Bandwidth Manipulated Leaky-Wave Antenna Using a Sinusoidal Ridge in Folded Substrate Integrated Waveguide

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***Abstract*—The impedance bandwidth for leaky-wave antennas (LWAs) is usually very broad, leading to wide signal interference from unwanted spectrums. For instance, the uplink signals will cause jamming effect to the downlink for Satellite communication systems. Hence, an integrated LWA with a bandpass filter is proposed in this paper. A folded substrate integrated waveguide (FSIW) LWA is utilized to reduce the SIW width to build a 2D LWA array with low side lobes. Periodic fan-shaped slots are etched on the top of the FSIW for circular polarization in a band centered at 11.5 GHz. A bandpass filter is investigated by elaborating a sinusoidal ridge in the FSIW LWA. It has been successfully validated through full-wave simulation that the bandpass filtering can be manipulated by varying the amplitude of the sine curve, whereas the circular polarization is well maintained. The proposed antenna is a very promising candidate for next-generation satellite communication systems.**

***Index Terms*—Circular polarization, filtering antennas, folded substrate integrated waveguide (FSIW), leaky-wave antennas (LWAs).**

I. INTRODUCTION

Satellite communication systems have a long-standing history of applications, and extensive research has been devoted to achieving lower costs and space. In these systems, downlink and uplink antennas often correspond to distinct arrays, potentially leading to unwanted interference. To mitigate such interference, filters are normally employed to enhance isolation between these links [1]. Substrate integrated waveguide (SIW) technology has emerged as a successful approach for antenna and filter designs across various frequency bands [2], [3]. SIW leaky-wave antennas (LWAs) offer an attractive combination of high efficient beam-steering, cost-effectiveness and easy integration with other circuitry [4], that can also provide CP and high gain [5]. The introduction of sinusoidal modifications in SIW has been explored, yielding notable stopband effects [6]. Additionally, ridged substrate integrated waveguide (RSIW) LWA featuring sinusoidal slots have demonstrated a reduction in cross-polarization effects [7]. Variants of SIW technologies, aimed at reducing the overall size, have been extensively investigated, including folded substrate integrated waveguides (FSIWs) [8]. Theoretical formulations for FSIW design have been developed, with comparative studies against SIW indicating a size reduction of approximately 50%, making it a promising avenue for future array and RF designs [9]. Research on FSIW filters has indicated valuable insights [10], [11] with an additional exploration of sinusoidally modulated FSIW filters and their adjustable widths [12]. Moreover, FSIW LWA antenna technology has been rigorously validated through simulations and experimental trials experimental [13].

II. ANTENNA DESIGN METHODOLOGY

A. Three-Fans Slot on FSIW

The primary objective of developing this antenna is to reduce the spacing between antennas along the *x*-axis, paving a way for future 2D antenna designs. This reduction in spacing allows for a lower periodicity, subsequently resulting in a decreased sidelobe level. Achieving this objective involves transforming SIW into a FSIW, as illustrated in Fig. 1. It's worth noting that the waveguide dimension of an SIW (denoted as W1) is larger than FSIW (denoted as W2) for a fixed operating frequency. This variation is due to the folding effect [9].

Fig. 2(e) offers a cross-sectional view of the antenna structure, depicting its different layers. Post-optimization, the FSIW parameters are intentionally designed for operation at in a band centered at 11.5 GHz. The thickness of each substrate is h = 0.508 mm using the Taconic TLY-5 with $\varepsilon_r = 2.2$, $tan\delta = 0.0009$ and the copper layer thickness of 0.035 mm.

The secondary aim of this antenna design is to facilitate circular polarization for the satellite communication, thus a three fans slot is selected to achieve the CP [5]. In our previous study, this particular slot has proven effective in achieving a commendable axial ratio for a periodic SIW LWA at 28 GHz. It accomplishes this by ensuring the electric fields are orthogonal with a 90-degree phase difference along the slot perimeter.

