

Frequency Scanning Reflectarray Based on Composite Right/Left-Handed Transmission Lines

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Abstract— This paper presents a new design method, based on composite right/left-handed (CRLH) transmission lines (TLs), to realize frequency scanning reflectarrays. The proposed technique enables continuous steering of the reflected beam toward both positive and negative elevation angles, by simply connecting customizable progressive phase advance/delay lines to the existing delay lines of a broadband reflectarray. This unique feature would otherwise not be possible using conventional right-handed delay lines due to impractical physical lengths and lack of control over the phase slope. A small prototype array of 4×3 elements operating at a center frequency of 2.5 GHz is designed, fabricated, and measured to demonstrate the frequency scanning enhancement provided by the CRLH TLs.

Keywords— Antennas, composite right/left-handed (CRLH), delay lines, frequency scanning, reflectors, reflectarrays.

I. INTRODUCTION

Reflectarrays are advantageous when compared to conventional parabolic reflector antennas due to their low-profile, light-weight, and easy-to-manufacture features [1]. Similarly to phased array antennas, reflectarrays can be designed to steer the radiated beam, except without the need for complex and lossy feed networks.

Compared to other aperture phase-tuning mechanisms to steer the beam (such as mechanical rotation [2] or the use of electronic devices [3], [4]), frequency scanning arrays are relatively low-cost due to their passive nature. However, current frequency scanning reflectarray technologies [5], [6] do not provide full frequency scanning and depend on parametric studies/optimization in EM simulation for their design.

Frequency scanning antenna arrays based on composite right/left-handed (CRLH) transmission lines (TLs) have been demonstrated in recent years for both corporate [7] and series [8] feed networks. Unlike conventional right-handed (RH) delay lines which require phase wrapping to achieve both negative and positive progressive phase shift α , CRLH TLs can provide systematically designed dispersion in a compact form. Such feature allows for a customizable scanning angle θ_0 that can point toward both forward and backward directions, as described by

$$\theta_0 = \sin^{-1} \left(\frac{\alpha}{k_0 d} \right), \quad (1)$$

where k_0 is the free-space wavenumber and d is the interelement spacing.

In this paper, we explore a new implementation of CRLH TLs to provide a similar full frequency scanning beam scanning for reflectarrays. The straightforward design approach involves adding open-ended CRLH phase

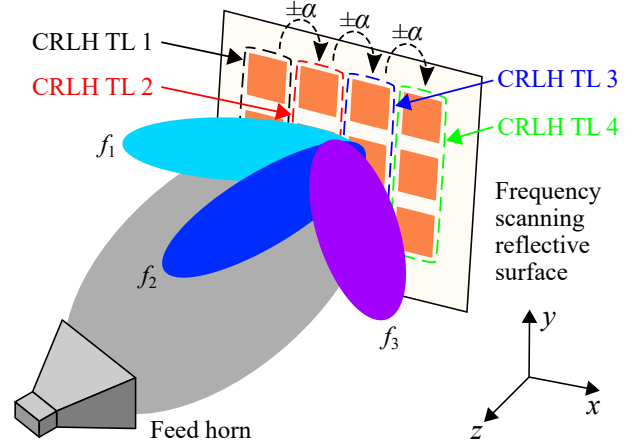


Fig. 1. Proposed CRLH-enhanced reflectarray with backward to forward frequency scanning capability.

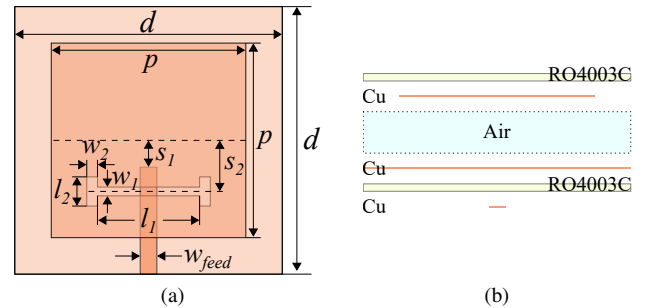


Fig. 2. Physical dimensions of radiating element. (a) Top view ($p = 40$ mm, $d = 55$ mm, $s_1 = 5.5$ mm, $s_2 = 10.5$ mm, $l_1 = 21$ mm, $w_1 = 1.4$ mm, $l_2 = 6$ mm, $w_2 = 2$ mm, and $w_{feed} = 3.41$ mm). (b) Exploded side view.

