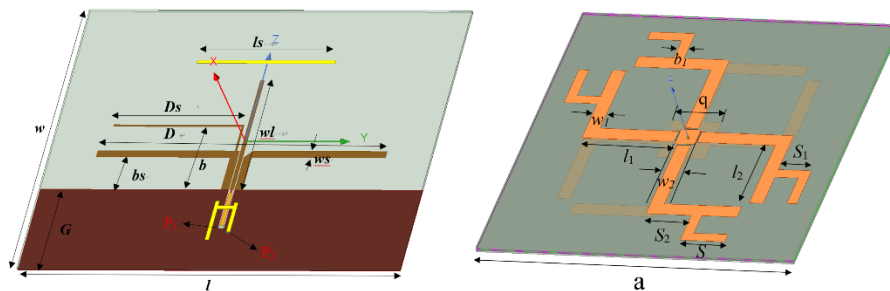


Figure 2: Antenna element composition: (a) Low-profile Broadside Pattern Reconfigurable Antenna Element; (b) Low-profile End-fire Beam Pattern Reconfigurable Antenna Element.

Table 1: Parameter Values of The Antenna (Unit: Mm).

Parameters	w	l	G	D _s	D	l _s
Value	80	100	25	34	71.6	36
Parameters	b _s	w _s	b	w _l	w ₁	w ₂
Value	13	2	21.5	33.75	2.8	4
Parameters	b ₁	l ₁	l ₂	a	S ₁	S ₂
Value	2	18.8	18	65	6.8	9.4
Parameters	S	q	h ₁	h ₂		
Value	9	10	0.4	0.381		

2.2 Analysis of Multimodal Working Principles

Based on the control mechanism of even- and odd-mode electromagnetic field distribution [15], this low-profile broadside-beam reconfigurable antenna integrates monopole and dipole elements to construct a composite radiation structure with both even and odd operating modes. When only port P1 is excited, the surface current on the radiator propagates upward along the monopole element,

couples electromagnetically to the arms of the dipole at its end, and maintains an overall even-mode electromagnetic field characteristic, enabling vertically polarized omnidirectional radiation. When only port P2 is excited, the surface current distributes horizontally along the dipole arms, and the antenna operates in odd mode, generating a horizontally polarized broadside-directional beam. When ports P1 and P2 are jointly excited with equal amplitude and in-phase feeding, the monopole and dipole excite even- and odd-mode field patterns, respectively. The induced currents of the two modes are opposite in phase and cancel each other on the left resonant arm of the dipole, forming a current null; on the right resonant arm, the two currents are in phase and their amplitudes add up, significantly enhancing the local current intensity. Due to the differential effect of cancellation on the left and enhancement on the right, the overall field distribution of the antenna loses symmetry, ultimately resulting in a radiation pattern with a beam deflected to the right. If the feeding method is changed to equal-amplitude but out-of-phase excitation of P1 and P2, the monopole still maintains an upward current flow, while the direction of the induced current in the dipole reverses. In this case, the currents on the left arm of the dipole add up constructively, while those on the right arm cancel each other and approach zero. The electromagnetic field distribution of the antenna again becomes asymmetric, causing the beam to deflect toward the left side of the space.

Figure 3 presents the simulated electric field distribution results of the antenna operating at the 2.40 GHz frequency point under four beam working modes. When only port P1 is independently excited, the electric field energy concentrates on the monopole structure, with opposite electric field phases on the left and right sides of the directors. The overall pattern follows the characteristics of an even-mode electromagnetic field, and the antenna achieves vertically polarized radiation, as shown in Figure 3(a). When a signal is fed solely into port P2, the electric field is mainly confined to the dipole, directors, and feeding circuit area, and the operating mode shifts to an odd mode, corresponding to horizontally polarized electromagnetic wave radiation, as illustrated in Figure 3(b). When P1 and P2 are excited with equal amplitude and in-phase signals, the electric field phases in the left half of the antenna cancel each other out due to their opposition, while the phases on the right side align, resulting in field superposition. The overall electric field distribution loses symmetry, and the beam deflects toward the right side of the antenna, as shown in the simulated field distribution in Figure 3(c). When dual-port equal-amplitude and anti-phase excitation is applied (P1 at 0° phase, P2 at 180° phase), the electric field vector of the monopole maintains its original direction, while the dipole's electric field phase shifts by 180° overall. The electric field energy on the left side of the antenna significantly increases, ultimately forming a directional beam deflected to the left, as shown in Figure 3(d). By switching between single-port excitation, dual-port in-phase excitation, and dual-port anti-phase excitation, the antenna can achieve radiation pattern reconfiguration among four states: omnidirectional radiation, broadside directional radiation, right-deflected beam, and left-deflected beam. According to the gain simulation data in Figure 4, the peak gains of the antenna under the four working modes are 2.86 dBi, 5.80 dBi, 4.61 dBi, and 4.47 dBi, respectively.

