CRLH Leaky Wave Antenna Based on ACPS Technology With 180° Horizontal Plane Scanning Capability

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***Abstract*—This study presents a novel composite right/left-handed (CRLH) leaky wave antenna (LWA) with horizontal plane scanning capability. This LWA consists of 10 CRLH unit cells and coplanar waveguide to coplanar stripline transitions. The proposed balanced CRLH unit cell is based on an asymmetric coplanar stripline structure (ACPS). The parameters of the CRLH unit cell can be determined analytically, enabling easy modification for any other frequency band. Because of its planar and horizontal plane scanning property, the proposed design can also be extended to a sector-shaped multisection LWA, achieving a scanning range of more than 180° in the horizontal plane. By varying the operating frequency, the CRLH leaky wave antenna shows the continuously beam-scanning property from backward to forward in the horizontal plane. A 10-cell prototype exhibits the beam-scanning capability in the horizontal plane, and a 20-cell multisection sector-shaped LWA confirms the approach of designing the wide-range beam-scanning LWA. Experimental results show that the proposed design is in good agreement with the simulation. The planar and low-profile characteristics of the novel CRLH LWA make it suitable for integration with other microwave circuits, and can be applied to applications that require a wider beam-scanning range.**

***Index Terms*—Beam steering, composite right/left-handed (CRLH) transmission line, leaky wave antennas, metamaterials.**

I. Introduction

WIRELESS communication systems have evolved rapidly in recent years. Therefore, increasing the channel capacity and data rates is an important topic. Transmission quality is a crucial factor in delivering high data rates in a limited frequency spectrum. Researchers have considered various methods of increasing channel capacity. Pattern diversity using multiple directional beams can provide a capacity gain in line-of-sight channels that have little multipath in fading channels [1]. Pattern diversity is required for antenna systems that offer beam-forming or beam-scanning capabilities [2]. Traditionally, an array antenna with the flexibility of full-space scanning property consists of arrays of radiating elements, phase shifters, and complex feeding networks, which increase the cost and complexity of circuits. Compared with this type of beam-scanning antenna, leaky wave antennas, which belong to the class of traveling wave antennas, have the beam-scanning property but have a simpler antenna structure. The scanning angle can be modified by a minor change in the operation frequency. Conventional uniform transmission line leaky wave antennas are based on the excitation of higher-order mode in microstrip lines with a positive wavenumber ($\beta > 0$). Therefore, the scanning range is only the half-space from the broadside to the end fire direction. These antennas also require special feeding structures to suppress the dominant mode (DM) [3]–[9]. To overcome these drawbacks, composite right/left-handed metamaterials have been used as leaky wave antennas in the past few years [10], [11]. This type of leaky wave antenna has the advantage of main lobe scanning in either backward or forward direction because of either the positive or negative phase constant. The phase constant increases from negative to positive values as the frequency increases; thus, the main lobe scans from backfire ($\theta = -90^\circ$) to endfire ($\theta = +90^\circ$) including broadside ($\theta = 0^\circ$) as the frequency is scanned from $\omega_{\rm BF}$ ($\beta = -k_0$) to $\omega_{\rm EF}$, ($\beta = +k_0$), follow the scanning law:

$$\theta(\omega) = \sin^{-1}\left[\frac{\beta(\omega)}{k_0}\right]$$

where $\beta(\omega)$ is the phase constant and k_0 is the free-space wavenumber.

Planar composite right/left-handed (CRLH) leaky wave antennas based on microstrips have received considerable attention [12]–[16]. However, these microstrip leaky wave antennas (MLWAs) exhibit a frequency scanning beam in the elevation plane (y–z plane), which is perpendicular to the circuit board [Fig. 1(a)]. [17] and [18] presented CRLH leaky wave antennas implemented in coplanar strip technology, but these antennas possess the same scanning property as MLWAs. Therefore, this study proposes a CRLH leaky wave antenna based on an asymmetric coplanar strip line structure with horizontal plane scanning capability. Fig. 1(b) shows that this design has a frequency-scanning beam in the horizontal plane (x–y plane), which is in the plane of the circuit board. Although the horizontal plane scanning can be achieved by rotating 90° along the propagation axis of the conventional leaky wave antennas (LWAs), but it is inconvenient to place the whole circuit board vertically or to separate the antenna from the device. Furthermore, the beam-scanning angle of conventional LWA is limited within approximately 135° because of the operational physics limitation of the LWA. Although mechanically bending the LWA structure can

