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RESEARCH ARTICLE

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High resolution beam switch antenna based on modified CRLH Butler matrix

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Abstract

A new beam switch antenna based on a composite right/left-handed (CRLH) Butler matrix is presented and experimentally validated. The CRLH transmission line (TL) is proposed to increase the number of beams. The proposed CRLH TL has more than 100° phase difference using variable bias voltages. Different combinations of phase shifts are achieved by applying different bias voltages between 0 and 8 V. The CRLH TL is added to the conventional Butler matrix to increase the progressive phase difference between adjacent ports, and consequently, the beam pattern. A 5° beam resolution within a spatial range of 100° is achieved. The measurement results are in good agreement with the simulations.

KEYWORDS

beam switch antenna, Butler matrix, CRLH, high resolution beam

1 | INTRODUCTION

Increased demand in wireless communications and moving toward a 5G implementation has increased attention on smart antennas and their applications.[1-7] It is essential to be able to point the signal waveform in a specific direction based on the user's demand. Beam switch antenna is one of the best solutions for such requirements. It allows saving energy, decreasing multipath fading by directing the desired signal toward the appropriate user, and adding more flexibility to the antenna. In a multi-beam–steering antenna, a beam-forming network should be designed and cascaded with the antenna array.

There are several methods for designing a beam switch antenna. For instance, beam switch antenna can be designed using conventional phased array antennas.[8-11] However, a phased array antenna needs an active circuit and, in many cases, a digital phase shifter, which makes the antenna complex and expensive. Beam switch antenna based on the lens structure shows excellent potential for high directivity radiation pattern.[12-14] However, lens antennas are limited in terms of coverage and resolution. A tunable beam-steering antenna by left-handed phase shifter has been presented.[15] However, the beam coverage is limited. Butler matrix antennas have been adopted widely because of their simplicity and ease of implementation.[16-18] Although the conventional Butler matrixes have relatively good coverage, they are limited in terms of the resolution. There are numerous papers reported using Butler matrixes as a feed network of the antenna.

Due to the ability to provide higher beam resolution, the multi-beam antennas based on 8×8 Butler matrix have received particular attention. Nevertheless, extending a conventional 4×4 conventional matrix makes the structure very large. A miniaturized SIW 8×8 on two layers is presented.[19] However, multilayer structures and vias used in SIW are not desirable in the fabrication process, particularly considering that it only adds four more beam patterns to the antenna. An

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8 × 8 beam switch Butler matrix antenna with a stripline phase shifter is reported.[20] Although a proper beam resolution can be found, the stripline design is more complicated and costly. Moreover, the reported phase shifter method introduces a relatively high insertion loss. In the last two decades, composite right/left-handed (CRLH) transmission lines (TLs) with right-handed (RH) and left-handed (LH) features have the benefits of low loss and extended bandwidth. These TLs have been broadly studied and utilized in radiated-wave circuits and devices.[21,22]

In this article, a new modified Butler matrix is presented. For a broader range of phase shift, a CRLH TL is proposed. Two varactor diodes, biased with the voltage between 0 and 8 V, are used to design a phase shifter. The proposed phase shifter achieves a maximum of 100° phase shift. Different topologies based on the bias voltages are applied to generate the different progressive phase required for the array antenna.

The article is organized as follows: First, the design of the phase shifter is explained. Next, the modified Butler matrix based on the proposed phase shifter is discussed, which supports by the simulation and measurement results of the feed network and array antenna. Finally, the conclusion is presented.

