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Circularly Polarized Substrate Integrated Waveguide Leaky-Wave Antenna with High Efficiency and Consistent Gain

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***Abstract*-This paper presents a compact circularly polarized (CP) substrate-integrated waveguide (SIW) leaky-wave antenna (LWA) with consistent gain and high total efficiency at millimeter-wave frequencies. The proposed antenna consists of two layers. The lower layer is a conventional slotted SIW LWA, while the upper layer is an S-dipole array. The S-dipole layer is introduced to achieve circular polarization and improve the total efficiency of the antenna. Simulated results demonstrate that the proposed antenna operates from 24.5 to 29.5 GHz and exhibits a continuous 32° CP beam scan with a realized gain variation between 13 and 14.2 dBic. Moreover, the axial ratio is maintained below 3 dB throughout the operating frequency band. The average realized gain and total efficiency are about 13.7 dB and 93%, respectively.**

Index Terms-Circular polarization, consistent gain, continuous beam scanning, leaky-wave antenna (LWA), millimeter-wave antenna, S-dipole, substrate-integrated waveguide (SIW).

I. INTRODUCTION

Leaky-wave antennas (LWAs) are defined as wave-guiding structures that use traveling waves on the guiding structure to leak power along the entire structure [1] - [3]. They have the merits of frequency beam-scanning capability, high directivity, low profile, and simple feed network. These unique characteristics make LWAs applicable to various fields such as automotive radar sensors [4], analog real-time spectrum analyzers [5], near-field mode synthesis [6], and satellite communication systems [7]. On the other hand, substrate integrated waveguide (SIW) has the advantages of light weight, low loss, and easy integration with other planar circuits, making it a popular candidate for implementing LWAs [8] - [10].

As is well known, circularly polarized (CP) antennas can avoid polarization mismatch, suppress multipath interference, and resist "Faraday rotation" compared with linearly polarized antennas [11]. In recent years, SIW-based CP LWAs have attracted considerable interests. In [12], a SIW-based CP LWA with inclined slots was proposed. But it cannot achieve beam scanning characteristics within the operating bandwidth. In [13], a CP SIW LWA with H-shaped slot was proposed, which generated two orthogonal electric field components with a phase difference of 90° between the longitudinal slot and the transverse slot. In [14], [15], the CP beam-scanning characteristic can be obtained by using two linearly polarized periodic LWAs with orthogonal polarizations. But this method makes the antenna rather bulky and requires an additional feeding network.

In this paper, a compact CP SIW LWA is proposed. By placing an S-dipole array [16] above a conventional slotted SIW, CP beam scanning and high total efficiency can be achieved. Simulated results demonstrate that the proposed antenna operates from 24.5 to 29.5 GHz and exhibits a continuous 32° CP beam scan. The average realized gain and total efficiency are about 13.7 dB and 93%, respectively.

II. ANTENNA GEOMETRY AND OPERATING PRINCIPLES

A. Antenna Geometry

The geometry of the proposed CP SIW LWA is shown in Fig. 1. The antenna consists of two layers. The lower layer is an SIW-fed longitudinal slot array LWA. Ten longitudinal slots are placed alternatively along the centerline with an offset distance of d_y. The upper layer is an S-dipole array which is excited by the longitudinal slots. Two ports are added at both ends of the LWA as the feed and matching load, respectively.

Fig. 2 shows the perspective view, top view and side view of the proposed antenna unit cell. Rogers 5880 substrates with a thickness of 1.575mm and a dielectric constant of 2.2 are used for both the upper and lower layers. The space between adjacent vias and the diameter of each via are S and D, respectively. The via spacing S should be small enough to restrict energy leakage.