Fig. 2(c) provides a top view at the Top Copper Layer, outlining the design parameters of the three fans slot. After careful designs and systematic analysis, the slot has been elaborately designed with the following parameters: RadiusSlot = 2.5 mm; RadiusOffsetCenter = 1.2 mm; SlotRotation = -150 degrees; SlotXPosition = -1.5 mm;

WaveguideX = 8.2 mm; RidgeX = 7 mm, and Periodicity = 16.4 mm.

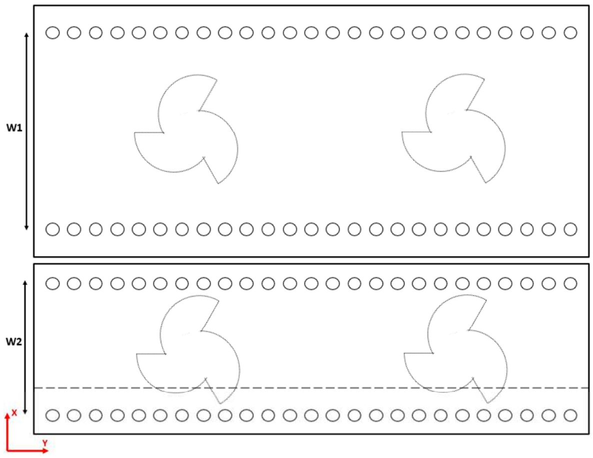


Fig. 1 SIW (W1) and FSIW (W2) schematics

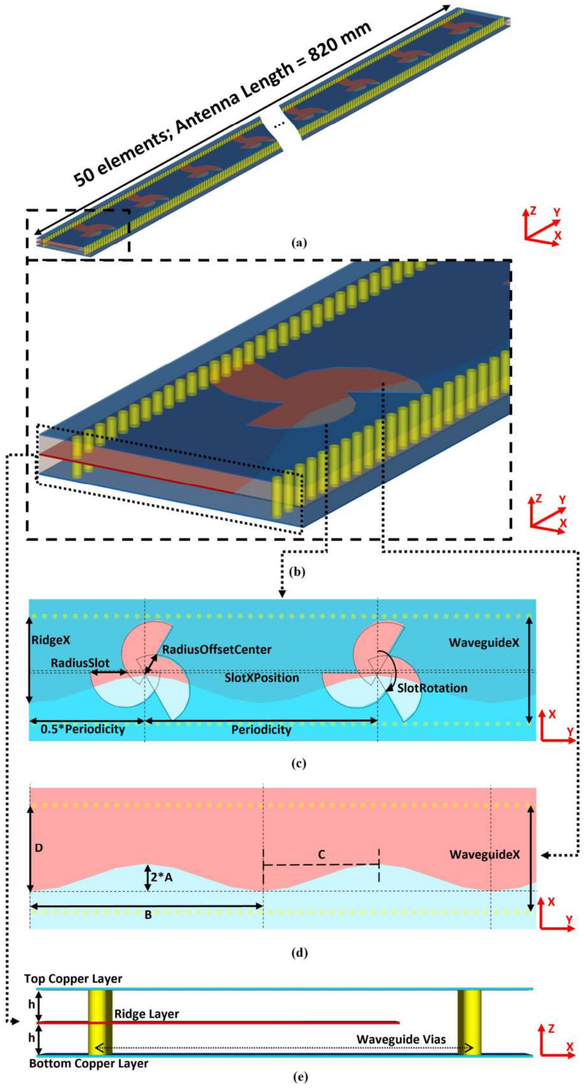


Fig. 2 Structure schematics. a) 50 elements Perspective View. b) Unit cell Perspective View. c) 3 Fans Slots Top View. d) Sinusoidal Ridge Top View. e) Layers Front View.

