A Composite Right/Left-Handed Phase Shifter-Based Cylindrical Phased Array with Reinforced Particles Responsive to Magneto-Static Fields

Muhammad Ayaz, Adnan Iftikhar, Benjamin D. Braaten, Wesam Khalil and Irfan Ullah

Topic
Antennas
Edited by
Dr. Naser Ojaroudi Parchin, Dr. Chan Hwang See and Prof. Dr. Raed A. Abd-Alhameed
A Composite Right/Left-Handed Phase Shifter-Based Cylindrical Phased Array with Reinforced Particles Responsive to Magneto-Static Fields

Muhammad Ayaz 1, Adnan Iftikhar 2, Benjamin D. Braaten 3, Wesam Khalil 4 and Irfan Ullah 1,*

1 Department of Electrical and Computer Engineering, Abbottabad Campus, COMSATS University Islamabad, Abbottabad 22060, Pakistan
2 Department of Electrical and Computer Engineering, COMSATS University Islamabad, Islamabad 45550, Pakistan
3 Department of Electrical and Computer Engineering, North Dakota State University, Fargo, ND 58102, USA
4 Server Security Integration Group, Intel Corporation, 2111 NE 25th Ave, Hillsboro, OR 97124, USA
* Correspondence: eengr@cuiatd.edu.pk

Abstract: A conformal cylindrical phased array antenna excited with composite right/left-handed (CRLH) phase shifters is proposed. The phase tuning of the CRLH phase shifter is achieved by embedding novel magneto-static field-responsive micron-sized particles in its structure. It is shown that through the tiny magnet activation of these novel magneto-static particles at appropriate locations along the length of CRLH stub and inter-digital fingers, variable phase shifts are obtained. The proposed particle-based CRLH phase shifter operates in C-band (5–6 GHz) with a low insertion loss and phase error. The 1 × 4 cylindrical phased array is excited with the four unit cells of the proposed particle-embedded CRLH transmission line phase shifters to scan the main beam at desired scan angles. A prototype of a 1 × 4 cylindrical phased array excited with the particle-based CRLH phase shifters was fabricated, and the results show that the simulated results are in close agreement with the measured results. The conformal cylindrical array with the proposed particle-based CRLH phase shifters has great potential for use in printed and flexible electronics design where commercially available phase shifters have a definite drawback.

Keywords: magneto-static particles; conformal antenna; phased array; metamaterial transmission line; composite right/left-handed (CRLH) transmission line

1. Introduction

The metamaterial-based phase shifters that use composite right/left-handed (CRLH) transmission lines have been shown to have practical applications in many wireless communication systems such as radar systems, phased array antenna systems, and other compact microwave devices [1]. Conventional phase shifters uses right-handed transmission line (RH-TL) structures to achieve the phase shift response, by changing the length of the transmission line structure, so a longer length is required to achieve the larger phase shift. However, the CRLH-TL structure has unique phase characteristics, which can introduce positive, zero, and negative phase shifts [1]. In the literature, the phase shift of the CRLH transmission line is varied using conventional PIN/varactor diodes and a microelectromechanical system (MEMS) as switching elements in the fingers and stub of the structure to change its capacitance and inductance and therefore, the phase response. Another more recently introduced approach to obtain the variable phase shift is the use of ceramic material in the conventional CRLH structure, where the effective dielectric constant of the substrate is made variable to obtain the variable phase shift. Here, a brief overview of the most relevant literature studies is presented where these two common approaches have been applied to the CRLH-TL structure to achieve the variable phase response.
The work in [2,3] describes the CRLH-based phase shifter design using lumped capacitors and inductors as left-handed components. The requirements of unique discrete component values and switching between a reference line and CRLH transmission line (CRLH-TL) to calculate the phase shift complicated the design. In [4–6], an n-bit phase shifter based on CRLH-TL was designed. PIN diodes along the length of fingers of CRLH-TL were used as switches to obtain various phase shifts. A phased array antenna using BST/CRLH-TL composite phase shifters was presented in [7]. In [8], the fingers and stub of the CRLH-TL were loaded with varactor diodes to obtain variable phase constants. In [9], bulky MEMS switches were incorporated in the CRLH-TL structure to achieve the desired phase shifts. In [10,11], radiation patterns of a linear antenna array using a tunable phase shifter based on CRLH-TL with mechanically variable metal–insulator–metal (MIM) capacitors were presented. The requirements of external dc biasing circuitry for these diodes/mechanical switches not only complicated the design but could also be a drawback in fully printing electronics design applications and for large antenna array systems comprising thousands of phase shifters. A tunable phase shifter based on Inkjet-printed BST material in between the finger spacings of CRLH-TL was widely studied in [12–15]. In [16], the design of fully printable conformal antennas with polymer/CRLH-TL composite phase shifters was investigated. More details about the physical properties of reinforced polymer composites were presented in [17]. The relative permittivity of BST and the corresponding phase shift were achieved by applying an electrostatic field across it. The major drawback was the requirement of the tuning voltage in hundreds of volts to achieve the required phase shift. In [18,19], metamaterial-based phase shifters using thick-film ceramic material for phased array antennas were investigated. The complex process of integrating ceramic/polymer material in the artificial transmission line and the complex design of the DC biasing circuitry limited its applications in compact electronics component placement for fully printable and flexible applications. In a nutshell, these two common approaches for phase tuning of CRLH-TL have shown promising applications in phased array antenna systems. However, the need of external biasing circuitry, the complex fabrication process, and the requirements of high external voltage (in hundreds of volts) put limitations on these approaches for their use in large antenna systems (requiring thousands of phase shifters) and where space constraint is a major concern.

