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Research Article

High Resolution Beam Switch Antenna Based on Modified CRLH Butler Matrix

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Abstract

A Novel beam switch antenna based on a CRLH Butler matrix is presented in this manuscript. The CRLH transmission line is proposed to increase the number of beams switch. The proposed CRLH TL has more than 100-degree phase deference with different bias voltages. By different bias voltages between 0 to 8 Volt, different combinations of phase shifts are achieved. The CRLH transmission line is added to the conventional butler matrix to increase the number of phase incremental combination and consequently the beam pattern. A 5-degree beam resolution is achieved. The measurement results follow well with the simulation result.

KEYWORDS

Beam Switch Antenna, CRLH, Butler Matrix, High resolution beam

1 | INTRODUCTION

By increasing the demand for wireless communication and especially the direction toward 5G the use of smart antenna receiving more attention [1-6]. It is very important that we could be able to point the signal in a specific direction based on user demand. Beam switch antenna is one of the best smart solutions for such demands. It allows saving energy, decreasing multipath fading by directing the desired signal toward the appropriate user, and adding more flexibility to the antenna. To achieve multi-beam steering, a beam-forming network (BFN) should be designed and cascaded with the antenna array.

There are various methods for designing a beam switch antenna. For instance, beam switch antenna can be done by using conventional phase array antennas [7-10]. However, a phase array antenna needs a lot of active circuits and in many cases a digital phase shifter which makes the antenna complex and expensive. Beam switch antenna based on lens structure shows great potential for high directivity radiation pattern [11-13]. Lens antennas though are limited in terms of the coverage and resolution. Butler matrix antennas have been adopted widely because of their simplicity and easy implementation [14-16]. Although the conventional butler matrixes have relatively good coverage, they are limited in terms of the

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resolution. There are numerous papers reported using Butler matrixes for their feeding network. Due to the ability to provide higher beam resolution, the multi-beam antennas based on 8×8 Butler matrix have received special attentions. Extending a conventional 4×4 conventional matrix makes the structure very big. A miniaturized SIW 8×8 on two layers is presented in [17]. Since the structure has two layers with vias because of the SIW technology make the prototype complicated. At the same time by extending the conventional butler matrix it will just add 4 more beams which are not dramatic change given the complexity and the size added to the structure. In the last two decades, Composite Right Left-Handed (CRLH) transmission lines with right-handed (RH) and left-handed (LH) features have the benefits of low loss and extended bandwidth, which have been broadly studied and utilized in radiated-wave circuits and devices [18-19].

In this paper, a novel modified Butler matrix is presented. To increase the number of flexibilities for phase shift, a Composite Right Left-Handed transmission line is proposed. Two varactor diodes biased with the bias voltage between 0 to 8 volts is used to design a phase shifter able to achieve more than 100-degree phase shift. Different topologies based on the bias voltage is used to have different phase incremental requirement for the array antenna.

The paper is organized as follow. First, the design of the phase shifter is explained. The modified butler matrix based on the proposed phase shifter will be discussed. The simulation and measurement results of the feed network and array antenna will be explained and finally, a conclusion is given at the end of the paper.

2 | DESIGN OF A PHASE SHIFTER BASED ON A CRLH TRASNMISSION LINE

Figure 1 (a) shows the configuration of the proposed Composite Right Left Handed (CRLH) Transmission Line (TL) and figure 1 (b) depicts the equivalent circuit model. The CRLH Transmission line consists of two varactor diodes, a fixed capacitor, and a single microstrip transmission line. The varactor diodes used in this project are SMV 1232-079 from Skyworks Solution Inc. and the fixed capacitor is a 0.7 pF from Coilcraft Company. In order to understand better the CRLH characteristics, the equivalent circuit of the model is depicted in figure 1(b). If we assume this case is lossless by using the ABCD matrix from the equivalent circuit model the phase constant can be solved by using the Floquet's theorem.