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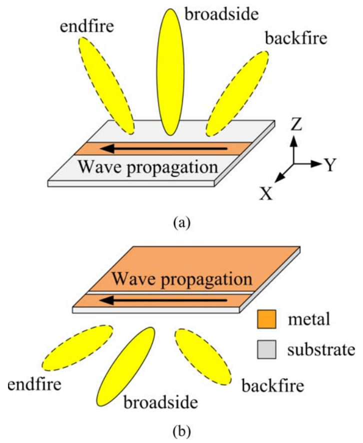

Fig. 1. (a) Conventional CRLH LWA with scanning beam in the elevation plane (y–z plane). (b) Proposed design with scanning beam in the horizontal plane (x–y plane).

increase the leaky mode pointing angle, the highly directive radiation patterns are strongly disturbed when they are conformed to a curved shape because of the traveling-wave nature of the LWA. Previous research investigates the effect of conforming a uniform CRLH leaky wave antenna and introduces a beam-refocusing technique [20]. Another study presented a fixed frequency, electrically controlled scanning conformal CRLH leaky wave transmission line using varactors [21]. However, these approaches have difficulty achieving a wide beam-scanning range. Based on the unique characteristic of the proposed horizontal plane scanning LWA, this study also proposes a sector shaped multisection CRLH LWA achieving 180° wide range scanning capability.

The novel design is relatively easy to fabricate and can be printed easily on the edge of a circuit board, enabling its simple integration with microwave circuit and increasing the efficiency of board usage. The unique planar scanning property can be applied to various applications, including multi-input-multi-output (MIMO) antenna systems with pattern diversity or radar systems, and the sector-shaped multisection LWA can also be applied to applications that require a wider beam-scanning range.

II. Determination of Parameters of the Right-Handed Asymmetric Coplanar Stripline

Fig. 2 shows the proposed design of the novel CRLH LWA. The leaky waveguide in this design has a complex propagation wave number $\gamma = \beta - j\alpha$, where β is the phase constant and α is the attenuation constant. The broadside direction is perpendicular to the leaky waveguide axis. Fig. 3 shows four types of transmission line structures, where the solid lines indicate the generated electric field and the dashed lines indicate the direction of the leakage. Fig. 3(a)–(c) show that the broadside radiation of the leaky wave is perpendicular to the circuit board, which results in beam scanning in the elevation plane (y–z plane). The asymmetric coplanar stripline with wide ground plane in Fig. 3(d) is a good candidate for designing a horizontal plane (x–y plane) scanning CRLH leaky wave antenna. In this structure, the wave propagates along y-axis and the structure can simply be considered as a 2-D problem where $\partial/\partial z = 0$ and assume that the guiding structure is located in the region of $x < 0$. When the structure operates in the fast wave region, the energy constantly leaks out from the guiding structure to $+x$ direction. Therefore, the constant-phase and the constant-amplitude plane lies in the circuit board plane (x-y plane) and the radiation main beam can scan in the horizontal plane as frequency (β) changes. The analytical solution for an asymmetric coplanar strip line presented in [22] can be applied to design a 50 Ω right-handed asymmetric coplanar strip line with an infinitely wide ground plane.

Fig. 4 shows the structure of an asymmetric coplanar strip line. This figure also indicates the strip width W_1 and the separation S between the strip and the ground, where the strip width and the slot width are $2a$ and $(b - a)$, respectively. A traditional coplanar stripline has two conductors with the same width $(W_1 = W_2)$. Because one line width is substantially wider than the other line width $(W_2 \gg W_1)$, the asymmetric coplanar strip line can be treated as a coplanar strip line with an infinitely wide ground plane (CPSWG).

Compared with a traditional coplanar waveguide, the disadvantage of this structure is that removing one of the lateral ground planes increases the characteristic impedance [22]. Thus, the 50 Ω characteristic impedance of the transmission line is difficult to achieve. However, since the characteristic impedance is proportional to the per-unit-length series inductance and is inverse proportional to the per-unit-length shunt capacitance, increasing strip width W_1 and decreasing the gap width S can help reduce the characteristic impedance to 50 Ω. In this case, W is selected as 3 mm because the spacing S has a minimum value of 0.3 mm because of manufacturing limitations. Therefore, a dielectric substrate with high relative permittivity was used to increase the per-unit-length capacitance. The proposed asymmetric coplanar stripline structure (ACPS) was designed on an RO3010 substrate, which has a relative permittivity of 10.2 and a loss tangent of 0.0035. Table I lists the optimized parameters of the proposed ACPS.

The calculated characteristic impedance of the proposed transmission line structure is 63.61 Ω and the simulation result of using a full wave simulator HFSS [23] is 61.3 Ω, indicating good agreement. Fig. 5 shows the simulated insertion loss and return loss of a 50-mm long right-handed ACPS. These simulated scattering parameters are for the case in which the port impedance is 50 Ω, creating a mismatch between the feeding ports and the transmission line. Although the achieved characteristic impedance of the transmission line is greater than 50 Ω, this result is acceptable because the resultant return loss still exceeds 10 dB.