advance/delay lines to the existing delay lines of a broadband reflectarray. The general concept is illustrated in Fig. 1, in which the CRLH TLs are designed to provide a progressive phase shift along the x-axis for scanning in the xz-plane.

The proposed reflectarray may serve as a low-cost/simple alternative to active reflecting surfaces such as reconfigurable intelligent surfaces (RIS) [9], intelligent reflecting surfaces (IRS) [10], and smart reflectarrays [11].

II. DESIGN OF FREQUENCY SCANNING REFLECTARRAY

A. Radiating Element and Initial Phase Distribution

For the reflectarray unit cell, an aperture coupled patch is built on two RO4003C substrates ($\epsilon_r = 3.55$, $\tan \delta = 0.0021$, thickness $h = 1.524$ mm), separated by an air gap of 8.5 mm.

Table 1. Physical lengths of delay lines added to antenna feed lines.

Initial delay line lengths for each element				
$\begin{matrix} \text{x} \\ \text{y} \end{matrix}$	1	2	3	4
3	0 mm	0.77 mm	0.77 mm	0 mm
2	3.22 mm	4.00 mm	4.00 mm	3.22 mm
1	5.68 mm	6.46 mm	6.46 mm	5.68 mm

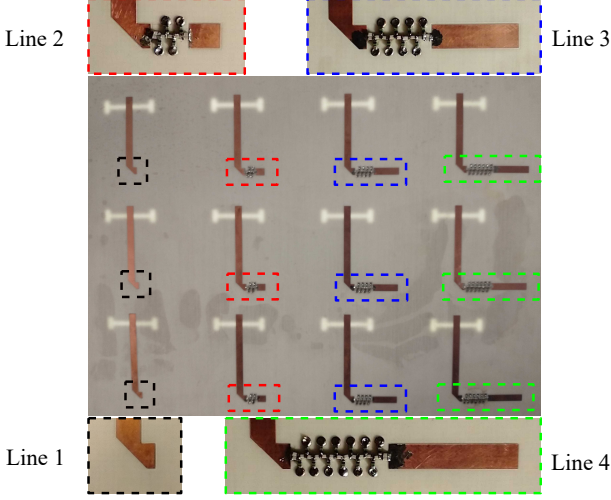


Fig. 3. Backside of the fabricated reflectarray.

The layout and physical dimensions of the aperture coupled patch are shown in Fig. 2. Interelement spacing is chosen to be $d = 55$ mm, considering the condition of no grating lobes [8]

$$d < \frac{\lambda_0}{1 + |\sin \theta_0|}, \quad (2)$$

where λ_0 is the free space wavelength, and θ_0 is the maximum pointing angle of the main beam.

To point the beam in the direction (θ_b, φ_b) , the required initial phase shift introduced at the element with coordinates (x_i, y_i) is calculated by

$$\phi_{init}(x_i, y_i) = k_0(r_i - (x_i \cos \varphi_b + y_i \sin \varphi_b) \sin \theta_b), \quad (3)$$

where k_0 is the free-space wavenumber and r_i is distance from (x_i, y_i) to the phase center of the feed (X_F, Y_F, Z_F) [12]. In our design, the reflector is fed by a horn antenna located at the position $X_F = 0$, $Y_F = -0.2$ m, $Z_F = 1.134$ m. The choice of this position is to ensure that the far field criteria are met, as well as to avoid obstructing the path to the receiving antenna in the measurement. An initial phase distribution is calculated for the traditional delay lines so that the beam points at broadside ($\theta_b = 0^\circ$). Then by adding the CRLH phase advance/delay lines after the traditional lines, frequency scanning in the xz -plane can be realized.

