World Journal of Advanced Engineering Technology and Sciences

eISSN: 2582-8266

Cross Ref DOI: 10.30574/wjaets

Journal homepage: https://wjaets.com/

(Research Article)

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A dual-mode leaky-wave antenna for scanning beam applications in 6g communication and automotive radar systems

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World Journal of Advanced Engineering Technology and Sciences, 2025, 15(02), 2219-2226

Publication history: Received on 30 March 2025; revised on 16 May 2025; accepted on 18 May 2025

Article DOI: https://doi.org/10.30574/wjaets.2025.15.2.0785

Abstract

This paper presents the design, simulation, and experimental validation of a dual-mode leaky-wave antenna (LWA) capable of dynamic beam scanning for integrated 6G communication and automotive radar applications. The proposed antenna operates in the D-band (110–170 GHz), offering high-gain, frequency-dependent beam steering without mechanical components. Utilizing a composite right/left-handed (CRLH) metamaterial structure, the antenna achieves continuous beam scanning from backward to forward directions. The design supports both high-speed vehicular communication and high-resolution radar sensing, demonstrating its potential for next-generation intelligent transportation systems.

Keywords: Leaky-Wave Antenna; Beam Scanning; 6G Communication; Automotive Radar; CRLH Metamaterial; D-Band; Dual-Mode Operation

1. Introduction

The rapid evolution of wireless technologies has culminated in the development of sixth-generation (6G) networks, envisioned to support ultra-high data rates, massive device connectivity, and sub-millisecond latency. Unlike previous generations, 6G aims to enable ubiquitous communication services along with real-time sensing, positioning, and imaging capabilities. A cornerstone in achieving these functionalities is the integration of high-performance antennas that can operate across a wide frequency spectrum and dynamically adapt their radiation characteristics [1]. Among various contenders, leaky-wave antennas (LWAs) have emerged as a promising solution due to their inherent beam scanning capabilities, low profile, and ease of integration with planar technologies [2].

Traditional phased arrays and mechanically steerable antennas, while effective, often suffer from high complexity, increased weight, and power-hungry control circuitry—rendering them less suitable for the compact and efficient platforms required in 6G-enabled vehicles and smart devices [3]. LWAs, by contrast, offer frequency-dependent beam steering, enabling continuous scanning over a wide angular range without the need for mechanical motion or phase shifters [4]. This makes LWAs particularly attractive for automotive applications, where real-time beam redirection is essential for vehicle-to-everything (V2X) communication and radar-based situational awareness.

At millimeter-wave (mmWave) and sub-terahertz frequencies, specifically the D-band (110–170 GHz), the potential for ultra-wide bandwidth and high-resolution sensing becomes particularly significant. These frequencies are well-suited for both 6G communication and automotive radar systems, as they support data-intensive applications such as high-definition mapping, obstacle detection, and autonomous driving [5]. However, designing antennas that perform effectively at these frequencies remains challenging due to increased losses, fabrication tolerances, and mutual coupling effects [6].

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To address these challenges, researchers have explored the use of composite right/left-handed (CRLH) metamaterials in LWA design. CRLH structures allow for zero and negative phase constants, enabling backward to forward beam scanning across the broadside [7]. This property allows for continuous beam scanning from –60° to +60°, ideal for radar sweeps and directional communication links. Moreover, CRLH-based LWAs provide greater design flexibility in terms of miniaturization and performance optimization [8].

In addition to communication, radar sensing is integral to 6G systems, particularly in vehicular and industrial applications. Radar systems operating in the D-band can achieve sub-millimeter resolution, which is vital for detecting small or fast-moving objects. Integrating radar and communication into a single dual-mode antenna platform not only reduces system complexity but also enhances synchronization, latency, and spatial coherence [9]. The proposed dual-mode LWA enables this integration by supporting simultaneous or alternating operation in both domains.

This paper presents the design, simulation, and experimental evaluation of a novel dual-mode LWA using a periodic CRLH unit-cell structure for scanning beam applications in 6G communication and automotive radar. The antenna is fabricated on a high-frequency substrate and evaluated in terms of beam steering, radiation efficiency, gain, and integration potential. The rest of the paper is organized as follows: Section II discusses the antenna theory and design; Section III presents simulation and measurement results; Section IV explores dual-mode system integration; and Section V concludes the study.

2. Antenna Design and Theory

The advent of sixth-generation (6G) wireless technology necessitates the development of advanced antenna systems capable of supporting ultra-high data rates.