III. Horizontal Scanning Leaky Wave Antenna Design

A. Implementation of CRLH Transmission Line

The distributed circuit model of the traditional transmission line consists of series inductors and shunt capacitors that exhibit the forward-wave propagation property. As presented in [19], the left-handed transmission line, which exhibits an unusual backward-wave propagation property, is essentially the dual of a conventional right-handed transmission line structure. A leaky wave antenna, which combines right-handed and left-handed transmission lines, can achieve a wide beam-scanning angle. This type of leaky wave antenna includes periodically

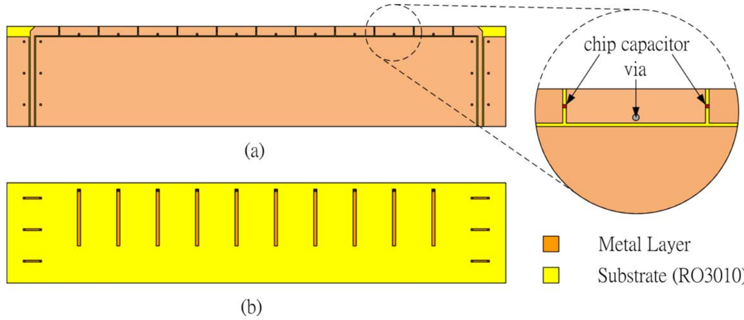

Fig. 2. Proposed CPW-fed CRLH CPS LWA. (a) Top view (b) Back view.

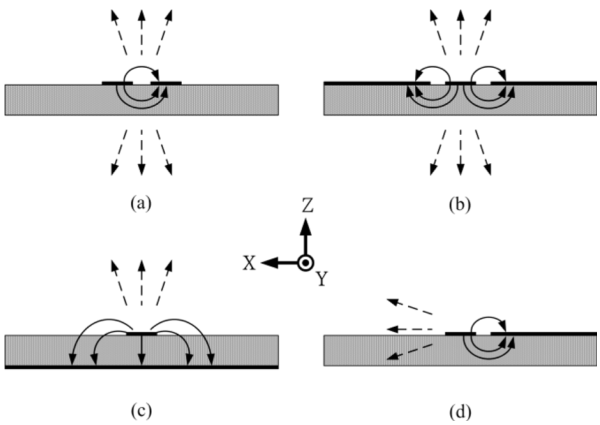

Fig. 3. Four types of transmission line structure. (a) Coplanar strip line. (b) Coplanar waveguide. (c) Microstrip line. (d) Coplanar stripline with infinitely wide ground plane.

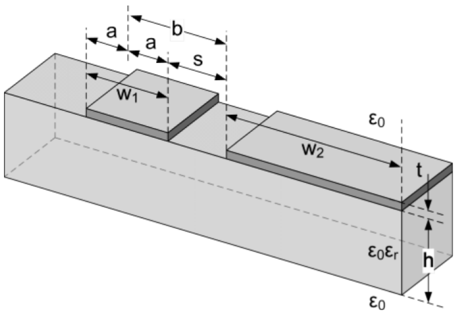

Fig. 4. Coplanar strip line with infinitely wide ground plane.

TABLE I
OPTIMIZED PARAMETERS FOR ACPS

Parameters	*Dimension*
Substrate thickness	0.64 mm
Line width (W)	3 mm
Spacing (S)	0.3 mm
Ground width	27 mm

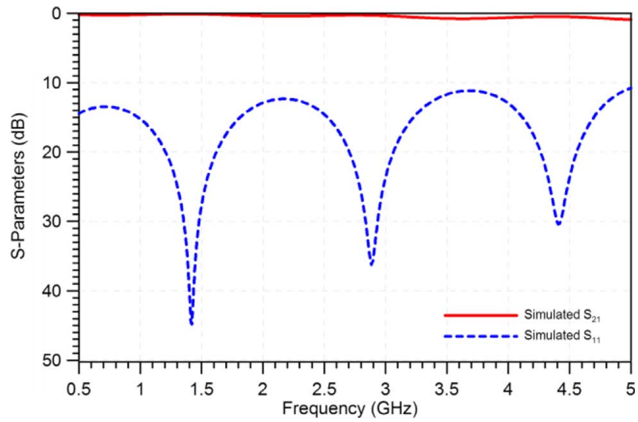

Fig. 5. Simulated insertion loss and return loss of the proposed ACPS.