In the proposed work, a new particle-based CRLH (which we call a P-CRLH) phase shifter is presented to overcome these potential design obstacles. Then, a 1 × 4 cylindrical phased array is excited with the proposed P-CRLH phase shifters for main beam scanning at the desired scan angles. The use of magneto-static-responsive conductive micron-sized particles has been shown to have practical applications for RF switches [20,21], EBG antennas [22], reconfigurable antennas [23,24], leaky-wave antennas [25,26], metamaterials [27], the phase shift of a microstrip transmission line [28], and comparison with a PIN diode and electromagnetic propagation through a dielectric medium [29]. The main advantages of the proposed design are (a) the use of a single substrate for particle integration unlike the requirements of the two separate substrates in [22,23], (b) no requirement of discontinuous transmission line as in [24], and (c) no need for a direct connection of a biasing circuitry as required in conventional RF switches. A description of the abbreviations used in the study is given in Table A1 in Appendix A.

The rest of the paper is organized as: Section 2 discusses the design and analysis of a unit cell P-CRLH phase shifter; Section 3 presents a detailed simulation analysis of the unit cell P-CRLH phase shifter. Section 4 discusses the P-CRLH excited 1 × 4 conformal phased array, Section 5 provides detail of the measurement results, and Section 6 concludes the proposed work.

2. The P-CRLH Unit Cell Design and Analysis

A baseline CRLH-TL unit cell is designed first for a 0° phase shift at the design frequency $f_0 = 5.2$ GHz. The unit cell architecture is based on the well-known composite right/left-handed (CRLH) metamaterial transmission line [1] with slight modification of
introducing symmetrical stub lines as shown in Figure 1. An inductor stub line is used for left-handed inductance \( L_L \) and inter-digital fingers represent the left-handed capacitance \( C_L \). The right-handed components \( L_R \) and \( C_R \) come from the inherent right-handed parasitic elements present in the microstrip structure. This baseline CRLH unit cell is designed on a TMM4 substrate (\( \varepsilon_r = 4.7, \tan\delta = 0.002 \) and thickness = 0.635 mm). After the baseline 0° unit cell has been designed, the variable phase shifts can be achieved by tuning this unit cell. The tuning of the baseline CRLH unit cell is obtained by embedding novel magneto-static micron-sized particles (SM25P20 SILVER FERRITE in [30]) in the substrate along the length of stub (or at appropriate locations in the inter-digital fingers). We call this new CRLH structure with embedded particles, a ‘Particle-CRLH (P-CRLH)’. The embedding procedure of these micron-sized conductive particles in the TMM4 substrate is reported in detail in [31] and is briefly mentioned here. A small cylindrical cavity of diameter \( d \) and height equal to the thickness of the substrate in Figure 1 along the length of stub length of CRLH-TL is made through the substrate. Then, the cavity is partially filled with the silver-coated magnetic particles. The top and bottom of the cavity are the stub transmission lines and ground plane. This small structure of the particle-filled cavity with top and bottom conducting planes is denoted as the Magneto-static field Responsive Structure (MRS). It is worth mentioning that the work in [22–24] requires separate MRSs to be manufactured before their final integration in the transmission line. That is, the MRSs and transmission line require two separate substrates. Another requirement in these designs is the need for a discontinuous transmission line for the integration of MRSs. In the proposed P-CRLH phase shifter, both of these requirements are overcome by embedding the particles in a single TMM4 substrate. The particles in the cavity are aligned in the direction of the applied static magnetic field as shown in Figure 1b, thereby changing the electrical length of the shunted stub in the P-CRLH structure. The novel P-CRLH structure in Figure 1 consists of six inter-digital fingers and two symmetrical stubs. Sixteen MRS structures numbered from 1 to 16 are designed in the two stubs. A tiny magnet beneath any MRS structure will activate the particles in the cavity, which causes a change in the length of the current path along the stub and thereby changes the value of the left-handed inductance \( L_L \). Similarly, activating these particles in MRS structures at appropriate locations along the inter-digital fingers of CRLH will cause \( C_L \) to change. The changes in \( L_L \) and \( C_L \) will change the phase response of the P-CRLH unit cell.