The lengths of the traditional delay lines are given by Table 1. Note that although the presented prototype has a large focal length to aperture size (F/D) ratio, broadband operation is still possible for small F/D ratios as long as true time delay (TTD) is maintained [13]. If necessary, meandered lines

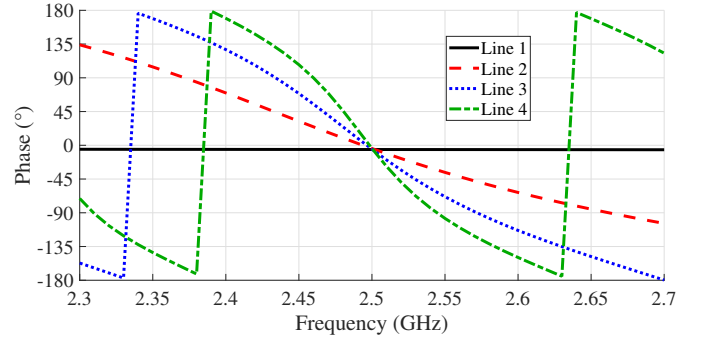


Fig. 4. Measured reflection phase of the open CRLH TLs.

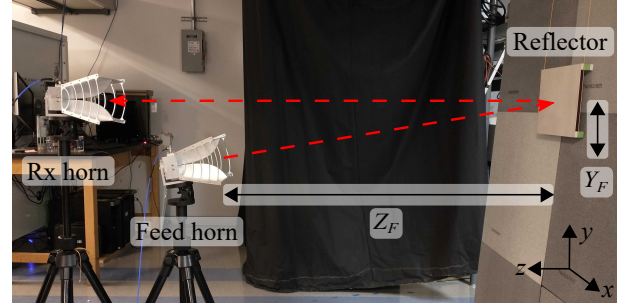


Fig. 5. Bistatic measurement setup of the reflectarray.

or CRLH TTD lines [14] may be used to further reduce the size.

B. CRLH Phase Advance/Delay Lines

The equivalent circuit model for a CRLH TL unit cell is a combination of the right-handed series inductor (L_R) and shunt capacitor (C_R), with the left-handed series capacitor (C_L) and shunt inductor (L_L). Under the balanced condition ($L_R C_L = L_L C_R$), the open-ended n -unit cell CRLH TL will have a reflection phase of

$$\phi_{CRLH} = 2(\phi_R + \phi_L) \approx -2n\omega\sqrt{L_R C_R} + \frac{2n}{\omega\sqrt{L_L C_L}}. \quad (4)$$

To obtain the circuit component values for the required phase, the design of the CRLH TLs here is based on the detailed design procedure outlined in [15]. In our design, n is chosen to be 0, 4, 8, and 12 for Line 1, Line 2, Line 3, and Line 4, respectively. The fabricated CRLH TLs located on the backside of the reflectarray are shown in Fig. 3. For the left-handed components, lumped component values of $L'_L = 1.5$ nH and $C_L = 0.7$ pF are used. Inductance of the vias (with diameter $2r = 0.8$ mm) connecting the lumped inductors to ground is calculated to be $L_{via} = 0.27$ nH, from [16]:

$$L_{via} = \frac{\mu_0}{2\pi} \left(h \cdot \ln \frac{h + \sqrt{r^2 + h^2}}{r} + \frac{3}{2} (r - \sqrt{r^2 + h^2}) \right). \quad (5)$$

This brings the total left-handed inductance to $L_L = 1.77$ nH, resulting $\sqrt{L_L/C_L} = 50.3 \Omega$. The right-handed components are realized by microstrip lines of length 0 mm, 4.35 mm, 12.4 mm, and 17.8 mm. The measured phase response of the four lines (fabricated separately) is shown in Fig. 4.