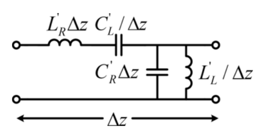

Fig. 6. Distributed circuit model for a CRLH transmission line.

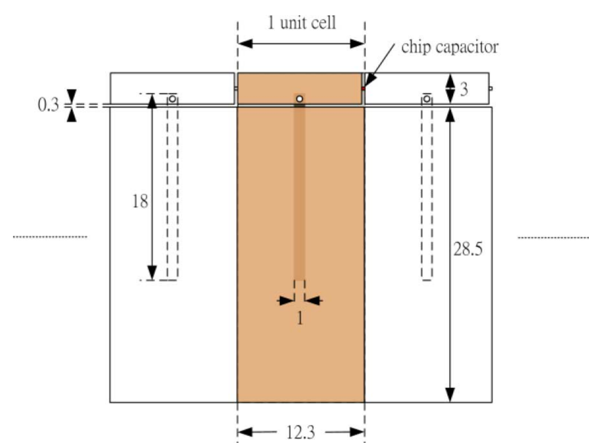

Fig. 7. Dimensions of a unit cell of the leaky wave antenna.

connected CRLH unit cells, and has the circuit model shown in Fig. 6. Fig. 7 shows the proposed CRLH unit cell based on ACPS technology used for realizing the horizontal scanned leaky wave antenna is shown in Fig. 7. In the proposed design, the chip capacitor provides left-handed series capacitance, whereas an open stub provides left-handed shunt inductance. To satisfy the homogeneity condition, the average cell size p must be substantially smaller than the guided wavelength λ_g.

A balanced CRLH unit cell requires that the resonant frequency of the shunt LC resonator equals that of the series LC resonator [19]. This condition can be used to determine the values of left-handed capacitance and inductance. By the method of superposition of partial capacitances [21], characteristic impedance, effective permittivity, and per unit length capacitance can be calculated. The effective dielectric constant of the proposed coplanar strip line is approximately 2.98, therefore, the effective wavelength of the guided wave at 2.45 GHz is approximately 70.93 mm. To satisfy the homogeneity condition, the length of a CRLH unit cell cannot exceed 17.7 mm. The length of a CRLH unit cell was set to be 12 mm because

TABLE II
CALCULATED PARAMETERS OF THE CRLH UNIT CELL

Parameters	*Value*
Characteristic Impedance Z_0^{CPSWG}	63.61 Ω
Per unit length cap. C_0^{CPSWG}	90.61 pF
Per unit length ind. L_0^{CPSWG}	0.37 μH
Effective permittivity $\varepsilon_{eff}^{CPSWG}$	2.98
Right-handed Capacitance C_R	1.09 pF
Right-handed Inductance L_R	4.39 nH
Left-handed Capacitance C_L	0.96 pF
Left-handed Inductance L_L	3.88 nH

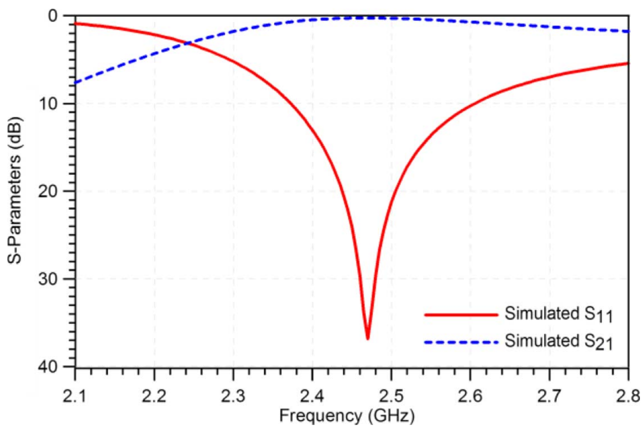

Fig. 8. Simulated insertion loss and return loss of the proposed CRLH unit cell.

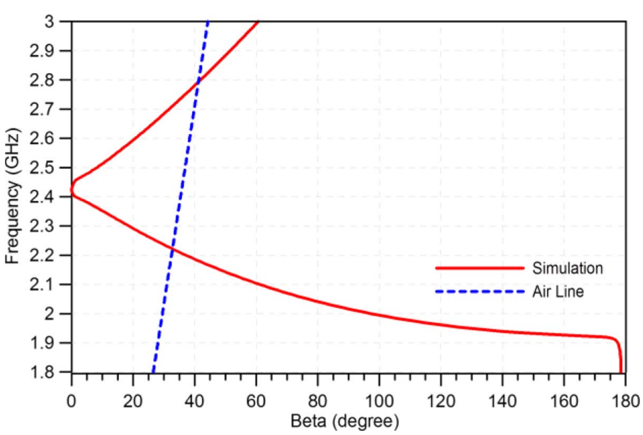

Fig. 9. Simulated dispersion diagram of one CRLH unit cell.

the operating frequency in the left-hand region was lower than the balanced frequency. Both right-handed and left-handed capacitance and inductance can be found after selecting the length of the CRLH unit cell.