The low-profile, broadsidedly-directed beam pattern reconfigurable antenna unit primarily employs four reflective dipole pairs as its main radiating structure. By appropriately bending and deforming the conventional dipole pairs, the current transmission path within the antenna can be effectively altered, enhancing the electromagnetic coupling strength between the radiating elements and the reflective structure. This results in a significant increase in the coupled current, thereby improving the antenna's radiation efficiency and directivity. The antenna uses a centrally positioned square metal patch as both the feeding network and the connecting carrier, with four PIN diodes

connecting the central patch to the four dipoles respectively. By switching the ON/OFF states of the PIN diodes, the antenna operates in only one reflector and one active radiating dipole per end-fire mode, generating a directional pattern oriented toward the active radiating dipole. The corresponding PIN diode states and current paths for the four operating modes of the antenna at 2.4 GHz are shown in Table 2 and Figure 5, with the corresponding radiation patterns illustrated in Figure 6.

The multi-mode pattern reconfigurable conformal antenna is composed of a pattern reconfigurable antenna unit with broadside beam radiation and a pattern reconfigurable antenna unit with end-fire beam radiation. By integrating the pattern reconfigurable antenna with wide broadside coverage capability onto the front side of the aircraft fuselage, its vertical-plane beam tilting and broadside radiation characteristics are utilized to achieve directional communication between the UAV and aerial platforms. Meanwhile, the pattern reconfigurable antenna with 360° full coverage capability in the horizontal plane is arranged beneath the fuselage. Leveraging its ability to switch between end-fire radiation and omnidirectional radiation modes in the horizontal plane, it achieves wide-angle spatial coverage, meeting the communication requirements for multi-mission coordination and networking applications of UAVs.

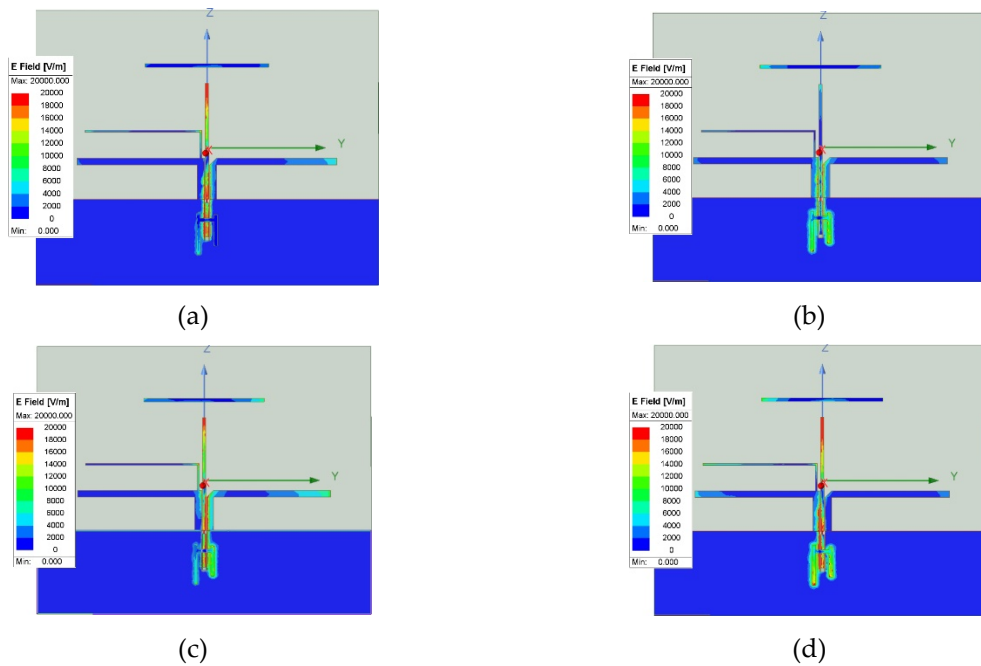


Figure 3: Electric field distributions of the low-profile broadside-beam pattern reconfigurable antenna under different excitation states: (a) P1 excitation; (b) P2 excitation; (c) in-phase excitation at dual ports; (d) out-of-phase excitation at dual ports.