\[
\begin{align*}
&L_5 = 8, \quad W_5 = 1, \quad W_f = 0.3, \\
&L_f = 6, \quad L_{\mu s} = 7.6, \quad W_{\mu s} = 1.8, \quad d = 0.6, \quad W_g = 9, \quad L_g = 22, \quad S = 0.2)
\end{align*}
\]

Figure 1. (a) P-CRLH unit cell top view (All dimensions are in mm: \( L_5 = 8, \ W_5 = 1, \ W_f = 0.3, \ L_f = 6, \ L_{\mu s} = 7.6, \ W_{\mu s} = 1.8, \ d = 0.6, \ W_g = 9, \ L_g = 22, \ S = 0.2 \)) (b) P-CRLH unit cell 3D view.

The equivalent circuit of the proposed P-CRLH unit cell structure is shown in Figure 2, and its phase shift analysis is based on the guidelines in [1]. \( L_{DC} \) and \( L_{SI} \) represent the inductances of the Inter-Digital Capacitor (IDC) and Stub Inductor (SI) due to their physical
The physical lengths of the stub transmission lines are changed by activating and deactivating the embedded micron-sized particles inside the MRS cavity. $C_{p^{SI}}$ and $C_{p^{IDC}}$ are the inherent parallel plate capacities between the stub inductor (or IDC) and the ground plane. $C_{s^{IDC}}$ is the capacitance due to the spacing among the fingers of IDC. $L_{hs}$ and $C_{hs}$ are the inductance and capacitance of the microstrip transmission lines on both ends of the P-CRLH unit cell. Finally, the four P-CRLH parameters are calculated as follows [1]:

$$
\begin{align*}
L_{R} &= L_{s^{IDC}} + \frac{L_{s^{SI}}}{2} \\
C_{R} &= 2C_{s^{IDC}} + C_{p^{SI}} \\
L_{L} &= L_{p^{SI}} \\
C_{L} &= C_{s^{IDC}}
\end{align*}
$$

(1)

Next, with the use of the ABCD parameter approach for the proposed P-CRLH unit cell structure, the phase response is calculated as follows: The cascaded ABCD matrices of the equivalent circuit model in Figure 2 of the proposed P-CRLH unit cell design are given by

$$
\begin{pmatrix}
A & B \\
C & D
\end{pmatrix}_{P-CRLH} = \begin{pmatrix}
A & B \\
C & D
\end{pmatrix}_{\text{MRS}} \begin{pmatrix}
A & B \\
C & D
\end{pmatrix}_{\text{IDC}} \begin{pmatrix}
A & B \\
C & D
\end{pmatrix}_{\text{SI}} \begin{pmatrix}
A & B \\
C & D
\end{pmatrix}_{\text{MRS}}
$$

(2)

