Realization of a Composite Right/Left-Handed Leaky-Wave Antenna with Circular Polarization

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***Abstract* — A leaky-wave antenna (LWA) with circular polarization based on the composite right/left-handed (CRLH) substrate integrated waveguide (SIW) is investigated and presented. Series interdigital capacitors have been introduced into the circuit by etching the slots on the waveguide surface achieving a CRLH functionality. Two symmetrical leaky traveling-wave transmission lines with orthogonal polarizations are placed side-by-side and excited with 90° phase difference generating a pure circular polarization mode. The main beam of this antenna can be steered continuously by varying the frequency while maintaining a low axial ratio (below 3 dB) within the main beam direction. The performance of this LWA is verified through both full-wave simulation and measurement of a fabricated prototype showing a good agreement.**

***Index Terms* — Circular polarization, composite right/left-handed (CRLH), leaky-wave antennas (LWA), substrate integrated waveguide (SIW).**

I. Introduction

Leaky-wave antennas (LWAs), both in uniform or periodic transmission line (TL) configurations, have been intensively studied and widely used for many different applications. They provide broad VSWR bandwidth performance, frequency scanning capabilities, and sharp directional beams. The conventional LWAs suffer from the limitation of their scanning ability specifically in broadside radiation. Recently, there has been significant interest in the composite right/left-handed (CRLH) metamaterials, which support the backward-wave propagation in its left-handed (LH) region [1]. CRLH LWAs have been considered as desirable radiating structures because of their ability to offer continuous backfire-to-endfire beam scanning. Various designs based on different technologies have been proposed and implemented [1-3]. Most of them are linearly polarized offering beam-steering through frequency scanning. In some applications, however, it is desirable to work with the circular polarization to improve the received signal quality during transmission. It is a challenge to maintain a pure circularly polarized mode for the main beam during scanning.

In this work, a CRLH LWA with circular polarization has been developed based on the substrate integrated waveguide (SIW) technology. SIW provides some desirable features like low-profile, low-cost, high quality factor and good capability for integration with other circuits. Two SIW LWAs were discussed and investigated in [3], [4], the former being CRLH type and the latter conventional type. The present design is achieved by symmetrically aligning two CRLH-SIW leaky-wave lines side-by-side. Each of them is realized by etching interdigital slots 45°-inclined on the metal surface. The slots act like a series capacitor, which, along with the