Table 3: Diode And Related Status Under the Four End-Fire Modes of The Antenna.

Mode	Pattern Direction	Diode State			
		PIN_1	PIN_2	PIN_3	PIN_4
Mode 1	-x axis	ON	OFF	OFF	OFF
Mode 2	+y axis	OFF	ON	OFF	OFF
Mode 3	+x axis	OFF	OFF	ON	OFF

3. Results and Discussion

Figure 7 shows the developed low-profile broadside-beam pattern reconfigurable antenna prototype. The corresponding simulated and measured S-parameter results for each beam working mode of the antenna are presented in Figure 8. The antenna exhibits a -10 dB impedance bandwidth of 2.23 GHz to 2.60 GHz, with a relative bandwidth of 15.4%. Due to the orthogonal characteristics of the odd and even modes, the isolation between ports P1 and P2 remains higher than 15 dB across the entire frequency band.

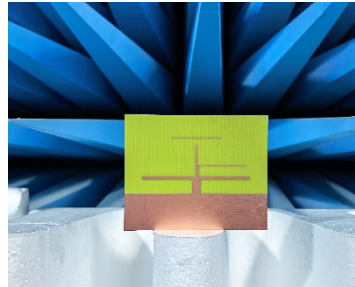


Figure 7: Prototype of a Reconfigurable Unit Antenna With a Broadside Beam Pattern.

Figure 9 shows the prototype of the developed low-profile end-fire beam pattern reconfigurable antenna. The simulated and measured S-parameters of the antenna are presented in Figure 10. The bandwidths under different modes are essentially identical, with a measured -10 dB impedance bandwidth of 570 MHz (2.26 GHz–2.83 GHz), corresponding to a fractional bandwidth of 23.8%.

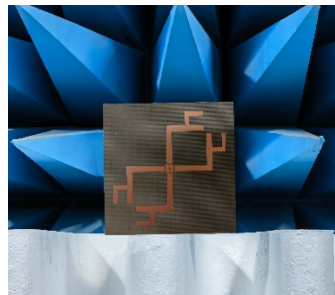


Figure 9: Low-Profile End-Fire Beam Reconfigurable Unit Antenna Prototype.

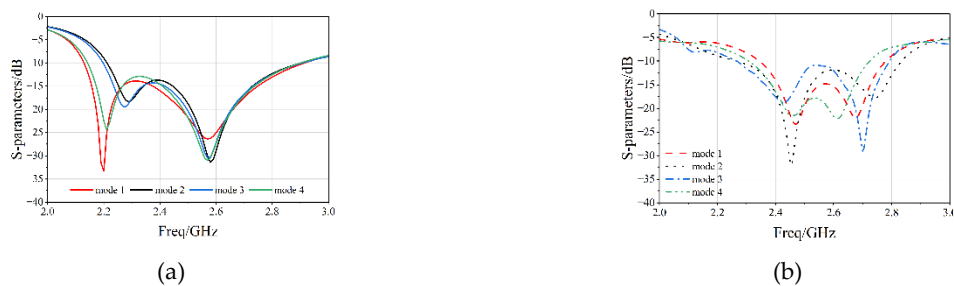


Figure 10: S-parameters of the Four End-fire modes: (a) Simulated values; (b) Measured values.

As shown in Figure 11, a schematic diagram of a multi-mode pattern reconfigurable conformal antenna applied to a UAV platform is presented. The two antenna elements are designed with independent feeding, and their corresponding S-parameter curves are shown in Figure 12. The low-profile broadside beam wide-coverage pattern reconfigurable antenna achieves a -10 dB impedance bandwidth of 370 MHz (2.23 GHz–2.60 GHz), with a relative bandwidth of 15.4%. The

low-profile end-fire beam pattern reconfigurable antenna achieves a -10 dB impedance bandwidth of 570 MHz (2.26 GHz–2.83 GHz), with a relative bandwidth of 23.8%. After conformal integration of the two antennas, the isolation between the feeding ports is better than 20 dB, the electromagnetic coupling effect between the antennas is weak, and there is no significant mutual interference in performance, allowing independent control of the beam states. The simulated radiation patterns of the low-profile full-space beam coverage multi-mode pattern reconfigurable antenna under different beam states are shown in Figures 13 and 14. By adjusting the antenna feeding states and the switching states of the PIN diodes, eight different beam states can be reconfigured to achieve full-space beam coverage, with the cross-polarization levels of all radiation modes below -20 dB.