2 | DESIGN OF A PHASE SHIFTER BASED ON A CRLH TL

Figure 1A shows the configuration of the proposed CRLH TL, and Figure 1B depicts the equivalent circuit model. The CRLH TL consists of two varactor diodes, a fixed capacitor and a single microstrip TL. The varactor diodes used in this project are SMV1232-079 from Skyworks Solution Inc., and the fixed SMD capacitor is a 0.7 pF from Coilcraft Company. In order to better understand the CRLH characteristics, the equivalent circuit of the model is depicted in Figure 1B. If we assume this case is lossless, and using the ABCD matrix from the equivalent circuit model, the phase constant can be calculated by using the Floquet's theorem.[23]

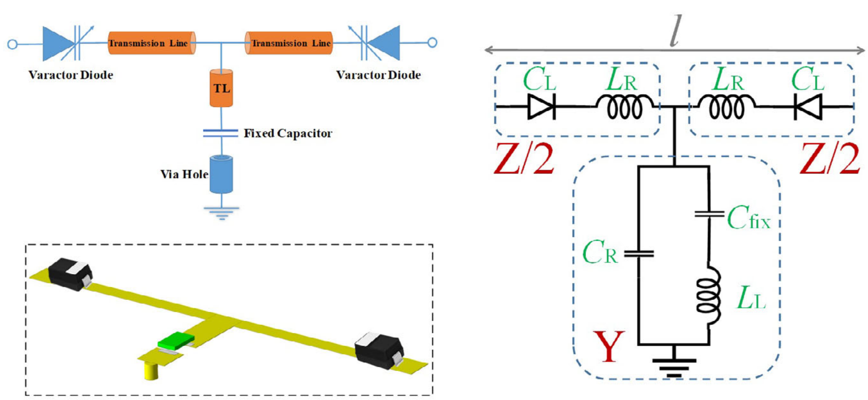
$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{\mathrm{CRLH}} = \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 1 \\ Y & 1+ZY \end{bmatrix} = \begin{bmatrix} 1+ZY & Z(1+ZY) \\ Y & 1+ZY \end{bmatrix} \tag{1}$$

$$\beta = \frac{1}{d}\left[\cos^{-1}\left(1+\frac{ZY}{2}\right)\right] \tag{2}$$

where Z and Y are the equivalent series and shunt impedance and admittance, respectively. The proposed structure consists of LH shunt inductance (L_{L}) and LH series capacitance (C_{L}) as well as parasitic RH series inductance (L_{R}) and RH shunt capacitance (C_{R}). In general, the conventional right-handed TL consists of a series inductor (L_{R}) and a parallel capacitor (C_{R}). Also, the varactor diodes act as a series capacitor (C_{L}) and the designed via hole acts as a parallel inductor (L_{L}). Finally, a fixed capacitor is considered in the shunt stub (C_{fix}) to adjust the line's capacitance. Then Z and Y are calculated as follow:

$$Z(\omega) = j\left(\omega L_R - \frac{1}{\omega C_L}\right) \tag{3}$$

$$Y(\omega) = j\left(\frac{1}{\frac{1}{\omega C_{fix}} - \omega L_L} + \omega C_R\right) \tag{4}$$



(A) (B)

FIGURE 1 A, The schematic circuit (top), the 3D final layout (bottom), B, equivalent circuit model of the proposed CRLH TL

The propagation constant can be derived from the following expression:

$$\beta(\omega)l = \cos^{-1}\left[1 - \frac{1}{2}\left(\omega L_R - \frac{1}{\omega C_L}\right)\left(\frac{1}{\frac{1}{\omega C_{fix}} - \omega L_L} + \omega C_R\right)\right] \tag{5}$$

where l is the unit cell length, which is shown in Figure 1B. The proposed TL is designed and simulated in a full-wave analyzer by considering different capacitance values of the varactor diode (C_L). It might confirm that the intended TL has both positive β (ie, RH mode) and negative β (ie, the LH mode) making a CRLH TL. As a result, it can be translated that the circuit is reconfigurable based on the biasing voltage.

The circuit analyses and the full-wave simulations are carried out in ADS and CST software, respectively. The measured S2P parameters of the varactor diode are used for the simulation results. The varactor diode that is implemented in the design is from Skyworks Solution. It should be noted that the simulation results are bound to a specific bias voltage due to the limited available S2P data provided by Skyworks. Nevertheless, there are no limitations to the measurement side.

Figure 2A and Figure 2B, respectively, depict the simulation and measurement results of the return loss and insertion loss of the proposed CRLH TL. The phase shifter is designed for 2.4 GHz and WLAN applications. It is clear from the figure that a better than −10 dB return loss is achieved for both simulation and measurement results for the desired frequency.

