Wideband Circularly Polarized Substrate Integrated Waveguide Endfire Antenna System With High Gain

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***Abstract*—A K-band endfire substrate integrated waveguide (SIW) circularly polarized (CP) antenna system on a single-layer printed-circuit board is proposed. A high-gain SIW H-plane horn and a Vivaldi antenna are developed to produce two orthogonal polarizations in the plane of the substrate. They are combined with a low-profile SIW 3-dB coupler to provide identical feeding amplitudes with 90° phase difference. The performance of the CP antenna system is demonstrated over the 23–27-GHz frequency range by comparing simulations and measurements in terms of gain, axial ratio, radiation pattern, and return loss. The results show that the proposed antenna system operates with a wideband 3-dB axial ratio from 24.25 to 26.5 GHz and a high and uniform gain of almost 8 dB. Measured results are found in good agreement with simulations.**

***Index Terms*—Axial ratio, circular polarization, circularly polarized (CP) antenna, substrate integrated waveguide (SIW).**

I. Introduction

With the advent of substrate integrated waveguide (SIW) technology, employment of compact, low-loss, and high-quality-factor microwave and millimeter-wave components has witnessed advancing progress. While SIW structures maintain most of the advantages of conventional rectangular waveguides, such as high-quality factor and high power-handling capability with self-consistent electrical shielding, the most significant advantage of SIW technology is the possibility to integrate all components on the same substrate, including passive components, active elements, and antennas [1].

The demand for high-gain circularly polarized (CP) antennas has increased considerably since they not only reduce the size and cost of communication systems, but also improve polarization match in multipath environments and offer higher flexibility between transmitters and receivers [2].

CP antennas are widely used in satellites, radar applications, and wireless communication systems. Their most desired properties are light weight, low profile, good return loss, and radiation performance; such attributes favor antennas based on SIW technology [3]. Thus, recently, SIW-based CP antennas have been proposed to provide higher degrees of freedom over conventional CP antennas [4]–[9].

To achieve circular polarization with a 3-dB axial ratio over a wide bandwidth, a dual-fed wideband CP patch antenna based on SIW technology is proposed in [10]. This design achieves an axial-ratio bandwidth of 21%. However, the gain bandwidth is narrow and its directional beam is broadside, i.e., not in line with the substrate. In [11], two single-fed cavity-backed slot antennas and a CP array are introduced. The individual antennas suffer from narrow bandwidth and low gain, but the array design has a wideband axial ratio and high gain in the operating frequency band. However, the radiation pattern of the array is in the vertical plane, and gain is not uniform over the entire bandwidth. A planar CP antenna element with four rectangular radiation slots is designed in [2] to obtain high gain, but CP radiation is perpendicular to the substrate, and the axial-ratio bandwidth is narrow. A square slot with an SIW cavity is introduced in [8] with a 3-dB axial ratio that covers a wide angular range of 150°, but it suffers from low gain levels. A compact endfire CP SIW horn antenna is designed in [12], which operates with a 3-dB axial-ratio bandwidth of 11.8% from 17.6 to 19.8 GHz. This design has good CP performance, but relies on using a thick substrate that makes the fabrication difficult. Also, two substrate layers make for a bulky feeding structure, which is not suitable for integration with planar structures.

For some applications, CP radiation in the substrate's plane, i.e., endfire, is required, but only few CP antennas satisfy this requirement. For instance, in [13] a combination of rectangular waveguide and dipole antenna is used to achieve circular polarization. Still, due to the three-dimensional structure, this antenna is costly for fabrication. Two other antennas are presented in [14] and [15], which have endfire CP radiation, but their gain is as low as 2.6 and 2.3 dBi, respectively. In [16], by proposing a cross type of two CP linearly tapered slot antenna (LTSA) arrays, a CP LTSA array is designed. The proposed array has two disadvantages: First, the 3-dB axial-ratio bandwidth is very narrow, and second, this design requires vertical substrate elements that make fabrication complicated. A high-gain CP antenna array is presented in [17], which generates CP by antipodal curvedly tapered slot antennas that are covered by two sheet-metals on both sides of the rectangle substrate, which make the structure large and nonplanar. A new CP horn-dipole antenna is proposed in [9] and demonstrates an effective bandwidth of 5% for an axial ratio

