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Design and Development of Butler Matrices for Circular Array Beamforming

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14. ABSTRACT

Antennas that have elements placed in a circular fashion require complex beamforming strategies as each element has a different pointing direction and thus the overall radiation pattern cannot be simplified as for planar arrays. However by transforming the circular elements into phase modes using a passive Butler matrix we can create elements that now behave similar to elements in a planar array. In this report we describe how to design these wideband Butler matrices using fixed-value differential phase shifters with microstrip techniques. The details of the design and simulated performance are presented for a complete 4 X 4 and a 8 X 8 Butler matrix.

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Design and Development of Butler Matrices for Circular Array Beamforming

R. Mital, W. R. Pickles and M. G. Parent

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1. INTRODUCTION

Antennas that have elements placed in a circular fashion have been studied but have not in the past gotten as much use as planar arrays. Cylindrical phased arrays satisfy many of the stringent requirements that are placed on multifunction apertures with their ability to offer a full 360^{o} view using omnidirectional or directional modes. Cylindrical arrays also do not require handoff between the multiple faces as is needed for planar arrays. Furthermore, cylindrical arrays have several advantages compared to multi-face planar arrays. One, the beam does not suffer from scan loss or beam broadening in the azimuthal direction. This means that the array does not have to be increased in size to maintain gain at larger scan angles. Secondly cylindrical arrays are able to form omnidirectional or sector beams without additional complexity.

A cylindrical array can theoretically be separated into a product of a linear array and a circular array, just as a planar array can be thought of as being made of two orthogonal linear arrays. With this simplification, it is possible to analyze the cylindrical array by analyzing the linear array and circular array separately. In this array we will only look at the circular array with the understanding that beamforming techniques for linear arrays are quite mature and well-known.

Scanning a beam from a circular array is more involved compared to planar arrays. The reason can be attributed to the fact that the element pattern of each element in a circular array is different as each element in this array points in a different direction. This means that each element's contribution toward a directional beam formation is not the same for the different scan angles. On the other hand, in a planar array, element points in the same direction, allowing the simplification in the radiation pattern calculation to a product of array factor and the element factor.

As discussed [1, 2], one way of simplifying circular beamforming is to form phase modes by combining all the elements of the circular array. Each phase modes has unit amplitude and phase that cycles between 0 and 2π, with the number of cycles depending on the mode number – see Figure 1. Each phase mode has a radiation pattern of $e^{jM\phi}$ where M indicates the phase mode number. In Figure 1, the phase of three of these modes is shown. The amplitude of each of these phase modes stays constant at unity. Mode 1 cycles once between 0 and 2π while Mode

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2 cycles twice. To form a scanning directional beam, these phase modes can be weighted, phased and summed together [2]. Thus phase modes can be thought of as analogous to elements of a linear array and phase mode beamforming can use the mature and well-known beamforming techniques of linear array beamforming.

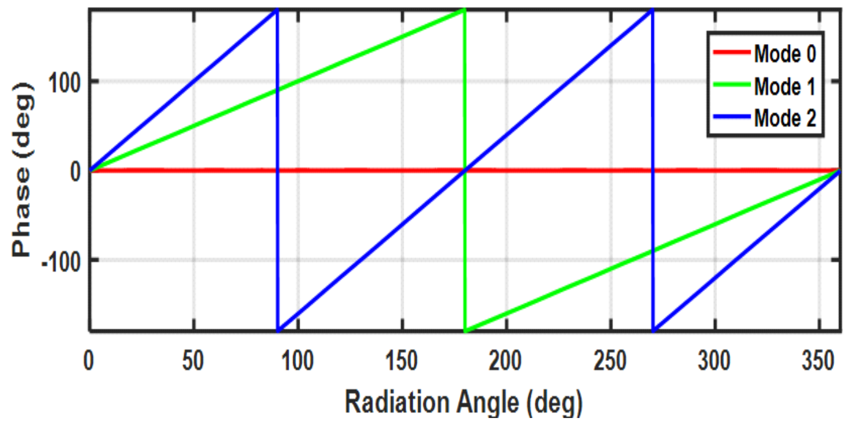


Figure 1: Examples of phase variation of phase modes of a circular array vs. radiation angle

One way to form phase modes is to use Butler matrices [2]. These can be designed to have N inputs and N outputs. The N inputs are the inputs of the circular array while the outputs will be each of the phase modes. This transformation is shown in Figure 2. Butler matrix uses hybrid couplers and fixed-values phase shifters. Details of how to determine the phase values of the fixed-value phase shifters was discussed in detail in Ref. [1] using equations found in [3]. In this report, we will discuss the methodology of designing and building the fixed-value phase shifters using microstrip techniques.