The phase response of the proposed CRLH TL line for both simulation and measurement results are shown in Figure 3A and Figure 3B, respectively. The results prove that more than 100° phase can be achieved with this phase shifter.

In order to have a better insight into the comparison between the simulation and measurement results, two bias voltages at 0 and 8 V are compared together. It should be noted that the phase comparison is not shown here as it needs an excellent phase compensation (ie, the effect of the SMA connector and the cables in network analyzer should be taken into account for the measurement).

Figure 4 represents the return loss comparison for 0 and 8 V of bias voltages applied to the varactor diode. The results show a slight difference between the simulation and measurement due to the fabrication process and material properties. However, both results indicate a functional return loss for the desired frequency of 2.4 GHz.

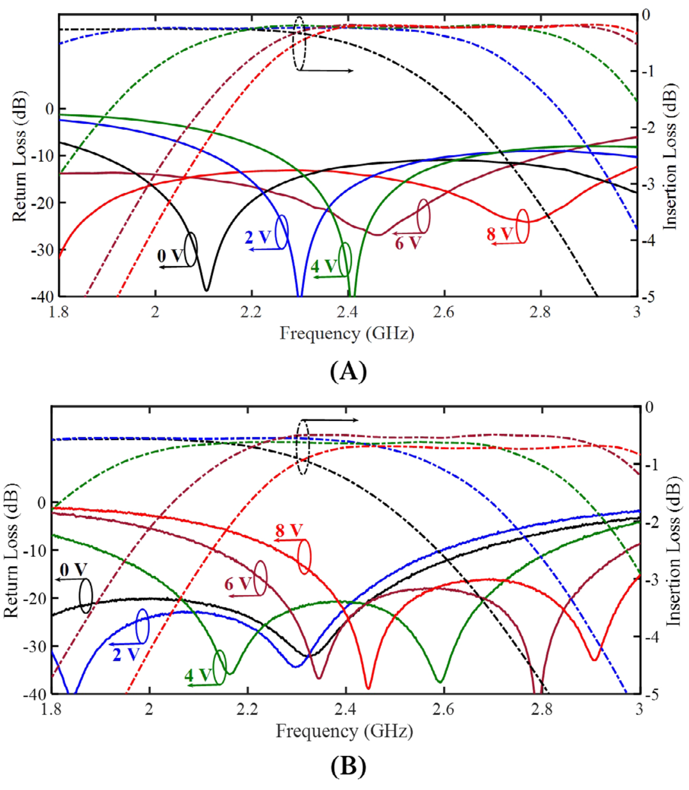


FIGURE 2 A, Simulation results, B, measurement results of return loss and insertion loss of the proposed CRLH TL for different bias voltages