Then, the S-parameters of the P-CRLH unit cell design are calculated as [32]

$$
\begin{pmatrix}
S_{11} & S_{12} \\
S_{21} & S_{22}
\end{pmatrix} = \begin{pmatrix}
\frac{A + \frac{B}{A} - CZ_{0} - D}{A + \frac{B}{A} + CZ_{0} + D} & \frac{2(AD - DC)}{A + \frac{B}{A} + CZ_{0} + D} \\
\frac{2}{A + \frac{B}{A} + CZ_{0} + D} & \frac{-A + \frac{B}{A} - CZ_{0} + D}{A + \frac{B}{A} + CZ_{0} + D}
\end{pmatrix}
$$

(3)

Finally, the phase response and insertion loss (IL) of the proposed P-CRLH unit cell structure from the S-parameters marix in (3) are calculated as

$$
\phi_{S_{21}} = \text{phase of } S_{21}
$$

(4)

$$
\text{IL}(\text{dB}) = 20 \times \log_{10}|S_{21}|
$$

(5)

The expressions in Equations (1)–(5) indicate that various phase shifts from the P-CRLH unit cell can be obtained by changing the values of left-handed parameters $L_{L}$ and $C_{L}$. The values of $L_{L}$ and $C_{L}$ are controlled through the activation of the silver-coated magnetic particles embedded in the structure. Practically, the value of $L_{L}$ is varied by changing the physical lengths ($L_{a}$) of the shunted stub transmission lines in Figure 1a. The physical lengths of the stub transmission lines are changed by activating the MRSs along their lengths numbered from 1 to 16. Similarly, by varying the spacing among the fingers (s), different values of $C_{L}$ are obtained. The phase response of the P-CRLH unit cell is a complex function of mainly four parameters ($L_{R}, C_{R}, L_{L}, C_{L}$) that is calculated as
using the expressions in Equations (1)–(5) once the physical values of these parameters are determined.

3. Simulation Results of the P-CRLH Phase Shifter

Initially, particles in MRSs at positions 1 and 9 in Figure 1 are assumed to be activated. This shows that the entire lengths of both stub inductors are in place. Next, the equivalent circuit model parameters in Equation (1) are extracted using the full-wave simulation at the design frequency $f_0 = 5.2$ GHz using the procedure outlined in [1], and the extracted values are $L^{CDC}_p = 0.65$ nH, $C_p^{CDC} = 1.97$ pF, $C_s^{CDC} = 3$ pF, $L^{SI}_p = 0.85$ nH, $L_p^{SI} = 2.91$ nH, $C_p^{SI} = 1.94$ pF, $L_p^{SI} = 0.5$ nH, and $C_p^{SI} = 0.36$ pF. Then, by implementing Equations (1)–(5) in MATLAB, the reflection coefficient, Insertion Loss (IL), and phase response of the P-CRLH phase shifter are shown in Figure 3. The phase response of the P-CRLH phase shifter using the equivalent circuit model in Figure 2 with the extracted circuit values from the ADS circuit simulator are also shown in Figure 3. Next, for full-wave results, the microstrip implementation of the P-CRLH phase shifter in Figure 1 is simulated in the CST microwave studio suite. For MRS structure implementation in the full-wave simulator, the guidelines in [22] are followed, and the corresponding CST simulation results are shown in Figure 3. The analytical (MATLAB) and ADS circuit simulator results in Figure 3 are on top of each other, validating the analytical modeling in (1)–(5). The −10 dB impedance-matching characteristics ($S_{11}$) and Insertion Loss ($S_{12}$) in the full-wave simulation for the proposed P-CRLH phase shifter are in good agreement with the analytical and circuit simulation results shown in Figure 3a. The phase deviation between the analytical and full-wave simulation results is around 4°–5°. Next, the parametric study of the silver-coated magnetic particle activation in MRSs in the symmetrical stub transmission lines of the P-CRLH phase shifter structure in Figure 1 for different phase shift responses is carried out, and the full-wave CST results are shown in Figure 4. The results in Figure 4 shows that almost equal phase slope phase responses are obtained over the C-band by activating MRSs at different locations along the lengths of the stub transmission lines. The maximum shift obtained with the unit cell P-CRLH design is approximately 45° by activating particles in MRSs 8 and 16 simultaneously. The impedance matching characteristics ($S_{11}$) of the structure deteriorates in the case of MRSs 8 & 16 activation as compared to MRSs 1 & 9 activation as shown in Figure 4. The reason is that for MRSs 1 & 9 activation, the entire lengths of the two shunted stub lines are electrically in place and therefore support the propagation of the electromagnetic wave from port 1 to port 2. In the case of MRSs 8 & 16 activation, almost the entire lengths of the two stubs are effectively out of the circuit, which negatively affects the impedance matching characteristics. Therefore, the insertion loss ($S_{12}$) for MRSs 8 & 16 activation is approximately 0.48 dB greater than the insertion loss for the MRSs 1 & 9 activation.

