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Design and Analyses of a CRLH-HMSIW-Based LWA with Low Cross-Polarization

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Abstract—A composite right/left-handed (CRLH) half mode substrate integrated waveguide (HMSIW) based leaky wave antenna (LWA) is designed and analyzed in this paper. Equivalent circuit of the unit cell is extracted, and the CRLH performance is clarified. Two HMSIW structures are placed back-to-back to obtain low cross-polarization performance, which is further validated by differential excitation principle. The presented LWA is demonstrated to be a balanced structure with a beam scanning range from $-60°$ to $+31°$. Besides, less than 1.7 dBi gain variation in the working band (46% centered at 13 GHz) is obtained. Simulated and measured results agree well as experiment shows.

1. INTRODUCTION

In recent years, leaky wave antenna (LWA) has received considerable attentions in radar systems and satellite communication fields for its frequency-scanning capability and wide bandwidth feature [1]. Among various kinds of leaky wave antennas, planar LWAs have found wide applications for their attractive properties such as low profile and light weight [2]. However, most conventional LWAs suffer from limited beam scanning range and poor broadside radiation, which is undesirable in cases where forward, backward and broadside radiation capabilities are simultaneously required. This is mainly because large percent of the incident power is reflected when the main beam scans to the broadside direction. Impedance matching techniques are usually used for this "open-stopband" suppression as mentioned in [3] and [4].

Recently, there has been increasing interest in composite right/left-handed (CRLH) substrate integrated waveguide (SIW) based LWAs for supporting both the forward and backward wave propagations in their right and left-handed regions [5–7]. In [5] and [6], a dual-band LWA and a tri-band LWA are proposed and designed respectively, and both of the antennas are based on the CRLH-SIW structure and support backward radiation. Moreover, double periodic structure is also utilized in CRLH LWA designs such as in [7], and with this arrangement, a new leaky-wave frequency band can be observed at low frequency below the regular left-handed passband. In addition to the SIW structure, half mode substrate integrated waveguide (HMSIW), which usually has a more compact size than the SIW, can also be used in CRLH LWA designs. In [8], a family of CRLH SIW and HMSIW leaky-wave structures is proposed. Four types of LWAs that use interdigital slots as series capacitors are implemented and analyzed. Continuous beam-steering capabilities are achieved. In [9], by using ramp-shaped slots as interdigital capacitors, a CRLH-HMSIW based circularly polarized LWA is designed with backward-broadside-forward radiation capability.

In this paper, a novel CRLH-HMSIW based LWA is designed and analyzed in detail. Mushroom-like radiators are used to obtain the left-handed transmission feature. Equivalent circuit of the unit cell is extracted, and its CRLH characteristic is demonstrated by both of the full-wave and circuit model simulation. Moreover, back-to-back arrangement is utilized for lower cross polarization levels (XPLs) in

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the beam scanning plane based on the differential excitation principle. Simulated and measured results show that the designed antenna herein is a balanced LWA operating in broad frequency band and that it is suitable for practical applications where continuous frequency scanning capability and low cross polarization feature are desired.

2. DESIGN AND ANALYSES OF THE UNIT CELL

The proposed HMSIW-based unit cell is shown in Figure 1. It consists of three layers: a top layer, a bottom layer and a substrate layer made of inexpensive FR4 with relative permittivity $\varepsilon_r = 4.4$ and thickness $h = 1\,\text{mm}$. The mushroom radiator is composed of two parts, a square patch and four grounded vias parallel to the SIW via walls. The series capacitor is introduced due to the capacitive coupling between the square patch and the SIW top layer while the shunt inductor is due to the grounded vias. Antenna parameter values are also given in Figure 1.