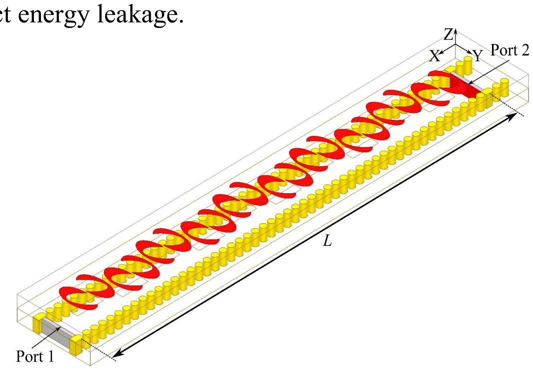
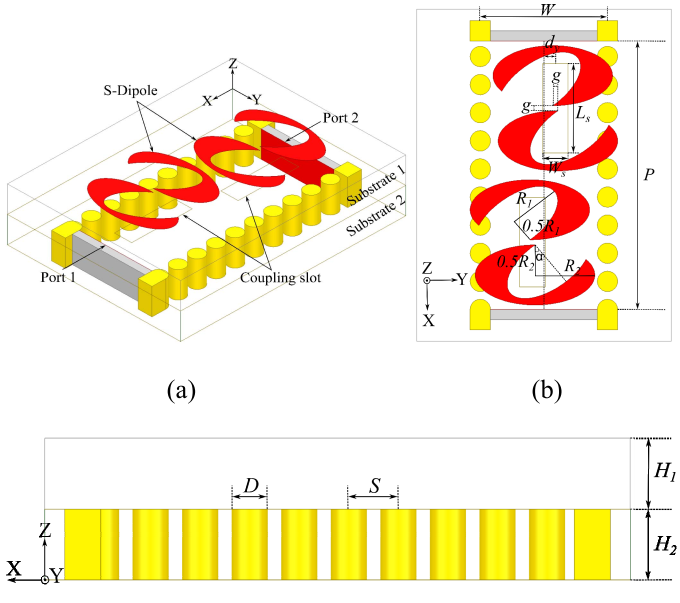


Figure 1. Perspective view of the proposed antenna



(a) (b)

(c)

Figure 2. Unit cell of the proposed antenna. (a) Perspective view, (b) top view, (c) side view.

Each unit cell has two longitudinal slots which are placed alternatively along the centerline with an offset distance of d_y. The length and width of each slot are L_S and W_S, respectively, and the spacing between adjacent slots is $P/2$. S-dipole elements are printed on the top substrate directly above the center of the corresponding slot, which consists of two rotational symmetric curved arms with a gap of g. Each curved arm is formed by a larger ellipse subtracted by a smaller ellipse rotated by an angle *a*.

B. *Operating Principles*

The radiation characteristics of LWA are determined by its phase constant β and attenuation constant α. The beam direction of a LWA can be approximately determined by the formula $\theta = sin^{-1} (\beta / K_0)$, where K_0 is the propagation constant of free space. And the beam width is proportional to the leakage constant α. The longitudinal slots of the proposed CP LWA are excited by traveling waves in the SIW. By changing the slots length L_s and the offset distance d_y, the amplitude and phase of the electric field excited across the slot can be changed. The slotted SIW will excite an infinite number of space harmonics, and the phase constant of each space harmonic can be expressed as $\beta_n = \beta_0 + 2\pi n/p$, where β_0 is the phase constant of the fundamental mode of slotted SIW, p is the period of slots, and n is the harmonic order. Normally $n = -1$ mode is used for radiation. The S-dipole array is excited by the longitudinal slots through electromagnetic coupling and co-radiates with the longitudinal slots. By introducing the S-dipole array on the conventional slotted SIW LWA, CP radiation and high total efficiency can be obtained.

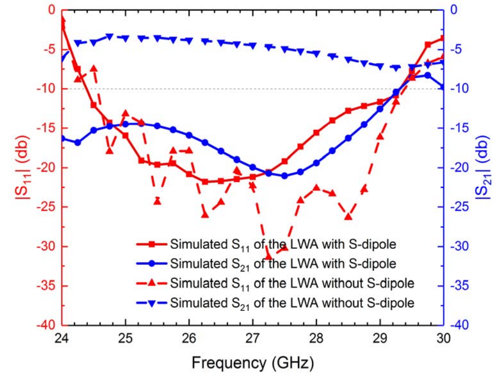


Figure 3. Simulated S-parameter for the LWA with S-dipole and without S-dipole.

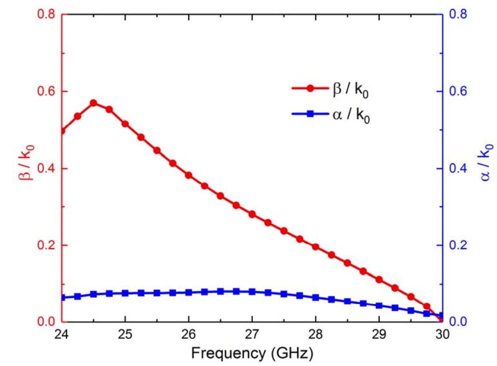


Figure 4. Dispersion diagram for the unit cell of the proposed antenna.