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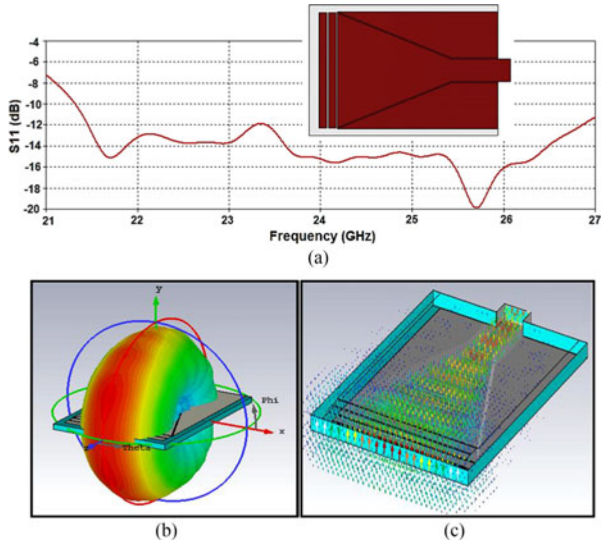


Fig. 1. (a) Simulated reflection coefficient, (b) radiation pattern, and (c) electric field of the H-plane SIW horn antenna with printed transitions.

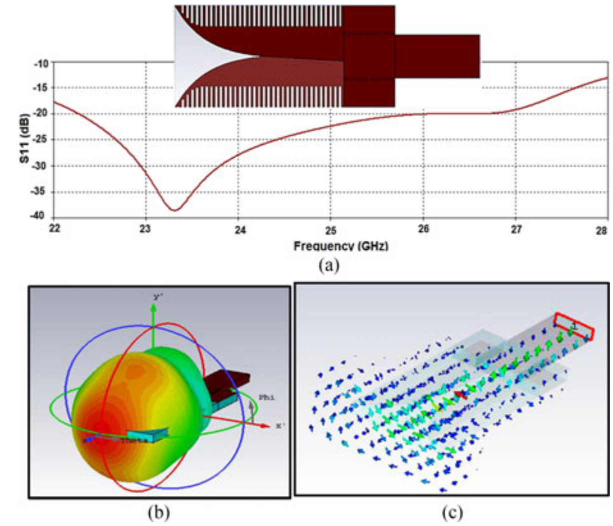


Fig. 2. (a) Simulated reflection coefficient, (b) radiation pattern, and (c) electric field of the SIW Vivaldi antenna.

less than 3 dB and return loss better than 10 dB between 11.8 and 12.4 GHz. However, it does neither have a uniform gain over the entire bandwidth nor does it cover a wide operational bandwidth.

Therefore, this paper presents a new design for providing CP endfire characteristic over a broad bandwidth and with almost flat and high gain. Two antennas, an H-plane SIW horn and an antipodal Vivaldi element, are employed to provide vertical and horizontal electric fields. A low-profile, compact, and low-cost SIW 3-dB coupler provides the same magnitudes and 90° phase difference at the antenna inputs. The printed transition in front of the horn antenna and length and dimensions of the Vivaldi antenna are optimized in CST to achieve a wide axial-ratio bandwidth and a high and uniform gain. To verify the design concept, a prototype is fabricated and measured. Good agreement between simulation and experimental results is established. All desired goals, such as wide 3-dB axial ratio versus frequency from 24.2 to 26.5 GHz, high and uniform gain of about 8 dB in the entire operating bandwidth of 23–27 GHz, and a return loss better than 10 dB are accomplished.

