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A Compact Single Radiator CRLH-Inspired Circularly Polarized Leaky-Wave Antenna Based on Substrate Integrated Waveguide

***Abstract*—A circularly polarized (CP) CRLH-inspired leaky-wave antenna (LWA) based on substrate integrated waveguide (SIW) and microstrip delay line is presented. The unit-cell of the proposed periodic antenna consists of two conventional CRLH SIW cells and two quarter-wavelength microstrip lines. The interdigital slots on the CRLH SIW are rotated at +45° and -45° with respect to the wave propagation direction and separated by 90° to create circular polarization. Utilizing the microstrip line instead of the SIW delay section, the total size of the five unit-cell antenna is reduced by 24.4% in comparison to the previous single radiator CP LWA. Furthermore, microstrip lines provide improved matching for broadside radiation as well as better CP purity. The unit-cell characteristics are investigated in detail through dispersion and Bloch impedance analysis. In addition, space harmonic analysis is carried out to explain the radiation mechanism of the proposed antenna. The proposed CRLH-inspired SIW CP antenna operates from 4.2 GHz to 4.85 GHz and frequency-scans from –25° to 26° along the elevation angle. Axial ratio is maintained below 3 dB throughout the operating frequency. The measured results show good agreement with the simulated results.**

***Index Terms*— Composite right/left handed (CRLH), circular polarization, leaky-wave antenna (LWA), substrate integrated waveguide (SIW).**

I. INTRODUCTION

LEAKY-WAVE antennas (LWAs) have attracted researchers for many years because of their unique frequency beam scanning capability and broad operational bandwidth [1]-[7]. Recent birth of metamaterial transmission line concept has even further accelerated the study of leaky-wave antennas [8]-[12]. Composite right/left handed (CRLH) transmission line (TL) is a type of metamaterial TL that can be systematically designed to have both positive and negative phase velocity that allows the antennas to steer the beam not only toward endfire but also toward backfired directions. Moreover, a CRLH TL even supports broadside radiation under the balanced condition. With above mentioned advantages, microstrip line based single radiator circularly polarized (CP) CRLH LWAs have been proposed [13]-[15]. The inherent quadrature phase relation of a series and a shunt radiation component for a CP radiation is analyzed in [15]. Such CP LWAs are particularly aimed for wireless application under dynamic motion, requiring high signal throughput. For example, satellites use CP antennas since it is difficult to align the antennas polarization in advance [16]. Likewise, devices receiving information from the satellites such as GPS are also equipped with CP antennas [17]. Nowadays, personal mobile devices such as WiFi modems and RFID systems have also started to use CP signal to enhance the wireless performance [18]. In general, for wireless devices that are under constant motion and operating in electromagnetically crude environments, CP antenna is the preferred choice.

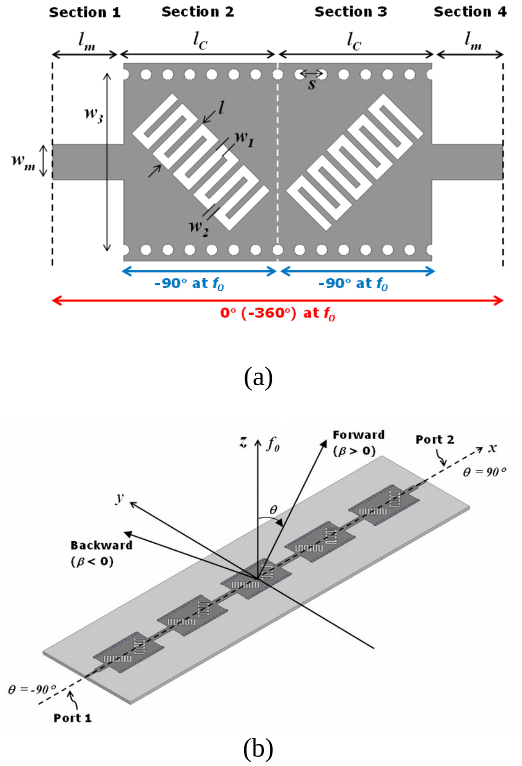

Fig. 1. (a) Unit-cell of the proposed single radiator CP LWA. (b) Whole structure of the proposed CP LWA. (Unit-cells parameters: l_m = 5.1 mm, l_C = 11 mm, l = 4.1 mm, w_1 = 0.63 mm, w_2 = 0.4 mm, w_3 = 12.54 mm, w_m = 2.5 mm, s = 1.57 mm.)