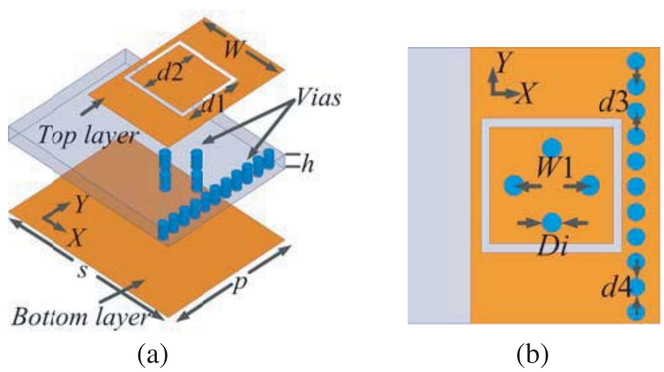


Figure 1. Structures of the HMSIW-based unit cell. (a) 3-D view, and (b) top view. The parameter values are: $s = 8.5\,\text{mm}$, $p = 11\,\text{mm}$, $h = 1\,\text{mm}$, $d1 = 5.3\,\text{mm}$, $d2 = 4.6\,\text{mm}$, $d3 = 1\,\text{mm}$, $d4 = 0.7\,\text{mm}$, $Di = 0.8\,\text{mm}$, $W = 6.5\,\text{mm}$, and $W1 = 3\,\text{mm}$.

The extracted lossless equivalent circuit model of the unit cell is presented in Figure 2. Mushroom structure is modeled as a shunt resonator tank. Series capacitors, labeled as C_{L}, are related to the square slot ring in broad face of the SIW structure, while metallic grounded vias contribute to shunt inductors (left-handed inductors labeled as L_{L1} and L_{L2}). Right-handed capacitors and inductors are marked as $C_{\text{R1(R2)}}$ and $L_{\text{R1(R2)}}$ respectively as shown in the figure [8]. The square slot ring corresponding to series capacitors also acts as a radiator from which the energy leaks out gradually, leading to leaky wave performance. Using simulated unit cell S-parameters as objectives, commercial electromagnetic simulator AWR is utilized to obtain values of the extracted lumped components with the data fitting

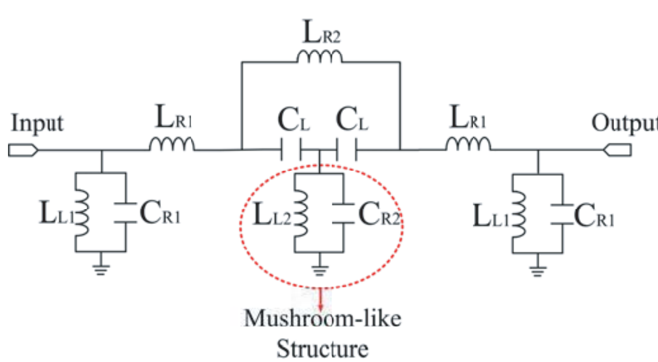


Figure 2. The extracted lossless equivalent circuit of the HMSIW-based unit cell.

method [10]. The component values are: $L_{\mathrm{R1}} = 1.1\,\mathrm{nH}$, $L_{\mathrm{R2}} = 5.3\,\mathrm{nH}$, $C_{\mathrm{R1}} = 0.3\,\mathrm{pF}$, $C_{\mathrm{R2}} = 0.98\,\mathrm{pF}$, $L_{\mathrm{L1}} = 0.68\,\mathrm{nH}$, $L_{\mathrm{L2}} = 0.13\,\mathrm{nH}$, $C_{\mathrm{L}} = 0.21\,\mathrm{pF}$.

S-parameters obtained from full-wave simulation and the extracted circuit are plotted in Figure 3. Acceptable agreement is observed, and therefore the circuit is verified. For the equivalent circuit, its series resonance frequency ω_{se} is 12.93 GHz, and its shunt resonance frequency ω_{sh} is 13 GHz, which means that the balanced condition is almost met at 13 GHz and that the LWA is a balanced CRLH structure with broadside radiation capability. The calculated effective constitutive parameters are shown in Figure 4(a). Double negative performance is obtained, and thus the CRLH performance of the designed unit cell is demonstrated. The unit cell dispersion characteristics obtained from full-wave simulation and circuit model are plotted in Figure 4(b). The radiation region starts from around 9.8 GHz, and the transition frequency point appears at around 13 GHz, at which the effective constitutive parameters are equal to zero.

