Leaky-Wave Steering in a Two-Dimensional Metamaterial Structure Using Wave Interaction Excitation

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***Abstract* — A two-dimensional composite right/left-handed (CRLH) metamaterial with an orthogonal feeding structure is demonstrated. By varying the magnitude of the input power to two orthogonal edges of the metamaterial, the net power flow direction can be controlled based on wave interaction. The CRLH metamaterial is analyzed and designed in terms of its equivalent circuit model and full-wave verification. The leaky-wave radiation from this metamaterial can be used for two-dimensional scanning without phase-shifters. Azimuth scanning is achieved by varying the magnitude of the input power at the two orthogonal edges of the structure, while elevation scanning is made possible by varying the operational frequency. Experimental radiation patterns of the metamaterial are shown and demonstrate an elevation scanning range of -61° to +60° and an azimuth scanning range of 0° to +90° with orthogonal two-edge feeding.**

***Index Terms* — Composite right/left-handed (CRLH) metamaterials, leaky-waves, left-handed materials.**

I. INTRODUCTION

Periodic structures have been widely investigated for microwave applications such as filter networks, frequency selective surfaces, and leaky-wave antennas [1]-[2]. Recently, left-handed (LH) periodic structures, known as LH metamaterials, have gained attention following their verification [3]. In particular, the transmission line approach based on the generalized composite right/left-handed (CRLH) metamaterial has lead to several new microwave devices [4]. The capability to support a fundamental backward wave is among the unique features of the CRLH metamaterial. In addition, since a portion of the CRLH metamaterial's dominant mode resides in the fast-wave region it has been used to realize a leaky-wave antenna [5]. Unlike conventional periodic leaky-wave antennas which require switching from excitation of a negative space harmonic to a positive space harmonic for backfire to endfire scanning, the CRLH leaky-wave antenna can continuously scan from backfire to endfire at its dominant mode.

Two-dimensional (2D) metamaterial realizations based on the CRLH theory have also been demonstrated. Interesting wave propagation phenomenon such as reversal of Snell's law has been observed [4], leading to the realization of flat lens focusing. Furthermore, leaky-waves have also been shown to exist in similar 2D structures [6].

In this paper, a 2D CRLH metamaterial structure is analyzed using a unique wave excitation method. Fig. 1 illustrates the main concept under investigation. By controlling the magnitude of the input power at the feeds, the direction of the net power flow in the metamaterial is controlled. This concept is based on the fact that the two input powers are in orthogonal directions. Therefore, the net power flow has both an x and y component. As a result, the net power flow of the resulting field distribution can be varied between 0° ≤ φ ≤ 90° with the proposed feeding structure. In the case where the CRLH metamaterial is operated in its leaky-wave region, backward or forward leakage can occur depending on the operational frequency. This leakage can be used for elevation scanning. By varying the input power ratio to the two feeds and the operational frequency, azimuth (0° ≤ φ ≤ 90°) and elevation (-90° ≤ θ ≤ +90°) scanning can be respectively achieved, suggesting interesting new possibilities in realizing full 2D phase-shifter-less beam scanning. This concept is verified by fabrication and measurement of a 2D CRLH metamaterial consisting of 8 x 8 unit-cells fed at two orthogonal edges. The analysis and design of the CRLH unit-cell is presented with emphasis on its operation in the leaky-wave region.

