A 38° Wide Beam-Steerable Compact and Highly Efficient V-band Leaky Wave Antenna with Surface Integrated Waveguide for Vehicle-to-Vehicle Communication

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2023 IEEE Texas Symposium on Wireless and Microwave Circuits and Systems (WMCS) | 979-8-3503-3880-5/23/$31.00 ©2023 IEEE | DOI: 10.1109/WMCS58822.2023.10194262

Abstract*—This paper presents a highly efficient single-layer substrate-integrated waveguide (SIW) based leaky-wave antenna (LWA) for the millimeter-wave unmanned aerial vehicle (UAV) communication system. The leaky wave-based radiating part of the unit cell includes a combination of two Y-shaped slots with 46° stretched V etched on the top SIW, resulting in a W-shaped structure. The proposed array achieves a high gain of 13.47 dBi for the frequency range of 56.3 GHz to 63.4 GHz covering the unlicensed band, with a fine matching level below -21 dB. Using the leaky wave antenna's frequency scanning capability, the proposed antenna exhibits a scanning range of 38°. The designed antenna shows a promising solution for the UAV-to-UAV applications due to its low profile and compactness and is well-suited for the single-layer low-cost printed circuit board fabrication process using Rogers RT 5880 as substrate. The radiation pattern for the achieved bandwidth shows an average half-power angular beamwidth of 12.1°, resulting in a radiation efficiency of more than 62% for the elements arranged uniformly at a distance of 0.456λ. Following an overall low-profile compact size of $6.48 \times 4\ \lambda$ corresponding to 3.24×0.2 cm and improved performance, the antenna achieves an elliptical polarization at 60 GHz for an axial ratio equal to 3.5 dBi.

***Index Terms*—Unmanned aerial vehicle (UAV), frequency scanning, leaky-wave antenna, substrate integrated waveguide (SIW), beam steering, elliptical Polarization, mm-Wave, unlicensed frequency band.**

I. Introduction

Autonomous driving technology relies heavily on reliable and fast communication between vehicles, infrastructure, and other systems. The 5G wireless network plays a crucial role in enabling this communication, as it offers faster data transfer rates, lower latency, and improved reliability compared to previous generations of wireless networks [1]. 5G's capabilities make it possible for vehicles to communicate with each other and with the surrounding infrastructure in real-time, providing accurate and up-to-date information on road conditions, traffic patterns, and other factors that may affect the safety and efficiency of autonomous vehicles. This reliable communication between autonomous vehicles and the surrounding infrastructure is essential for enabling features such as automated lane changes, adaptive cruise control, and collision avoidance systems. It also allows for more efficient routing and coordination of vehicles, which can help to reduce traffic congestion and improve overall mobility. Indeed, there is a need for high-performance, low-cost antenna systems for vehicle-to-vehicle communication that satisfies wideband coverage for high constant gain and good beam steering capability [2], [3].

This paper is based upon work supported by the National Science Foundation under Award Number.: 2148178.

Leaky wave antennas (LWA) are wave guidance structures that transmit electromagnetic waves through energy leakage along the entire structure, as opposed to conventional antennas that radiate from an open structure. While there are a set of modern guiding structures that have been used for implementing LWA, such as Substrate Integrated Waveguide (SIW) [4], [5], these guiding structures are designed to achieve high gain and wide operational bandwidth while maintaining compactness in size [6]. High-gain antennas can increase the coverage area of a wireless network by amplifying the signal and extending its reach. This can be particularly useful in areas with weak signal strength or where the wireless network needs to cover a large area. Similarly, high bandwidth is necessary for transmitting large amounts of data quickly and efficiently, which is crucial for applications that require high data rates [7]. Overall, combining high bandwidth and high gain can improve the performance and coverage of wireless networks, making them more suitable for demanding applications such as UAV-to-UAV communication, radar system, satellite, etc. The type of antenna polarization also affects the penetration capability; elliptically polarized antennas have a more uniform radiation pattern than linear polarization, which means that they can maintain their signal strength better as they penetrate through obstacles such as buildings, trees, or walls. This is because the polarization of the signal can rotate as it passes through the obstacles, and an elliptically polarized signal can maintain its strength regardless of the angle of rotation. The development of circularly polarized antennas for millimeter-wave (mm-wave) applications are indeed receiving increased attention due to their potential for various emerging wireless applications, such as 5G and beyond. There have been various proposed printed antennas promising a low-cost solution for