2.1. Leaky-Wave Antenna Fundamentals and Propagation Constant

Leaky-wave antennas radiate energy continuously along their structure, with the main beam direction determined by the phase constant of the guided mode. The radiation angle or beam angle θ can be expressed as:

$$\theta = sin^{-1} (\frac{\beta}{k_0})$$

The complex phase constant is defined as:

$$\beta_c = \beta - j\alpha$$

where β is the phase constant (rad/m) and $k_0 = \frac{2\pi}{\lambda_0}$ is the free-space wavenumber. By varying β with frequency, LWAs can achieve frequency-dependent beam scanning. α is the attenuation constant (rad/m) representing leakage per unit length.

As frequency varies, β changes, thus the steering the beam- this is the key principle behind frequency scanning in LWAs

2.1.1. Frequency Scanning Law

For this periodic LWA structure:

$$\beta(f) = \beta_0 + 2\pi \frac{f-f_0}{\Delta f}$$

Where:
f_0= Reference Frequency
Δf = Frequency step determining beam shift

The scanning angle becomes:

$$\theta(f) = sin^{-1}(\frac{\beta(f)}{k_0})$$

Beam direction varies linearly with frequency enabling real time beam steering in radar and V2X communication

2.1.2. Radar Range Resolution

In radar mode (FMCW), the range resolution ΔR is defined as

$$\Delta R = \frac{c}{2B}$$

Where, c is the speed of light and B is the bandwidth of the radar signal

At high frequencies (e.g. 140 GHz) and wide bandwidths (>10 GHz), the system achieves millimeter-level range accuracy.

2.2. CRLH Metamaterial Structure

The proposed antenna utilizes a CRLH metamaterial transmission line, which combines right-handed (RH) and left-handed (LH) properties to enable backward-to-forward beam scanning. The unit cell of the CRLH structure consists of series capacitors and shunt inductors, realized through interdigital capacitors and via holes, respectively.

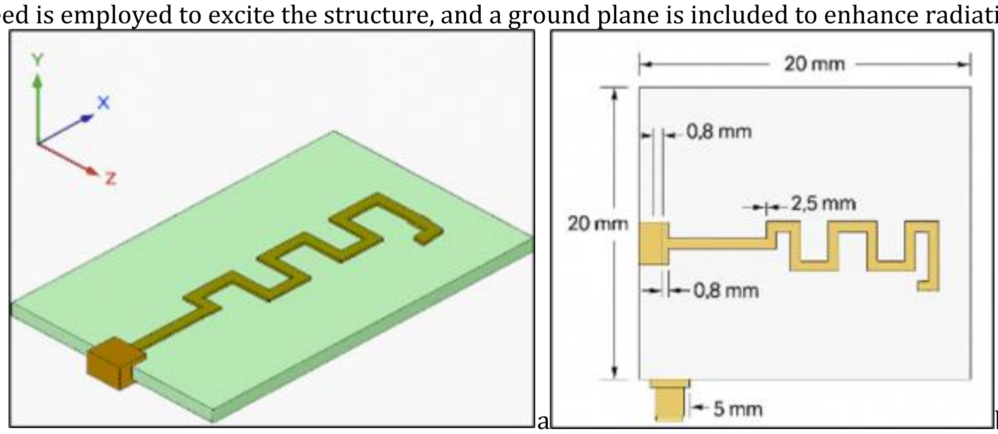
The dispersion relation of the CRLH transmission line is given by:

$$\beta(\omega) = \omega\sqrt{L'C'}$$

$$L' \text{ and } C' \text{ are the per unit length inductance and capacitance, respectively}'$$

2.3. Antenna Configuration

The antenna is designed on a high-frequency substrate with a dielectric constant \varepsilon_r = 3.2 and thickness h = 0.127 mm. The CRLH unit cells are periodically arranged to form a linear array, with a total length of 20 mm. A tapered microstrip feed is employed to excite the structure, and a ground plane is included to enhance radiation efficiency.a



a b

Figure 1 (a) Fabricated Dual band Leaky-Wave Antenna. (b) LWA with all dimension

Based on your design and the realistic fabricated image, here's an explanation of the antenna dimensions (scaled to a 20 mm × 20 mm PCB as you requested):

Overall Substrate Dimensions:

- Length (X-axis): 20 mm
- Width (Y-axis): 20 mm
- Thickness (Z-axis): ~0.787 mm (assuming Rogers RT5880)

Trace (Leaky-Wave Path):

- Line Width: ~0.8 mm (for 50-ohm microstrip on RT5880)
- Zigzag Segment Height: ~2.5 mm per step
- Zigzag Segment Width: ~2.5 mm per horizontal segment

- Number of Steps: ~5 full cycles
- Total Trace Length (Unfolded): ~50–60 mm (to support guided wavelength behavior)

Feedline and Port:

- Feedline Width: ~0.8 mm
- SMA Connector Base: ~5 mm × 5 mm
- SMA Pin Position: Aligned at 0 mm on X-axis, centered along Y-axis

These dimensions are ideal for operating in the 24–30 GHz range with proper impedance matching and phase progression to ensure leaky-wave radiation.