III. Results and Discussions

Simulated S-parameters for the SIW LWA with S-dipole array and without S-dipole array are plotted in Fig 3. As shown, by introducing the S-dipole array, the S_{21} can be significantly reduced, which indicates that the total efficiency of the LWA can be greatly improved. For the periodic LWA, the phase constant and attenuation constant can be obtained by analyzing a unit cell, and then the radiation characteristics of the periodic LWA can be obtained. The dispersion diagram for the unit cell of the proposed antenna is plot in Fig 4. Using the dispersion diagram, we can calculate the maximum radiation direction angle θ by the formula $\theta = sin^{-1} (\beta / K_0)$. Figure 5 shows the simulated normalized radiation patterns of the proposed antenna at various frequencies in the *x-z* plane. As shown, when the frequency changes from 24.5GHz to 29.5GHz, the maximum radiation direction angle θ changes from 36° to 4° and is in line with the angle θ calculated by the formula. Simulated axial ratio and realized gain of the proposed antenna are plotted in Fig 6, which demonstrates that the proposed antenna has a consistent realized gain across the frequency range from 24.5GHz to 29.5GHz, and the axial ratio is maintained below 3 dB throughout the operating frequency band. Figure 7 shows the simulated total efficiency of the proposed antenna. As shown, the total efficiency of the proposed antenna is greater than 90% within almost the entire operating frequency band.

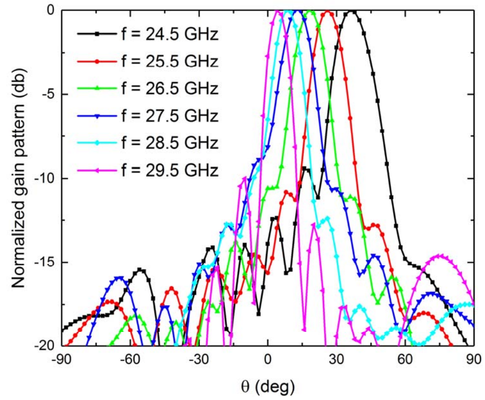


Figure 5. Simulated x-z plane normalized radiation patterns of the Proposed antenna at various frequencies.

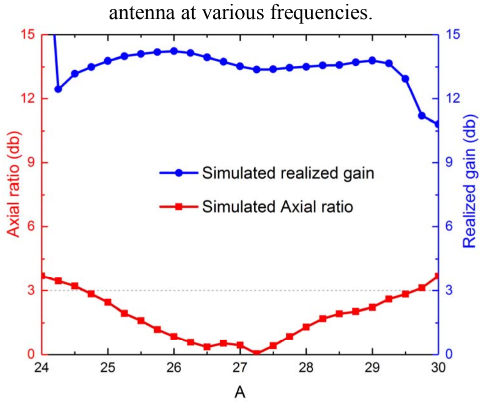


Figure 6. Simulated axial ratio and realized gain of the Proposed antenna.

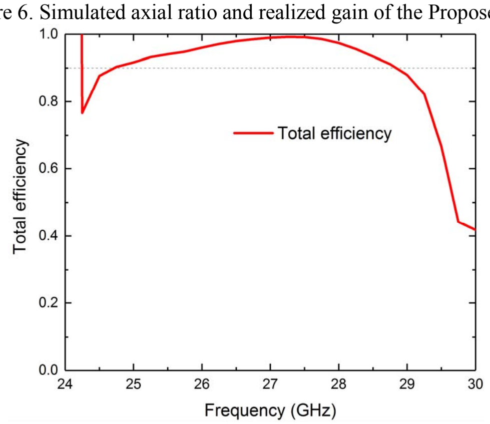


Figure 7. Simulated total efficiency of the proposed antenna.

IV. Conclusion

This paper presents a compact CP SIW LWA with consistent gain and high total efficiency at millimeter-wave frequencies. By introducing an S-dipole array on a conventional slotted SIW LWA, CP radiation and high total efficiency can be obtained. Simulated results demonstrate that the proposed antenna operates from 24.5 to 29.5 GHz and exhibits a continuous 32° CP beam scan with a realized gain variation between 13 and 14.2 dBic. The axial ratio is maintained below 3 dB throughout the operating frequency band. The average realized gain and total efficiency are about 13.7 dB and 93%, respectively.

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