II. Antenna System Design

A. SIW Horn Antenna

The design procedure of an H-plane SIW horn antenna is identical to that of a conventional one [18], the only difference being the equivalent waveguide width of the SIW, which is calculated according to [19]. The printed transitions in front of the aperture are designed and optimized to improve the matching between the thin substrate and air; the working principles are explained in [20]. The thickness h, width a, operating frequency, and dielectric constant are chosen to only excite the dominant TE_{10} mode. Fig. 1(a) shows the proposed SIW H-plane horn antenna and its return loss, which is better than 10 dB between 21.5 and 27 GHz. Fig. 1(b) and (c) shows a 3-D view of the far-field radiation pattern and TE_{10}-mode electric fields excited in the horn antenna, respectively. Note that the polarization of the horn is vertical, with horizontal polarization (TE_{01} mode) blocked by the thin substrate.

B. Vivaldi Antenna

The antipodal Vivaldi antenna is horizontally polarized and designed based on a parametric study in [21]. Some adjustments and optimizations for the type of substrate, length, and shape of the antipodal flare slot are applied to the primary design to change the operating frequency [22]. Along the outside edges of the antenna, regular comb-like corrugations are cut into the metallized top and bottom layers to suppress vertical polarization, which corresponds to the electric field distribution in the feeding SIW. The return loss and graphic of the antenna are presented in Fig. 2(a). The return loss is better than 15 dB between 22 and 27 GHz. The radiation pattern and E-fields are indicated in Fig. 2(b) and (c), respectively.

C. CP Antenna System

By combining the SIW H-plane horn and Vivaldi antenna with a 90° hybrid, a CP antenna system is obtained. In order to excite the two antennas with the same amplitude and 90° phase difference, a broadband, low-profile SIW 3-dB coupler is designed and optimized based on [23]. The return loss and isolation of the coupler are better than 23 dB between 22 and 30 GHz. Note that both Vivaldi and SIW horn antennas provide the same field amplitude in endfire direction.

The final structure of the proposed CP antenna system and its dimensions are shown in Fig. 3. For measurement purposes, the coupler's input ports are bent 90°. In order to excite the SIW antenna system, a microstrip-to-SIW transition is designed to connect to a K-connector.

The critical point in achieving circular polarization in this design is optimizing both structures such that they produce the same E-field amplitude in endfire direction. Thus, the printed transitions to the SIW horn, the width and length of the comb-shaped corrugations at the edges of the Vivaldi antenna, and the

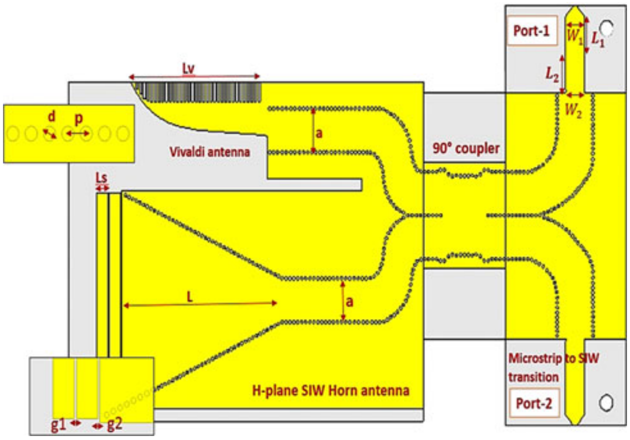
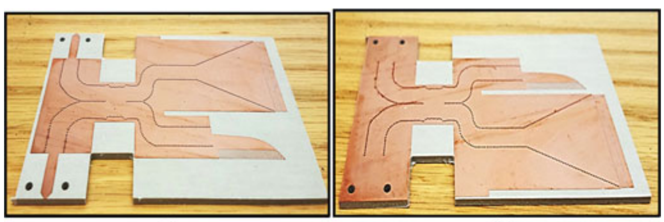


Fig. 3. Layout and dimensions of the CP antenna system. Parameters (in mm) are: a = 5.4, p = 0.6, d = 0.397, $W_1 = 3.001$, $W_2 = 2.787$, $g_1 = 0.15$, $L = 24.38$, $L_s = 1.75$, $L_1 = 4.39$, $L_2 = 4.45$, $L_v = 20$, $g_2 = 0.25$.



(a) (b)

Fig. 4. (a) Top and (b) bottom views of the fabricated SIW antenna system.