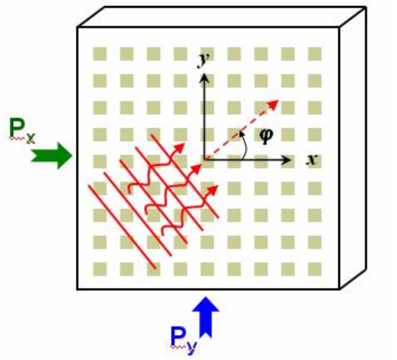
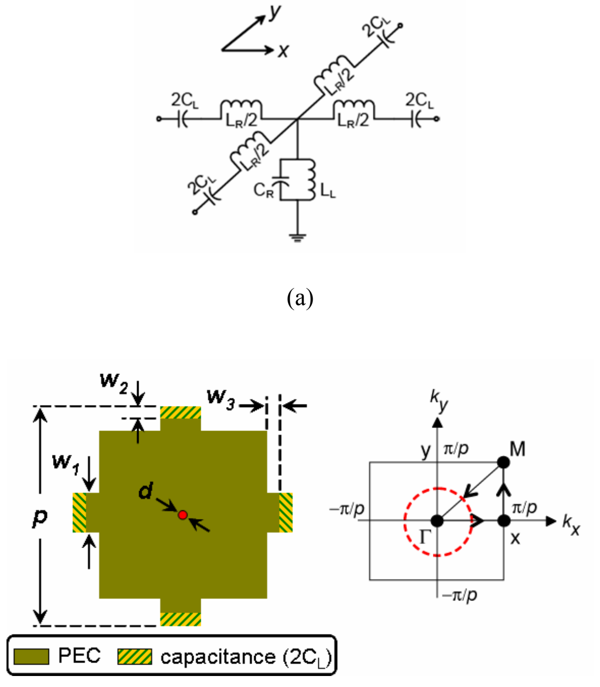


Fig. 1. CRLH metamaterial with orthogonal feeding. Net power flow direction in x-y plane is determined by the input power ratio.

II. CRLH METAMATERIAL ANALYSIS

A. CRLH Unit-Cell

The unit-cell of the proposed 2D CRLH metamaterial is based on the Sievenpiper mushroom structure, which in general consists of a square metal patch connected to the ground plane by a via. The CRLH unit-cell can be represented



(a)

(b)

Fig. 2. CRLH unit-cell. (a). Equivalent circuit model. (b). Implemented unit-cell with p = 5.2 mm, w_1 = 1.0 mm, $w_2 = w_3$ = 0.2 mm, and via diameter, d = 0.24 mm on Rogers/RT 6010 (h = 1.27 mm, ε_r = 10.2; Brillion zone diagram of unit-cell.

by an equivalent circuit model as shown in Fig. 2(a). The LH capacitance (C_L) is provided by the capacitive coupling between adjacent patches and the LH inductance (L_L) is provided by the via. The implemented CRLH unit-cell is shown in Fig. 2(b) with period p along with the 2D Brillouin zone diagram in which Γ ($k_xp = k_yp = 0$), X ($k_xp = \pi$, $k_yp = 0$), and M ($k_xp = \pi$, $k_yp = \pi$). Surface mount capacitors with values of 0.75 pF were used to provide C_L in order to create a balanced structure, $L_LC_L = L_RC_R$. Parameter extraction of the implemented CRLH unit-cell yielded C_L = 0.75 pF, L_L = 0.70 nH, C_R = 2.00 pF, and L_R = 2.10 nH.

Fig. 3 shows the calculated dispersion diagrams of the CRLH unit-cell shown in Fig. 2(b). Several numerical methods were used to generate the dispersion diagrams. Periodic boundary conditions (PBCs) were used to generate the dispersion diagram for an infinite structure, while the resonance condition of a single unit-cell were used to generate the dispersion diagram for a finite structure. In addition, the dispersion diagram was also generated with the extracted circuit model (LC) values. All three methods agree well below f = 7.0 GHz. Since the structure is to be effectively homogeneous, it is operated in the regions satisfying the homogeneity condition, $p < \lambda_g/4$. In the fast wave region ($\beta < k_o$), the CRLH structure is able to support leaky-waves and radiation occurs at an angle determined by

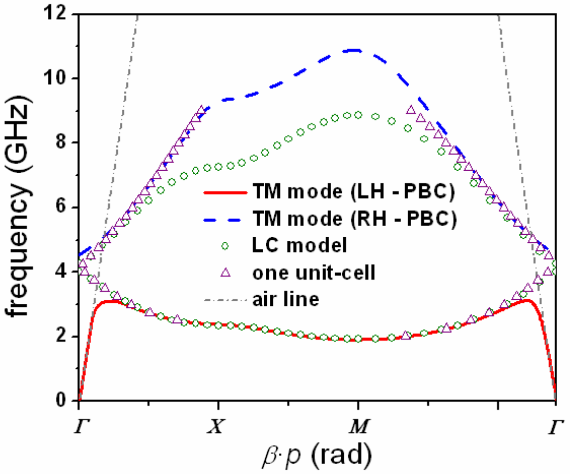


Fig. 3. Dispersion diagrams of CRLH unit-cell depicted in Fig. 2(b) calculated using several numerical methods.