First, the per-unit-length capacitance of the line is approximately 90.61 pF. Therefore, the right-handed capacitance C_R of a 12-mm-long CRLH unit cell is 1.09 pF. Once C_R is known, the right-handed inductance L_R can be found using the relation

$$L_0^{\mathrm{CPSWG}} = \frac{1}{\nu^2 \times C_0^{\mathrm{CPSWG}}} \tag{1}$$

where ν is the velocity of the guided wave; i.e.,

$$\nu = \frac{\text{speed of light}}{\sqrt{\varepsilon_{\mathrm{eff}}^{\mathrm{CPSWG}}}} = \frac{3 \times 10^8}{\sqrt{2.98}} = 1.73 \times 10^8. \tag{2}$$

The right-handed inductance L_R of a 12-mm-long CRLH unit cell is then 4.39 nH. By using the balanced condition, it is possible to obtain the values of the left-handed capacitance C_L and inductance L_L, which is 0.96 pF and 3.88 nH, respectively. Table II lists the calculated parameters of the CRLH unit cell. Because the 0.3 mm gaps between each unit cells provide series capacitance of approximately 0.37 pF, the optimized value of the chip capacitors is 0.47 pF because of some parasitic capacitance. The length of the open stub, which provides inductance of 3.88 nH, can then be calculated as follows:

$$Z_{in} = Z_0 \frac{Z_L + jZ_0 \tan \beta l}{Z_0 + jZ_L \tan \beta l}. \tag{3}$$

For open stubs, $Z_L \to \infty$

$$Z_{in} = -j\frac{Z_0}{\tan \beta l} \tag{4}$$

$$\omega L = -\frac{Z_0}{\tan \beta l} \tag{5}$$

$$\beta l = \tan^{-1}\left(\frac{-Z_0}{\omega L}\right) + \pi. \tag{6}$$

This study sets the width of the open stub to be 1 mm, where its characteristic impedance Z_0 is 38.35 Ω. Substituting Z_0, ω and L to (15) shows that l is $0.409\lambda = 18.73$ mm. The optimal value of the length l is 18 mm because the 0.64 mm via also contributes to the electrical length of the stub.

Fig. 8 shows the simulated insertion loss and return loss of the proposed CRLH unit cell. Fig. 9 shows the balanced dispersion diagram obtained from the simulated S-parameters of one unit cell [19], where the solid line is the dispersion curve and the dashed line is the airline. The leaky wave range of operation lies to the left of the airline, and the wave propagation constant β of the proposed ACPS CRLH TL is less than that of the free-space. Therefore, the wave progressively leaks out as it travels along the line. The fast wave region starts from approximately 2.21 to 2.79 GHz, which can also be observed from the figure. Simulation results show that the leaky wave antenna has 10 CRLH unit cells to permit over 70% of the power in the guiding structure to leak away.

B. *Simulation and Experiment Result*

The proposed design uses a coplanar waveguide (CPW) to coplanar stripline (CPS) transition to integrate the proposed CPS LWA with a microwave circuit. Fig. 10 shows the CPW to CPS transition of the proposed LWA. The printed air-bridges of the CPW, which connect each part of the ground plane, eliminate the odd mode of the CPW to CPS transition. Fig. 11 shows the simulation results of the feeding scheme. The insertion loss of this structure is acceptable in the band of operation, although the bandwidth of the transition is not very wide.

A prototype was constructed and tested. Fig. 12 shows the realized horizontal-scanned CRLH LWA comprising 10 unit-cell and CPW to CPS transitions. This antenna was fabricated on a RO3010 substrate with a relative dielectric constant of 10.2, a loss tangent of 0.0035, and a thickness of 0.64 mm. The size of the chip capacitor is 0402, and all vias have a radius of 0.28 mm. The proposed design measures 155.85 mm × 31.8 mm including the LWA structure and feeding sections. The antenna is fed using a 50 Ω SMA connector and terminated

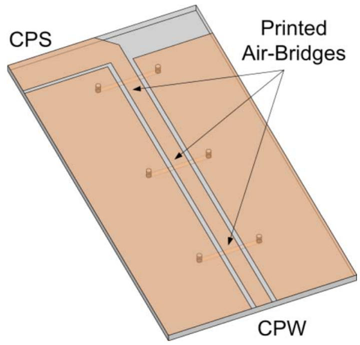

Fig. 10. CPW to CPS transition.