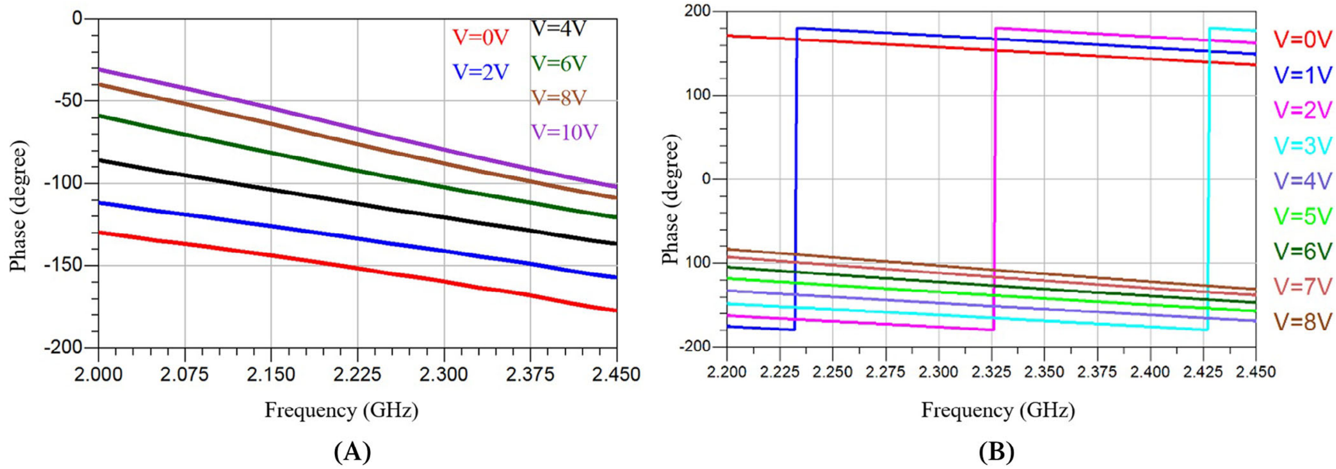


FIGURE 3 A, Simulation results, B, measurement results for the phase response of the proposed CRLH TL for different bias voltages

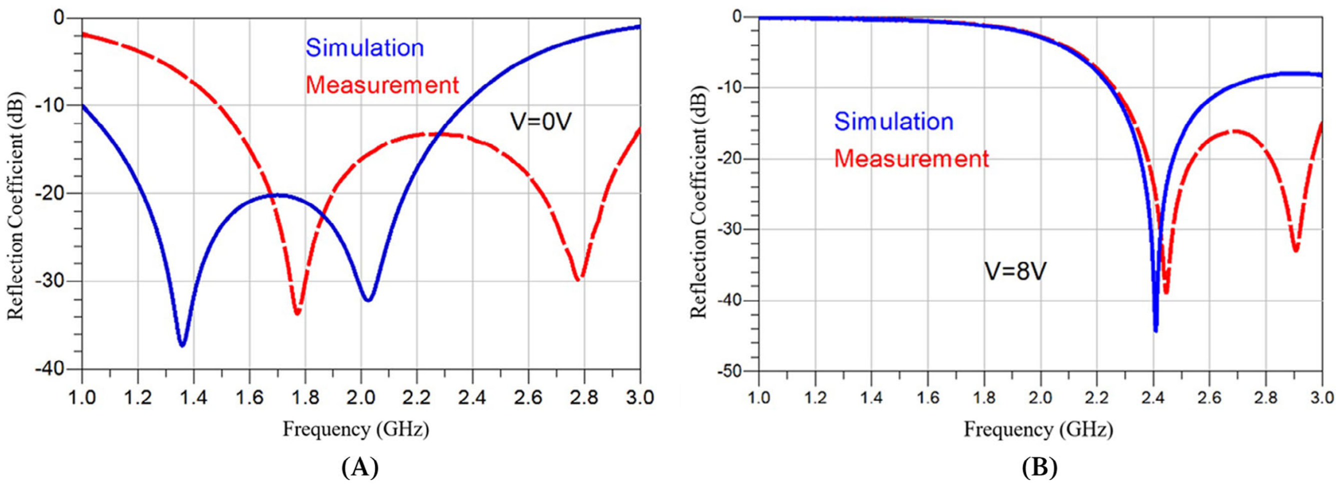


FIGURE 4 Reflection coefficient comparisons of simulation and measurement result for, A, 0 V, B, 8 V bias voltages

3 | MODIFIED BUTLER MATRIX BASED ON THE PROPOSED CRLH TL

In this section, the design process, the scattering parameters, and the far-field results of the proposed beam switch antenna will be elaborated.

The geometry of the extended Butler matrix feed network and a sample implemented a prototype of the antenna are shown in Figure 5A and Figure 5B, respectively.

The proposed feeding network structure was simulated by CST and measured for the scattering parameters by the VNA CE5651 of Agilent. The comparison between the simulation and measurement results of the feed network is presented in Figure 6. Two parameters (ie, S_{11} and S_{15}) were compared. In this figure, S_{11} represents the return loss of port 1, and S_{15} represents the insertion loss between port 1 and port 5. The annotated layout in Figure 5A depicts the port numbers (ie, ports 1-4 are the input and ports 5-8 are the outputs). It should be mentioned here that all bias voltages are set to zero in this case. A good agreement between simulation and measurements can be seen in Figure 6.