B. *Sinusoidal Ridged FSIW LWA*

When exciting a periodic LWA featuring a sinusoidal ridge, the phase constants (βn) for various space harmonics are defined by the following formula [7]:

$$\beta_n = \beta_0 + \frac{(2n+1)\pi}{p}. \tag{1}$$

In this equation, p represents the periodicity of the sinusoidal FSIW, as depicted in Fig. 2(d) where it is represented as $B = 2\pi$/Periodicity and remains constant. The variable n signifies the relevant space harmonic mode, also held constant. β_0 denotes the phase constant of the relevant mode n at 11.5 GHz. Variations in β_0 within a structural context lead to distinct main lobe directions and dispersion diagrams.

The motivation behind employing this sinusoidal FSIW structure is to investigate the impacts of the impedance bandwidth, dispersion, axial ratio (AR) and efficiency on a circular polarized FSIW LWA.

In Fig. 2(a), a perspective view of the full antenna structure is shown with a wave Port 1 on the left and a wave Port 2 on the right. Fig. 2(b) presents a perspective view of a unit cell. Fig. 2(d) provides a top view of the ridge layer, illustrating the design parameters of the sinusoidal ridge in the FSIW.

The analytical curve of the ridge edge is expressed by the formula:

$$y = A * sin(B * t + C) + D \tag{2}$$

In this equation, A signifies the amplitude of the sinusoidal curve; $B = 2\pi$/Periodicity, representing the periodicity of the sinusoidal curve; C determines the phase of the sinusoidal curve and is adjusted to maximize amplitude at the center of the Slot; D governs the movement of the function along the x direction. Their values are set as follows: $A = 0.34$ mm; $B = 0.38$; $C = -55$; D = RidgeX = 7 mm.

III. RESULTS AND DISCUSSION

In this section, the scattering parameters results are presented and compared for both ridge cases. Results of the radiation performance of three fans slot with linear ridge FSIW LWA and sinusoidal ridge FSIW LWA are presented and discussed. Furthermore, manipulation of the impedance bandwidth, the radiation dispersion, the AR and efficiency is discussed.

A. *Scattering Parameters*

Comparison between the linear ridged FSIW ($A = 0$) and the sinusoidal ridged ($A = 0.34$) is presented in Fig. 3. It is discernible that the impedance is both matched well for both scenarios, as evidenced by S_{22} values below −15 dB, whereas the S_{12} values less than −9 dB indicates very little power absorbed at the terminal Port 1 so as to high radiation efficiency.

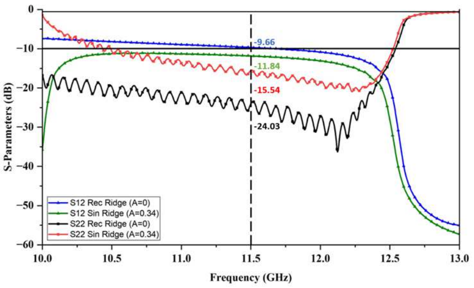
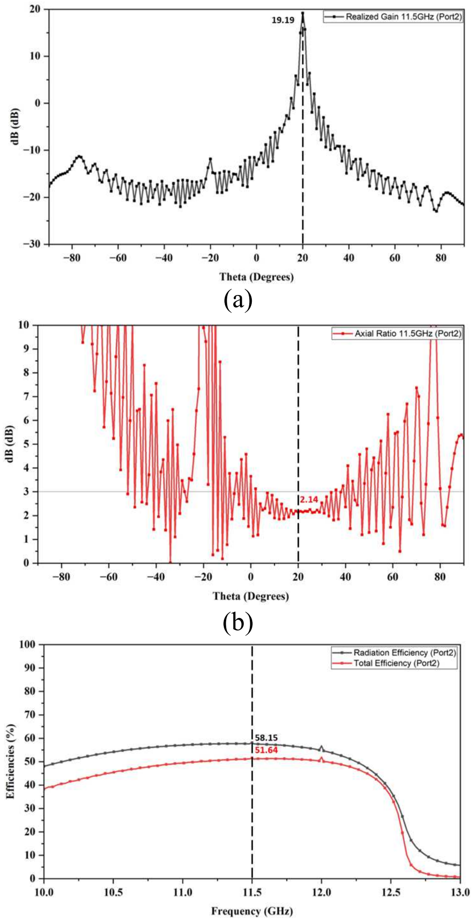


Fig. 3 Scattering parameters of the linear ridged FSIW LWA ($A = 0$) and the sinusoidal ridged FSIW LWA ($A = 0.34$).