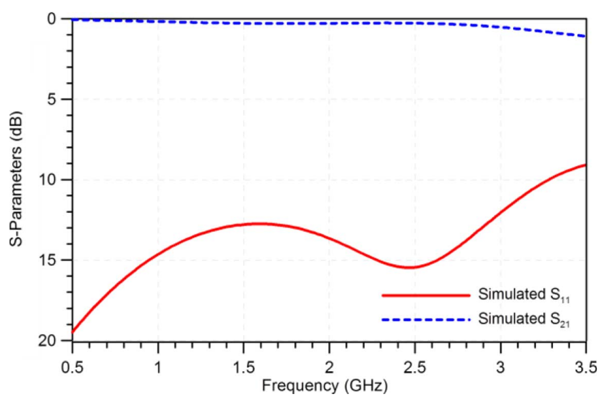

Fig. 11. Simulated return loss and insertion loss of the CPW to CPS transition section.

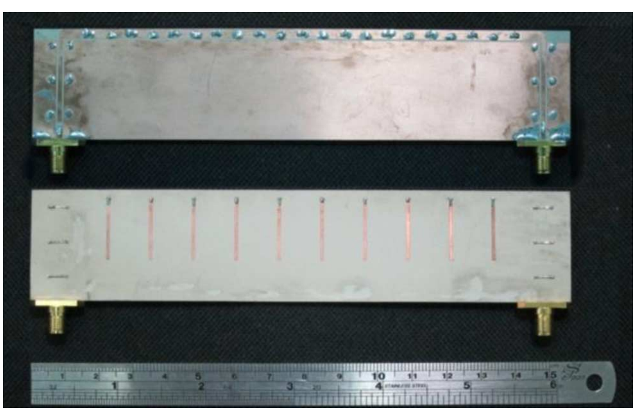

Fig. 12. Fabricated CPW fed 10-cell CPS CRLH LWA.

by a broadband 50 Ω coaxial load. Fig. 13 shows the measured and simulated S-parameters of the proposed ACPS LWA. The measured S-parameters was obtained by an HP-E5071B vector network analyzer, where the measured result is in good agreement with the simulated one, only small difference which may be attributed by the effects of manufacturing tolerances. Besides the fast wave region from 2.21 to 2.79 GHz, the return loss exhibits well from 2.2 to about 3.5 GHz because it covers the radiation region and the guided-wave region of the CRLH TL. Therefore, Fig. 13 also shows the measured and simulated insertion losses to provide more information. Note that at the frequency band above the fast wave region, most power passing through the guiding structure, no leaky wave phenomenon occurs. Fig. 13 further presents the measured radiation efficiency

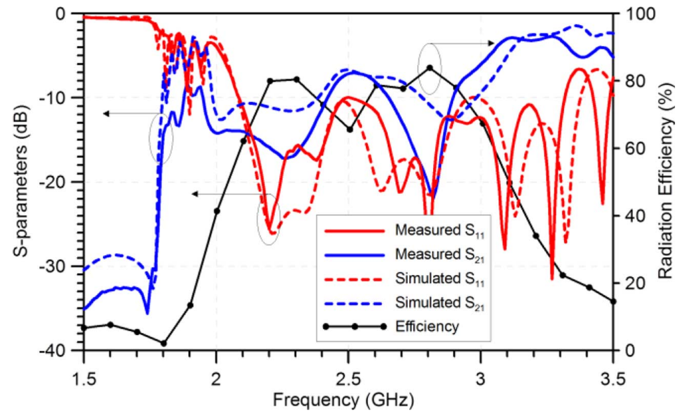

Fig. 13. Measured and simulated S-parameters and the measured radiation efficiency of the proposed 12-cell CRLH LWA.

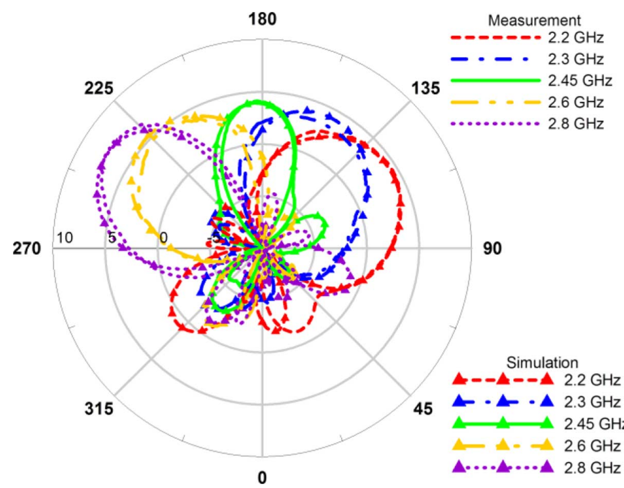

Fig. 14. Measured and simulated radiation patterns of the proposed CPW fed 10-cell CPS CRLH LWA.

to verify that the radiation only takes place in the fast wave region, which are qualitatively matched with the dispersion characteristic analysis shown in Fig. 9.