Recently, CP LWA has been developed using CRLH SIW technologies [19], [20]. Fields radiated by the interdigital slots produce relatively pure polarization, thus CRLH SIW LWAs have recently attracted much attention. In [19], two CRLH LWAs with interdigital slots rotated in an orthogonal direction with respect to each other are placed side-by-side. CP polarization is then generated by feeding the antennas with quadrature hybrid coupler. In [20], an improved CP CRLH-inspired SIW LWA has been developed in which an external quadrature feeding network is eliminated and a single radiating element is used instead of using two radiators. The unit-cells consist of four components, two conventional CRLH SIW cells with 45 rotated interdigital slots and two 90 long conventional SIW structures.

In this paper, a single element CP CRLH-inspired SIW LWA [20] is further improved by replacing the conventional SIW delay sections with microstrip lines to reduce the unit-cell size. In a certain antenna size, a smaller unit-cell allows larger number of radiators thereby increasing an antenna efficiency. The modification not only enables miniaturization

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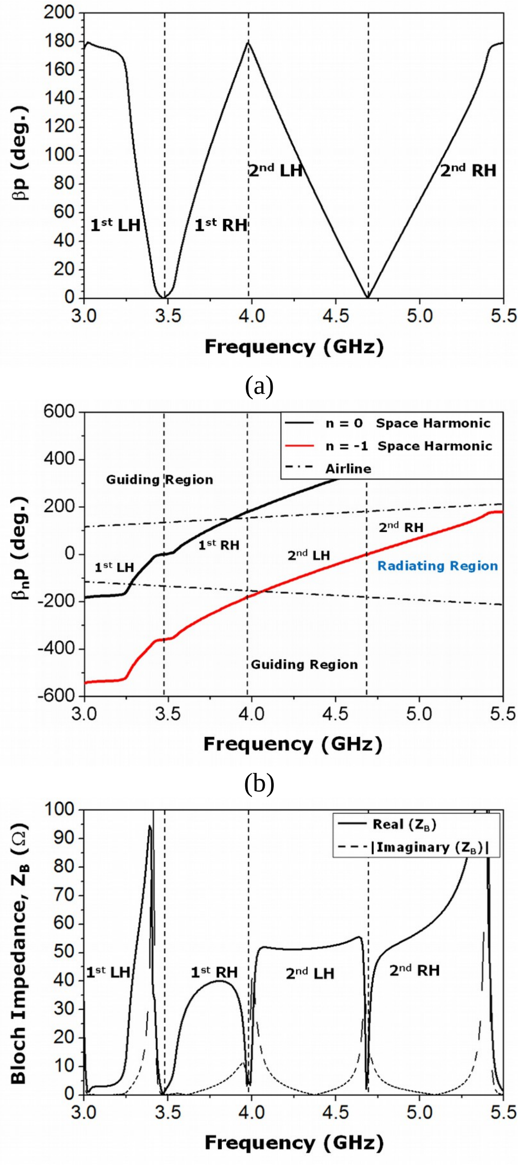


(a)

(b)

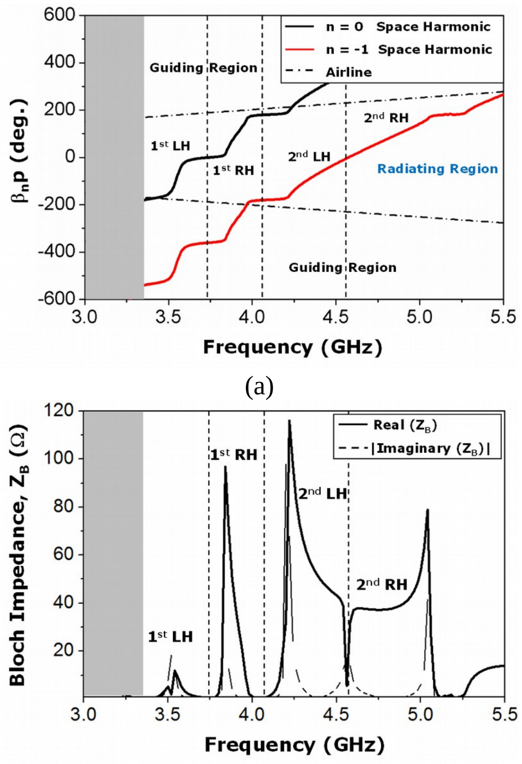
(c)

Fig. 2. Characteristics of the proposed CP antenna unit-cell. (a) Dispersion diagram ($p = 2\times l_m + 2\times l_C$). (b) Space harmonics reconstructed from the dispersion diagram of the proposed unit-cell (n is mode number). (c) Bloch Impedance.

of the unit-cell but also adds intrinsic matching network within the antenna, thus eliminating the need of external matching circuits and improving CP purity. Furthermore, similar to [7], periodically integrated microstrip delay lines enable efficient broadside radiation. The paper is organized as follows: The proposed antenna unit-cell structure and the operating concept are explained in section II. Design procedures of a CRLH cell and a microctrip line are explained in detail in section III. Lastly, the simulated and measured results of the proposed antenna are provided in section IV.