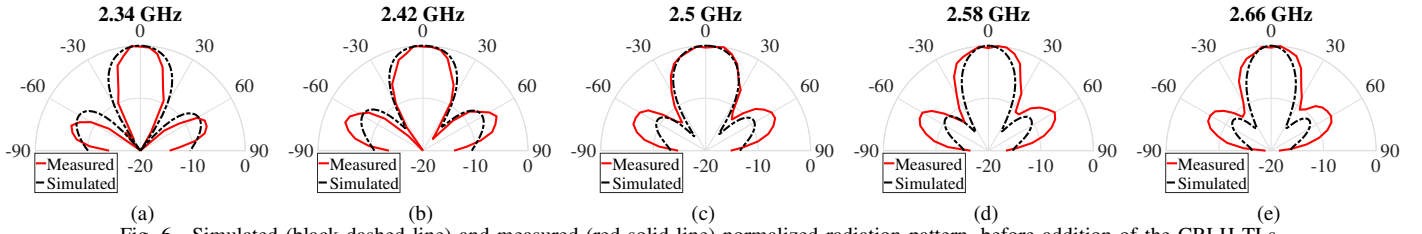


Fig. 6. Simulated (black dashed line) and measured (red solid line) normalized radiation pattern, before addition of the CRLH TLs.

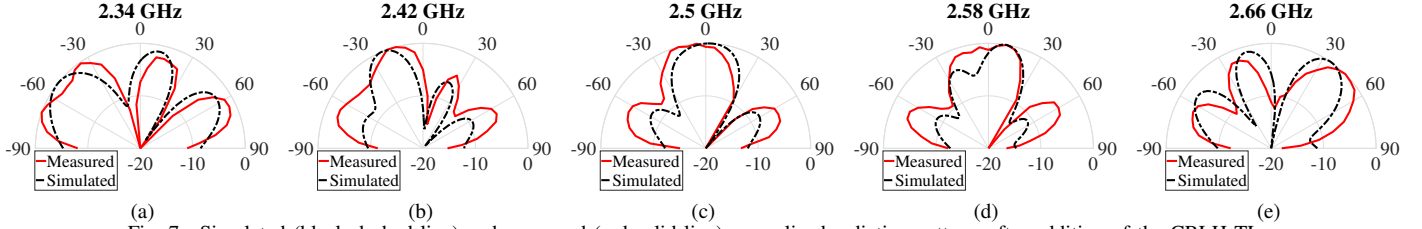


Fig. 7. Simulated (black dashed line) and measured (red solid line) normalized radiation pattern, after addition of the CRLH TLs.

III. EXPERIMENTAL VALIDATION OF THE REFLECTARRAY

A pair of Pasternack PE-9887-11 antennas is used to measure the normalized radiation pattern with one horn feeding the array, as shown in Fig. 5. The receiving antenna is placed at a fixed distance from the reflector and its angle is varied from $\theta = -90^\circ$ to $\theta = 90^\circ$.

Fig. 6 shows the measured and simulated radiation patterns of the reflector without any CRLH TLs added (prior to soldering the left-handed components), which verifies its lack of scanning capability. The simulated and measured radiation patterns of the reflector after adding the CRLH TLs are shown in Fig. 7, which demonstrate the frequency scanning capability.

Due to partial absorption in the lumped components, the beam shape has been relatively distorted when compared to the non-scanning reflector. However alternative implementations such as distributed CRLH stripline [17] may be used to achieve the same phase response with much lower loss.

IV. CONCLUSION

A method to design frequency scanning reflectarray based on CRLH TLs is presented. By introducing phase advance/delay lines to a broadband reflectarray made of aperture-coupled patches, full frequency scanning can be achieved. A prototype of 4×3 elements is designed, and its frequency scanning capability is demonstrated in both simulation and measurement.