The corresponding far-field patterns of the fabricated LWA prototype were measured in an anechoic chamber using an HP8530A vector network analyzer. Fig. 14 shows the measurement results at the horizontal plane. All of the radiation patterns show the characteristic of the balanced CRLH LWAs, the radiation main beam of which can scan continuously from backward to forward angles as the operating frequency increases. The radiation patterns at 2.2 and 2.3 GHz shown in Fig. 14 correspond to the LH radiation regions, 2.45 GHz corresponds to the broadside region, and 2.6 and 2.8 GHz correspond to the RH radiation regions. Measured peak gain remained at approximately 3.2 dBi from 2.2 to 2.8 GHz, and a scanning range of nearly 135° was achieved in the proposed design. Small back lobes of the measured patterns were observed because of the imperfect shielding of the coplanar ground plane. A maximum peak gain of -13.1 dBi appeared at 2.5 GHz in the cross-polarization, which is still 10 dB lower than that of the copolarization.

IV. Achieving Wide-Angle Beam-Scanning LWA

Based on the ACPS leaky wave antenna proposed in the previous section, the design can be extended to a planar sector-shaped LWA achieving 180 scanning range in the horizontal

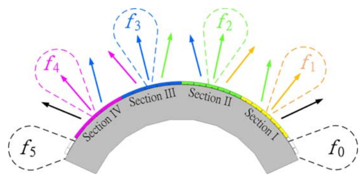

Fig. 15. Illustration of the proposed multisection section-shaped LWA.

TABLE III
DESIGN PARAMETERS OF THE PROPOSED SECTOR-TYPE LWA

	Section I	Section II	Section III	Section IV
$f_{balanced}$	2.46 GHz	2.6 GHz	2.8 GHz	3.06 GHz
C_L	0.5 pF	0.4 pF	0.3 pF	0.2 pF
L_{Stub}	18 mm	17.5 mm	15.9 mm	14.4 mm

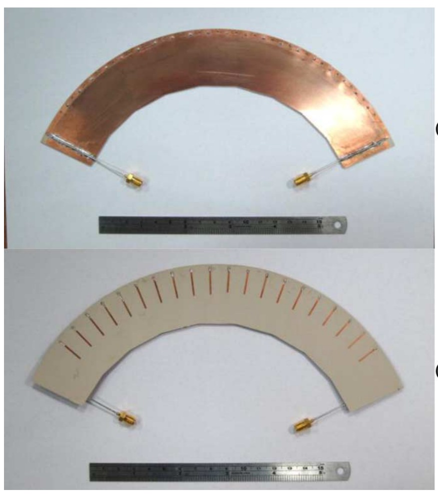
(a)
(b)

Fig. 16. Fabricated coaxial fed 4-section 20-cell section-shaped LWA (a) Top view (b) Back view.

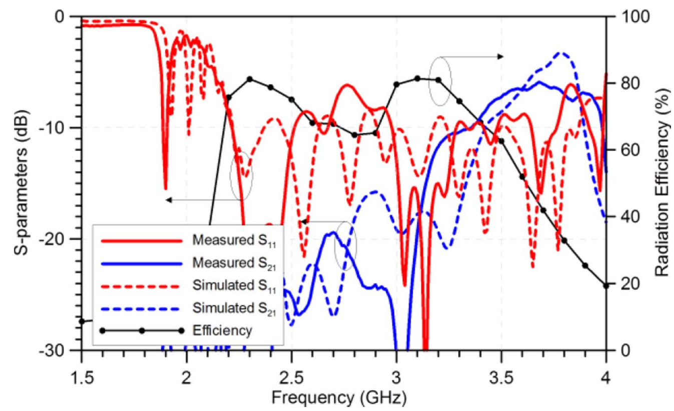

Fig. 17. Measured and simulated S-parameters and the measured radiation efficiency of the proposed sector-shaped multisection LWA.