II. UNIT-CELL STRUCTURE AND OPERATING CONCEPT

The unit-cell of the proposed CP CRLH-inspired SIW LWA consists of two conventional CRLH SIW cells with the interdigital slot rotated by +45° and -45° with respect to the wave propagation direction [19] and two microstrip lines shown in Fig. 1 (a). At the center frequency f_0, two interdigital slots are separated by 90° phase delay. The two radiating slots etched on top of the SIW generate two orthogonal linearly polarized waves with quadrature phase difference, thus radiating circularly polarized wave. The two microstrip lines sections attached on each side of the SIW structure also have 90° phase delay at f_0, therefore adds additional 180° phase delay. This ensures the radiated fields from each SIW unit-cells to add constructively in the far-field. The unit-cell of the proposed antenna shown in Fig. 1(a) thus has 0° (360°) phase delay response at the center frequency. Fig. 1(b) shows the prototype of the proposed five-element LWA and the coordinate system. While maintaining the same operational concept, the unit-cell of the proposed structure can be realized with smaller overall dimension in comparison to the unit-cell of the previously proposed single radiator CP CRLH-inspired antenna entirely based on SIW structure [20]. The dimensions of the unit-cells are also provided in Fig.1.



(a)

(b)

Fig. 3. Characteristics of the previous CP antenna unit-cell [20]. (a) Space harmonics reconstructed from the dispersion diagram of the previous unit-cell (n is mode number). (b) Bloch Impedance.

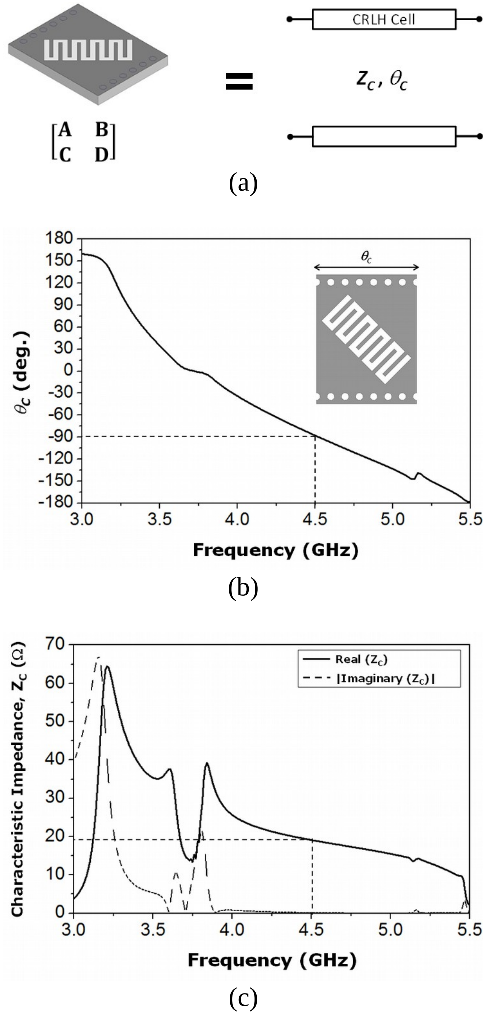


Fig. 4. (a) CRLH SIW cell and its transmission line model. (b) Phase response of the CRLH cell. (c) Characteristic impedance of the CRLH cell.