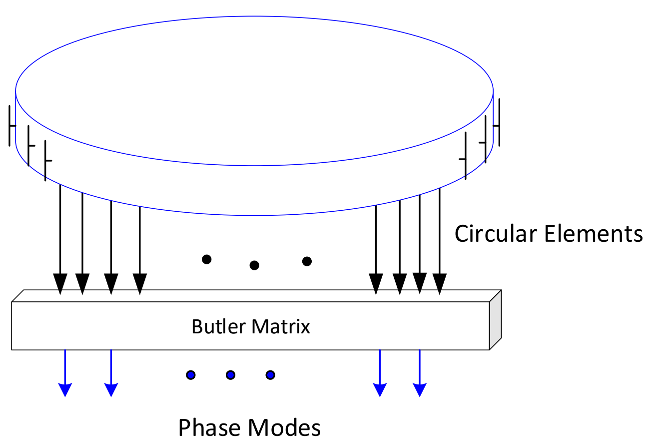


Figure 2: Forming phase modes from circular array elements

In a Butler matrix design, the phase shifter normally has a limited bandwidth performance. Research is on-going to design phase shifters that are wideband especially using microstrip techniques [4, 5, 6, 7, 8]. The objective of our work here in this program is not to design ultra-wideband Butler matrices but rather to use these phase shifters to form passive Butler matrices that can be used to form phase modes. We will follow a simple coupled line methodology design phase shifters over a band of 2 – 5 GHz and use these to design the required Butler matrix designs. As a part of this report, we will discuss the steps to design a 4×4 and 8×8 Butler matrix, as well as the steps to design simple Shiffman phase shifters.

2. WIDEBAND PHASE SHIFTERS

As we know, phase shifters are extremely common microwave devices that are widely used in electronic beam steered phased arrays, microwave instrumentation and modulators among others applications. A lot of work is being done to design and develop wideband phase shifters. A detailed discussion of these devices can be found in literature [9, 10, 11]. Shiffman phase shifters are common and easy to design and build. Compared to other coupled designs [7, 9], these may have smaller bandwidths of operation, but the ease of modeling and building make them ideal for our effort here. For the design methodology, we will discuss the steps taken to design the Shiffman phase shifter [12].

2.1 Shiffman Phase Shifter

The Shiffman phase shifter is a differential phase shifter that consists of two transmission lines, one of which is a coupled transmission line. By properly selecting the length of the two lines as well as the degree of coupling, it is possible to obtain a flat phase shift over a relatively broad bandwidth. Shiffman's original designs used the stripline structures where the odd and even mode propagating along the coupled lines have equal phase velocities. In the presented design, we have decided to use microstrip structures instead of stripline structures, to simplify manufacturing. However, using microstrip structures result in unequal even and odd velocities which causes reduced coupling and narrows the bandwidth over which the constant phase shifts can be formed. To improve this performance, it is possible to consider other wideband phase shifter designs found in literature [4, 6]. However these were found to be not as mature and as designing a broad-band phase shifter is not the objective of this effort, we decided to stay with the Shiffman phase shifter methodology.

Figure 2 shows an example of a simple Shiffman phase shifter using transmission lines. A quick overview of the steps that were followed to design this phase shifter is provided in the next section.

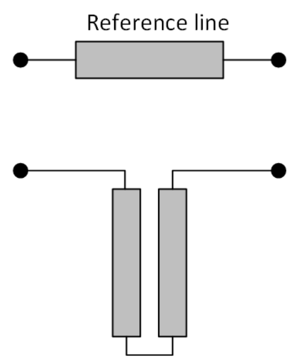


Figure 3: An example of a single stage Shiffman phase shifter

To start the process of designing a wideband phase shifter, we followed Ref [9] to determine the steps needed to design a 90° differential phase shifter. For this project, we need to design phase shifters to operate at a center frequency of 3500 MHz.

2.1.1 Designing a Shiffman Phase Shifter

The differential phase shifter provides the desired phase by subtracting the phase response of the coupled section with the phase response of the adjacent uniform line.

$$\Delta\phi = K\theta - \cos^{-1}\left(\frac{\rho - \tan^2\theta}{\rho + \tan^2\theta}\right) \tag{1}$$

In Eq. (1) θ is the electrical length of the coupled section and ρ is its impedance ratio. The impedance ratio is defined as

$$\rho = \frac{Z_{0_e}}{Z_{0_o}} \tag{2}$$

In Eq. (2) Z_{0_e} and Z_{0_o} are the even and odd impedances of the coupled section line respectively. For microstrip lines, these two impedances are not the same but still meets the following requirement at all frequencies of operation

$$Z_0 = \sqrt{Z_{0_e} \times Z_{0_o}}. \tag{3}$$

.