Figure 11: Multimode Pattern Reconfigurable Conformal Antenna (a) Antenna prototype; (b) Radiation beam Pattern.



Figure 12: S-parameters of the Simulated and Tested Multi-mode Pattern Reconfigurable Conformal Antenna: (a) Reflection Coefficient; (b) Port Isolation.

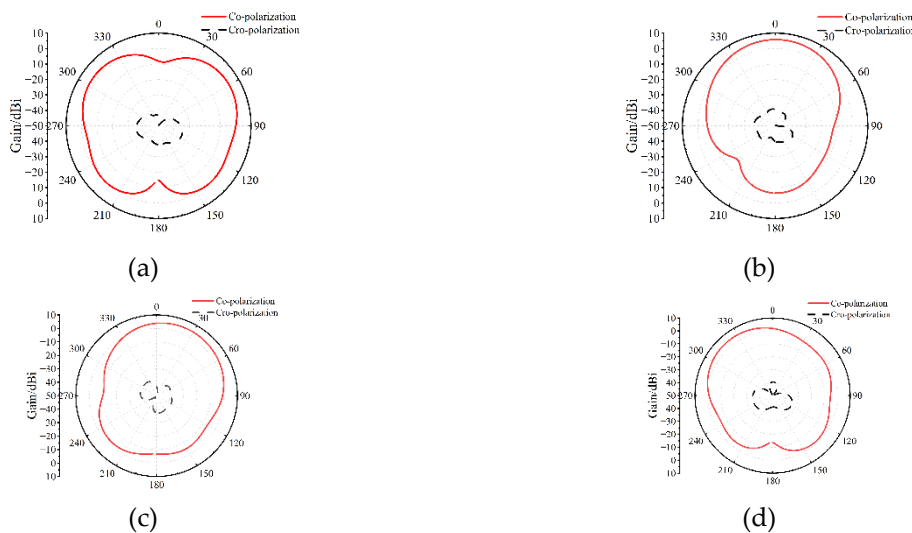


Figure 13: Shows the Simulated Normalized Radiation Patterns of the Antenna in the Yoz-plane: (a) Omnidirectional mode; (b) Broadside mode; (c) Right-skewed radiation mode; (d) Left-skewed radiation mode.

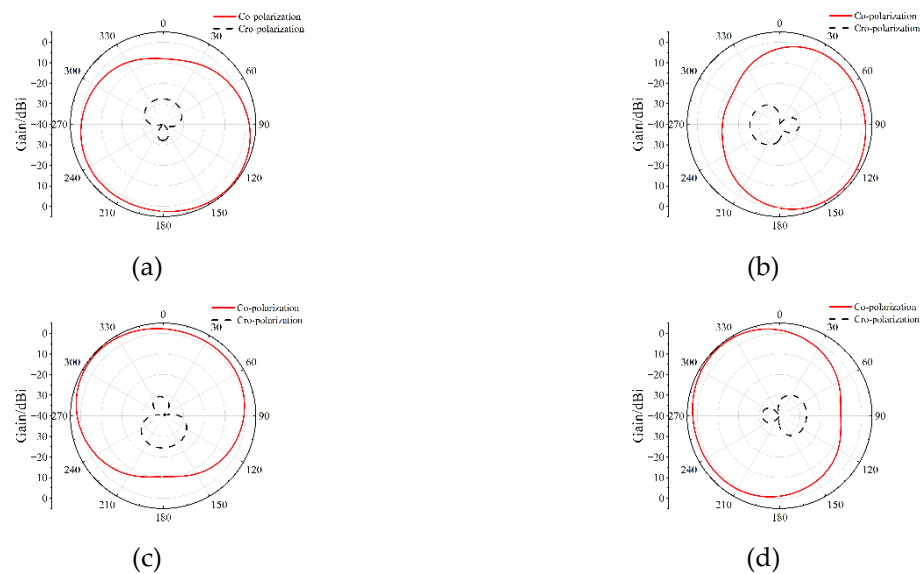


Figure 14: Simulated Normalized Radiation Patterns in the Xoy-plane: (a) Endfire mode 1; (b) Endfire mode 2; (c) Endfire mode 3; (d) Endfire mode 4.