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

$$\beta = \frac{\cos^{-1}(1+ZY)}{d} \quad (2)$$

where Z and Y are the equivalent series and shunt impedance and admittance respectively and are calculated as follow:

$$Z = j(wL_R - \frac{1}{wC_R}) \quad (3)$$

$$Y = \frac{1}{jwL_L + \frac{1}{jwC_L}} + jwC_P \quad (4)$$

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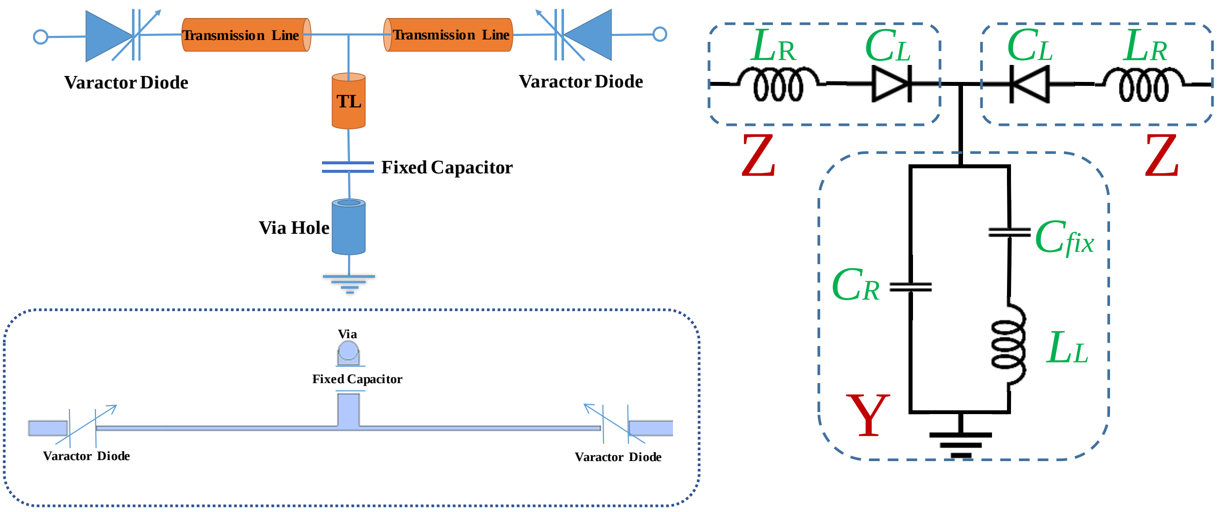
Where C_P is the parasitic capacitance of the shunt stub, and finally the phase constant can be derived from the following expression:

$$\beta = \frac{\cos^{-1}\left(\frac{1-S_{11}S_{21}+S_{12}S_{21}}{2S_{11}}\right)}{L} \quad (5)$$

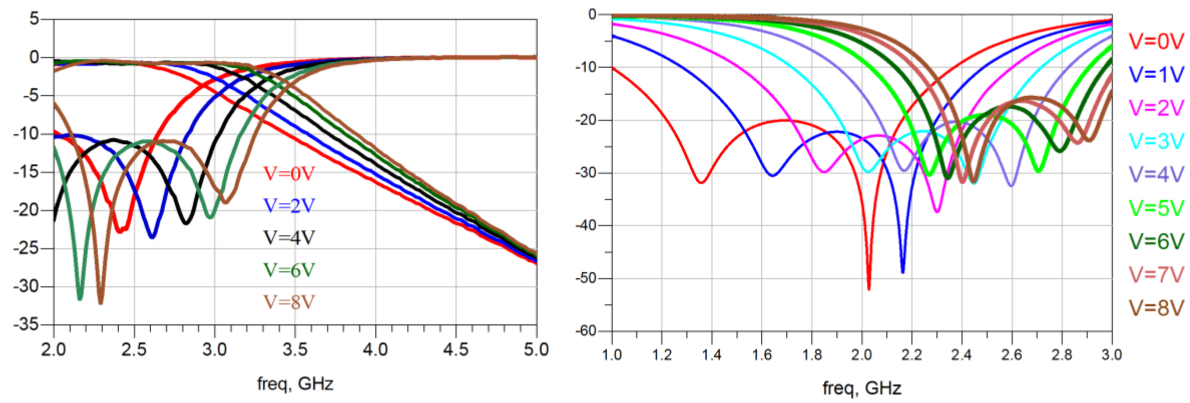


(a) (b)