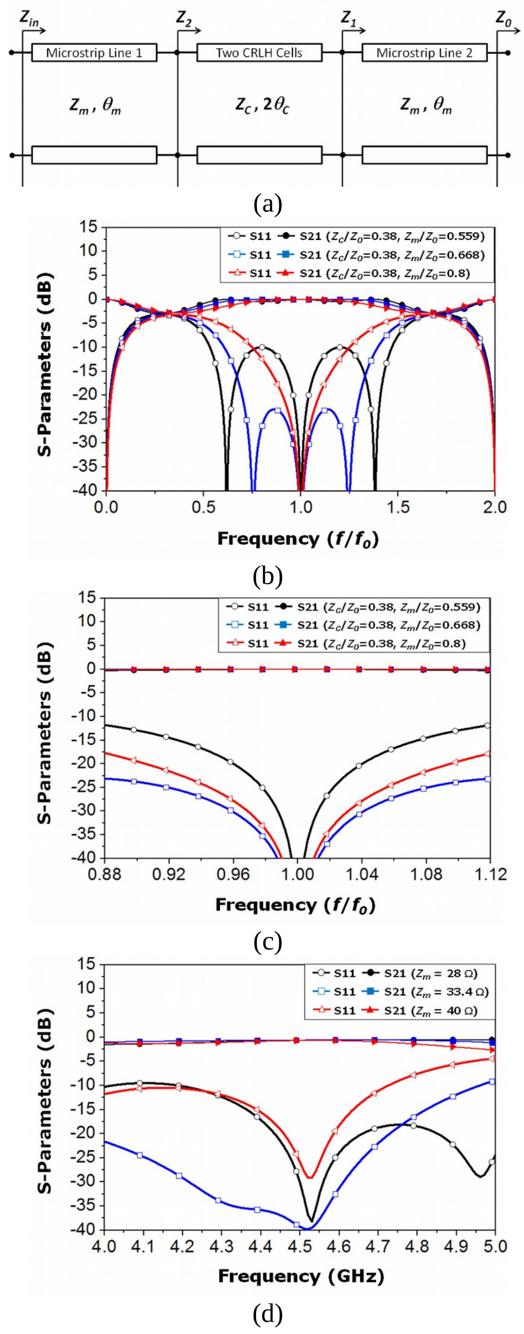


Fig. 5. (a) Transmission line model of the proposed CP LWA unit-cell. (b) Scattering parameters of the TL model (with all ideal TLs) changing the characteristic impedance of the microstrip line, Z_m, with fixed Z_C. (c) Zoom view of Fig. 4(b) around the center frequency. (d) S-parameters of the TL model using the ABCD matrix of the CRLH cell (ideal TLs are used for microstrip lines).

Fig. 2(a) shows the dispersion diagram of the proposed unit-cell (from section1 to 4). In this graph, we notice that the proposed unit-cell structure has multiband characteristic. This is similar to that of a dual-band (DB) CRLH unit-cell [21]. The center frequency of the proposed unit-cell is 4.67 GHz and broadside radiation occurs at this frequency. In order to rigorously analyze the radiation mechanism of the proposed antenna, space harmonics of the proposed unit-cell are shown in Fig. 2(b) [22], [23]. Fundamental space harmonic is redrawn from the dispersion diagram of the unit-cell. Note that the proposed unit-cell supports first radiation band (3.28 GHz ~ 3.88GHz) in the fundamental space harmonic and the second radiation band (from 4.06 GHz) is supported by the n = -1 space harmonic. Conventional CRLH based leaky-wave antennas generally operate in the fundamental mode (n = 0). However, since the proposed CP antenna operates in n = -1 mode, it is periodic type rather than quasi-uniform type of LWA in the operating range [22]. The Bloch impedance of the proposed structure (shown in Fig. 2(c)) is maintained around 50 Ω throughout the n = -1 radiation band. Therefore exterior matching circuit is not necessary. Fig. 2(c) is plotted assuming the periodic structure is infinitely long. The abrupt change in impedance around each transition frequency (frequency at which LH dispersion becomes RH) is due to the destructive cancelation of the incident wave and infinite sum of the reverse propagation waves generated at the imperfect discontinuities between the unit-cells. But for finite periodic condition, summation of reverse propagated waves could be negligible and minimally degrade the impedance mismatch loss at the transition frequency. Fig. 3(a) demonstrates space harmonics of the previous unit-cell. Similar to the proposed structure, circularly polarized wave is radiated in the second band which is supported by n = -1 space harmonic. The Bloch impedance of the unit-cell solely based on SIW shown in Fig. 3(c) however produces much broader impedance mismatch condition in comparison to the proposed case.

III. ANTENNA DESIGN

The design procedure of the proposed antenna has two steps. First, a single CRLH cell is designed. Then, the dimensions of microstrip lines are determined.

A. Single CRLH Cell

The single CRLH SIW cell (section 2 or 3 of Fig. 1(a)) is expressed as a transmission line section in Fig. 4(a). The phase response θ$_C$ and characteristic impedance Z_C of the TL can be calculated from the ABCD matrix as follows [24]:

$$q_C = \arccos(A) = \arccos(D) \tag{1a}$$

$$Z_C = \frac{B}{j\sin(q)} = \frac{j\sin(q)}{C}. \tag{1b}$$

In addition, at the center frequency of the proposed antenna (f_0), the single CRLH cell provides 90° phase delay:

$$q_C(f_0) = -\frac{p}{2} \tag{2}$$

The corresponding phase response of a single CRLH SIW cell is shown in Fig. 4(b). The simulated center frequency is at f_o = 4.52 GHz. This slight down shift of center frequency is due to parasitic effects at the microstrip line and SIW discontinuity in the total unit-cell shown in Fig. 1(a). If needed, additional tuning may be carried out to obtain the exact desired center frequency. The characteristic impedance of the single CRLH cell is shown in Fig. 4(c). This impedance value is used to determine the width of a microstrip line (w_m) as will be shown in the following section. In the prototype antenna design, the ABCD matrix of the single CRLH cell is investigated based on the HFSS simulation.