B. *Radiation Performance of Linear Ridged FSIW LWA*



(a)

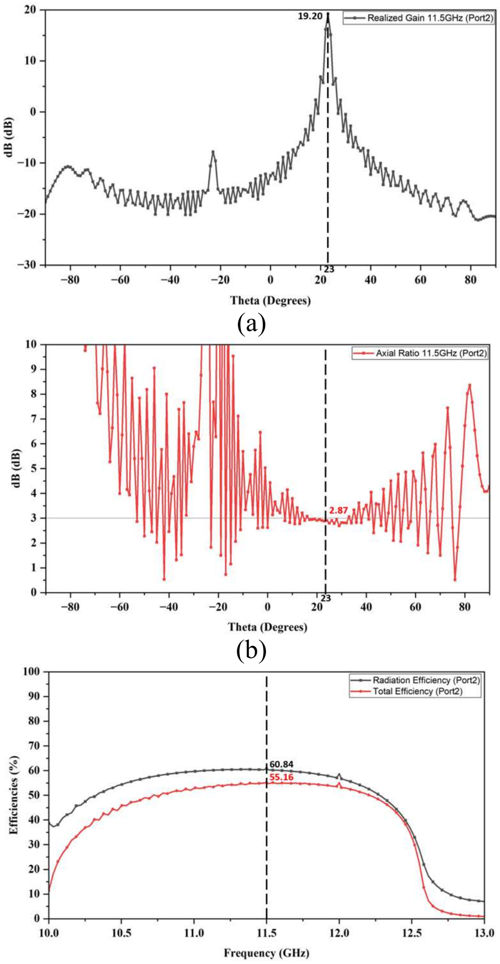
(b)

(c)

Fig. 4 Three fans slot linear ridged FSIW LWA. a) Realized Gain. b) AR. c) Efficiencies.

In Fig. 4(a), the analysis reveals that at 11.5 GHz from Port 2, the main lobe direction is positioned at 20 degrees from broadside, exhibiting a realized gain of 19.19 dBi and a measured side lobe level of −12.4 dB, indicative of a highly directive LWA. Shifting to Fig. 4(b), the AR at 11.5 GHz from Port 2, measured at the 20 degrees direction from broadside, registers 2.14 dB, denoting excellent circular polarization performance. In Fig. 4(c), radiation and total efficiency are standing at 58.15% and 51.64% at 11.5 GHz, respectively.

C. *Radiation Performance of Sinusoidal Ridged FSIW LWA*



(a)

(b)

(c)

Fig. 5 Three fans slot sinusoidal ridged FSIW LWA. a) Realized Gain. b) AR. c) Efficiencies.

In Fig. 5(a), the main lobe direction is positioned at 23 degrees from broadside, yielding a realized gain of 19.2 dBi and a side lobe level of −12.28 dB. Fig. 5(b) reveals a notable AR of 2.87 dB at 11.5GHz, measured from Port 2 at 23 degrees from the broadside, not surpassing the linear ridged FSIW case by −0.73 dB but still ensuring commendable circular polarization performance. Finally, Fig. 5(c) showcases the radiation and total efficiency, both substantially improved at 11.5 GHz, with values of 60.84% and 55.16%, representing enhancements of 2.7% and 3.5%.

D. *Impedance Bandwidth Manipulation*

Fig. 6 displays the S_{12} plots for various values of the sine curve amplitude A. It is obvious to observe that as A increases, the bandpass width decreases, resulting in a narrower bandpass filter. This observation holds significance, particularly when integrating the bandpass filter with a LWA, as minor adjustments in A do not impose additional manufacturing space requirements.