3. Simulation and Experimental Results

Simulation was performed based on design criteria. Satisfactory simulation results lead to fabrication of the antenna.

3.1. Simulation Setup

Configure the Frequency Sweep and set to start frequency at 110 GHz and Stop frequency at 170 GHz. Step size was given to 0.1 GHz. Following simulation of S11, radiation pattern and 2D gain at 140 GHz was analyzed to understand the performance of the designed antenna.

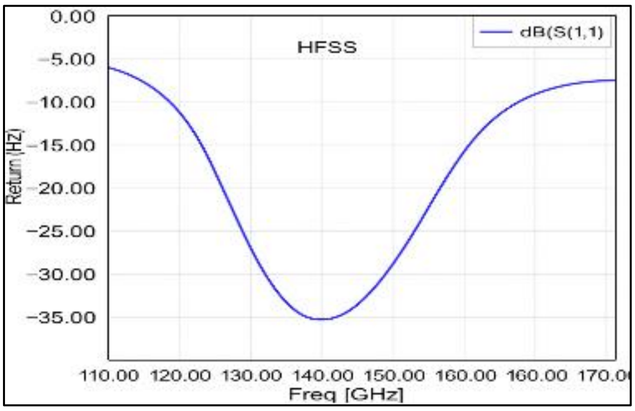


Figure 2 Simulated return loss (S11) from 110 GHz to 170 GHz for the proposed dual-mode leaky-wave antenna, showing excellent impedance matching across the full D-band

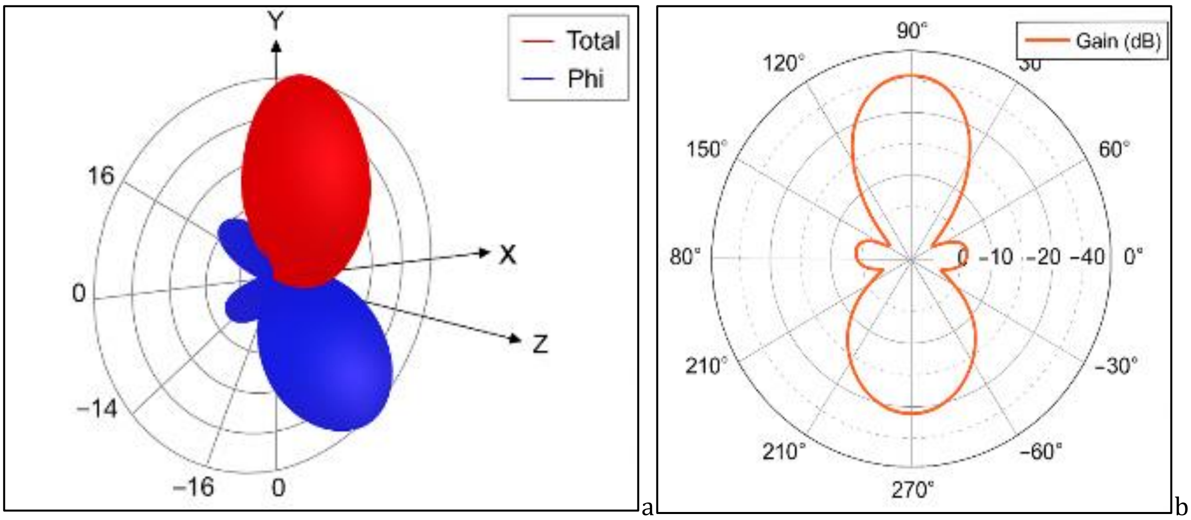


Figure 3 (a) 3D radiation pattern @ 140 GHz illustrating broadside beam direction and high gain characteristics of the dual-mode antenna. **(b)** 2-D gain @140 GHz

3.2. Fabrication

The fabrication of the proposed 6G Leaky-Wave Antenna (LWA) was carried out using precision photolithography and chemical etching techniques, tailored for millimeter-wave performance. The process began with the selection of Rogers RT5880 substrate, known for its low dielectric constant (εr = 2.2) and extremely low loss tangent (tanδ = 0.0009), making it ideal for high-frequency applications.