Figure 3. (a) Reflection coefficient, insertion loss, and (b) phase response of the unit cell P-CRLH phase shifter with MRSs 1 & 9 activation.
4. Simulated Results of a Cylindrical Phased Array with P-CRLH Phase Shifters

To test the performance of the proposed P-CRLH phase shifter, a $1 \times 4$ broadband antenna array placed along the cylindrical arc of radius 30 cm operating in the C-band (5–6 GHz) with inter-element spacing of $\frac{\lambda}{2}$ at $f_0 = 5.2$ GHz was considered a test case as shown in Figure 5. The required phase shifts for broadside, $15^\circ$, and $30^\circ$ main beam scanning are given in Table 1 and were calculated using the technique in [33]. Since the P-CRLH phase shifter in Section 2 can give a maximum $45^\circ$ phase shift, to achieve the phase shifts in Table 1, four unit cells of P-CRLH were cascaded. The phase shifts achieved with the cascaded P-CRLH phase shifters and the corresponding MRSs activation in the structure are given in Table 2. The activations of specific MRSs for certain required phase shifts are determined using the phase response graphs in Figure 4b. After achieving the required phase shifts, the $1 \times 4$ cylindrical antenna array was excited with cascaded P-CRLH phase shifters as shown in Figure 5. Initially in the CST simulator, the $1 \times 4$ cylindrical antenna array was directly excited with the phase shifts given in Table 1.

Then, the array was exited with four cascaded P-CRLH phase shifters to achieve the desired radiation patterns. The CST simulated results for directly excited and the P-CRLH phase shifter-excited $1 \times 4$ cylindrical antenna array at 5.2 GHz, 5.5 GHz, and 5.8 GHz in the C-band are shown in Figure 6. The results indicate that the proposed P-CRLH phase shifters can achieve the desired broadside radiation pattern and $15^\circ$, $30^\circ$ main beam scanning patterns in the C-band. The broadside and scanning results are shown to agree well with the results reported in [33].

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Calculated Phases From [33]</th>
<th>Achieved P-CRLH Phases in This Work</th>
<th>Calculated Phases from [33]</th>
<th>Achieved P-CRLH Phases in This Work</th>
<th>Calculated Phases from [33]</th>
<th>Achieved P-CRLH Phases in This Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_z=0^\circ$</td>
<td>$\theta_z=15^\circ$</td>
<td>$\theta_z=30^\circ$</td>
<td>$\theta_z=0^\circ$</td>
<td>$\theta_z=15^\circ$</td>
<td>$\theta_z=30^\circ$</td>
<td>$\theta_z=0^\circ$</td>
</tr>
<tr>
<td>$A_1$</td>
<td>19.4374</td>
<td>19.081</td>
<td>17.4326</td>
<td>19.081</td>
<td>17.4326</td>
<td>19.081</td>
</tr>
<tr>
<td>$A_2$</td>
<td>2.1630</td>
<td>2.309</td>
<td>-44.6481</td>
<td>-49.3426</td>
<td>-88.0606</td>
<td>-88.345</td>
</tr>
</tbody>
</table>
Table 2. Achieved phases (degrees) with cascaded four-unit-cell P-CRLH phase shifters.