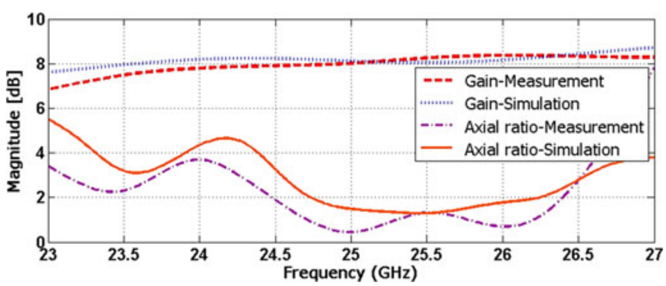


Fig. 5. Simulated and measured axial ratio and gain of the CP SIW antenna system.

total length are optimized to satisfy CP requirements. Note that this design can provide both right-hand (RHCP) and left-hand circular polarization (LHCP) by exciting either port 1 or port 2, respectively, in Fig. 3.

III. Results

The proposed antenna system is designed on a single layer of Rogers 6002 substrate with relative permittivity of 2.94, thickness of 1.524 mm, and loss tangent of 0.0012. It is simulated in CST Studio Suite 2016 and then fabricated and measured for the verification of the design procedure. Fig. 4 depicts top and bottom views of the prototype. Measurements have been carried out in a far-field antenna test chamber using an Anritsu 37397C vector network analyzer.

Fig. 5 compares simulated and measured gain and axial ratio, and good agreement is observed. Since both Vivaldi antenna and SIW horn are designed individually with noticeably high gain, the CP antenna system has fairly high and almost uniform gain in the entire frequency band plotted in Fig. 5. The maximum measured gain is 8.4 dB. The measured 3-dB axial ratio bandwidth extends from 24.25 to 26.5 GHz.

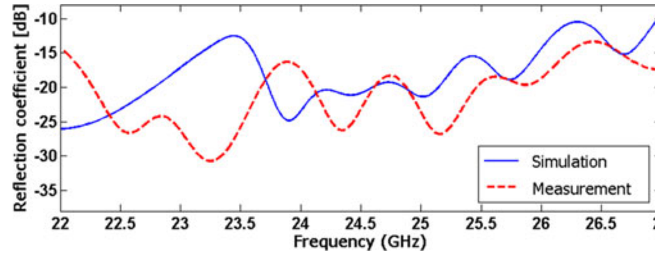


Fig. 6. Simulated and measured reflection coefficients in dB.

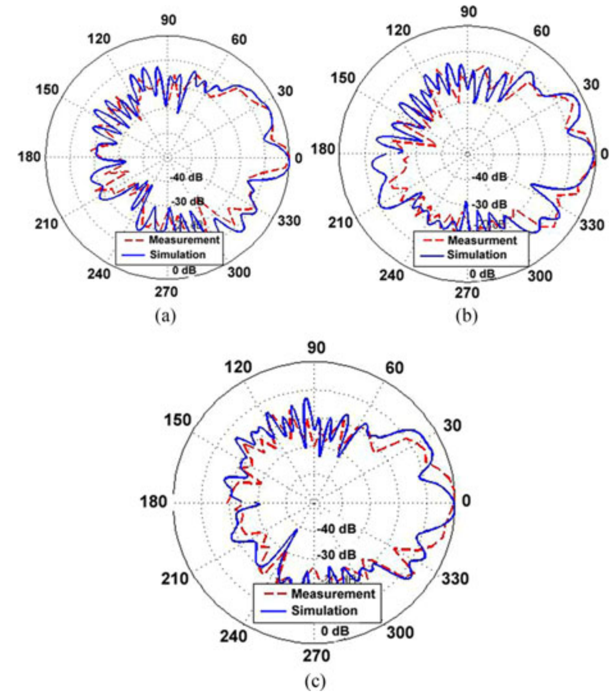


Fig. 7. Simulated and measured co-pol radiation patterns; (a) 23.5, (b) 25, and (c) 26.5 GHz (θ in degrees versus dB).