It should be noted that for reducing the complexity and having a better resolution for comparison purposes, only two parameters are displayed in Figure 6. A similar good agreement was also found in other scattering parameters. Moreover, an excellent return loss and an acceptable insertion loss can be seen in Figure 6.

By employing a conventional Butler matrix, one can achieve four different radiation patterns. To increase the number of radiation patterns (ie, more fine resolution), one needs to tune the phase of each port of the feed network in a progressive

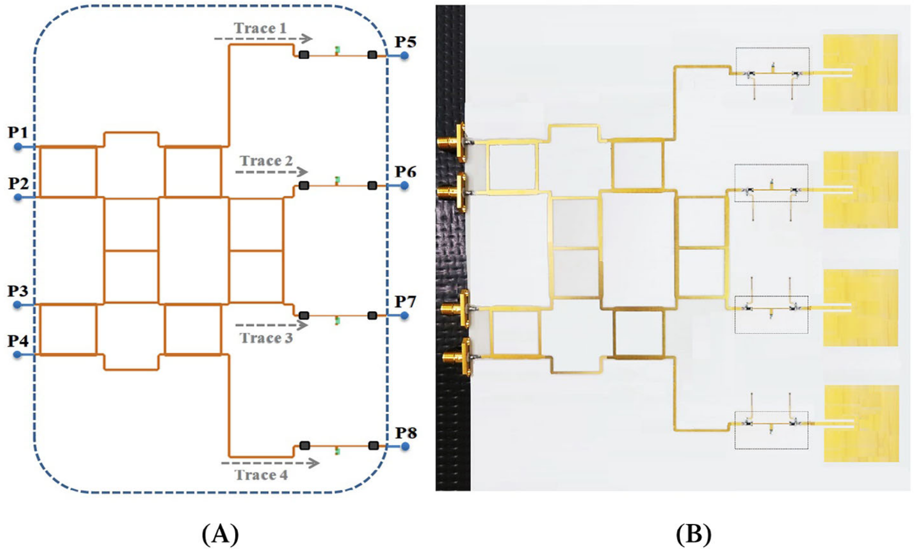


FIGURE 5 A, Geometry of the proposed extended Butler matrix feed network, B, an implemented beam switch antenna with the designed feed network structure

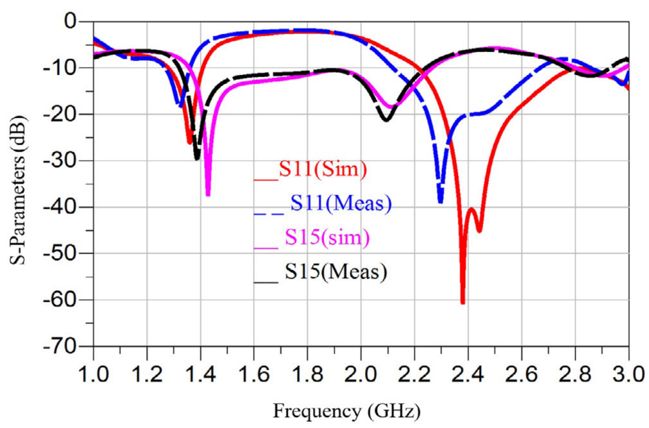


FIGURE 6 Comparison between simulation and measurement results of some scattering parameters