$$\theta(\omega) = \sin^{-1}\left(\frac{\beta(\omega)}{k_o}\right). \qquad (1)$$

For the infinite structure, the supported TM modes couple to the air-line. As a result, the infinite structure is not able to support backward leaky-waves, however this is not the case for 2D structures with finite size as will be shown through measurement.

B. Proposed Two-Dimensional CRLH Structure

By periodically repeating the CRLH unit-cell of Fig. 2(b) along two directions, a 2D CRLH structure can be formed. The perspective view of the proposed structure is shown in Fig. 4. The CRLH metamaterial consists of 8 x 8 unit-cells. Two orthogonal edges of the structure are used as feeds. Each feed edge consists of eight microstrip transmission lines connected to a unit-cell by a capacitor of $2C_L$. Since the Bloch impedance (Z_B=Z_R=Z_L for balanced case) of the CRLH unit-cell is 32 Ω, a 32 Ω-to-50 Ω taper is used to connect the eight input ports at each edge to an 8:1 microstrip corporate feed network. Both edges are fed in-phase, only the magnitude of the power is varied. The unit-cells at the non-feeding edges are terminated with 50 Ω to minimize reflections.

By varying the input power ratio (P_y:P_x), the net power flow of the resulting field distribution can be steered along the x-y plane. This is based on the fact that the modes excited at each edge are quasi-TEM [6] with an electric-field directed along the z-direction. The wave excited along the x-direction has a y-directed magnetic field, while the wave excited along the y-direction has an x-directed magnetic-field. Therefore, the net power flow has both an x and y component. By varying the input powers, these orthogonal components are varied and the net power flow direction is controlled. Using a first-order

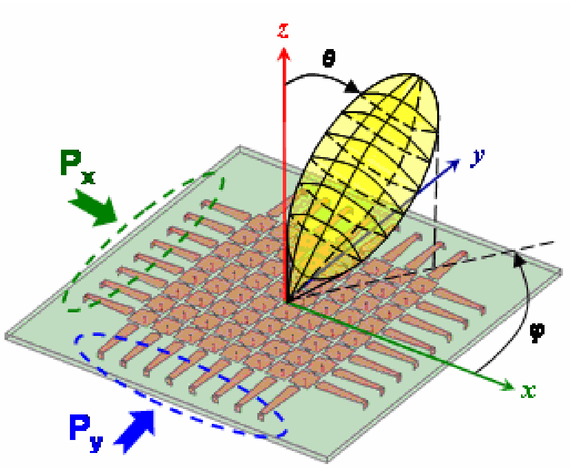


Fig. 4. Picture of the CRLH metamaterial with orthogonal feeding showing operation in the forward leaky-wave region.

approximation and neglecting scattering, the direction of the net power flow is related to the input power ratio by

$$\varphi \approx \tan^{-1}(P_y / P_x). \tag{2}$$

With only two feeding edges, φ can range from 0° to 90°. This condition holds for both the slow- and fast-wave regions. Furthermore, this effect manifests itself in the fast-wave region as radiation leakage along the direction of power flow; therefore the resulting radiated beam's elevation is determined by (1), while the beam's azimuth is determined by (2). This concept is illustrated in Fig. 4 which shows forward leakage resulting in a radiated beam with a peak located at θ, φ.

Since the proposed CRLH structure is finite and is excited along each row and column of the structure, the air mode coupling is weak. As a result, the structure can have both backward leakage and broadside leakage in addition to forward leakage. This was observed both in full-wave simulation and experiment.