Electric field distributions in two different structures are shown in Figure 5 to clarify the back-

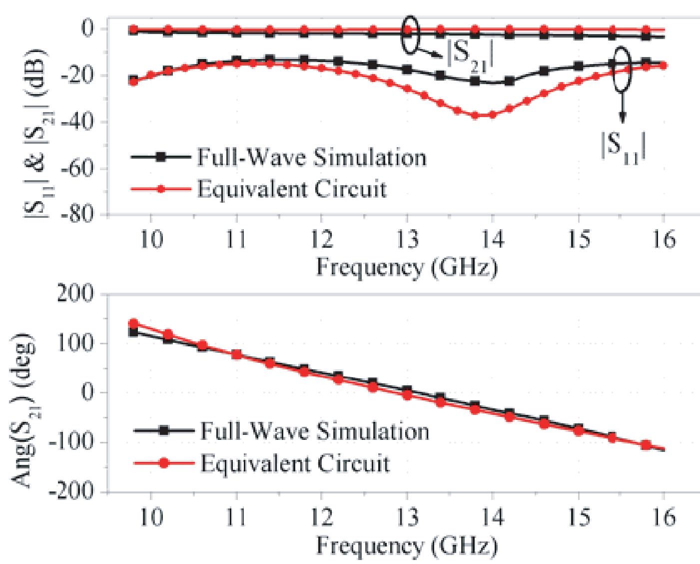


Figure 3. S-parameters of the HMSIW-based unit cell.

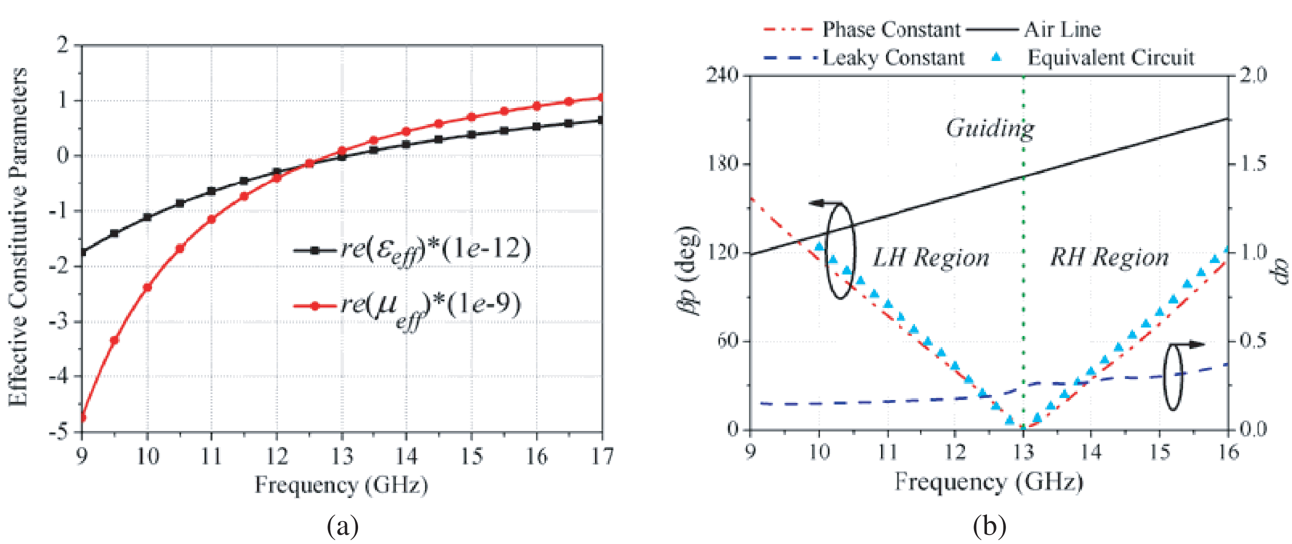
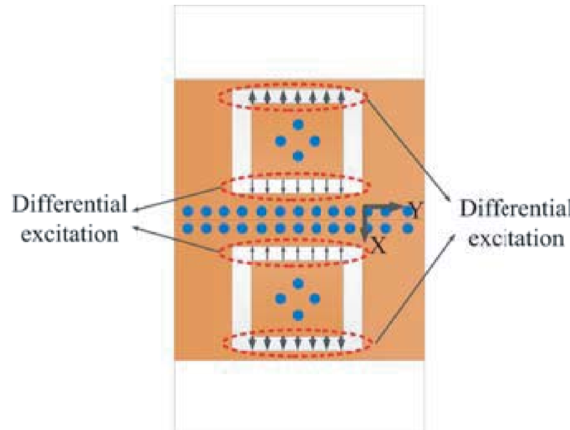