The coupling factor C and the impedance ratio can be related as shown below.

$$C = -20 \times \log_{10}\left(\frac{\rho - 1}{\rho + 1}\right) \tag{4}$$

An example of a Shiffman phase shifter response is shown in Fig. 4 below. The coupling factor and the odd and even impedances can be varied to determine the error in the phase shift across the band of interest. Figure 4 relates several factors such as θ_{max}, θ_{min} and $\Delta\phi_{max}$ and $\Delta\phi_{min}$. The θ_{max}, θ_{min} relate the minimum and maximum frequencies of operation while ϕ_{max} and ϕ_{min} relate the maximum and minimum phase deviation from desired phase shift. In other words, the horizontal axis represents the bandwidth (with θ_0 being the center frequency) over which a relative phase shift of $\Delta\phi_0$ can be obtained. The parameters $\Delta\phi_{min}$ and $\Delta\phi_{max}$ represent the minimum and maximum deviation of the angle from $\Delta\phi_0$. If a larger phase uncertainty can be tolerated, then the phase shifter will operate over a wider bandwidth.

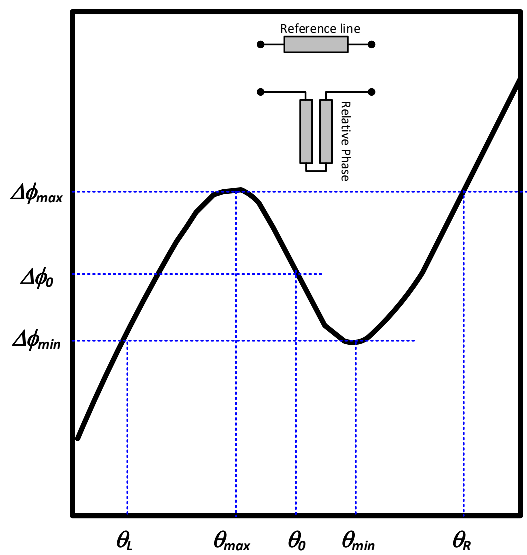


Figure 4: Standard Shiffman phase shifter with a typical phase response [after Ref [9]]

An example of how a given even and odd impedance and coupling factor and impedance ratio can be used to determine the phase deviation is shown below. For most of the calculations K is assumed to be 3 (three) or $K\theta = 270^o$, i.e. the angle provided by the reference line at the center frequency is 270°. The coupled line has to provide 180° of phase shift resulting in a relative phase shift of 90°.

Using equations from Ref. [9], the maximum phase deviation, ϕ_{max} can be related to K and impedance ratio, ρ as

$$\Delta\phi_{max} = K\tan^{-1}\sqrt{\frac{K\rho - 2\sqrt{\rho}}{2\sqrt{\rho} - K}} - \cos^{-1}\left(\frac{\rho + 1 - K\sqrt{\rho}}{\rho - 1}\right). \tag{5}$$

Assuming that the maximum allowable deviation in angle for this design is ±2°, the value of $\Delta\phi_{max} = 92^o$ and $\Delta\phi_{min} = 88^o$. Thus, for the calculation shown in Fig. 5, the value of ρ had to be optimized to provide $\Delta\phi_{max}$ of 92°. With $K = 3$, and $\Delta\phi_{max} = 92^o$ the value of ρ works out to be 2.6233. For this value of impedance ratio, the coupling, C can be obtained using Eq. (4) to be 6.975.

Input Impedance, Z_I	50	Ω
Even Impedance, Z_e	80.9784	Ω
Odd Impedance, Z_o	30.8724	Ω
Impedance Ratio, ρ	2.623	
Coupling, C	6.975	dB
K	3	
Phase deviation. ε	2	deg
Bandwidth	60.2311	%
θ_R	117.104	deg
θ_L	62.896	deg
θ	90	deg
Δϕ	90	deg
ϕ_{max}	92	deg
ϕ_{min}	88	deg

Figure 5: An example to relate min/max frequency to phase deviation

The maximum phase deviation, ϵ can be related to minimum and maximum relative phase as

$$\epsilon = \Delta\phi_{max} - \Delta\phi_0 = \Delta\phi_0 - \Delta\phi_{min}. \tag{6}$$

Thus, the ratio of the lowest frequency of operation to center frequency (i.e. θ_L) can be related to $\Delta\phi_{min}$ as shown in Ref. [9].