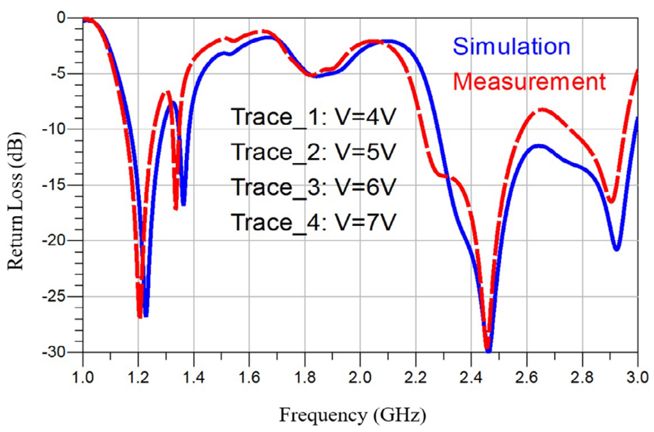
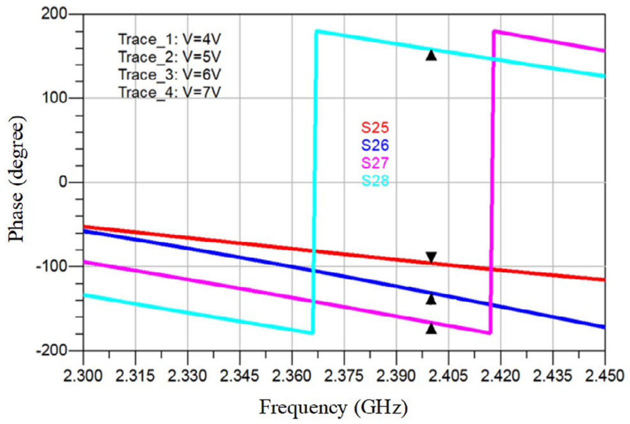


FIGURE 7 Reflection coefficient comparison between simulation and measurement results for a different bias voltage of trace 1 to 4 to have a 10° added progressive phase to a conventional Butler matrix (the trace number are shown in Figure 5B)

mode. For a conventional Butler matrix, a 45° progressive phase can be achieved if one excites port 1. For increasing the progressive phase (eg, +55°), a 10° progressive phase needs to be added to each trace of the proposed feed network. Figure 7 compares the simulation and measurement results of port 1 for a +55° progressive phase. A +55° means Trace_2 needs to add 10°, Trace_3 needs to add 20°, and Trace_3 needs to add 30° to the previous phase (ie, 45°) from the conventional Butler matrix. This added progressive phase to the typical Butler matrix translates to bias voltages of 4 to 7 V for the traces of 1 to 4, respectively.



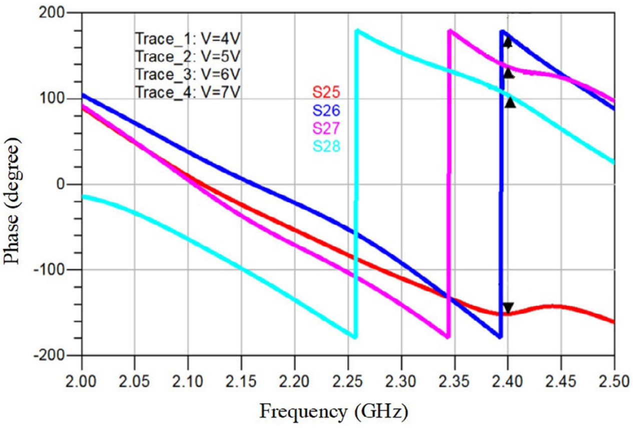


FIGURE 8 The phase response when switch No. 2 is on, A, simulation results, B, measurement results