Figure 4. Characteristics of the unit cell. (a) Calculated effective constitutive parameters, and (b) unit cell dispersion curves.



(a) (b)

Figure 5. Excitations in HMSIW-based structures. (a) The reference unit cell, and (b) the proposed back-to-back unit cell.

to-back arrangement. Conventional HMSIW structures support quasi-TEp-0.5, 0 ($p = 1, 2, \ldots$) modes. Magnitude of the electric field near the via wall is much weaker than that near the open side, as shown in Figure 5(a). Considering the radiation in *yoz* plane (beam scanning plane), higher XPLs are therefore introduced. For the back-to-back arrangement shown in Figure 5(b), when two unit cells are placed back to back and excited with the same phase and equal amplitude, two differentially excited slot pairs are introduced. Thus, XPLs in the beam scanning plane will be greatly improved.

3. ANTENNA ARRAY ANALYSES

The back-to-back unit cells are cascaded in series to construct the proposed LWA. The variation of antenna gain versus the unit cell number is given in Figure 6. The antenna gain changes slightly when the unit cell number is larger than 9, and nine unit cells are therefore enough for energy leakage. The structure of the proposed LWA with nine back-to back unit cells is given in Figure 7. Tapered microstrip lines are utilized for better impedance matching, and T-shaped power dividers are used as shown in the figure.

The antenna is fabricated and measured with S-parameters plotted in Figure 8(a). The measured -10 dB impedance band ranges from around 9.5 GHz to more than 16 GHz, and covers the whole

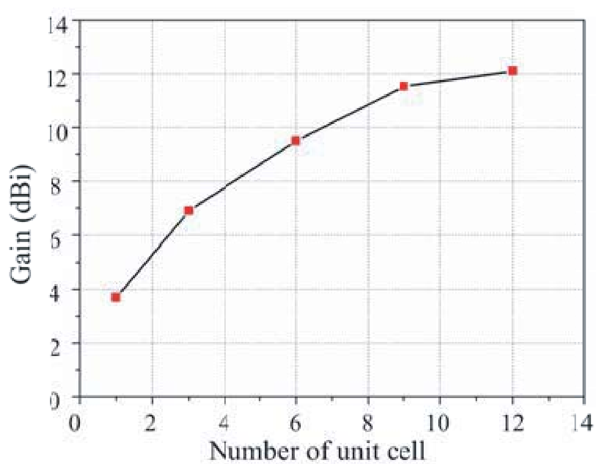


Figure 6. Gain versus number of the HMSIW-based back-to-back unit cell.

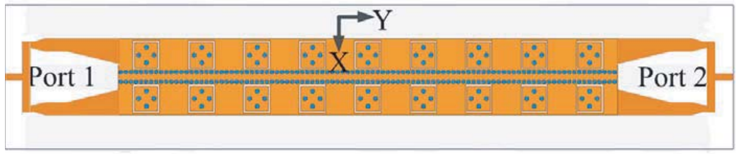


Figure 7. Structure of the proposed HMSIW-based LWA.