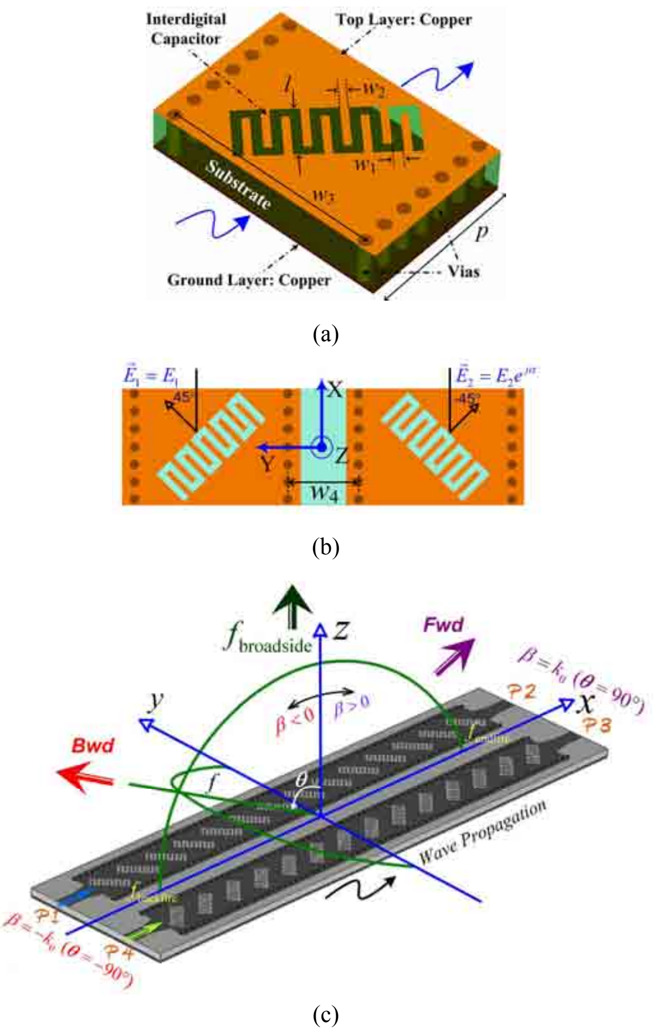


Fig. 1. Configuration of the proposed structures (a) Single CRLH-SIW radiating element, (b) Unit-cell of the circularly polarized LWA, and (c) Overall circularly polarized LWA prototype.

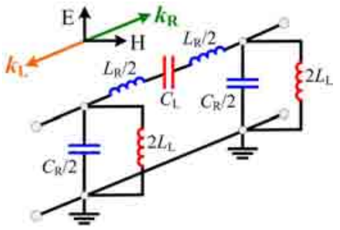


Fig. 2. Equivalent circuit model of the CRLH-SIW element.

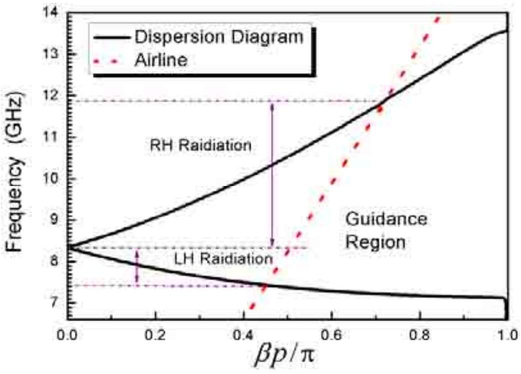


Fig. 3. Dispersion diagram of the CRLH-SIW unit-cell shown in Fig. 1(a) obtained from HFSS *S*-parameter simulation. The parameter values are: w_1 = 0.545 mm, w_2 = 0.4 mm, w_3 = 12.4 mm, p = 9.1 mm, and l = 3.1 mm.

waveguide inherent shunt inductance, create the necessary condition to support backward-wave propagation. A half-mode SIW 3-dB directional coupler [5] is also designed to feed the antenna. Circular polarization thus is obtained by equally exciting two orthogonally-polarized traveling waves with 90° phase difference. Its backfire-to-endfire beam scanning and circular polarization performance are demonstrated in both the simulation and the measurement.

II. Proposed Structure and the Working Principle

The proposed leaky-wave structure is shown in Fig. 1, in which the configuration of the one period element (Fig. 1(a) and (b)) and the prototype of the whole LWA with its orientations in the coordinate system (Fig. 1(c)) are displayed. As shown the unit-cell is surrounded by vias on the two sides and grounded by a solid metallic plane. The slot embedded on the waveguide surface is 45° inclined compared with propagation direction. Two symmetrical leaky TLs are side-by-side arranged and separated with a small distance to improve the isolation as depicted in Fig. 1(b) and (c). They can generate two orthogonal linearly-polarized waves leading to a circular polarization when excited with 90° phase difference. The LWA is synthesized on a substrate of Rogers 5880 with a thickness of 1.27 mm and a relative permittivity of 2.2. The metallic via holes are chosen to have a diameter of 0.8 mm and a center-to-center spacing around 1.5 mm.

Fig. 2 shows the equivalent circuit of the CRLH-SIW unit-cell as presented in Fig. 1(a). The metal surface and the

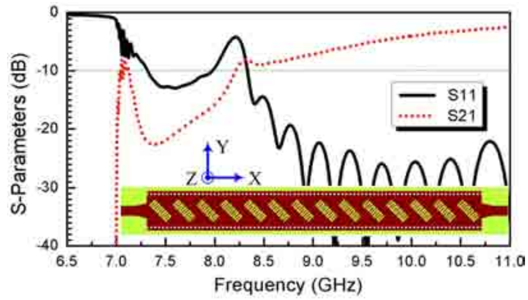


Fig. 4. Simulated *S*-Parameters for the single radiating TL.