Figure 1 (a) Geometry of the proposed CRLH TL (b) Equivalent circuit model

where L is the unit cell length. By simulating the CRLH TL in a full-wave analyzer and by taking different values for varactor diode capacitor (C_L) one might conclude that the proposed transmission line has both positive β which means LH mode and negative β which means the RH mode making a CRLH transmission line. As a result, it can be translated that the circuit is reconfigurable based on the biasing voltage.

The circuit analyses were done in ADS and the simulations were carried out in CST. It should be mentioned that the S2P parameters received by the measurement results of Skyworks Solution Inc. were utilized in the simulation. However, the numbers of samples (bias voltage) were limited for the simulation results while in the measurement results the flexibility was much better.



(a) (b)

Figure 2 (a) Simulation results (b) measurement results of return loss for different bias voltages

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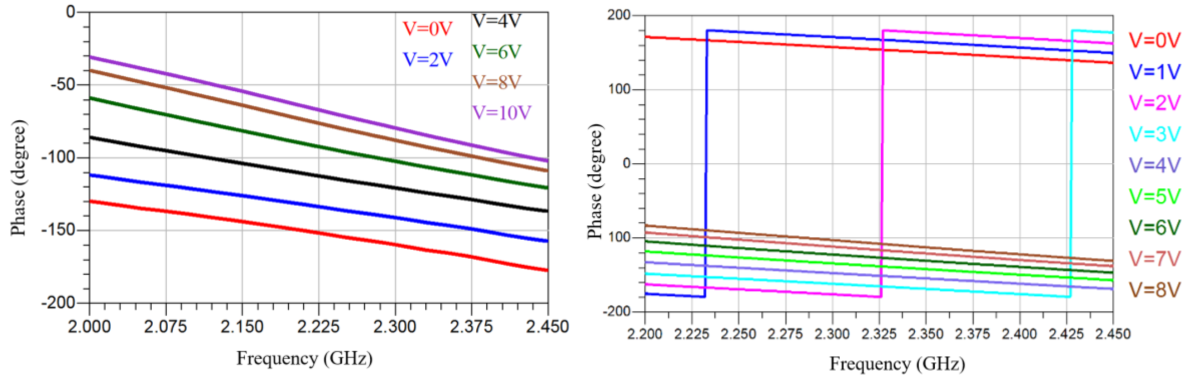

(a) (b)

Figure 3 (a) Simulation results (b) measurement results for the phase response of the proposed CRLH TL for different bias voltages.

Figure 2 (a) and (b) respectively depicts the simulation and measurements result of the return loss for the proposed CRLH TL. The phase shifter is designed for 2.4 GHz and WLAN Applications. It is clear from the figure than a better than -10 dB return loss is achieved for both simulation and measurement results.
The phase response of the proposed CRLH TL line for both simulation and measurement results are shown in Figure 3 (a) and (b) respectively. The results prove that more than 100-degree phase can be achieved with this phase shifter.

In order to compare the simulation and measurement results two comparisons for zero and 8-volt bias voltage were carried out. Note that precise phase compassion is not shown here as it needs a very fine phase compensation taking into the account of SMA connector in network analyzer measurement.