TABLE 1 Phase incremental response for simulation and measurement data

Phase incremental	$\measuredangle TR2 - \measuredangle TR1$		$\measuredangle TR3 - \measuredangle TR2$		$\measuredangle TR4 - \measuredangle TR3$	
	Sim	Meas	Sim	Meas	Sim	Meas
+45°	+44.74	+43.2	+45.48	+47.2	+45	+45.9
+55	+54.34	+55.4	+55.46	+56.17	+54.67	+56.4
−45	−44.53	−46.2	−45.47	−45.5	−44.23	−44.8
−35	−35.41	−34.6	−35.17	−36.57	−35.1	−34.5
+135	+135.52	+132.5	+135.64	+134	+134.82	+133.3
+145	+145.14	+143.2	+145.3	+145.7	+144.34	+143.7
−135	−134.31	−131.9	−135.6	−135.6	−135	−134.6
−125	−125.22	−126.8	−124.94	−124.9	−125.88	−123.8
+40	N/A	+42.2	N/A	+41.13	N/A	+39.6
+35	N/A	+33.8	N/A	+36.19	N/A	+34.4
+30	N/A	+29.1	N/A	+32.2	N/A	+30.6
+25	N/A	+26.3	N/A	+25.8	N/A	+25.9
+20	N/A	+19.6	N/A	+18.68	N/A	+21.1
−40	N/A	−42.6	N/A	−41.18	N/A	−40.9
−35	N/A	−34.4	N/A	−35.2	N/A	−35.9
−30	N/A	−28.9	N/A	−29.3	N/A	−29.8
−25	N/A	−25.2	N/A	−25.6	N/A	−23.5
−20	N/A	−21.1	N/A	−20.85	N/A	−19.3
−130	N/A	−128.8	N/A	−128.2	N/A	−130.4
−125	N/A	−125.6	N/A	−123.3	N/A	−127.5
−120	N/A	−119.1	N/A	−118.8	N/A	−119.6
−115	N/A	−116.7	N/A	−117.1	N/A	−114.5
−110	N/A	−109.2	N/A	−111.1	N/A	−110.6
+130	N/A	+130.3	N/A	+131.2	N/A	+133.1
+125	N/A	+127.1	N/A	+126.8	N/A	+124.4
+120	N/A	+121.2	N/A	+119.6	N/A	+120.9
+115	N/A	+114.5	N/A	+114.8	N/A	+112.9
+110	N/A	+108.2	N/A	+113.1	N/A	+111.2

