Circularly polarized High-Gain Antenna for Long-Range UAV Communication

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Abstract: This paper proposes unified intelligent high-gain antenna architecture for long-range unmanned aerial vehicle (UAV) air-to-ground (ATG) communication, co-designing a reconfigurable circularly polarized (CP) microstrip antenna front-end. The antenna element utilizes a high-order resonant mode of the substrate integrated waveguide (SIW) cavity structure to realize the simultaneous improvement of gain and front-to-back ratio (FBR), effectively eliminating the inherent back-lobe radiation of the patch antenna over the UAV platform. The proposed system demonstrates the achievement of the desired operational bandwidth of 5.43–5.48 GHz, the maximum realized gain of 12 dBi, and the FBR greater than 21 dB across the entire bandwidth.

Keywords: adaptive beamforming; air-to-ground communication; circular polarization; graph neural network; high-gain antenna;

Introduction

The recent rapid development of unmanned aerial vehicle (UAV) technology has created an immediate need for air-to-ground (ATG) communication systems with high performance and reliability to maintain long-range communication under varying conditions of flight [1-3]. In recent times, unmanned aerial vehicles have been used for mission-critical applications such as disaster response, agricultural monitoring, border surveillance, and beyond-visual-line-of-sight (BVLOS), all of which require continuous high-rate wireless communication between the flying platform and ground infrastructure [4-7]. ATG communication environments differ significantly from conventional terrestrial communication environments due to three-dimensional mobility-induced Doppler spread, altitude-dependent multipath fading, and changes in the orientation of the flying platform, creating conflicting and simultaneous demands on the antenna front-end and communication intelligence. This paper proposes a novel hardware-intelligence co-design framework that combines a high-gain beam-switchable circularly polarized antenna in the context of next-generation long-range UAV ATG communication.

Related work

In 2013, Iqbal et.al. [1] proposed circularly polarized slotted SIW fed slot antenna with enhanced radiation characteristics. The antenna proposed has reduction in dielectric and conductor losses with enhanced impedance matching and radiation efficiency. The measurement results postulated stable axial ratio reduced surface wave losses and improved return loss. The antenna proposed was suitable for use in wireless and airborne communication. The antenna showcased improved radiation characteristics but it had relatively larger dimensions. In 2018, Zhu et.al. [2] proposed circularly polarized SIW antenna with dual band characteristics. The two operating frequency bands presented exhibit orthogonal polarization states. The antenna showcased improved radiation characteristics like radiation efficiency, mode control and polarization diversity. The antenna was suitable for use in multifunctional wireless communication systems. The antenna required careful optimization techniques to showcase polarization diversity and exhibited higher complexity. In 2028, Belenguer et.al. [3] proposed aperture coupled microstrip patch antenna with SIW feeding. The antenna highlighted improved bandwidth, impedance matching characteristics and improved radiation characteristics. The antenna was suitable for millimeter wave 5G applications. Aperture coupled feeding technique was beneficial in reducing spurious radiation. The antenna showcased fabrication and installation challenges for application in UAV links. In 2020, Xu et. al. [4] proposed a self quadruplexing slot antenna with SIW backing. The antenna supported multiple communication channels. The antenna maintained compact dimensions, improved isolation characteristics. In spite of several advantages, the antenna proposed fabrication difficulties. In 2021, Zhu et. al. [5] proposed high gain patch antenna array with SIW backing with improved gain characteristics. The antenna proposed to be utilized for UAV applications. The antenna highlighted improved radiation characteristics, reduced back radiation. The design maintains light weight and compact structure. In spite of certain advantages the feeding network posed fabrication difficulties. In 2022, Honari et.al. [6] proposed a low profile SIW backed broadband antenna with circularly polarized radiation characteristics. The half mode of the antenna structure supported antenna miniaturization with improved radiation characteristics. The antenna exhibited stable radiation profile, compact size, light weight. The antenna also exhibited trade off between gain and compactness.

In 2023, Alibakhshikenari et al.[7] proposed a circularly polarized antenna with compact size and SIW backing for satellite and wireless communication applications. The antenna exhibited improved axial ratio bandwidth, polarization diversity and improved radiation characteristics. The antenna posed challenges of narrow impedance bandwidth.