B. Microstrip Line

Conventional TL sections (section I and IV) not only provide additional phase delay, but also provide good matching at the center frequency. Thus the proposed antenna and the previous work [20] behave as efficient broadside radiators. The conventional SIW used in the previous antenna [20] operates in TE$_{10}$ mode in which the wave impedance is frequency dependent [24]. This frequency dependent impedance degrades the CP purity as the operating frequency is shifted away from the optimal point. However, microstrip lines used in the proposed antenna has constant line impedance for broader frequency range thereby providing high quality CP radiation for much wider beam scanning angle. To design the width (w_m) and the length (l_m) of the microstrip line, the transmission line model of the proposed antenna unit-cell is investigated. Fig. 5(a) shows the transmission line model consisting of three TL sections. The characteristic impedance Z_C and the phase response θ$_C$ of the CRLH SIW cell is calculated in (1). Since two CRLH SIW cells are used in the proposed antenna unit-cell, the phase delay of the CRLH SIW section in Fig. 5(a) is π radian or 180° at the center frequency from (2). The phase response of each microstrip line is θ$_m$ = -90° at the center frequency.

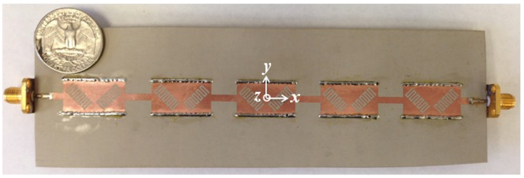


Fig. 6. Fabricated novel CP CRLH-inspired SIW leaky-wave antenna.

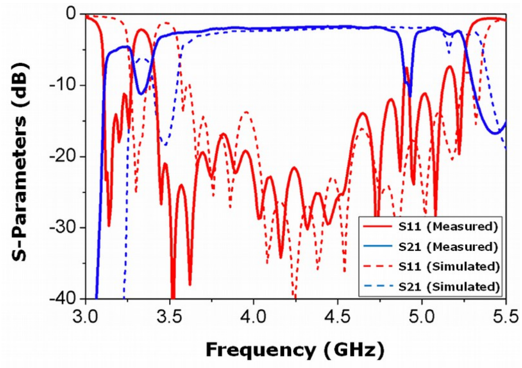


Fig. 7. Measured and simulated S-parameters of the proposed CP LWA antenna.

As shown in Fig. 5(a), the input impedance of a transmission line with an arbitrary load Z_o is expressed as follows [24]:

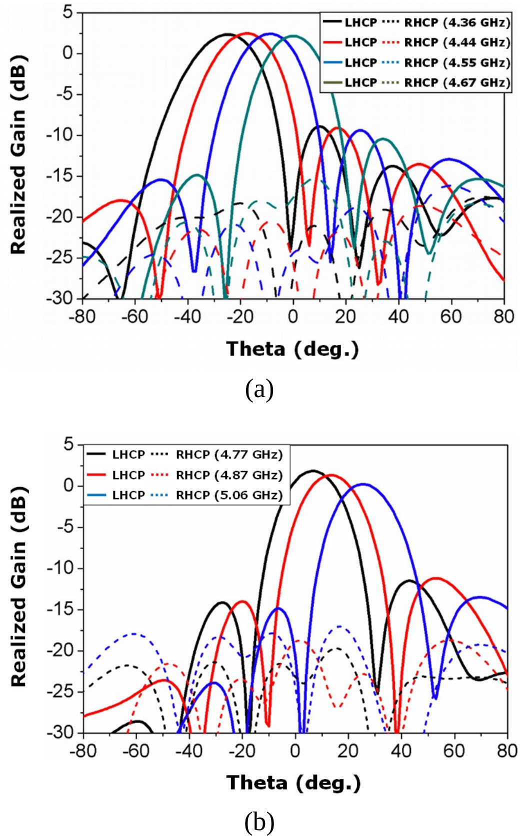
$$Z_1 = Z_m \frac{Z_0 + jZ_m \tan q_m}{Z_m + jZ_0 \tan q_m} \tag{2a}$$

where Z_m is the characteristic impedance of the microstrip line. For θ_m = -90°, above equation reduces to

$$Z_1(f_0) = \frac{Z_m^2}{Z_0}. \tag{2b}$$

The input impedance value for each section is calculated in a similar manner. Then, we can express the input impedance looking to the right of the microstrip line 1 (Z_2) and the input impedance of the unit-cell (Z_{in}) as follows:

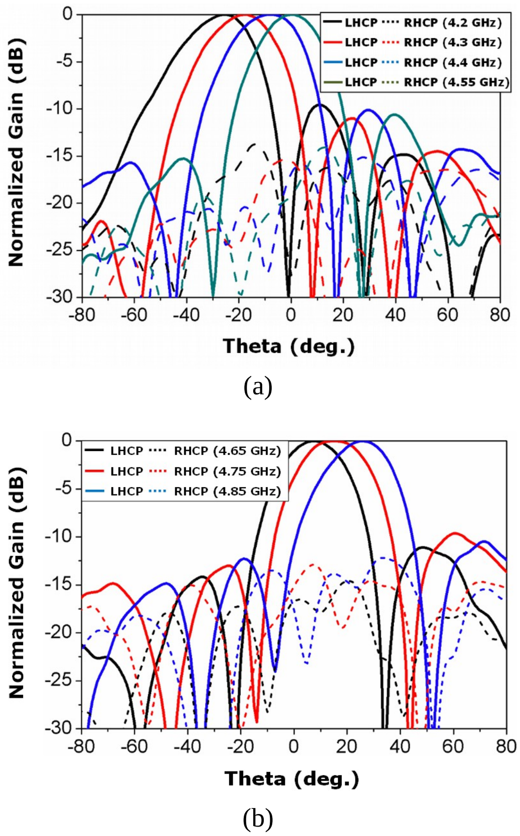
$$Z_2(f_0) = Z_1(f_0) = \frac{Z_m^2}{Z_0} \tag{3}$$



(a)

(b)

Fig. 8. Simulated realized gain patterns of the proposed circularly polarized antenna in x-z plane. (a) From LH to broadside region. (b) RH region.



(a)

(b)

Fig. 9. Measured radiation patterns of the proposed circularly polarized antenna in x-z plane. (a) From LH to broadside region. (b) RH region.

$$Z_{in}(f_0) = Z_0. \tag{4}$$

When all microstrip sections are quarter wavelength long, regardless of the characteristic impedances Z_C and Z_m, the input impedance of the proposed antenna unit-cell will always be the same as the load impedance Z_0 at the center frequency. Therefore the proposed antenna can provide good broadside radiation without the need of an external matching circuit (this works with any arbitrary load impedance values). Fig. 5(b) shows the scattering parameters of the TL model (with all ideal TLs) shown in Fig. 5(a). With different microstrip line impedances (Z_m) values, we can observe various corresponding return loss responses [25]. Fig. 5(c) is the magnified view of Fig. 5(b). Fig. 5(d) shows the *S*-parameters of the TL model with the ABCD matrix of the CRLH cell simulated by HFSS and two ideal TLs. Considering both Fig. 5(c) and (d), Z_m is determined to be $0.668 \times Z_0$ or 33.4 Ω in the proposed antenna thereby having high return loss in the operating range.

IV. COMPACT CP LW ANTENNA

Based on the procedure shown in section III, a compact five-cell circularly polarized antenna is designed and fabricated using RT/Duroid 6010 substrate ($\varepsilon_r = 10.2$, $h = 1.27$ mm). Via holes with the diameter of $d = 0.8$ mm are placed on each sides of the SIW structure with the via center-to-center spacing of s = 1.57 mm to emulate side wall effects of the SIW. Fig. 6 shows a photograph of the fabricated antenna. Comparing to the previous five-cell CP antenna, the proposed antenna shows 24.4 % size reduction.

The simulated and measured S-parameters of the proposed antenna are shown in Fig. 7. Slight frequency discrepancy between the simulated and measured results is due to fabrication errors. The measured S_{11} is below -14 dB throughout the entire operating frequency band including at the center frequency.

The proposed antenna supports both left-handed circular polarization (LHCP) and right-handed circular polarization (RHCP) depending on the port of excitation. LHCP and RHCP are generated when the antenna is fed from port 1 and port 2, respectively. In this paper, the antenna is fed at port 1 to produce LHCP. Fig. 8 shows the simulated gain patterns of the proposed antenna. The full-space beam-steering by frequency scanning is observed. For higher efficiency and realized gain, the proposed antenna can simply be elongated by cascading more unite cells.