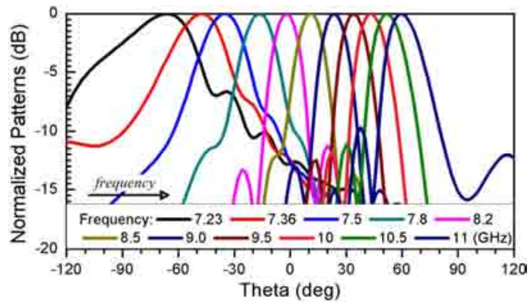


Fig. 5. Simulated *E*-plane radiation patterns in *x-z* plane at different frequencies.

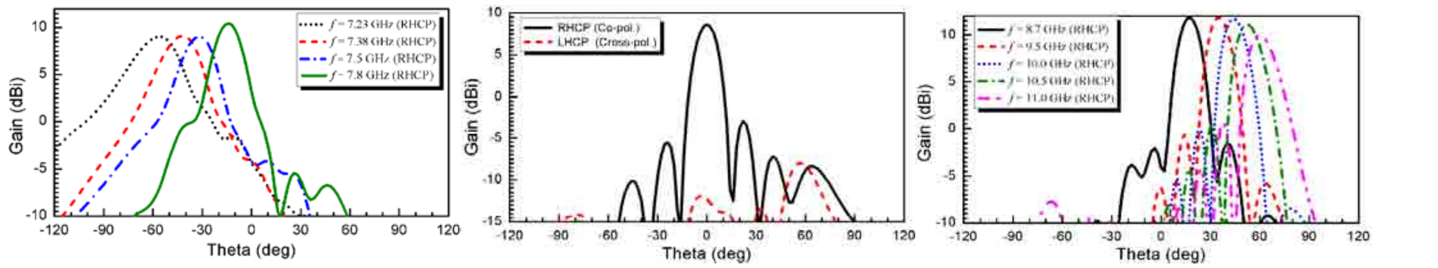
ground can be modeled as a two-wire TL with distributed series inductance and distributed shunt capacitance. The vias provide the shunt inductance. The interdigital capacitor has been introduced into the model as C_L to realize a CRLH structure. The LH contribution comes from the series capacitor C_L and the shunt inductor L_L. The interdigital slot is rotated by 45° resulting in a 45°-inclined linear polarization. Efficient radiation can be realized by increasing the slot width or the slot length.

Fig. 3 shows the simulated dispersion diagram obtained from the *S*-parameters for the unit-cell depicted in Fig. 1(a). It is seen that a balanced case (without a stop band) is achieved with the transition frequency located at 8.25 GHz. It should be noted that in general there is a band gap between the LH and right-handed (RH) regions when it is not balanced. The air line is also plotted which gives rise to two distinct regions: the radiating region (fast wave) above the line and the guiding region (slow wave) below the air line.

III. Simulation

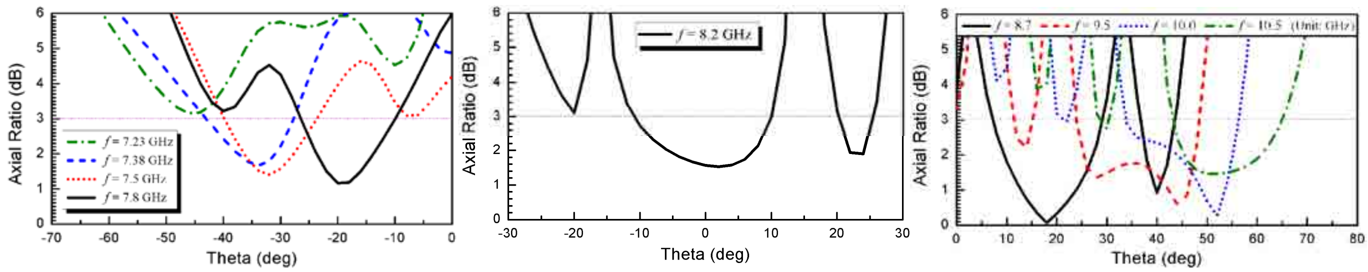
Based on the unit-cell analysis shown in the previous section, here a single radiating TL with 14 elementary cells is first designed to verify its leaky-wave performance. Then a circularly-polarized antenna by symmetrically configuring such two TLs together is simulated and investigated. All the simulation is based on the Ansoft's High Frequency Structure Simulator (HFSS) software package.