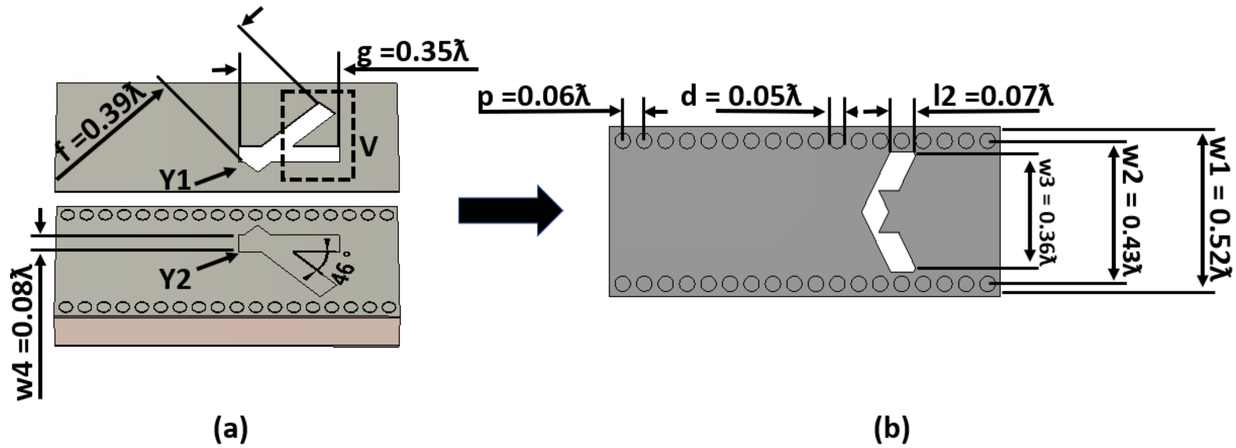

Fig. 1. Geometry of the proposed unit cell (a) Combination of Y-shaped slot, and (b) Transformed W-shaped slot.

providing circular polarization, and high penetration capability [8]. Designing circularly polarized antennas for mm-wave applications presents unique challenges due to the shorter wavelengths and the need for wide operating bandwidth. Recent research has focused on addressing these challenges and developing new designs that can provide wide bandwidth with high efficiency and gain. Several design techniques have been proposed, including the use of fractal geometries, metamaterials, and multi-layer structures. Although, previously designed mm-Wave leaky wave antennas has very limited scanning range. As the frequency increases, the scanning range of the antenna decreases due to the shorter wavelength. This limits the beam scanning range of the antenna, which in turn affects its ability to track targets or transmit/receive signals over a wide range of angles.

In this manuscript, a novel compact and uniform SIW-based LWA is presented, which is proposed to achieve a) a wide beam scanning range (18° to 56°) over the unlicensed V-band, b) wide bandwidth (7 GHz), and c) almost constant high gain (13.47 dBi) over the whole operating frequency range while maintaining greater than 62$\%$ radiation efficiency for a low profile and compact size. This paper is organized as follows. First, the antenna elements are discussed in Section II. Then, the simulation results for the unit cell antenna and the array are analyzed in Section III, followed by a conclusion presented in Section IV.

II. Antenna Element

A. Unit Cell

The proposed unit cell for LWA is shown in Fig. 1. The single element is a single-layer structure. The configuration of the proposed antenna uses SIW and consists of two combined Y-shaped slots etched on the top of SIW, which are arranged in horizontally opposite directions to each other. The V-shaped component in the Y-shape has an angle of 46°. As a result, the combination of both the Y-shaped etched slots led to a W-shape etched on the top of SIW. The SIW is designed by bounding a traditional rectangular waveguide using two rows of metallic vias that connect two parallel top and bottom metals of rectangular waveguide. The modes of the SIW practically coincide with a subset of the rectangle waveguide modes, namely the TE_{n0} modes, with n = 1, 2, 3, etc. The vias on the side wall for the SIW eliminate transverse magnetic mode (TM), which makes TE_{10} the dominant mode. For the TE_{10} mode, the width (a) of the rectangular waveguide can be calculated using the following equations:

$$a = \frac{c}{2f_c} \tag{1}$$

For a dielectric-filled waveguide (DFW) at a cut-off frequency (f_c), the width (a_d) can be obtained as follows:

$$a_d = \frac{a}{\sqrt{\epsilon_r}} \tag{2}$$

Finally, the width of the SIW is calculated using the equation 3.