$$\Delta\phi_{min} = K\theta_L - \cos^{-1}\left(\frac{\rho - \tan^2\theta_L}{\rho + \tan^2\theta_L}\right) \tag{7}$$

Once again, the value of θ_L was optimized until the value of $\Delta\phi_{min}$ was close to the desired value of 88deg. This worked out to be 62.896deg. The maximum and minimum of values of θ are related as

$$\theta_L = 180^o - \theta_R. \tag{8}$$

Finally, the maximum bandwidth over which this phase shift can be obtained can be determined by

$$B = \left(\frac{\theta_R - \theta_L}{\theta_0}\right). \tag{9}$$

In this example a 90° phase shifter with ±2° error will be designed with a 60% bandwidth. Using the equations discussed earlier, this phase shifter will need a coupling of 6.975 dB from the coupled line and an impedance ratio of 2.623. With these input the odd and even impedance were calculated to be 30.9Ω and 81.0Ω respectively. The values for θ_R and θ_L were found to be 117.104° and 62.896°. Note, these equations are all independent of frequencies. Once these parameters have been calculated, the microstrip lengths can be found based on the electrical length and the desired frequency of operation. Using these equations, the next step was to actually design a phase shift to provide 90deg phase shift at center frequency of 3500 MHz.

2.2 Designing a Shiffman Phase Shifter in Microstrip

To design a phase shifter in microstrip, a combination of tools were utilized. To start off, we will present the steps that were followed to develop the phase shifter. In the next section, we will present the final 4×4 and 8×8 Butler matrix designs.

Initially, using the calculator shown in Fig. 5, a design for a 90° phase shifter was put together. An example of this is shown in Fig. 6. This phase shifter is designed to have a phase deviation of less than 0.5° over an operating frequency band of 3200MHz to 4200MHz. This is a bandwidth of 30%. If a higher bandwidth is desired than a larger angle deviation will have to be accepted. The details of the design are shown in Figure 6a while the phase performance is shown in Figure 6b.

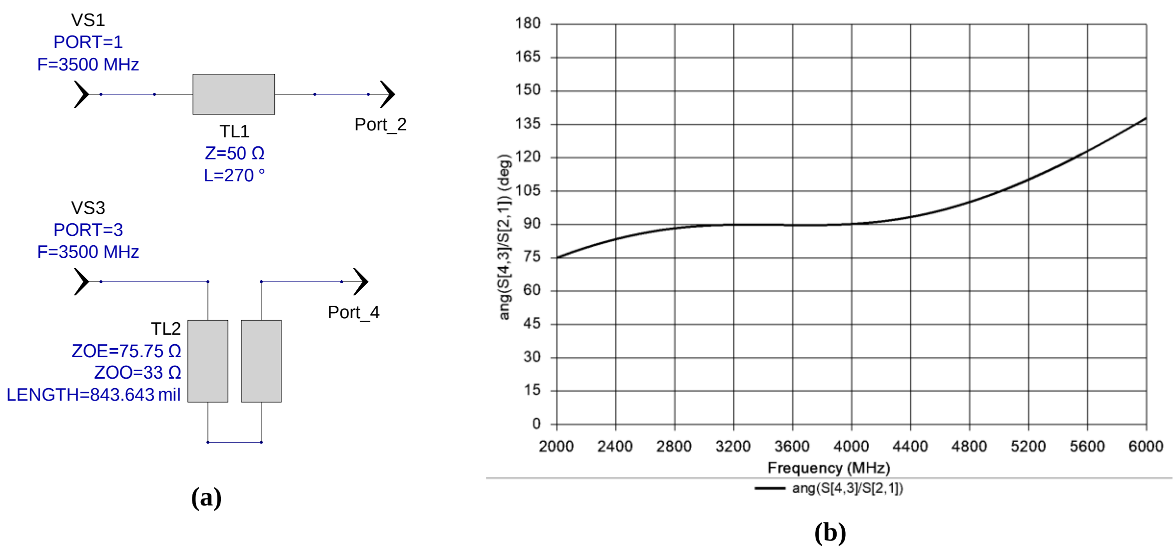
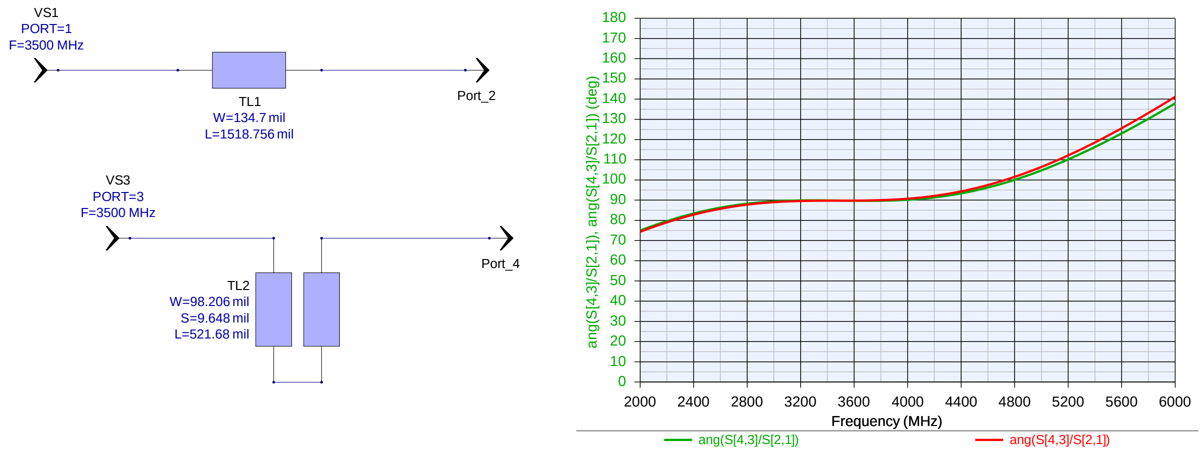