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REFERENCES

- [1] E. Carrasco and J. A. Encinar, "Reflectarray antennas: A review," *Forum Electromagn. Res. Methods Appl. Technol.*, vol. 16, Jul./Aug. 2016.
- [2] V. F. Fusco, "Mechanical beam scanning reflectarray," *IEEE Trans. Antennas Propag.*, vol. 53, no. 11, pp. 3842–3844, Nov. 2005.
- [3] M. Riel and J. Laurin, "Design of an electronically beam scanning reflectarray using aperture-coupled elements," *IEEE Trans. Antennas Propag.*, vol. 55, no. 5, pp. 1260–1266, May 2007.
- [4] E. Carrasco, M. Barba, and J. A. Encinar, "X-band reflectarray antenna with switching-beam using pin diodes and gathered elements," *IEEE Trans. Antennas Propag.*, vol. 60, no. 12, pp. 5700–5708, Dec. 2012.
- [5] S. Qu, L. Xiao, H. Yi, B. Chen, C. H. Chan, and E. Y. Pun, "Frequency-controlled 2-D focus-scanning terahertz reflectarrays," *IEEE Trans. Antennas Propag.*, vol. 67, no. 3, pp. 1573–1581, Mar. 2019.
- [6] S. Li, C. Li, X. Zhang, and G. Fang, "Achievement of beam steering in terahertz band based on frequency-scanning grating-reflector antenna," *Electron. Lett.*, vol. 50, no. 3, pp. 136–138, Jan. 2014.
- [7] J. H. Choi, J. S. Sun, and T. Itoh, "Frequency-scanning phased-array feed network based on composite right/left-handed transmission lines," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 8, pp. 3148–3157, Aug. 2013.
- [8] D. Ren, J. H. Choi, and T. Itoh, "Series feed networks for dual-polarized frequency scanning phased array antenna based on composite right/left-handed transmission line," *IEEE Trans. Microw. Theory Techn.*, vol. 65, no. 12, pp. 5133–5143, Dec. 2017.
- [9] E. Basar, M. Di Renzo, J. De Rosny, M. Debbah, M. Alouini, and R. Zhang, "Wireless communications through reconfigurable intelligent surfaces," *IEEE Access*, vol. 7, pp. 116 753–116 773, Aug. 2019.
- [10] Q. Wu and R. Zhang, "Towards smart and reconfigurable environment: Intelligent reflecting surface aided wireless network," *IEEE Commun. Mag.*, vol. 58, no. 1, pp. 106–112, Jan. 2020.
- [11] X. Tan, Z. Sun, D. Koutsonikolas, and J. M. Jornet, "Enabling indoor mobile millimeter-wave networks based on smart reflect-arrays," in *Proc. IEEE Conf. Comput. Commun.*, Apr. 2018, pp. 270–278.
- [12] J. Huang and J. A. Encinar, *Reflectarray Antennas*. Hoboken, NJ, USA: Wiley, 2008.
- [13] E. Carrasco, M. Barba, and J. A. Encinar, "Reflectarray element based on aperture-coupled patches with slots and lines of variable length," *IEEE Trans. Antennas Propag.*, vol. 55, no. 3, pp. 820–825, Mar. 2007.
- [14] J. Zhang, S. W. Cheung, and T. I. Yuk, "Compact composite right/left-handed transmission line unit cell for the design of true-time-delay lines," *IET Microw. Antennas Propag.*, vol. 6, no. 8, pp. 893–898, Jun. 2012.
- [15] J. H. Choi and T. Itoh, "Dual-band composite right/left-handed (CRLH) phased-array antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 732–735, Jun. 2012.
- [16] M. E. Goldfarb and R. A. Pucel, "Modeling via hole grounds in microstrip," *IEEE Microw. Guided Wave Lett.*, vol. 1, no. 6, pp. 135–137, Jun. 1991.
- [17] M. D. Enders and J. H. Choi, "A series feed network based on a distributed CRLH stripline for frequency scanning applications," in *IEEE MTT-S Int. Microw. Symp. Dig.*, May 2016, pp. 1–3.