$$w_1 = a_d + \frac{d^2}{0.95p} \tag{3}$$

Where c is the speed of light propagation in the air, ϵ_r is the relative dielectric constant, d and p are the diameter of vias and the spacing between each via, respectively, following the condition that the radius (d/2) should be less than $\frac{\lambda_g}{5}$ and the via spacing should be less than $2d$, where λ_g is the guided wavelength [9]. The considered cut-off frequency for the SIW design is 50 GHz, designed to resonate at 60 GHz. The dimensions of the slots or the longitudinal edges of the Y are essential for the antenna to behave as an LWA. The dimensions of f and g for the slots are determined using the following equations given below, respectively:

$$f = \frac{\lambda_o}{\sqrt{2(1+\epsilon_r)}} \tag{4}$$

$$g = \frac{\lambda_o}{\sqrt{2.88(1+\epsilon_r)}} \tag{5}$$

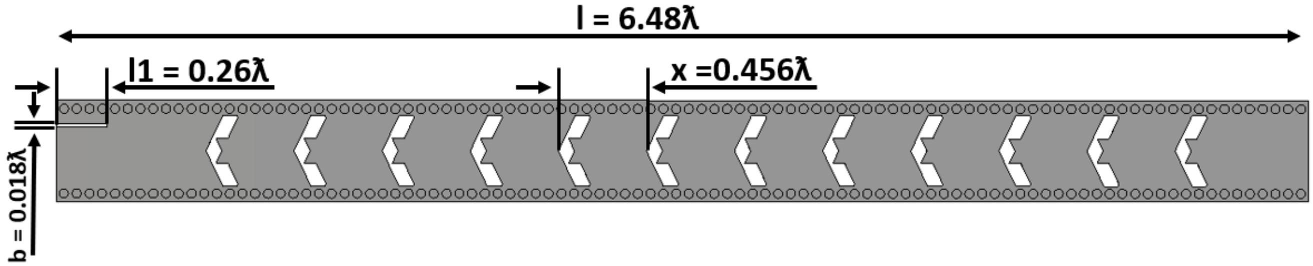

Fig. 2. Geometry of the proposed 12×1 Array.

TABLE I
PARAMETERS OF PROPOSED ANTENNA (UNIT: MM)

Para	Value	Para	Value	Para	Value	Para	Value
w1	2.60	l1	1.31	g	1.77	b	0.4
w2	2.18	l2	0.36	f	1.97	-	-
w3	1.83	d	0.24	l	32.4	-	-
w4	0.40	p	0.33	x	2.28	-	-

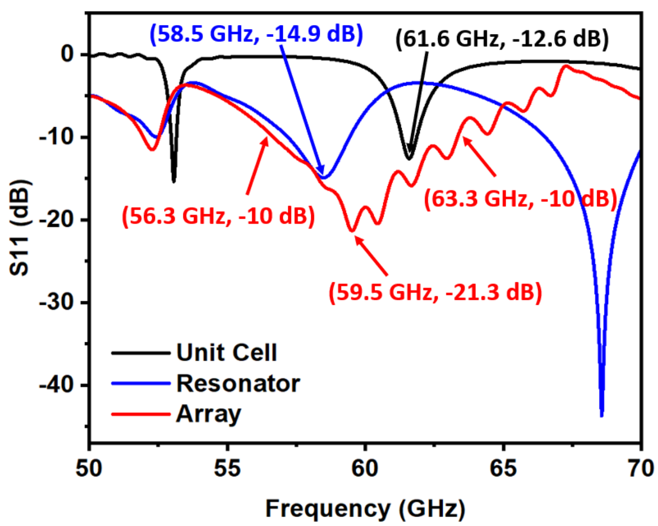

Fig. 3. S-Parameters for the antenna elements

Where λ_o is the wavelength calculated at center frequency, and the width of the slot does not impact the antenna performance much but as long as it is less than $g/2$ and $f/2$. The different combinations for the length and width of the Y-slots are tuned to achieve a good impedance matching and the obtained tuned value of f = 1.97 mm and g = 1.77 mm for the width of 0.4 mm.