4. Conclusion

This paper proposes a multi-mode pattern reconfigurable conformal antenna for UAV platforms. The antenna consists of two types of pattern reconfigurable elements, which can be applied to UAV platforms without increasing the overall size or profile height, achieving a wide beam in the vertical plane and full coverage in the horizontal plane. The multi-mode reconfigurability and wide-area beam coverage characteristics of the antenna enable complementary beam coverage across the entire airspace, significantly enhancing the dynamic beam control capability of the antenna. It provides reliable radio frequency front-end support for multi-UAV cooperative networking and holds significant application value and development prospects in the field of UAV communications.

References

- [1] Hong W, Jiang Z H, Yu C, et al. Multibeam antenna technologies for 5G wireless communications. *IEEE transactions on antennas and propagation*, 2017, 65(12): 6231-6249.
- [2] Zhao S, Wang Z, Dong Y. A planar pattern-reconfigurable antenna with stable radiation performance. *IEEE Antennas and Wireless Propagation Letters*, 2022, 21(4): 784-788.
- [3] Guo Y J, Qin P Y, Chen S L, et al. Advances in Reconfigurable Antenna Systems Facilitated by Innovative Technologies. *IEEE Access*, 2018, 6: 5780-5794.
- [4] Yang Y, Simorangkir R B V B, Zhu X, et al. A Novel Boresight and Conical Pattern Reconfigurable Antenna With the Diversity of 360 degrees Polarization Scanning. *IEEE Transactions on Antennas and Propagation*, 2017, 65(11): 5747-5756.
- [5] Ke Y H, Yang L L, Chen J X. Pattern-reconfigurable endfire antenna employing magnetoelectric dipoles. *IEEE Antennas and Wireless Propagation Letters*, 2022, 22(5): 970-974.
- [6] Chen M, Hu H, Lei S, et al. Azimuth-pattern reconfigurable antenna based on dipoles[C]//2022 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (AP-S/URSI). *IEEE*, 2022: 1478-1479.
- [7] Wang Z, Liu S X, Dong Y D. Compact Wideband Pattern Reconfigurable Antennas Inspired by End-Fire

- Structure for 5G Vehicular Communication. *IEEE Transactions on Vehicular Technology*, 2022, 71(5): 4655-4664.
- [8] Ouyang J, Pan Y M, Zheng S Y. Center-fed unilateral and pattern reconfigurable planar antennas with slotted ground plane. *IEEE Transactions on Antennas and Propagation*, 2018, 66(10): 5139-5149.
- [9] Zhao S, Wang Z, Dong Y. Pattern-Reconfigurable Antenna Using Low-Profile Electric and Magnetic Radiators. *IEEE Antennas Wireless Propagation Letters*, 2023, 22(3): 616-620.
- [10] Wu Z T, Tang M C, Li M, et al. Ultralow-Profile, Electrically Small, Pattern-Reconfigurable Metamaterial-Inspired Huygens Dipole Antenna. *IEEE Transactions on Antennas and Propagation*, 2020, 68(3): 1238-1248.
- [11] Tang M C, Zhou B Y, Ziolkowski R W. Low-Profile, Electrically Small, Huygens Source Antenna With Pattern-Reconfigurability That Covers the Entire Azimuthal Plane. *IEEE Transactions on Antennas and Propagation*, 2017, 65(3): 1063-1072.
- [12] Deng H, Zhu L, Liu N W, et al. Single-Layer Dual-Mode Microstrip Antenna With No Feeding Network for Pattern Diversity Application. *IEEE Antennas and Wireless Propagation Letters*, 2020, 19(12): 2442-2446.
- [13] Ali E M, Awan W A, Alkanhel R, et al. Design of a compact size dual-band frequency reconfigurable conformal antenna for heterogeneous applications. *AEU-International Journal of Electronics and Communications*, 2025: 155988.
- [14] Bai J, Li X, Zhang Z, et al. A Design of a Small-Aperture Low-Profile Omnidirectional Conformal Antenna[J]. *Micromachines*, 2025, 16(2): 217.
- [15] Balanis C A. *Antenna theory: analysis and design*. New York: Wiley-IEEE Press, 2005.