Figure 6: A starting design of wideband Shiffman Phase Shifter

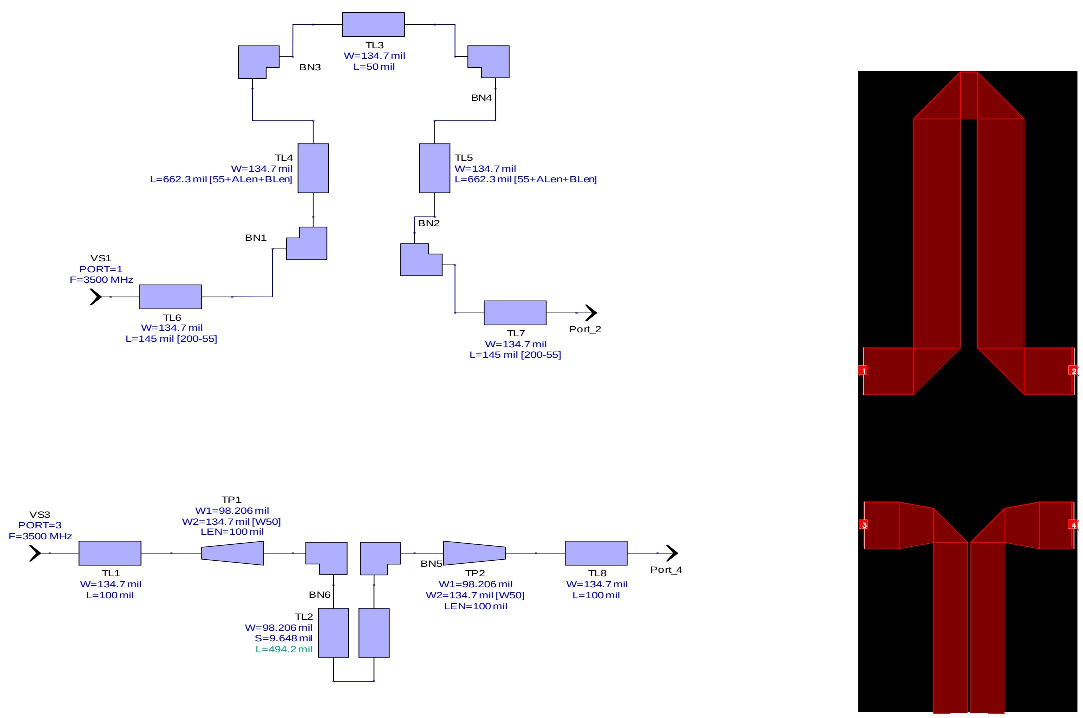
The next step is to convert the transmission line design into a microstrip line design. The TLINE function in the GENESYS® tool can be used to do the initial conversion. Choosing the center frequency of 3500MHz the converted microstrip design is shown in Fig. 7. For this conversion, the substrate chosen is Rodgers 4350 board which is 60mil thick, with a dielectric constant of 3.48 and a loss tangent of 0.004. The performance for this ideal conversion is also shown in Fig. 7. After this conversion, there is a good match in performance between the microstrip and ideal designs.