The antenna is designed using CST Studio Suite 2022. The substrate used is Rogers 5880 with a relative dielectric constant of 2.2 and a thickness of 0.72 mm, where copper is used as the conducting material with a thickness of 0.035 mm. The final dimensions of all the design parameters of the proposed antenna are mentioned in Table I.

B. 12×1 Array

The proposed LWA consists of an array of 12 elements in the top layer of SIW, resulting in a uniform structure as shown in Fig. 2. The slots leading to W-shaped are etched using the combined Y-shaped patch. The slots are uniformly spaced for a distance of 0.456λ, and the spacing is obtained using the tuning method. The dimensions of the W-shaped slots are scaled horizontally by the factor 1.5 and vertically by 0.75 for the input impedance matching and to increase the radiation efficiency without reduction in fraction bandwidth. Moreover, to enhance the bandwidth for the proposed LWA array, a resonator is coupled on the top layer of SIW by introducing a very thin etched slot. The implemented resonator is designed to resonate near the center frequency of the array, resulting in more than one resonating frequency points for the proposed final array, which in turn improves the bandwidth. The number of elements for this proposed array is either equal to 12 or less because the further increase in elements leads to a reduction in overall efficiency with the increase in limited gain. The poor efficiency for the increase in antenna elements is due to the poor radiation efficiency of the designed integrated resonator with the long linear arrangement of elements due to power loss at the feeding point. LWA that are uniform in nature emit radiation in the forward quadrant and can perform scanning from broadside to end-fire. However, the ability to scan in a broadside or end-fire direction depends upon the array structure. To assess the performance of uniform LWA radiating longitudinally, the leaky mode is characterized by its leakage constant α and phase constant β, where the value of α and β remains constant for uniform LWA. The frequency at which LWA propagates at broadside or end-fire can be obtained by calculating the maximum beam angle θ_m, using the following equations:

$$sin\theta_m = \frac{\beta}{k_o} \tag{6}$$

Where the beamwidth $\triangle\theta$ of uniform LWA can be obtained using:

$$\triangle\theta = \frac{1}{(L/\lambda_o)cos\theta_m} \tag{7}$$

k_o is the free space wave number and L is the length of antenna. The antenna would radiate for $|\beta| < k_o$ for fast