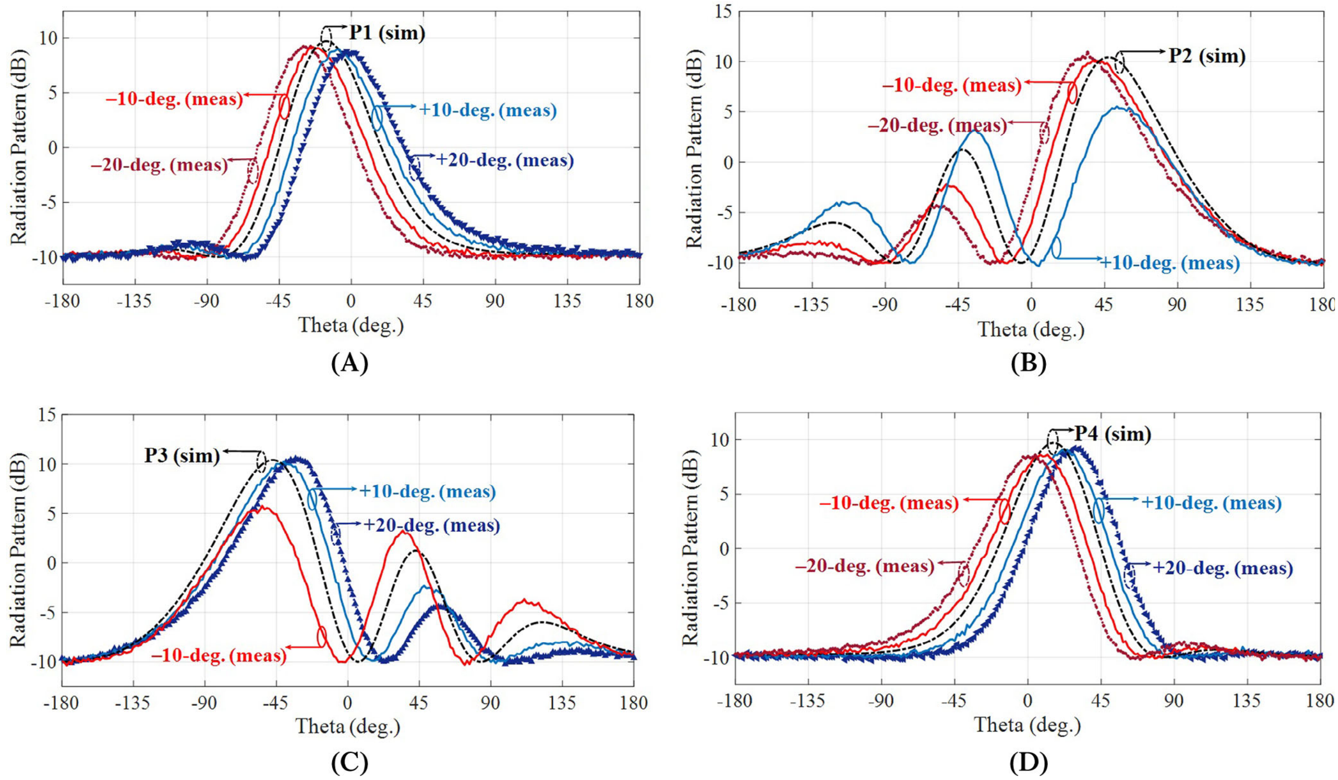


FIGURE 9 The simulation and measurement results of far-field responses of the proposed network when the excited port is, A, Port 1 (P1), B, Port 2 (P2), C, Port 3 (P3), D, Port 4 (P4)

Figure 7 validates that an excellent return loss (less than −15 dB) has been received for simulation and measurement results at the operating frequency.

To explorer, the proposed feed network's phase responses, a specific case in which the port number 2 is excited is considered. In this particular case, the bias voltages for traces 1 to 4 are 4 to 7 V, with 1-V steps, respectively.

Figure 8A and Figure 8B, respectively, represent the simulation and measurement results for the case that port 2 is excited. To better understand this specific scenario, one needs to start with the conventional Butler matrix. This fact that the progressive phase of a conventional Butler matrix when port number 2 is excited is −45°. As it was explained, the bias voltages yield to an added 10° progressive phase. That translates to a −35° progressive phase for the whole feed network.

As displayed in Figure 8A, a pretty close to −35° progressive phase is reached according to the simulation result. Figure 8B shows a little discrepancy but close to −35° desired phase incremental. It should be mentioned here that a perfect calibration (eg, the effect of the SMA and cables should be calibrated) is needed to measure the phase response. As a result, it is expected to have some discrepancies in the measurement responses.

Note that numerous simulation and measurement results were done and compared, but Figure 8 represents a specific case to understand the mechanism better. Due to limitations of simulation results (ie, limited S2P data for the varactor diodes provided by Skyworks Solution Inc.), the number of simulation iterations is less than the measurement results. All the simulation and measurement progressive phase values are listed in Table 1 for reference. There is a good agreement between simulation and measurement results.

Figure 9A-D shows the far-field responses of the proposed network for four different excitation ports. For each plot of Figure 9, the black dash curve shows the simulation results when the bias voltage is zero, and the rest are the measurement results. For better illustration, 10° progressive phases are shown here. However, the achieved resolution is 5°.

For radiation patterns resulting from more than +135° and less than −135° progressive phase, the antenna gain will be degraded, and sidelobe levels will be undesirable. As a result, any radiation patterns more than +135° and less than −135° were not considered as applicable radiation patterns. Hundred-degree radiation coverage is guaranteed in this article.

4 | CONCLUSION

A new CRLH TL able to generate different phase response is discussed in this article. The phase shifter can generate up to 100° phase response. The phase shifter was added to a conventional Butler matrix to increase the number of progressive phase values for different bias voltages. The simulation and measurement results of the scattering parameters, including the phase responses, showed they were aligned with each other. The far-field results also prove that the proposed structure has perfect coverage and resolution. Simultaneously, it has not added too much complexity and size to the whole conventional Butler matrix. As a result, the proposed structure can be the right candidate for beam array application, especially in the 5G frequency bands.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this article.

PEER REVIEW INFORMATION

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PEER REVIEW

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AUTHOR CONTRIBUTIONS

Reza Karimian: Conceptualization; data curation; formal analysis; methodology; software; validation; writing-original draft. **Mansoor Dashti Ardakani:** Software; validation; visualization; writing-review and editing. **Shahrokh Ahmadi:** Supervision; writing-review and editing. **Mona Zaghloul:** Resources; supervision.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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