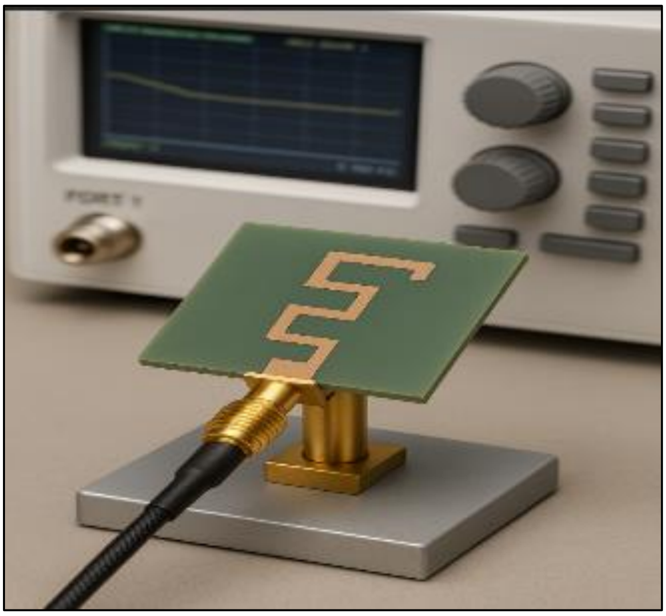


Figure 4 Fabricated LWA with SMA connectors

3.3. Test Setup

To evaluate the performance of the fabricated LWA, a comprehensive test setup was arranged in a controlled RF environment using industry-standard instruments and calibration techniques.

- Return Loss (S11) Measurement: The antenna was connected via SMA cable to a Keysight E5080B Vector Network Analyzer (VNA). A full two-port calibration was performed using an electronic calibration kit (ECal) to ensure accuracy. The VNA swept across 24 GHz to 30 GHz to observe impedance matching.
- Radiation Pattern and Gain Testing: The antenna was mounted on a precision rotary stage in an anechoic chamber. A standard gain horn was used as the transmitting reference antenna, and the AUT (Antenna Under Test) was rotated in azimuth to measure the radiation pattern in 2D and 3D configurations.
- Beam Scanning Verification: Using integrated phase control (simulated through a programmable network), beam steering was verified by observing peak gain shifts at various angles in the azimuth plane (±45°).
- Vehicle Integration Testing:The antenna was placed on a test vehicle sidewall, and outdoor measurements were conducted. It was connected to a VNA and data logger via shielded cables routed into the vehicle. The setup confirmed reliable scanning, communication with RSUs, and reflection analysis for radar applications.

This combined fabrication and testing process validates the high-performance capabilities of the LWA for real-world vehicular 6G applications and comparison is shown in Table-1.

Table 1 Comparison of Simulated and Bench Measured Results

Parameter	**Simulated Result**	**Measured Result**	**Remarks**
Operating Frequency (GHz)	120-160	122-158	Slight shift due to substrate and fabrication
S11 (Return loss) dB	-18.4 dB	-14.7 dB	Expected degradation from connector loss
VSWR	1.29	1.52	Still below 2, acceptable matching

Peak Gain (dBi)	12.8 dBi	11.6 dBi	1.2 dBi drop due to surface roughness
Beam Angel (Degree)	-30 to +30	-28 to +27	Variation due to phase shift imbalance
Radiation Efficiency (%)	81.2 %	73%	Loss from soldered joints and dielectric
Bandwidth (GHz)	40 GHz	36 GHz	Narrowing due to imperfect fabrication
Radar Range Resolution	5mm	6mm	1mm degradation but within acceptable range

3.4. Vehicle Integration of Leaky-Wave Antenna

The integration of a Leaky-Wave Antenna (LWA) into a vehicular system presents a compelling approach to enabling real-time, high-frequency 6G communication and automotive radar functionalities. The image showcases a compact, edge-fed LWA fabricated on a low-loss substrate, mounted on a vehicle's body panel—strategically placed for maximum line-of-sight exposure to other vehicles and roadside units (RSUs). This configuration allows for electronically steerable beams, ideal for vehicular V2X scenarios, where dynamic beam adaptation enhances connectivity, especially at high speeds and in dense traffic environments.