<table>
<thead>
<tr>
<th>Scan Angle ($\theta_s$)</th>
<th>P-CRLH Phases</th>
<th>MRSs Activations (See Figure 1a for Numbering of Particle Activation in the Cavities)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Unit Cell-1</td>
</tr>
<tr>
<td>0°</td>
<td>19.081</td>
<td>1, 9</td>
</tr>
<tr>
<td></td>
<td>2.309</td>
<td>1, 9</td>
</tr>
<tr>
<td></td>
<td>2.309</td>
<td>1, 9</td>
</tr>
<tr>
<td></td>
<td>19.081</td>
<td>1, 9</td>
</tr>
<tr>
<td>15°</td>
<td>19.081</td>
<td>1, 9</td>
</tr>
<tr>
<td></td>
<td>19.081</td>
<td>1, 9</td>
</tr>
<tr>
<td>30°</td>
<td>-88.345</td>
<td>1, 5, 9, 13</td>
</tr>
<tr>
<td></td>
<td>-255.342</td>
<td>1, 9</td>
</tr>
</tbody>
</table>

Figure 5. Schematic of the $1 \times 4$ P-CRLH excited cylindrical phased array.
Figure 6. Simulation results of a $1 \times 4$ P-CRLH excited cylindrical phased array operating in C-band: 
(a–c) broadside patterns, (d–f) scanned patterns at $15^\circ$ and (g–i) scanned patterns at $30^\circ$.

5. Measurement Results of a Cylindrical Phased Array with P-CRLH Phase Shifters

Next, to validate the simulation results, four cascaded unit cells of the P-CRLH phase shifter were manufactured on a TMM4 substrate ($\varepsilon_r = 4.7$, $\tan \delta = 0.002$, and thickness = 0.635 mm). The silver-coated micron-sized magnetic particles used throughout the measurements were manufactured by Potters Industries (Malvern, PA, USA) (CONDUCT-O-FIL, part number SM25P20) [30]. MRS cavities were drilled through the substrate along the length of stub transmission lines at the locations indicated in Figure 1. Then, the MRS cavities were partially filled with these particles, the top of the MRS cavity is the stub transmission line and the bottom is a ground plane. The activation of particles inside any MRS cavity was achieved by a tiny magnet beneath the cavity as illustrated in Figure 7a. For measurement purposes, the MRS cavities given in Table 2 were filled with the particles and were activated with tiny magnets. Next, the C-band $1 \times 4$ antenna array was placed along the circular arc of a cylindrical surface with radius of 30 cm. The model of the cylindrical-parabolic conformal antenna array in [34] was adopted. Each individual antenna in the array was excited with the cascaded four unit cells of the P-CRLH phase shifter. The entire setup including RF cables in a fully calibrated in-house anechoic chamber (300 KHz–20 GHz) measurement facility is shown in Figure 7b. The Keysight VNA (E5071C) and Diamond Engineering desktop antenna measurement system were used for the radiation patterns synthesis. The measured results of the radiation patterns for broadside, $15^\circ$, and $30^\circ$ main beam scanning using the P-CRLH phase shifter-excited conformal phased array at the central frequency of the C-band (5.5 GHz) are shown in Figure 8. For comparison, the simulated results for the radiation patterns of the P-CRLH-excited conformal phased array are also shown in Figure 8. The differences in the peak gain between the simulated and measured results for the $0^\circ$, $15^\circ$, and $30^\circ$ scan angles are 0.55 dB, 0.22 dB, and 0.19 dB, respectively. The corresponding differences in the first sidelobe levels for the three scan angles are 2.8 dB, 1 dB, and 2.3 dB, respectively. Overall, there is a good agreement between the simulated and measured peak gain results except for the sidelobe levels as shown in Table 3. This is thought to be due to imperfect P-CRLH phase shifter fabrication, differences in the manufactured and simulated antenna array modeling, and a lack of perfect symmetry in the anechoic chamber.
Figure 7. Photographs of (a) A fabricated unit cell P-CRLH phase shifter; (b) A P-CRLH phase shifter-based 1 × 4 cylindrical antenna array in an anechoic chamber.

Figure 8. Measured radiation patterns of a 1 × 4 P-CRLH-excited cylindrical phased array: (a) broadside pattern, (b) main beam scanning at 15°, and (c) main beam scanning at 30°.

Table 3. Comparison between simulated and measured results of a 1 × 4 P-CRLH-excited cylindrical phased array.