Fig. 4 shows the simulated *S*-parameters of the single leaky line which is indicated in the inset of the figure. The dimensions of the 14 unit-cells are identical with that



(a) (b) (c)

Fig. 6. Simulated gain patterns of the circularly polarized antenna in *x-z* plane in (a) LH region, (b) Broadside (at 8.2 GHz), and (c) RH region.



(a) (b) (c)

Fig. 7. Simulated AR of the circularly polarized antenna in *x-z* plane in (a) LH region, (b) Broadside, and (c) RH region.

Fig. 8. Photograph of the fabricated components.

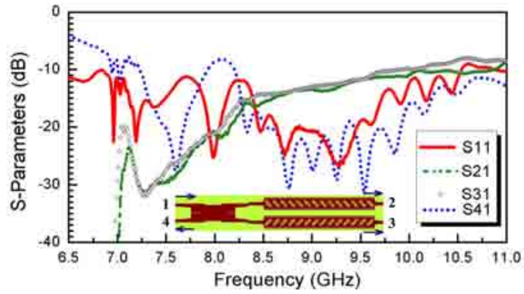


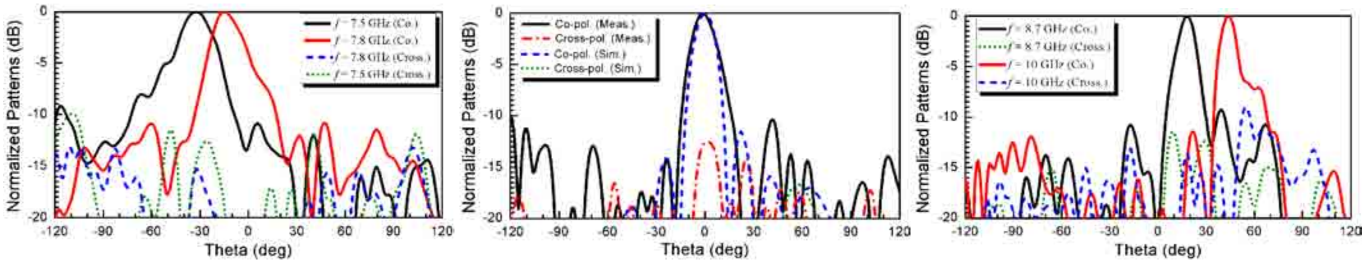
Fig. 9. Measured *S*-Parameters of the entire circularly polarized LWA.

analyzed in Fig. 3, where the parameters are listed. A taper line is employed at the input and output to optimize the impedance matching in a wide bandwidth. The LH region and RH region are separated by the transition frequency of 8.2 GHz. As observed although the dispersion curve of unit-cell presents a seamless transition between the LH and RH regions the whole TL is not perfectly balanced. This is due to the fact that the finitely long leaky line cannot guarantee a periodic boundary condition for the unit-cell. Fig. 5 shows the simulated radiation patterns for the leaky SIW TL. Full-space steering with increase of the frequency of the radiated beam is clearly observed. It is noted that due to the decrease of the antenna equivalent aperture size the beam-width is larger at lower frequencies. It is also important to bear in mind that its co-polarization plane is along the direction of the slots, which is the 45°-rotated *x-z* plane.

The circularly polarized antenna is obtained by exciting two orthogonally polarized radiating lines with 90° phase difference. In the simulation setup two signals with equal magnitude and 90° phase difference are applied at *port* 1 and *port* 4, respectively. Fig. 6 shows the simulated gain patterns in the LH region, broadside, and RH region. The antenna is RH circularly-polarized and the cross-polarization (LHCP) at 8.2 GHz is also plotted in Fig. 6(b) which is about 20 dB lower in the beam direction. Generally speaking, the realized gain in the RH region is higher than that in the LH region due to the increase of antenna size in terms of wavelength. It is also expected that the gain at broadside is relatively low because of the noticeable reflection. Fig. 7 shows the simulated axial ratio (AR) of the main beam at different frequencies. Apparently the region for AR less than 3 dB is also scanning along with the beam. It should also be pointed out the circular polarization performance deteriorates at low frequencies as shown in Fig. 7(a) because of the non-negligible coupling between the two radiating lines.