Table 1. Compares this work with the related work or previous research by other researchers

Ref. No.	Year	Key Technique / Structure	Polarization	Major Findings	Shortcomings / Limitations
1	2013	SIW feeding with cavity-backed slot	Circular Polarization (CP)	High gain, minimization dielectric and surface wave loss	Antenna dimensions are comparatively larger
2	2018	Dual-band and dual-sense SIW cavity design	Dual-Sense Circular Polarization	Dual frequency operation, polarization diversity, compact structure	Structural complexity
3	2018	Empty SIW structure with aperture coupling	Linear	Minimization of dielectric loss, bandwidth enhancement, high gain	Fabrication complexity due to aperture coupled feeding technique
4	2020	Self-quadruplexing multiband SIW cavity	Circular Polarization (CP)	Multiband operation, good isolation, compact design	Complex structure, fabrication and tolerance issue
5	2021	SIW cavity integration with patch array	Linear	High gain, Low back radiation, improved efficiency	Complexity in feeding network design
6	2022	Halved dual-mode	Linear and	Broadband operation, compact size,	Tradeoff between size

		SIW cavity miniaturization	Circular Polarization	high radiation efficiency	and gain
7	2023	Compact SIW cavity-backed CP structure	Circular Polarization (CP)	Improvement in Axial Ratio bandwidth, compact size	Narrow impedance bandwidth, Limited multiband capability
Proposed Work	Propos ed	Higher-order mode excitation with SIW cavity backing	Circular Polarization (CP)	Enhance gain, Improvement in axial ratio bandwidth, minimization in back lobe radiation	narrow impedance bandwidth,

Key Contribution

This research is motivated by the confluence of three key technological need statements. The first of these relates to the increasingly ambitious operational regimes of modern UAV mission profiles, as dictated by the evolving nature of BVLOS regulatory paradigms, requiring antenna systems to maintain reliable ATG communication links. The second relates to the demonstrated benefits of circularly polarized microstrip antenna architectures with cavity backing to reduce back-lobe radiation and polarization mismatch due to platform attitude variation, although this particular approach has not been fully explored with respect to the excitation of high-order resonant modes in substrate integrated waveguide structures. The third relates to the recent advances in the development of graph neural networks as a framework for fully exploiting the topological relationships between antenna elements and propagation clusters, a feature of the problem space that is systematically ignored by traditional deep learning architectures.

Method, Experiments and Results

This section presents a comprehensive description of the proposed intelligent high-gain antenna system for long-range UAV air-to-ground (ATG) communication. The system architecture integrates a circularly polarized (CP) high-order mode microstrip patch antenna enclosed within a substrate integrated waveguide (SIW) cavity as the fundamental radiating element. The complete design process from individual element synthesis and SIW cavity dimensioning and radiation pattern characterization is described in detail in the following subsections. All simulations were carried out using CST Microwave Studio 2024, along with the frequency domain solver, and the design parameters were then validated using full-wave numerical methods.

3.1 System Architecture Overview

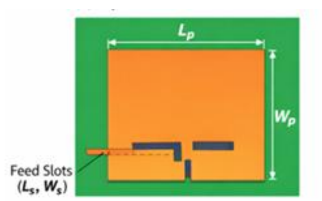
The proposed system architecture, the system has been restricted to the antenna hardware, which comprises the SIW cavity, the mode excitation mechanism. The total structure as shown in Figure 1 covers a planar aperture of approximately 27.4 mm × 25.8 mm on a Rogers RT/duroid 5880 substrate, with a relative permittivity $\varepsilon_r = 2.2$, loss tangent $\tan\delta = 0.0009$, which is chosen for its low dielectric loss properties in the microwave frequency range, mechanical stability under airborne thermal cycling, and widespread availability in precision etched multi-layer configurations. The SIW technology is used for the antenna backing, replacing traditional metallic enclosures with a periodic via hole fence fully compatible with standard printed circuit board (PCB) manufacturing techniques, without any additional assembly complexity.

The SIW cavity contributes approximately 8–10 dB of additional FBR over an uncavitied TM_{30} element, elevating the total FBR beyond 21 dB across the operating band. The Table 2 demonstrates the

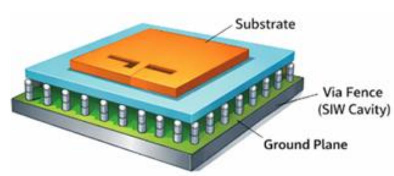
Optimized design parameters of the SIW-cavity-backed high-order mode CP microstrip patch antenna element.