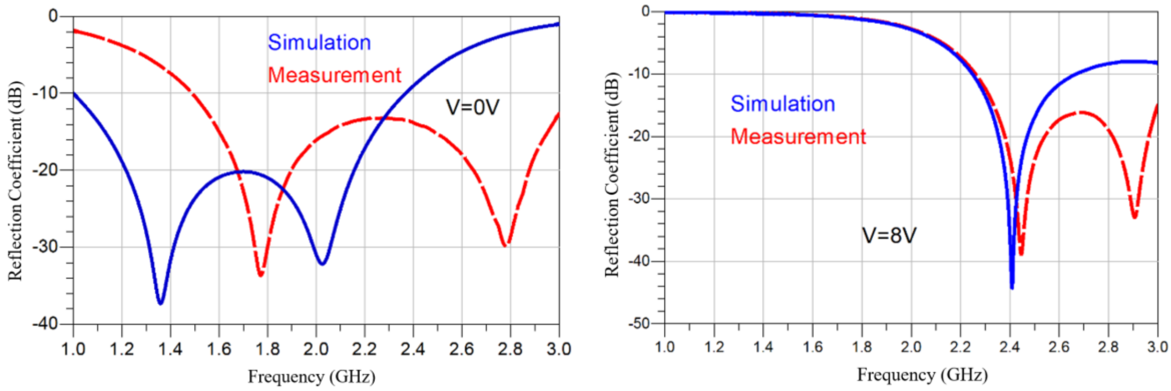

Figure 4 Reflection coefficient comparisons of simulation and measurement result for 0 and 8-volt bias voltages.

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

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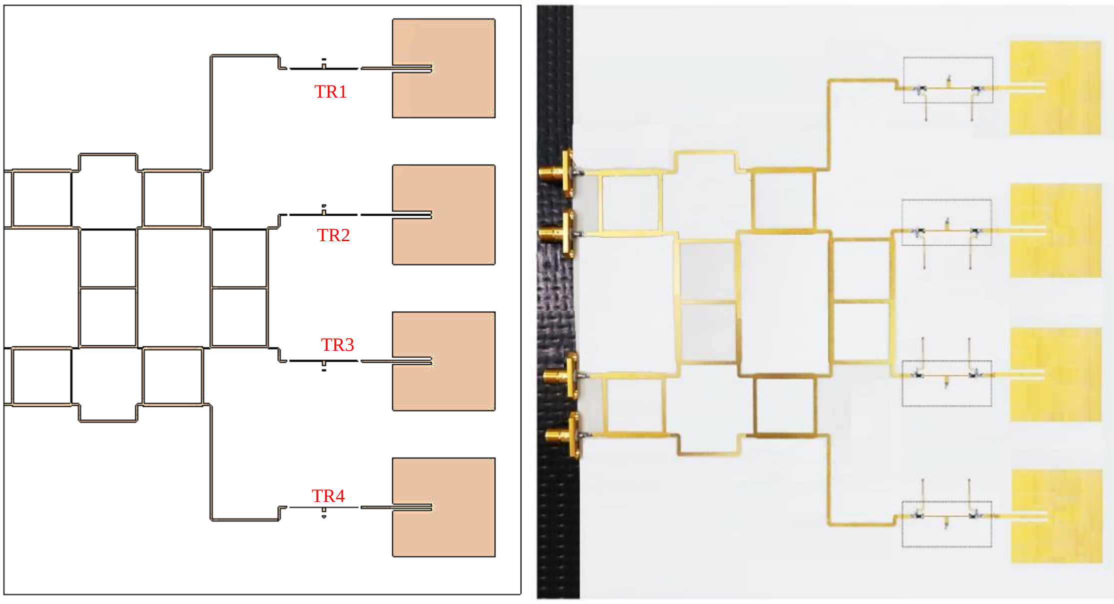
2.1 | MODIFIED BUTLER MATRIX BASED ON THE PROPOSED CRLH TL

In this section the design process and the scattering parameters and far-field results will be elaborated.