The far field pattern and AR of the proposed CP antenna are measured in the near-field chamber. The normalized measured radiation patterns from backward to broadside direction (*in x-z plane*) are shown in Fig. 9(a). Fig. 9(b) shows the radiation patterns for forward direction. The cross-polarization (RHCP) patterns are also plotted. Simulated cross-pol level is 24 dB lower and measured cross-pol level is 15 dB lower than co-

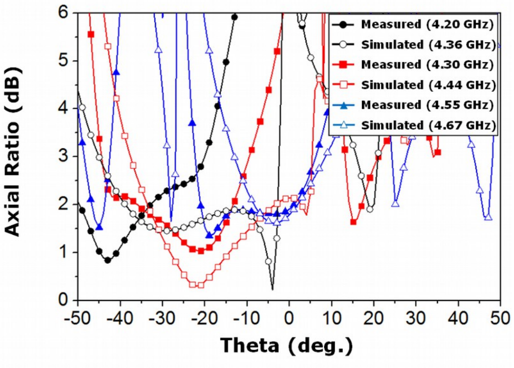
TABLE I
SIMULATED AXIAL RATIO COMPARISON

Scan Angle (deg.)		-29	-18	-10	0	12	18	24
Axial Ratio (dB)	Proposed Antenna	2.8	0.6	0.1	1.8	0.8	0.9	1.4
	Previous Antenna [20]	3.2	0.2	0.6	2.7	1.5	2.5	3.3

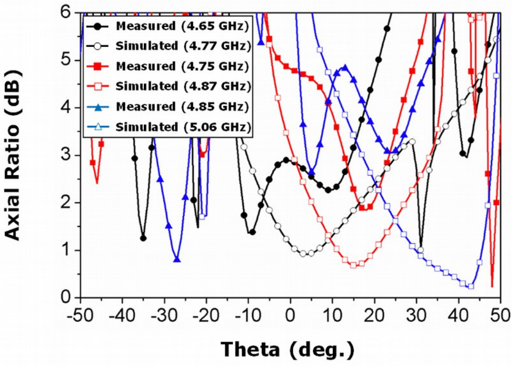
polarization patterns in the simulated measured results, respectively. The simulated and measured AR (*in x-z plane*) is plotted in Fig. 10. Because of the frequency shift of the fabricated antenna, simulated axial ratio at slight higher frequencies are used to compare the measured results. The proposed antenna shows good axial ratio of less than 3 dB within the beam scanning range. The discrepancy of simulate and measured AR at 4.85 GHz (measured frequency) is due to the self-resonance of interdigital slots. Table I compares the simulated axial ratio (AR) levels of the proposed antenna and the previous antenna with same scanning angles (). As we expected, the quality of CP radiation of the proposed antenna is better than the previous work. Overall, the experimental results are consistent with the simulation results.

V. CONCLUSION

This paper presents an improved single radiator circular polarized CRLH-inspired SIW leaky-wave antenna. The antenna provides CP frequency scanning with only a single radiator, thereby eliminating complex feeding network [19]. The size of the proposed unit-cell is much smaller than the previously designed structure [20]. The measured and simulated results show consistency and we have found that the proposed antenna provides high-quality CP beams with full-space scanning capability including broadside direction. Hence the proposed antenna may serve as a good candidate for wireless applications requiring CP frequency scanning features.



(a)



(b)

Fig. 10. Measured and simulated AR of the proposed circularly polarized antenna in x-z plane. (a) From LH to broadside region. (b) RH region.

REFERENCES

[1] A. Oliner and D. R. Jackson, “Leaky-wave antennas,” in *Antenna Engineering Handbook*, C. J. L. Volakis, Ed. New York: McGraw-Hill, 2007.

[2] D. R. Jackson and A. A. Oliner, “Leaky-wave antennas,” in *Modern Antenna Handbook*, C. Balanis, Ed. New York: Wiley, 2008.

[3] D. R. Jackson, C. Caloz, and T. Itoh, “Leaky-wave antennas,” *IEEE Proceedings*, vol. 100, no.7, pp. 2194-2206, July 2012.

[4] D. R. Jackson and A. A. Oliner, “A leaky-wave analysis of the high-gain printed antenna configuration,” *IEEE Trans. Antenna Propag.*, vol. 36, no.7, pp. 905-910, Jul. 1988.

[5] M. Guglielmi and D. R. Jackson, “Broadside radiation from periodic leaky-wave antennas,” *IEEE Trans. Antenna Propag.*, vol. 41, no.1, pp. 31-37, Jan. 1993.

[6] P. Burghignoli, G. Lovat, and D. R. Jackson, “Analysis and optimization of leaky-wave radiation at broadside from a class of 1D periodic structures,” *IEEE Trans. Antenna Propag.*, vol. 54, no.9, pp. 2593-2604, Sep. 2006.