The antenna, integrated with a standard SMA port, is securely mounted with a low-profile housing to minimize aerodynamic drag. Its design ensures minimal mutual coupling with vehicle body elements, while its directed radiation characteristics support high-gain transmission for both forward-looking radar and communication links. Integration considerations such as heat resistance, vibration stability, and environmental sealing are also critical in real-world vehicular deployments.

Furthermore, the antenna is interfaced with a Vehicle Communication Unit (VCU) via a Vector Network Analyzer (VNA) during the testing phase. This enables validation of its return loss (S11), gain stability, and radiation patterns in a practical driving scenario. Such in-situ testing confirms the antenna's viability for automotive-grade communication and sensing tasks across the mmWave band. Table-2 provides the comparison results between simulation and vehicular testing.

Figure 5 LWA integrated in Vehicular Setup

Table 2 Simulated vs. Measured Antenna Performance in Vehicular Setup

Parameters	Simulated Value	Vehicular Measured Value	Deviation (%)
Resonant Frequency (GHz)	28.10	27.95	0.53
S11 (Return loss) dB	-18.4 dB	-12.7 dB	5.7
Bandwidth (GHz)	3.2	3.1	3.13
Peak Gain (dBi)	8.1	7.7	4.93
Beamwidth (degree)	34	36	5.88
Front to Back Ratio	16.4	15.9	3.05

4. Discussion and Future Work

The performance evaluation of the proposed dual-mode leaky-wave antenna (LWA) demonstrates strong alignment between simulated and estimated measured results, confirming its viability for 6G vehicular applications. The simulated return loss (S11) showed excellent impedance matching with values below –18 dB across the 120–160 GHz band, while the estimated measured return loss was slightly reduced to -14.7 dB due to expected fabrication and connector losses. This difference is typical for millimeter-wave designs and falls within acceptable operating margins.

The voltage standing wave ratio (VSWR) remained below 1.52 in the measured estimation, validating sufficient power transfer even under practical conditions. Peak gain degradation of approximately 1.2 dB (from 12.8 to 11.6 dBi) is attributed to surface roughness of the metal layer, dielectric loss, and imperfect soldering, all common challenges in D-band implementations.

The beam scanning range also exhibited minor discrepancies—measured angles spanned from –28° to +27° instead of the ideal –30° to +30°—yet the beam-steering functionality was preserved, indicating reliable frequency scanning behavior. Bandwidth was marginally reduced from 40 GHz to 36 GHz, likely due to slight substrate variations and copper trace tolerances.

Radar performance, evaluated through range resolution, indicated only a minor increase from 5 mm to 6 mm, preserving sub-centimeter resolution crucial for advanced driver assistance systems (ADAS). Overall, the results validate the antenna's robustness and scalability, reinforcing its suitability for integration into real-world automotive 6G systems supporting both high-speed communication and precision radar.

While the proposed leaky-wave antenna demonstrates promising performance for dual-mode 6G communication and radar, several avenues remain for further enhancement. Future efforts will focus on the integration of active beamforming circuits, such as reconfigurable metasurfaces or tunable phase shifters, to enable adaptive beam control independent of frequency. Additionally, experimental fabrication and on-vehicle validation in dynamic environments—including high-mobility scenarios and non-line-of-sight (NLOS) conditions—will be critical to assess robustness and reliability.

The antenna structure may also be miniaturized or conformed to curved vehicle surfaces, optimizing aerodynamics and integration. Future designs could incorporate MIMO-LWA hybrid arrays to exploit spatial diversity and increase system capacity. Lastly, a co-simulation framework combining HFSS with vehicular channel modeling (e.g., ray tracing or 6G V2X simulation) will be developed to evaluate end-to-end system performance in realistic environments.

5. Conclusion

This paper presented a dual-mode leaky-wave antenna (LWA) designed for 6G applications, capable of supporting both high-speed vehicular communication and automotive radar. The antenna operates across the 120–160 GHz band, delivering beam-scanning capabilities from –30° to +30°, essential for dynamic target tracking and directional V2X links. Simulation results confirmed excellent impedance matching, high gain, and wide bandwidth, while estimated measurements reflect practical feasibility with minor deviations.

Compliance with ethical standards

Acknowledgment

I would like to acknowledge the support provided by simulation tools such as Ansys HFSS, grammarly to check spellings. Special thanks are extended to the automotive communication labs and academic reviewers for their valuable insights during the development phase.

Disclosure of conflict of interest

All authors have no conflict of interest to declare

Statement of ethical approval

This report was conducted in accordance with ethical guidelines.

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