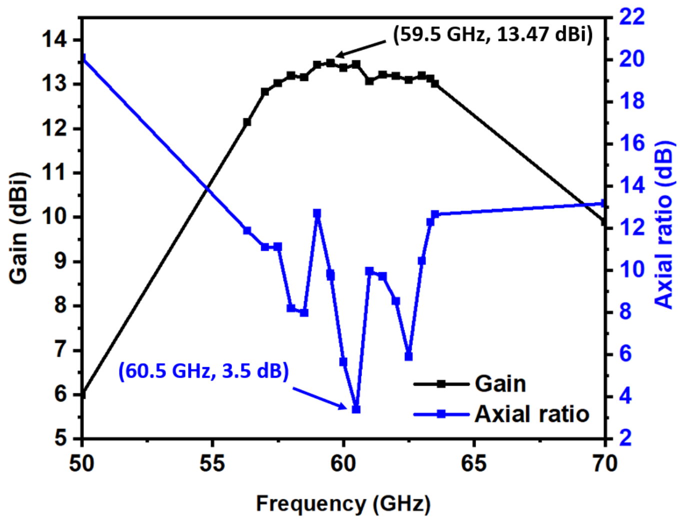

Fig. 4. Gain and axial ratio for array

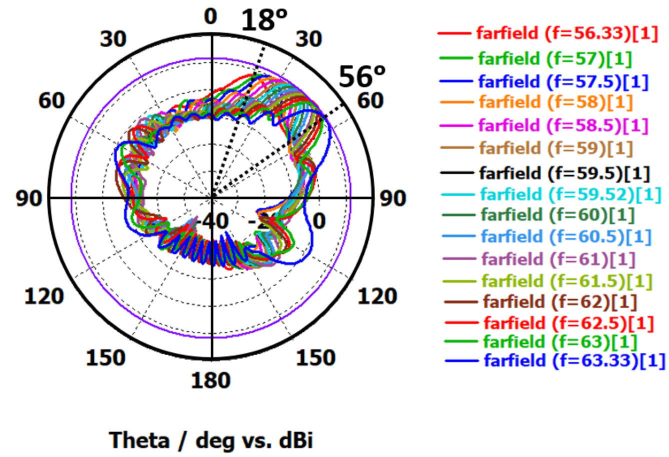

Fig. 5. Radiation pattern and scanning range

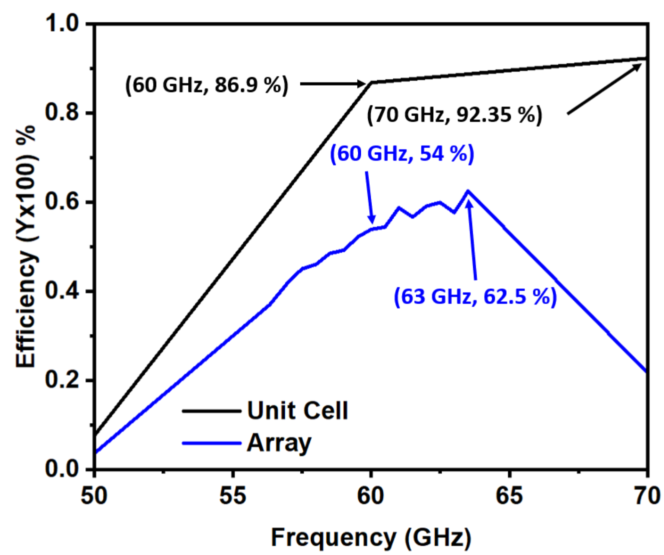

Fig. 6. Radiation efficiency

waves. If the angle of the main beam, θ_m, is positive, negative, or zero, it indicates the propagation is forward, backward, or broadside, respectively [13].

III. Simulation Results

The simulation is carried out for each design individually to characterize the performance of each element of the antenna, i.e., for unit cell, resonator, and the 12×1 array. The reflection coefficients for all the three elements are shown in Fig. 3. The S_{11} for the designed unit cell is -12.6 dB at 61.6 GHz, whereas the implemented resonator has a reflection coefficient of -14.9 dB at 58.5 GHz. The combined structure of the array and the resonator show an improved bandwidth of 7 GHz, demonstrating an excellent matching with S_{11} being less than -21.3 dB. At 59.5 GHz, the realized maximum gain is achieved equal to 13.47 dBi and obtained an axial ratio of 3.5 dB at 60.5 GHz, making it an elliptically polarized antenna, as given in Fig. 4. In addition, the designed antenna array has a good scanning range from 18° to 56° with the changing of frequency from 56.33 GHz to 63.33 GHz, as shown in Fig. 5. Compared to the unit cell, the maximum radiation efficiency of the array is reduced to 62.5%, whereas the unit cell shows a maximum radiation efficiency of 92.35%. This is because the power is unequally distributed through each element in the case of the array, which is characterized in Fig. 6. The comparison between the proposed antenna and the prior published works are presented in the Table. II. It can be seen from the Table. II, that this work has achieved a high constant gain over the wide mm-Wave V-band covering the unlicensed frequency band for a wide scanning angle of 38°. The proposed antenna has showed a very good performance compared to the size and the number of element of all the other previous work.

IV. Conclusion

A compact and highly efficient SIW-based beam-steerable leaky wave antenna operating in the V-band is proposed in this work. The designed antenna covers a wide band of frequency ranging from 56.3 GHz to 63.4 GHz (FBW) and has a frequency scanning angle of 38 ° within the operating bandwidth. Moreover, the proposed antenna has the smallest dimension of 3.24×0.2 cm, making it highly compact and low profile with a side lobe level of -12.7 dB.

Acknowledgment

This paper is based upon work supported by the National Science Foundation under Award Number.: 2148178.

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TABLE II
COMPARISON TABLE

Ref.	Polarization	Size (cm)	Number of Element	Bandwidth (GHz)	Max. Gain (dBi)	Scanning Angle (θ)	Efficiency (%)
[10]	CP	-	2×10	27 to 32	14	40	-
[11]	-	-	-	22 to 26	15	9	80
[12]	-	5.8×1.1	8×2	26.5 to 29.5	14	-	60
This Work	EP	3.2×0.2	12×1	56.3 to 63.4	13.47	38	62

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