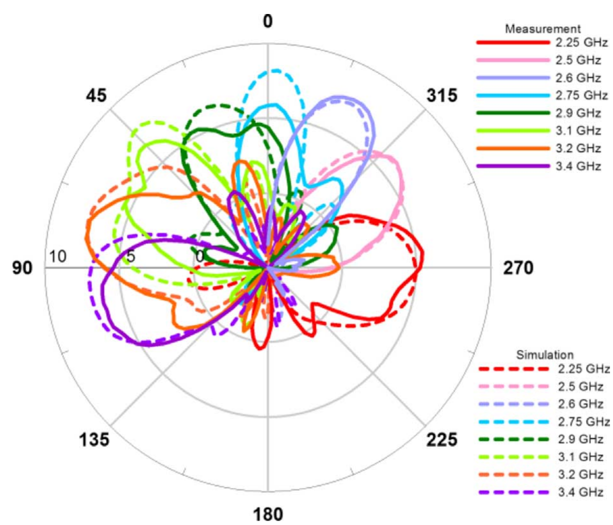

Fig. 18. Measured and simulated radiation patterns in the horizontal plane of the proposed sector-shaped LWA.

plane. Fig. 15 shows the proposed CRLH LWA with a wide scanning range. This antenna has 20 cells that can be divided into four sections; each has five elements and are balanced transmission lines. Fig. 15 also shows the operation mechanism. The balanced frequency of each section is different, and can be referred to as f1, f2, f3, and f4, as Table III shows. Therefore, as indicated by arrows with different colors in Fig. 15, when Section I operates at its balanced frequency, Section II operates at its left-handed fast wave region, producing a radiation beam in the same direction as Section I. At this point, Sections III and IV operate in the left-handed guided-wave region, which does not radiate power. As the operating frequency increases to f3, Section III radiates at its broadside and the adjacent two sections, such as Sections II and IV, operate in the right-handed and left-handed regions, respectively. Therefore, Sections II–IV radiate power in the same direction, and Section I enters right-handed guided-wave region.

The proposed sector-type leaky wave antenna was fabricated and tested. The proposed sector-shaped leaky wave antenna with a 180° scanning range consisted of four sections, with each section containing five elements. The balanced frequencies of the four subsections were set as 2.46 GHz, 2.52 GHz, 2.7 GHz, and 3.04 GHz, to have a focused beam continuously scanned from 0° to 180°. The unit cells in each subsection were the same length, but the left-handed series capacitance and the shunt inductance were different. Table III lists the design parameters of the unit cell of these four subsections. The proposed structure is a 20 unit-cell arc CRLH TL conformed to a radius of 25.0 cm. Fig. 16 shows a photograph of the fabricated prototype. This leaky wave antenna is fed using two semi-rigid coaxial cables with SMA connectors on both ends of the leaky wave antenna. Fig. 17 shows measured and simulated S-parameters. The simulated results show that the antenna is matched in the operating band from 2.2 GHz to 3.5 GHz. The mismatches in some frequencies between the simulated and measured results are caused by the tolerance of SMD capacitors and the imperfect prototype fabrication process. To verify the wide-range beam-scanning property, the measurement of radiation patterns was performed in an anechoic chamber. The measured radiation efficiency is plotted with Figs. 17 and 18 shows the measured and the simulated radiation patterns in the horizon plane as the antenna operated from 2.2 GHz to 3.5 GHz. Measured peak gain is approximately 6.3 dBi at 2.5 GHz Since the sector-shaped LWA is longer and comprises more unit cell as compared to the linear one, directivity of the radiation patterns is higher and so as the achieved peak gains. The solid lines in this figure show the measured results, while the dashed lines show the simulated results. These results exhibit good overall agreement, except for some frequency shift and mismatch caused by the imperfect prototyping process. This figure shows that the antenna achieves a wide-range beam-scanning property, which is over 180°.

V. Conclusion

This study presented a printed CPS CRLH leaky wave antenna that exhibits horizontal scanning characteristic by varying the operating frequency in the design band. This study also proposed a balanced CRLH unit cell based on a coplanar stripline structure, the dimensions of which can be determined analytically. The balanced CRLH leaky wave antenna with horizontal scanning capability can be realized by cascading the proposed CRLH unit cell. The prototype was realized in a planar manufacturing technology. The advantage of this planar design and the novelty of its horizontal scanning property facilitate extending this design to a multisection sector-shaped LWA, achieving wide beam-scanning range over 180°. The measured and simulated results in this study validate the proposed design. By varying the operational frequency, the CRLH LWA can achieve the beam-scanning capability. The continuous and wide-range beam-scanning capability in the horizontal plane makes this design suitable for integration in mobile devices and radar systems. Following the proposed design methodology, the proposed ACPS CRLH LWA can be changed easily to operate at other frequency bands, and the scanning range can be increased effectively.

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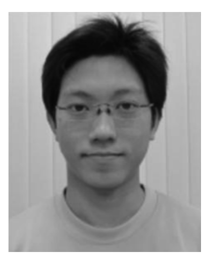

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