(a) (b)

Figure 7: Design and performance for an ideal microstrip design

Taking the line lengths in Fig. 7, a layout was constructed using mitered lines. The electrical design and the microstrip layout is shown in Fig. 8 below. When forming a mitered design, it is essential to ensure that the overall line lengths do not get modified significantly, thereby changing the phase shifter performance



(a) (b)

Figure 8: Electrical and layout of Shiffman Phase Shifter

With the layout as shown in Fig. 8, the phase shifter performance across the band of interest is shown in Fig. 9. The overall errors increase due to the use of mitered line, in the reference line, which results in increased coupling due to the limited spacing between the lines. The parameter that still requires analysis or optimization is the width of the microstrip line that connects the coupled line. In the current design, it is modeled as a short, however practically, it is not possible to short this, so a finite width line will have to be utilized. The thicker this line is, the more the degradation is seen in the overall performance.

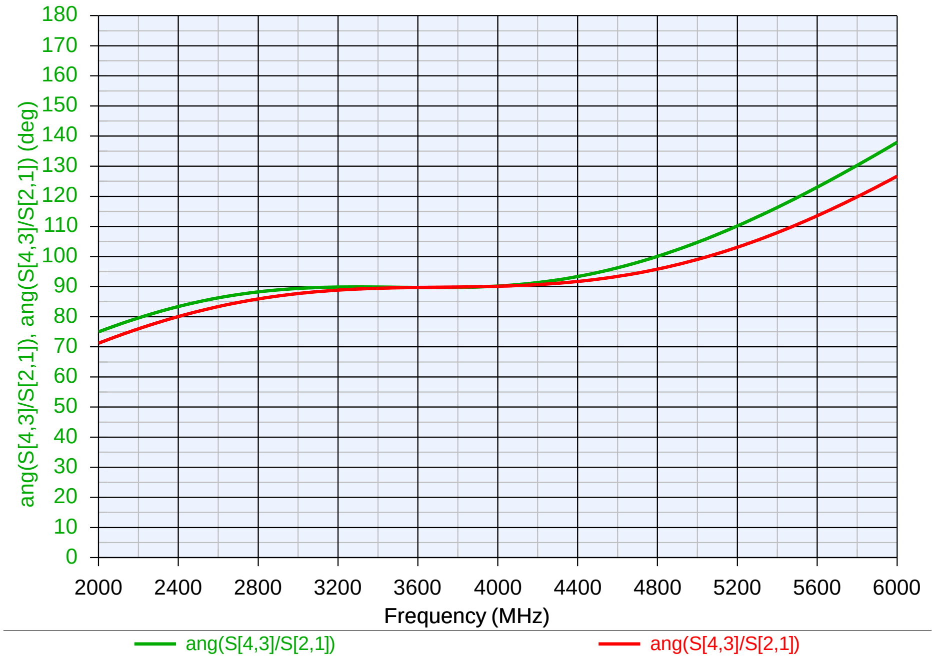


Figure 9: Comparing theoretical and practical phase shifter design performance

To complete the design, we used High Frequency Structure Simulator (HFSS), a commercially available finite element method solver for electromagnetic structure from Ansys, to optimize the design of the phase shifter. The use of this software allows us to optimize the design for best possible performance.

Taking the preliminary design from Genesys, we exported the design into HFSS. This exported design is shown in Fig. 10. The “red” boxes in the figure indicate the location of Electromagnetic (EM) ports. With these ports in place, HFSS is able to carry out a finite-element simulation of how EM fields radiate and couple between the two microstrip lines.