Simulated and measured reflection coefficients are compared in Fig. 6. The measured return loss of the CP SIW antenna system is better than 10 dB from 22 to 27 GHz.

The polarization efficiency is calculated at mid-band frequency and three different angles based on the method presented in [24]. The CP antenna system has a good performance of 99% polarization efficiency in endfire direction. However, the performance is not as good at other angles since the ratio of co-pol radiated power to total radiated power decreases rapidly when moving away from the axis. The polarization efficiency is 28% at 10° and 55% at −10°, which means that compared to that at mid-band frequency, 71% and 44% of the radiated co-pol power are lost at 10° and −10°, respectively.

This behavior is confirmed in Figs. 7 and 8, which display simulated and measured co-pol (RHCP) and cross-pol (LHCP) radiation patterns at three different frequencies of 23.5, 25, and

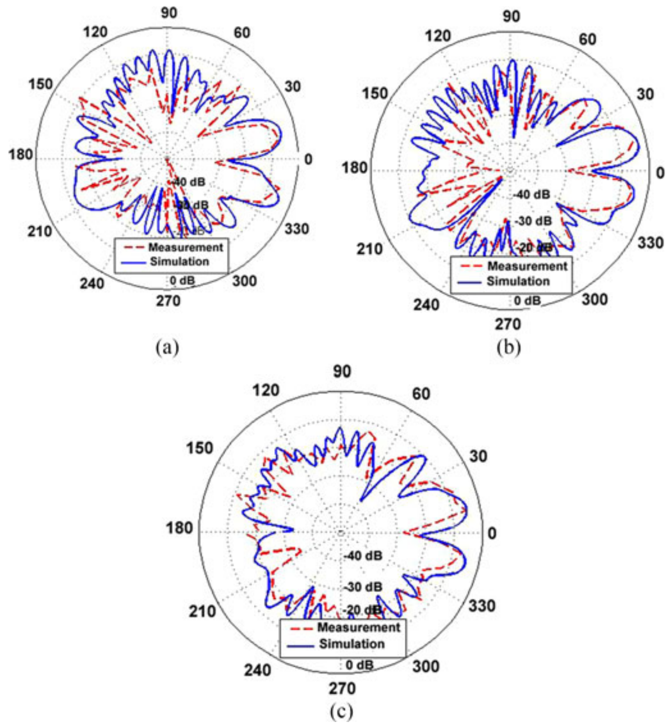


Fig. 8. Simulated and measured cross-pol radiation patterns; (a) 23.5, (b) 25, and (c) 26.5 GHz (θ in degrees versus dB).

26.5 GHz. All radiation patterns show a good agreement between simulated and experimental results. The measured cross-polarization level at $\theta = 0°$ is between -20 and -30 dB in different frequencies, and the maximum cross-pol at $\theta \sim \pm 10°$ is better than -5 dB.

The high cross polarization at $\pm 10°$ is a direct result of the antenna system's planar geometry. Since the two antennas are located side by side with about 20-mm distance from the center of the Vivaldi to that of the horn antenna, and with different aperture widths, the electric field phase is slightly more than one third of a wavelength off at $+10°$, and slightly less than that value at $-10°$, thus causing high cross-pol values in these angles.

IV. Conclusion

By combining a Vivaldi antenna and a planar horn antenna with a 90° hybrid in SIW technology, a K-band CP endfire antenna system, radiating in the plane of the substrate, is obtained that provides wide 3-dB axial ratio and high and uniform gain over its entire operating frequency range. A uniform gain of 8 dB from 23 to 27 GHz and a 3-dB axial ratio from 24.2 to 26.5 GHz are achieved. The maximum measured gain is 8.4 dB including the loss of the attached K-connector. The 3-dB SIW hybrid contributes merits such as low profile, low loss, and wideband 3-dB power division with 90° phase difference. Both LHCP and RHCP can be facilitated by switching the exciting ports. Good agreement between simulated and measured results is observed over the entire bandwidth, thus validating the proposed design procedure of the CP SIW antenna system.

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