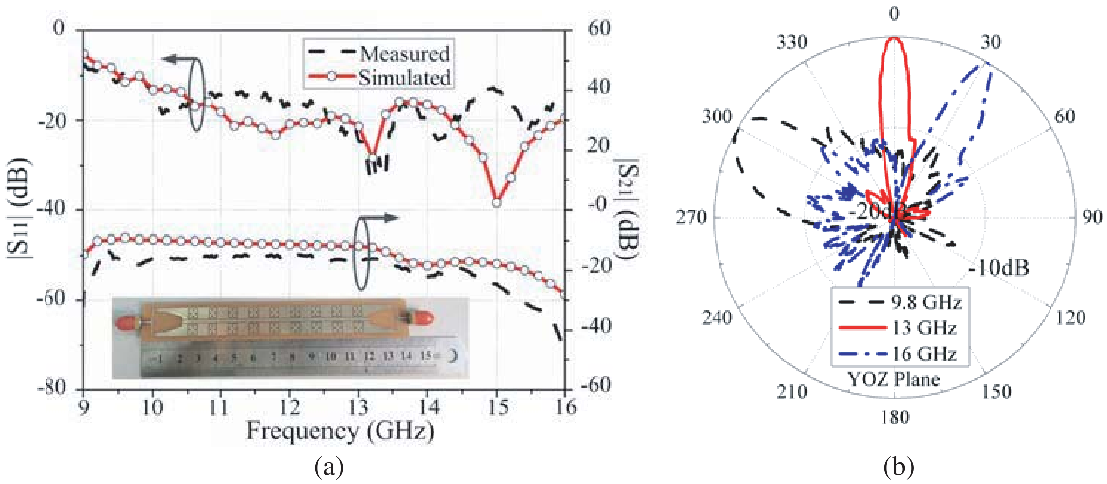


Figure 8. Antenna performances. (a) Simulated and measured S-parameters, and (b) measured radiation patterns.

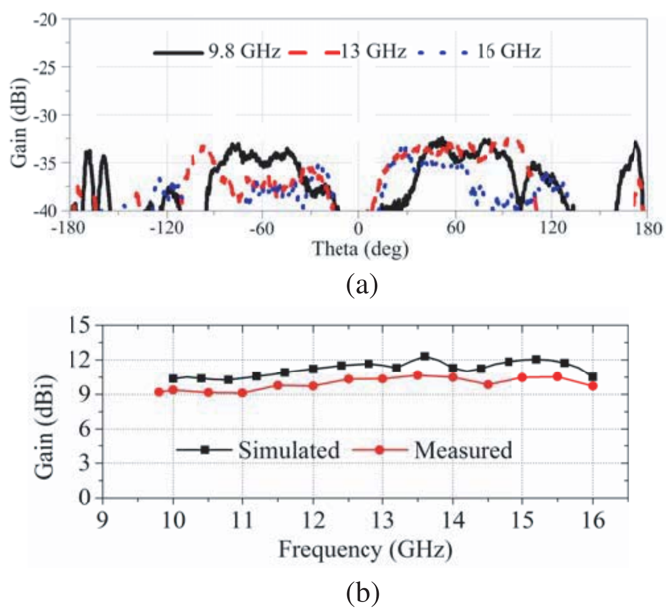


Figure 9. Far field characteristics of the proposed back-to-back LWA. (a) Cross-polarization in the beam scanning plane, and (b) antenna gain versus frequency.

radiation region. The $|S_{21}|$ values are less than -10 dB across the impedance band, indicting sufficient energy leakage. Measured radiation patterns at three different frequencies are presented in Figure 8(b). The main beam points to -60° at 9.8 GHz and $+31^\circ$ at 16 GHz. Broadside radiations are obtained, and the transition point is well predicted by the dispersion characteristics. The measured normalized

XPLs in the beam scanning plane are given in Figure 9(a). Less than -30 dB XPLs are obtained for the proposed LWA, validating the aforementioned discussion on the cross-polarization reduction. The measured antenna gains are all above 9 dBi, and the variation is less than 1.7 dBi across the whole working frequency band as shown in Figure 9(b).

4. CONCLUSION

A CRLH-HMSIW-based LWA with low cross polarization is proposed. First, an HMSIW-based unit cell and its extracted equivalent circuit are analyzed. To obtain low cross-polarization levels in the beam scanning plane, back-to-back arrangement is adopted. The proposed CRLH LWA with nine improved unit cells is simulated and fabricated. Measured results show that the proposed LWA has a beam scanning range of 91° ($-60°$ to $+31°$) in its operating frequency band 9.8–16 GHz. Moreover, due to the differential excitation principle, the cross-polarization levels in the beam scanning plane are below -30 dB.

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