III. EXPERIMENTAL RESULTS

A. Near-Field Measurements

Near-field measurements of the electric-field were taken atop the CRLH structure to confirm backward wave phenomena, with a measurement area of 46.0 x 46.0 mm^2. Fig. 5 shows the phase distribution when the structure is excited only along the x-direction and in the LH region for f = 2.40 GHz, 2.70 GHz, and 3.20 GHz.

The results of Fig. 5 show that the wavelength increases as the frequency increases, which confirms the LH nature of the structure. In addition, near-field measurements where taken with two edge in-phase excitation of the structure; the ratio of P_y to P_x was varied. Fig. 6(a) and 6(b) respectively show the electric-field magnitude and phase atop the CRLH structure with different $Py{:}Px$ ratios at f = 3.80 GHz, which corresponds to a backward leaky mode.

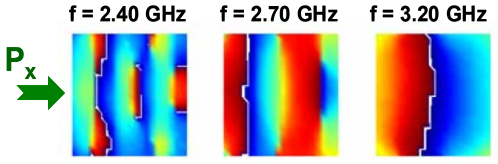


Fig. 5. Experimental near-field plot of electric-field phase.

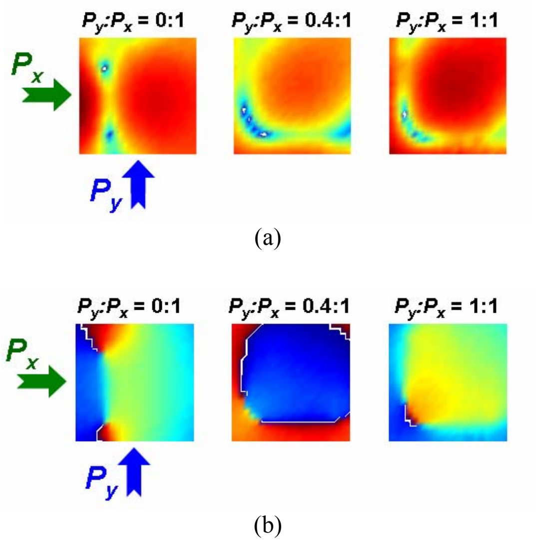


Fig. 6. Experimental near-field plots atop CRLH structure at f = 3.80 GHz with various input power ratios. (a) Magnitude. (b) Phase.

The results of Fig. 6 confirm that simultaneously feeding the structure changes the field distribution. However, since it is difficult to determine the net power flow direction from Fig. 6, far-field measurements are taken.

B. Far-Field Measurements

Far-field measurements are used to verify the dispersion characteristics of the CRLH structure and the orthogonal feeding principle. When the CRLH structure is operated in the leaky-wave region, radiation occurs as a result of leakage. By measuring the elevation (θ) of the resulting radiated beam, the propagation constant of the CRLH unit-cell can be verified. Consequently, the net power flow direction can be confirmed by measuring the azimuth (φ) of the resulting radiated beam. Fig. 7 shows the measured dispersion diagram in the leaky-wave region with $P_y{:}P_x$ = 0:1 versus the calculated dispersion diagram derived from the extracted parameters. Both endfire and backfire radiation is observed, suggesting that both RH and LH leaky modes exist. In the LH region, as the frequency is decreased from 4.2 GHz to 3.2 GHz, θ decreases from 0° to -61°, and the radiated beam scans toward backfire. In the RH region, as the frequency is increased 4.2 GHz to 5.1 GHz, θ increases from 0° to 60°, and the radiated beam scans toward endfire. The deviation of the measured dispersion diagram to

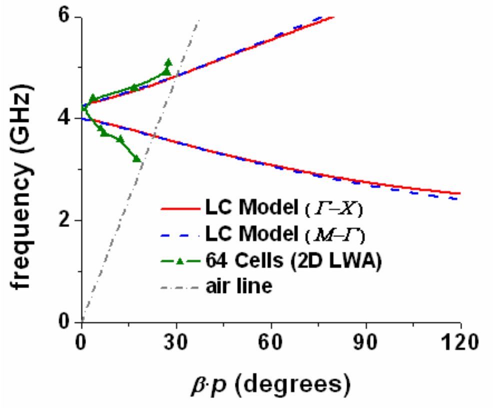


Fig. 7. Experimental versus calculated dispersion diagram.

the calculated diagram can be attributed to the implemented 0.75 pF capacitors, which have a tolerance of ±0.25 pF.