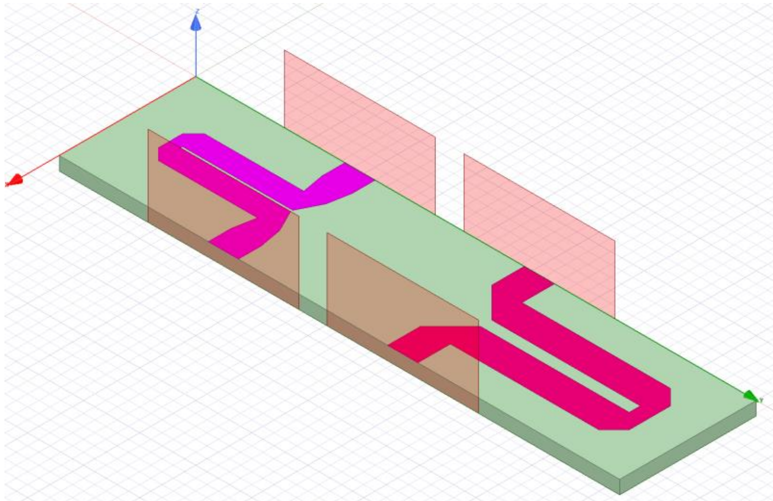
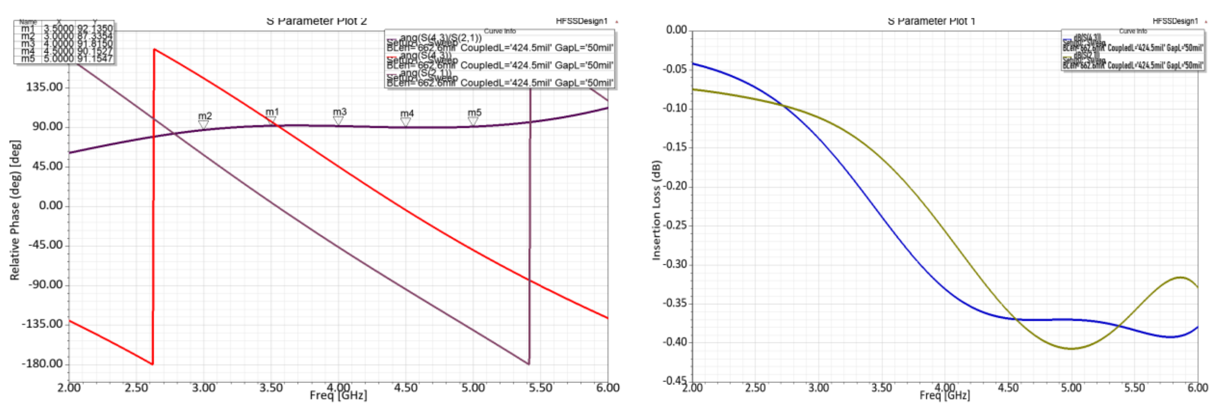


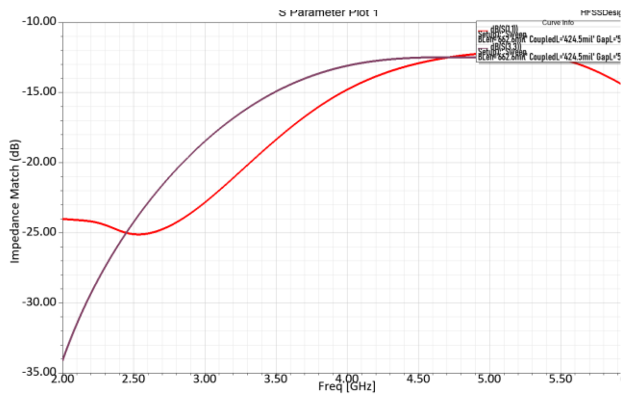
Figure 10: HFSS layout of the 90deg Shiffman phase shifter

In Fig. 10, the microstrip on the lower right-hand side is the reference line (~ 270°) while the line near the top of the figure is the coupled line. The phase performance estimated via the HFSS tool is shown in Fig. 11a. The designed phase shifter has an increased error ($\pm 2^{o}$) and a wider bandwidth (50%) than designed using GENESYS®. This difference from the original design was because an ideal design/layout from Genesys was converted into a physical realization of the design. The Genesys tool is not able to provide a good prediction of coupling effects or corner dispersions and the effect of these affect the overall performance of the component. This is the reason why an HFSS simulation is essential before manufacturing the final component.

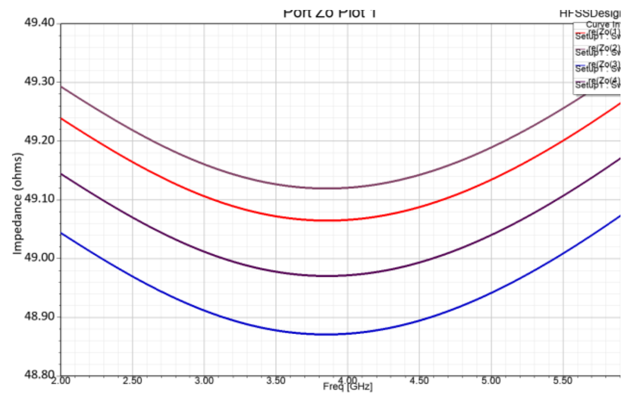
The insertion loss and reflection performance of this design is shown in Figs. 11b and 10c. Finally Fig. 11d shows the simulated impedance of the four ports, which is close to 50Ω for each of the four ports. The insertion loss is less than 0.5dB for both the reference and coupled lines and the reflection performance is lower than -10dB across the frequency band of interest.



(a) **(b)**



(c)



(d)

Figure 11: (a) Phase performance (b) insertion loss (c) reflection loss and (d) impedance of designed Shiffman Phase shifter

Using the same approach, a 0deg phase shift can be designed. In this case, we do not need to use a coupled line. The reference line is duplicated across each of the two sets of ports.