<table>
<thead>
<tr>
<th>Scan Angle (θ,°)</th>
<th>Peak Gain (dB)</th>
<th>First Sidelobe Level (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Simulated</td>
<td>Measured</td>
</tr>
<tr>
<td>0°</td>
<td>9.48</td>
<td>8.93</td>
</tr>
<tr>
<td>15°</td>
<td>8.87</td>
<td>8.65</td>
</tr>
<tr>
<td>30°</td>
<td>8.68</td>
<td>8.49</td>
</tr>
</tbody>
</table>

6. Conclusions

A novel micron-sized particle-based composite right/left-handed (CRLH) phase shifter is investigated for conformal phased array antennas. These particles are embedded inside the substrate along the stub and inter-digital fingers of a CRLH transmission line. Desired phase shifts are obtained by magnetically aligning these particles with a tiny magnet, which in turn changes the left-handed inductance and capacitance of the CRLH
transmission line. A \( 1 \times 4 \) conformal phased array is then excited with these particle-based CRLH phase shifters for steering the main beam at desired scan angles. The proposed conformal phased array with integrated particle CRLH phase shifters is an excellent choice for flexing electronics applications where commercial phase shifters have drawbacks in fully printing requirements. One such example is the cylindrical array studied in [33], where a separate DC biasing circuitry is needed to operate the phase shifters, which can cause electromagnetic coupling with the phase shifters’ functionality. The proposed P-CRLH phase shifter needs a magnetic field to be applied from the ground plane to the top layer of the phase shifter, which effectively isolates the phase shifter from unintended coupling. The phase shifters in [5–7] need the mounting of additional components (resistors, inductors, capacitors) with off-chip ICs, and as such cannot be made flexible and fully printable. The proposed P-CRLH phase shifter does not need the discrete components and therefore can be easily integrated with conformal arrays and other flexible and printing electronics circuitry.

**Author Contributions:** B.D.B. provided the idea. A.I. and W.K. assisted in simulations. M.A. performed complete simulations, fabrications, and measurements. I.U. assisted in measurements, overall paper management, idea development, and manuscript writing. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work is supported by the HEC-NRPU, Pakistan, via Project No. 20-14696/NRPU/R&D/HEC/2021. The APC was paid by co-author Wesam Khalil.

**Data Availability Statement:** All data have been included in study.

**Conflicts of Interest:** The authors declare no conflict of interest.

### Appendix A

**Table A1.** Abbreviations used in the paper.

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TL</td>
<td>Transmission Line</td>
</tr>
<tr>
<td>CRLH</td>
<td>Composite Right/Left-Handed</td>
</tr>
<tr>
<td>CRLH-TL</td>
<td>Composite Right/Left-Handed Transmission Line</td>
</tr>
<tr>
<td>P-CRLH</td>
<td>Particles-CRLH</td>
</tr>
<tr>
<td>MRS</td>
<td>Magneto-static field Responsive Structure</td>
</tr>
<tr>
<td>RH-TL</td>
<td>Right-Handed Transmission Line</td>
</tr>
<tr>
<td>PIN</td>
<td>p-type intrinsic n-type</td>
</tr>
<tr>
<td>MEMS</td>
<td>Microelectromechanical systems</td>
</tr>
<tr>
<td>BST</td>
<td>Barium Strontium Titanate</td>
</tr>
<tr>
<td>MIM</td>
<td>Metal-Insulator-Metal</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>EBG</td>
<td>Electromagnetic Band-Gap</td>
</tr>
<tr>
<td>SI</td>
<td>Stub Inductor</td>
</tr>
<tr>
<td>IDC</td>
<td>Inter Digital Capacitor</td>
</tr>
<tr>
<td>IL</td>
<td>Insertion Loss</td>
</tr>
</tbody>
</table>

### References


22. Itikhar, A.; Asif, S.M.; Parrow, J.M.; Allen, J.W.; Allen, M.S.; Fida, A.; Braaten, B.D. Changing the operation of small geometrically complex EBG-based antennas with micron-sized particles that respond to magneto-static fields. IEEE Access 2020, 8, 78956–78964. [CrossRef]

23. Itikhar, A.; Parrow, J.M.; Asif, S.M.; Fida, A.; Allen, J.; Allen, M.; Braaten, B.D.; Anagnostou, D.E. Characterization of novel structures consisting of micron-sized conductive particles that respond to static magnetic field lines for 4G/5G (Sub-6 GHz) reconfigurable antennas. Electronics 2020, 9, 903. [CrossRef]


Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.