Fig. 8 shows the measured three-dimensional far-field patterns for various power ratios at $f = 3.80$ GHz. When P_y:P_x = 0.16:1, the radiated beam occurs at $\varphi = 3°$, $\theta = -15°$. When P_y:P_x = 0.4:1, the radiated beam occurs at $\varphi = 33°$, $\theta = -15°$. When P_y:P_x = 1:1, the radiated beam occurs at $\varphi = 43°$, $\theta = -15°$. These results are in agreement with the angles predicted by (1) and (2). Deviations from the expected angles can be attributed to mismatch at the terminated edges of the CRLH structure.

IV. CONCLUSION

A two-dimensional CRLH metamaterial with an orthogonal feeding structure has been proposed. The orthogonal feeding of the metamaterial allows for net power flow direction control in the plane of the structure. By operating the CRLH structure in the fast-wave region, the CRLH structure is capable of backward, broadside, and forward leakage. The dispersion diagram in the leaky-wave region is verified by measurement of the radiation patterns, which shows elevation scanning of the radiated beam as a function of frequency. By controlling both the magnitude of the input power feed and the operational frequency, a two-dimensional leaky-wave structure capable of azimuth and elevation scanning has been realized.

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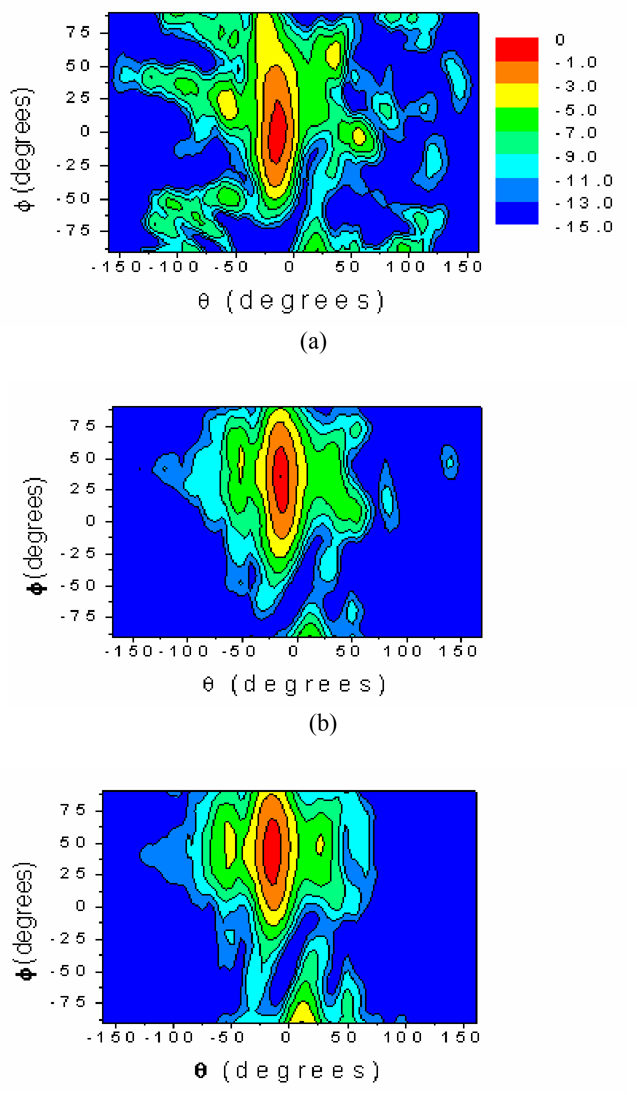

(a)

(b)

(c)

Fig. 8. Measured three-dimensional far-field pattern (normalized dB-scale) of the CRLH structure at $f = 3.80$ GHz. (a) P_y:P_x = 0.16:1. (b) P_y:P_x = 0.4:1. (c) P_y:P_x = 1:1.

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