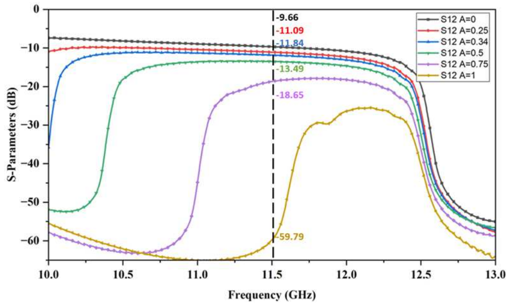


Fig. 6 The manipulation of the impedance bandwidth with repards to bandpass filtering effect.

E. Radiation Dispersion

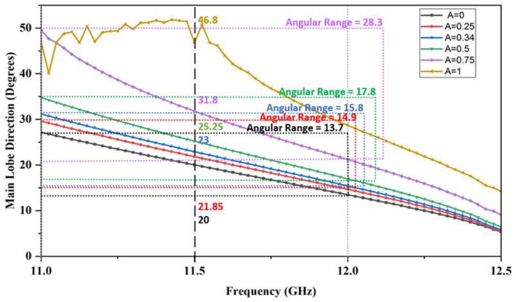


Fig. 7 Main lobe directions vs frequency varying with A.

In Fig. 7, it illustrates the relationship between the main lobe directions versus the frequency for various values of the amplitude A. Notably, higher values of A result in discernible changes in the main lobe direction at a fixed frequency of 11.5 GHz, although these changes are relatively minor with smaller A values (approximately 3 degrees shift from A = 0 mm to A = 0.34 mm). Furthermore, the dispersion, quantified as the angular range, is depicted. This measurement is determined by observing the angular deviation from the main lobe direction from 11 GHz to 12 GHz. It is evident that the antenna dispersion increases with a higher A value, with an angular range that is notably more extensive (approximately 14.6 degrees difference from A = 0 mm to A = 0.75 mm). However, when using lower A values, this difference is much more modest, with an angular range that expands by only 2.1 degrees from A = 0 mm to A = 0.34 mm.

F. AR and Efficiency

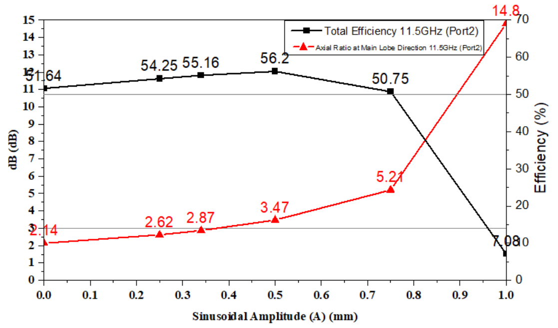


Fig. 8 Antenna AR and total efficiency vs the amplitude A.

Fig. 8 illustrates the behavior of AR and total efficiency at 11.5 GHz across various values of the amplitude A. The analysis reveals that higher A values result in deteriorating AR, with values up to A = 0.35 maintaining AR below the 3-dB threshold. Conversely, total efficiency experiences a noteworthy increase as A is elevated, peaking at A = 0.5 with 56.2%. This surge in efficiency is attributed to the higher energy radiated. The balance between AR and total efficiency should be taken into account to not compromise circular polarization performance.

IV. CONCLUSION

In this study, it has been undertaken the design and optimization of a three fans slot LWA in a ridged FSIW for operation in Ku band for the satellite communication systems. Additionally, a sinusoidal ridge is introduced to modulate the β_0 parameter of the FSIW LWA to analyze the realized Gain, bandwidth, dispersion (main lobe direction versus frequencies), AR and efficiency. The proposed sinusoidal ridged FSIW exhibits the potential to integrate a bandpass filter effect into a circular polarized FSIW LWA without the need of extra components, by judiciously selecting the sine cure amplitude.

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