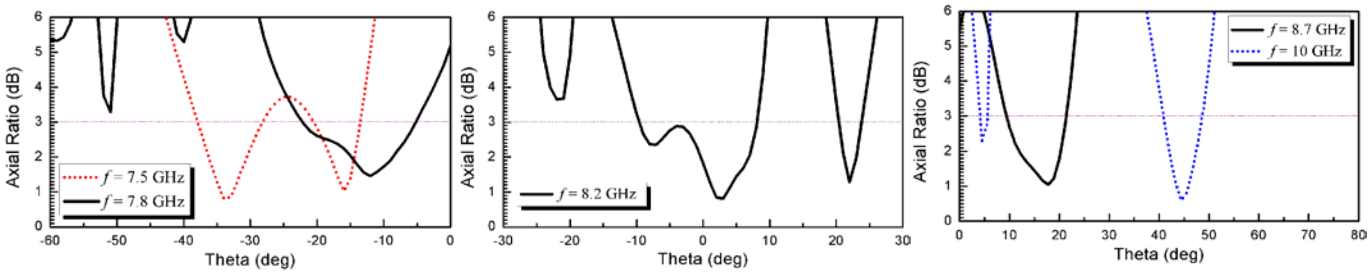
IV. Experiment

In order to generate two signals with equal amplitude and 90° phase difference, a 3 dB half-mode SIW directional coupler, which is proposed and detailed in [5], is also



(a) (b) (c)

Fig. 10. Measured *E*-plane patterns of the circularly polarized antenna in *x-z* plane in (a) LH region, (b) broadside, and (c) RH region.



(a) (b) (c)

Fig.11. Measured AR of the circularly polarized antenna in *x-z* plane in (a) LH region, (b) broadside, and (c) RH region.

fabricated with the antenna. They are implemented by our standard PCB process on the substrate of Rogers RT/Duroid 5880 with a thickness of 1.27 mm. Fig. 8 shows a photograph of the fabricated components.

The circularly-polarized antenna is obtained by connecting the fabricated coupler and the antenna. Fig. 9 shows the measured *S*-parameters of the whole antenna. It is seen that the total reflection (S_{11}) is below -11 dB in the whole region. The isolation (S_{41}) experiences a peak around 8.2 GHz and deteriorates below 7.2 GHz. This is reasonable since the reflected waves from the two leaky lines arrive at *port* 1 with 180° out-of-phase thus they cancel each other. However, they are inphase when arriving at *port* 4 thus it is the superposition of the two waves due to the 90° directional coupler. Therefore the S_{41} behaves similarly to the reflection of the single radiating line.

The radiation patterns and AR of this antenna are measured in a near-field chamber in our High Frequency Center. Fig. 10 shows the normalized radiation patterns measured at five different frequencies. Both the co-polarization (RHCP) and cross-polarization (LHCP) are provided in the figure. Beam scanning is verified by the backward-wave, broadside and forward-wave radiation as shown in Fig. 10(a), (b) and (c), respectively. The measured directivity is 10.45 dBi at 7.5 GHz, 10.71 dBi at 7.8 GHz, 11.52 dBi at 8.2 GHz, 13.22 dBi at 10.71 GHz, and 14.556 dBi at 10 GHz. The measured AR at the above frequencies is plotted in Fig. 11. It is seen that at the main beam direction the obtained AR is always below 3 dB. Discrepancy is observed between the simulated and measured AR which is expectable since the 3 dB coupler is not perfect and band-limited. Also the fabrication error could result in different performances of the two leaky lines which would affect the AR.

VI. Conclusion

A frequency-scanned CRLH-SIW LWA with circular polarization has been developed. It consists of a 3-dB directional coupler and two orthogonally polarized radiating TLs. The antenna is fabricated by our low-cost PCB process. The working principle has been illustrated. The measured results are consistent with the simulation. The antenna is low-profile, low-loss, and suitable for integration. This antenna is expected to find many applications in wireless systems.

Acknowledgement

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