The geometry of the extended butler matrix and a sample implemented prototype is shown in figure 5 (a) and (b) respectively. It should be noted that due to limitation for anechoic chamber the feed network of the structure which is the extended butler matrix along with CRLH TL was just fabricated and as a result the measurement result for the farfield is basically a combination of the measurement results of the feed network and the simulation of the antenna array based on the feed network measurement results.



(a) (b)

Figure 5 (a) Geometry of the proposed beam switch antenna by using a modified Butler matrix (b) implemented prototype

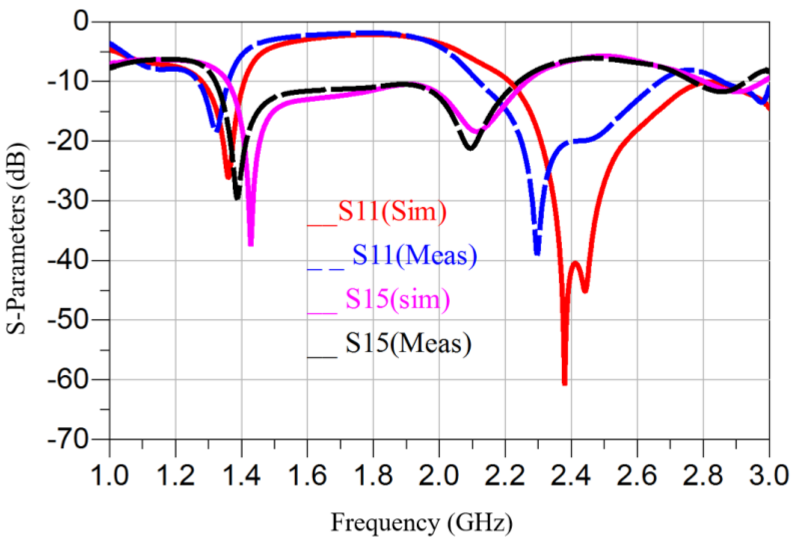


Figure 6 Comparison between simulation and measurement results of some scattering parameters

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DOI: xxx/xxxx

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 feeding network is presented in figure 6. Two parameters (i. e. S_{11} and S_{15}) were compared. A good agreement can be seen from the figure. It should be noted that in order to reduce the complexity and have a better resolution for comparison just two parameters were compared and this good agreement can be found on other parameters as well. A very good return loss and an expected insertion loss can be seen from the figure. The results in figure 6 are for zero bias voltage.

From the fundamental of a Butler matrix, there are four different incremental phases which yield four different radiation patterns. In order to increase the number of beam one need to tune the phase incremental for all ports of the Butler matrix. It means that if we want to change the +45 degree to +55 one need to bias the voltage on the Butler matrix traces in the way that the trace 2 has 10 degree, trace 3 has 20 degree and trace 4 has 30 degree phase differences. The trace numbers are shown in figure 5(a).