[7] S. Paulotto, P. Baccarelli, F. Frezza, and D. R. Jackson, “A novel technique for open-stopband suppression in 1-D periodic printed leaky-wave antennas,” *IEEE Trans. Antenna Propag.*, vol. 57, no.7, pp. 1894-1906, Jul. 2009.

[8] L. Liu, C. Caloz, and T. Itoh, "Dominant mode (DM) leaky-wave antenna with backfire-to-endfire scanning capability", *Electron. Lett.*, vol. 38, no. 23, pp.1414 -1416, Nov. 2002.

[9] S. Lim, C. Caloz, and T. Itoh, “Metamaterial-based electronically-controlled transmission line structure as a novel leaky-wave antenna with tunable radiation angle and beamwidth,” *IEEE Trans. Microwave Theory Tech.*, vol. 53, no. 1, pp. 161-173, Nov. 2005.

[10] T. Kokkinos, C. D. Sarris, and G. V. Eleftheriades, “Periodic FDTD analysis of leaky-wave structures and applications to the analysis of negative-refractive-index leaky-wave antennas,” *IEEE Trans. Microwave Theory Tech.*, vol. 54, no. 4, pp. 1619-1630, Jun. 2006.

[11] Y. Weitsch, T.F. Eibert, "A Left-Handed/Right-Handed Leaky-Wave Antenna Derived from Slotted Rectangular Hollow Waveguide", *2007 European Microwave Conference*, Oct. 2007.

[12] Y. Dong and T. Itoh, “Composite right/left-handed substrate integrated waveguide and half mode substrate integrated waveguide leaky-wave structures,” *IEEE Tran. Antenna Propag.*, vol. 59, no. 3, pp. 767-775, Mar. 2011.

[13] K. Kitatani, Y. Mitsuhata, Y. Okamura, “Circularly polarized leaky wave antenna without phase shifter using CRLH transmission line,” *2012 European Conference on Antennas and Propagation (EUCAP)*, Mar. 2012.

[14] M. Ishii, T. Fukusako, A. Alphones, “Design of leaky wave antenna with composite right-/left-handed transmission line structure for circular polarization radiation”, *Progree In Electromagnetics Research C*, Vol. 33, 109-121,2012.

[15] S. Otto, Z. Chen, A. Al-Bassam, A. Rennings, K. Solbach, and C. Caloz, "Circular polarization of periodic leaky-wave antennas with axial asymmetry: Theoretical proof and experimental demonstration," *IEEE Trans. Antennas Propagat.*, vol. 62, no. 4, pp. 1817-1829, April 2014.

[16] F. Ferrero, C. Luxey, G. Jacquemod, and R. Staraj, “Dual-band circularly polarized microstrip antenna for satellite applications,” *IEEE Antennas Wireless Propag. Lett.*, vol. 4, pp. 13–15, 2005.

[17] Y. Zhou, C. Chen, and J. L. Volakis, “Single-fed circularly polarized antenna element with reduced coupling for GPS arrays,” *IEEE Tran. Antenna Propag.*, vol. 56, no. 5, pp. 1469-1472, May 2008.

[18] T. Wu, H. Su, L. Gan, H. Chen, J. Huang, and H. Zhang, “A compact and broadband microstrip stacked patch antenna with circular

polarization for 2.45-GHz mobile RFID reader," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 623–626, May 2013.

[19] Y. Dong and T. Itoh, "Substrate Integrated Composite Right-/Left-Handed Leaky-Wave Structure for Polarization-Flexible Antenna Application", *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 2, pp. 760 - 771, Feb. 2012.

[20] H. Lee, J. H. Choi, Y. Kasahara, and T. Itoh, "A circularly polarized single radiator leaky-wave antenna based on CRLH-inspired substrate integrated waveguide," *2014 IEEE MTT-S Int. Microwave Symp.*, June 2014.

[21] M. R. Hashemi and T. Itoh, "Dual-band composite right/left-handed metamaterial concept," *IEEE Microwave and Wireless Components Letters*, vol. 22, no. 5, pp.248-250, May 2012.

[22] A. Hessel, "General characteristics of traveling-wave antennas," in Antenna Theory, Part 2, R. E. Collin and F. J. Zucker, Eds. New York: McGraw-Hill, 1969.

[23] O. Breinbjerg, "Properties of Floquet-Bloch space harmonics in 1D periodic magneto-dielectric structures," *2012 ICEAA*, pp. 1125-1128, Sep. 2012.

[24] D. M. Pozar, *Microwave Engineering*, New York: Willey, 2005.

[25] J.-S. Hong and M.J. Lancaster, *Microwave Filters For RF/Microwave Applications*, New York: Willey, 2011.