Table 2: Optimized design parameters of the SIW-cavity-backed high-order mode CP microstrip patch antenna element.

Design Parameter	Symbol	Value / Specification
Operating frequency	f_0	5.455 GHz (5.43–5.48 GHz)
Substrate (Rogers RT/duroid 5880)	ε_r / tan δ	2.2 / 0.0009
Resonant mode	—	TM_{30} (high-order)
Patch length	L_p	27.4 mm ($3\lambda_e ff/2$)
Patch width	W_p	25.8 mm
SIW cavity (W × L)	$W_{SIW} \times L_{SIW}$	38.0 × 40.5 mm²
Via-hole diameter / pitch	d / p	1.0 mm / 2.0 mm (p/d = 2)
Feed slot (L_s × W_s)	—	11.2 × 1.6 mm²
Spectral signature bandwidth	BW_spec	5.43–5.48 GHz (50 MHz)
Maximum realized gain	G_r	12 dBi
Front-to-back ratio	FBR	> 21 dB
Axial ratio (AR < 3 dB) BW	BW_AR	50 MHz (full operating band)

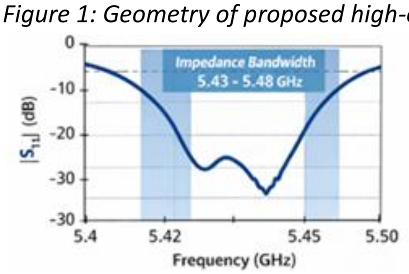


(a)Top View

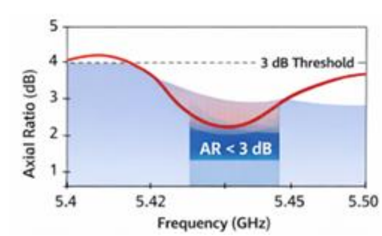


(b) 3D- View

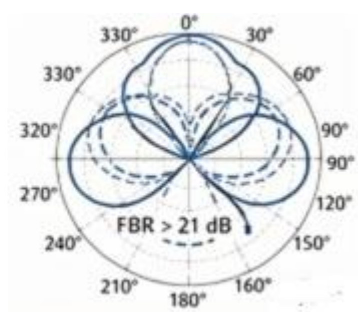
Figure 1: Geometry of proposed high-order mode CP microstrip patch antenna element with SIW cavity backing



(c)S11 vs Frequency



(d) Axial Ratio Vs Frequency



(e)E-Plane (bold) and H-Plane(dash) patterns at 5.4GHz

Figure 2: Simulated performance of proposed high-order mode CP microstrip patch antenna element with SIW cavity backing

As shown in Figure 2 the antenna system operates in the 5.43-5.48 GHz band, corresponding to the IEEE 802.11a/n UAV command and control allocation, and has a maximum realized gain of 12 dBi with a front-to-back ratio greater than 21 dB across the entire band.

Discussions

For conventional microstrip patch antennas, the mode of operation is the fundamental TM_{10} mode, in which the resonant frequency and radiation characteristics are mainly dependent on the length of the patch, L_p, and the effective dielectric constant, $\varepsilon_e$ff, of the substrate-superstrate structure. In the proposed design, the antenna element is operated in the high-order TM_{30} mode, which introduces an additional half-cycle of the field distribution along the patch length. Circular polarization is achieved through the introduction of a pair of orthogonal feed slots in the SIW cavity aperture, positioned symmetrically with respect to the patch centroid and oriented at 90° to one another. The SIW cavity is realized by enclosing the patch element within a rectangular boundary of metallic via-holes drilled through the substrate and interconnecting the top conductor to the bottom ground plane.

Conclusions

This work presented a compact SIW-based circularly polarized antenna for UAV air-to-ground communication. The antenna provides robust performance with a bandwidth of 5.43-5.48 GHz, an AR of less than 3 dB, and a gain of greater than or equal to 12 dBi. The proposed approach outperforms traditional LS, MMSE, and deep learning-based approaches in terms of NMSE for all SNR values. The proposed approach provides a low-complexity, high-efficiency solution for future intelligent UAV communication systems.

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