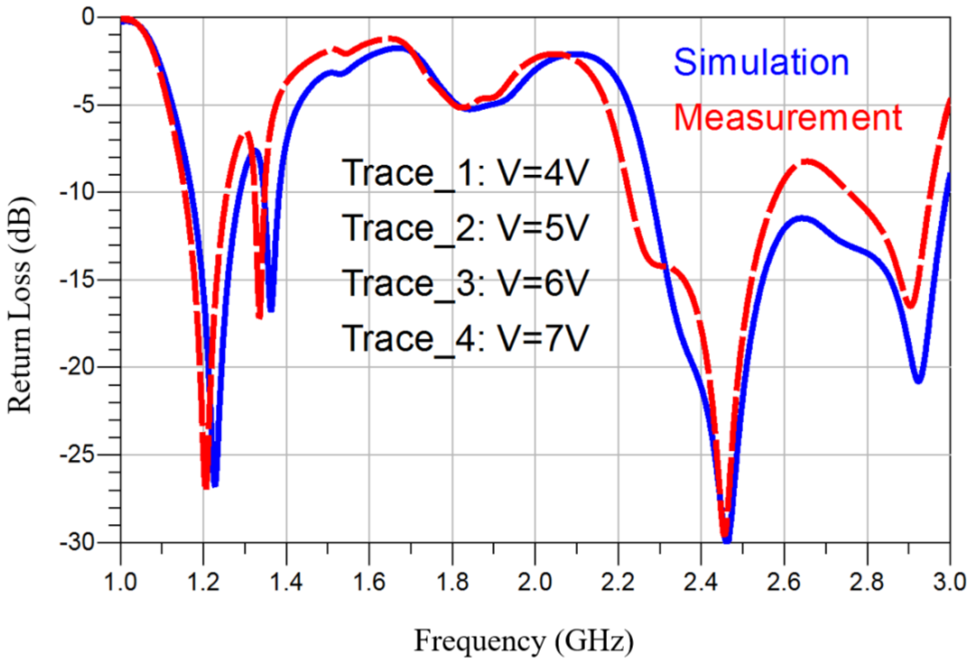


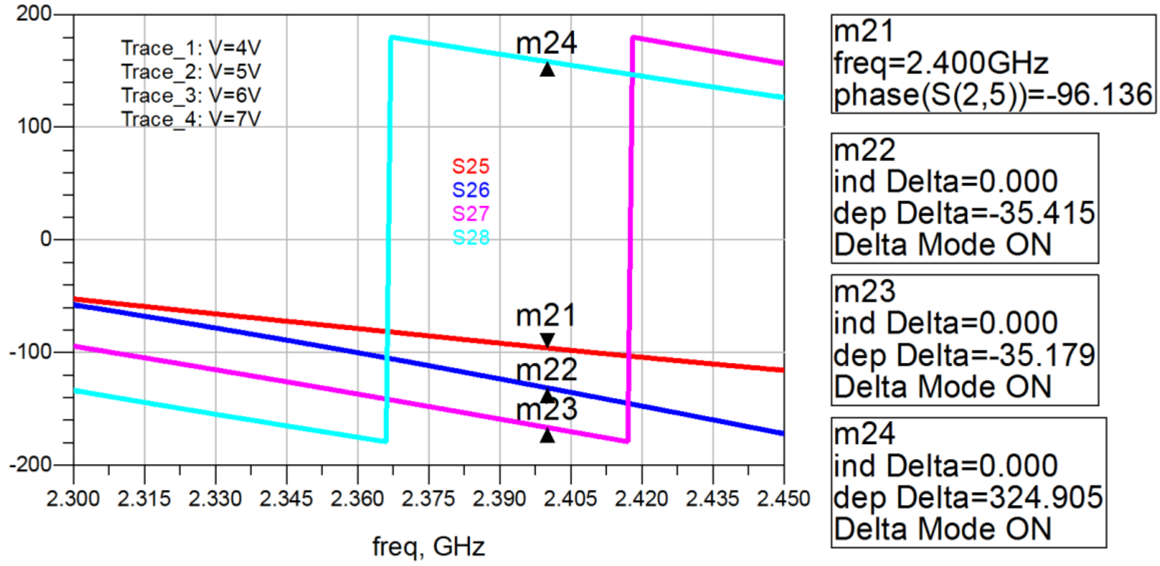
Figure 7 Reflection coefficient comparison between simulation and measurement results for different bias voltage through trace 1 to 4.

Figure 7 depicts the comparison between simulation and measurement result for different bias voltage for trace 1 to 4 which yield to +10 degree phase incremental in addition to the conventional Butler matrix phase differences. As it is clear a very good return loss has been achieved for both simulation and measurement results.

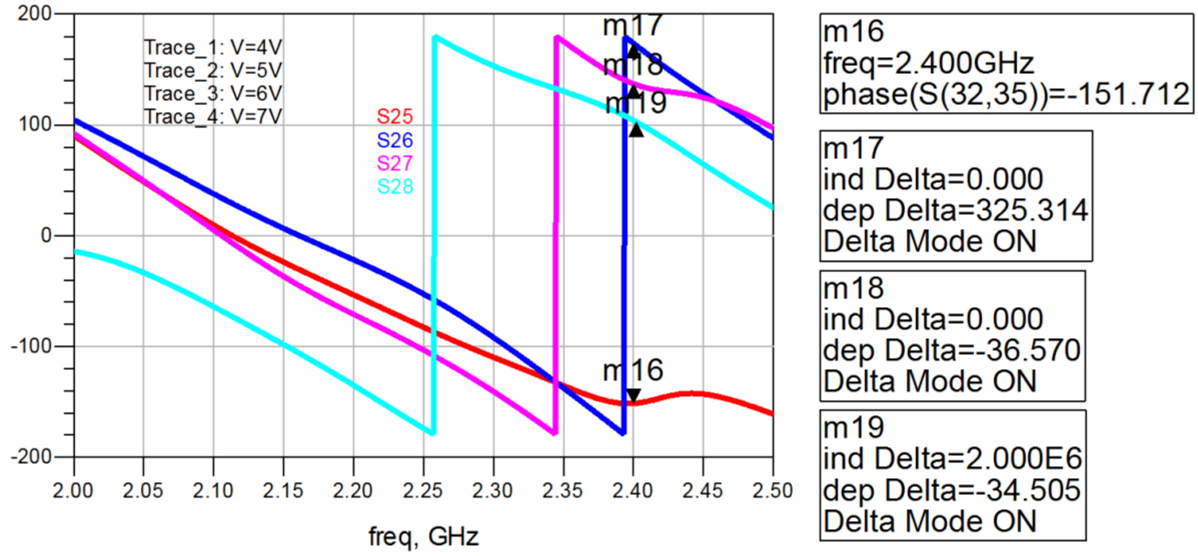
In order to explorer the phase response for this specific bias voltage the phase response of the feed network for the case that switch No.2 is on is considered.

Figure 8 (a) and (b) represents the simulation and measurement result for the case that switch No.2 is on respectively. To better understand this specific case one need to start with the conventional Butler matrix and this knowledge that the phase incremental of a conventional Butler matrix when port number 2 is on is -45 degree. Now by taking into the account of phase incremental equal to +10 degree yields to -35 degree phase incremental for the whole feed network.

Received: Added at production | Revised: Added at production | Accepted: Added at production
DOI: xxx/xxxx



(a)



(b)

Figure 8 The phase response when switch no.2 is on (a) Simulation results (b) Measurement results.

As it can be seen from figure 8(a) a very close to -35 degree phase incremental is achieved according to the simulation result and also figure 8(b) has a little discrepancy but close to -35 degree desired phase incremental.

It should be noted that numerous simulation and measurement results were done and compared but figure 8 represents a specific case in order to understand better the mechanism. Due to limitation for simulation results the number of simulation iteration is less than the measurement results. All the simulation and measurement phase incremental values are listed in Table.1 for reference. There is a good agreement between simulation and measurement results.

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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 degree	+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	〃	+33.8	〃	+36.19	〃	+34.4
+30	〃	+29.1	〃	+32.2	〃	+30.6
+25	〃	+26.3	〃	+25.8	〃	+25.9
+20	〃	+19.6	〃	+18.68	〃	+21.1
-40	〃	-42.6	〃	-41.18	〃	-40.9
-35	〃	-34.4	〃	-35.2	〃	-35.9
-30	〃	-28.9	〃	-29.3	〃	-29.8
-25	〃	-25.2	〃	-25.6	〃	-23.5
-20	〃	-21.1	〃	-20.85	〃	-19.3
-130	〃	-128.8	〃	-128.2	〃	-130.4
-125	〃	-125.6	〃	-123.3	〃	-127.5
-120	〃	-119.1	〃	-118.8	〃	-119.6
-115	〃	-116.7	〃	-117.1	〃	-114.5
-110	〃	-109.2	〃	-111.1	〃	-110.6
+130	〃	+130.3	〃	+131.2	〃	+133.1
+125	〃	+127.1	〃	+126.8	〃	+124.4
+120	〃	+121.2	〃	+119.6	〃	+120.9
+115	〃	+114.5	〃	+114.8	〃	+112.9
+110	〃	+108.2	〃	+113.1	〃	+111.2

The simulation and measurement farfield results for the proposed modified butler matrix witch beam array antenna are depicted in figure 9 (a) and (b) respectively. Not that the simulation results are less than the measurement results due to the number of measured scattering parameters provided by Skyworks solution. Note also the measurement results are the combination of the scattering measurement results for the feed network along with the simulation of farfield radiation pattern based on the measurement results.

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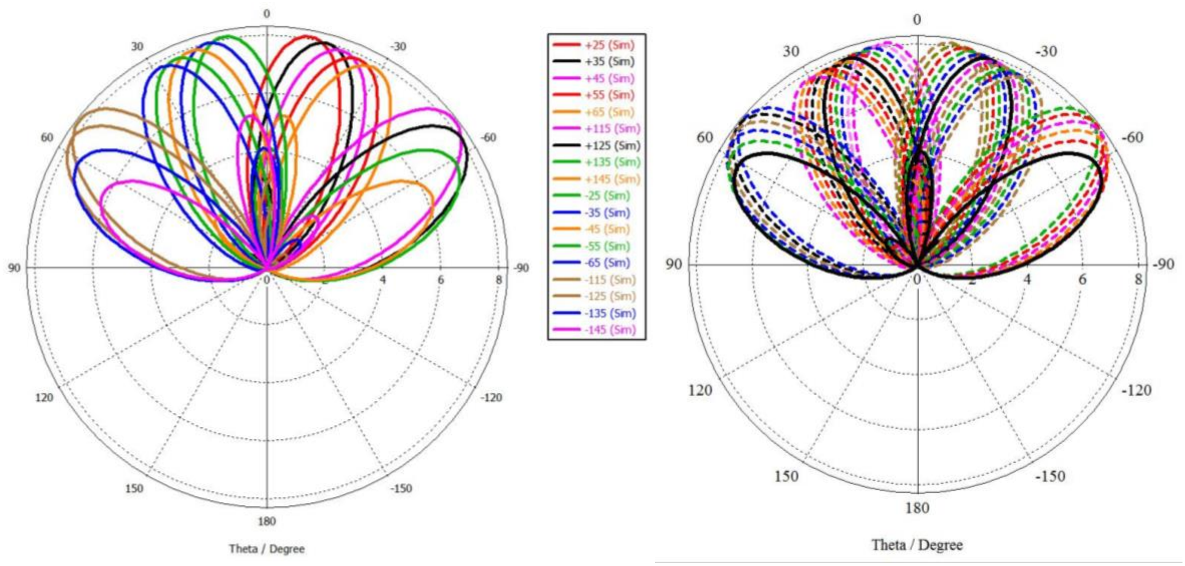

(a) (b)

Figure 9 The farfield response (a) simulation results (b) measurements results of scattering parameters along with the simulation of the farfield based on the measurements data

In Figure 9 (b) the solid back curve represents the radiation pattern of four fundamental beam of the conventional Butler matrix and the rest of the number of the beam we have added to due utilizing our proposed CRLH TL.

3 | CONCLUSION

A new CRLH TL to be able to generate different phase response is discussed in this paper. The phase shifter can generate up to 100 degree phase response. The phase shifter was added to a conventional Butler matrix to increase the number of phase incremental value for different bias voltage. The simulation and measurements results of the scattering parameters including the phase response shows they are aligning with each other. The farfield results also prove that the proposed structure has a very good coverage and resolution while it has not added too much complexity and size the whole conventional Butler matrix and as a result can be a good candidate for beam array application especially in the 5G frequency bands.

CONFLICT OF INTEREST

Authors have no conflict of interest relevant to this article.

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