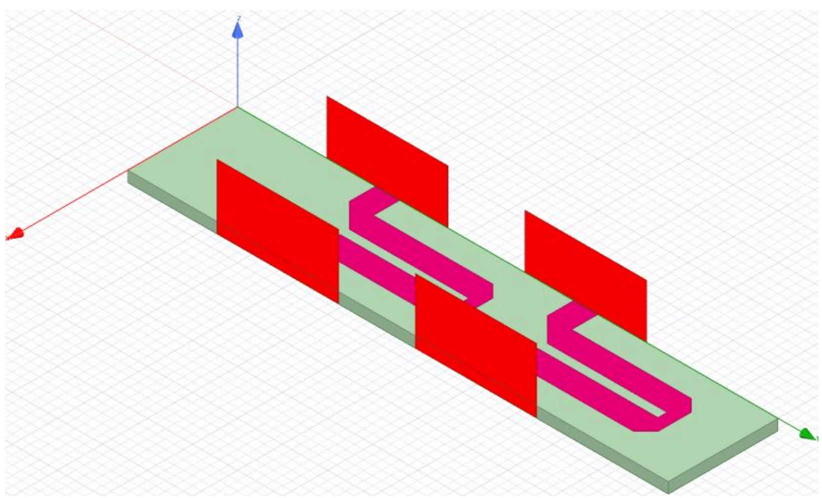
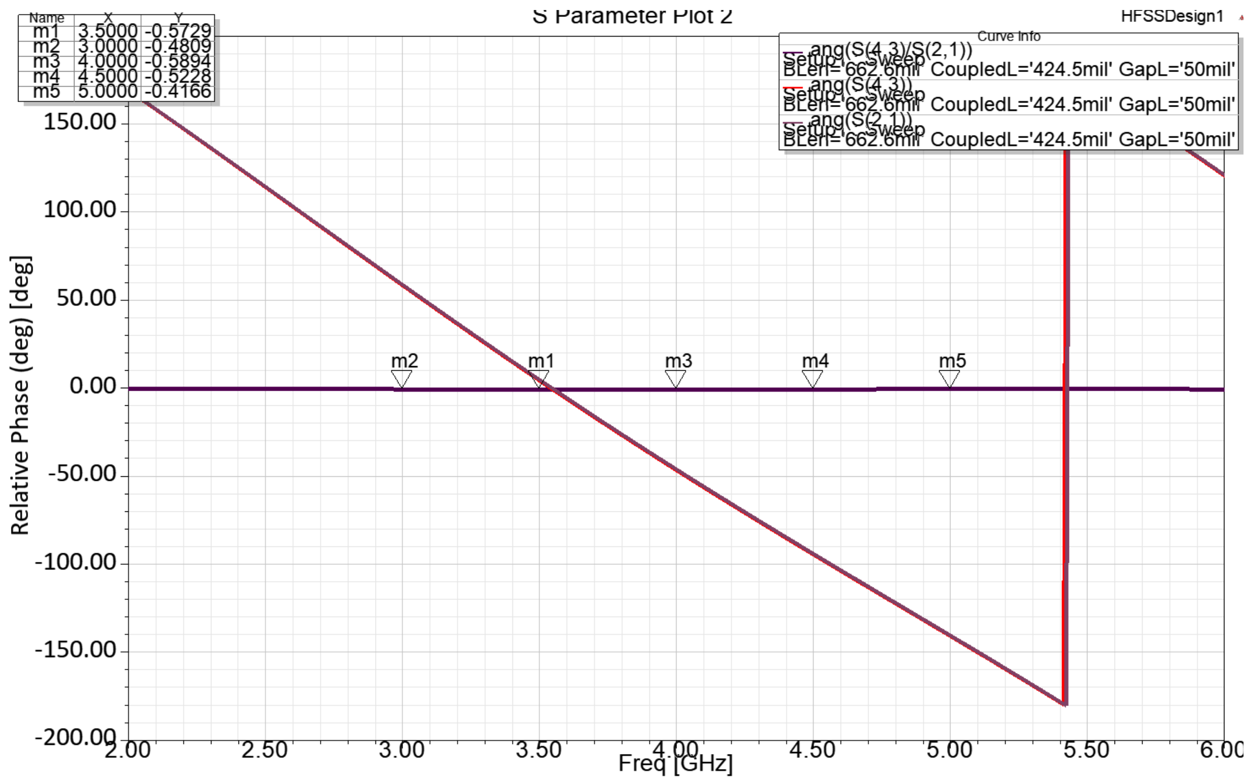
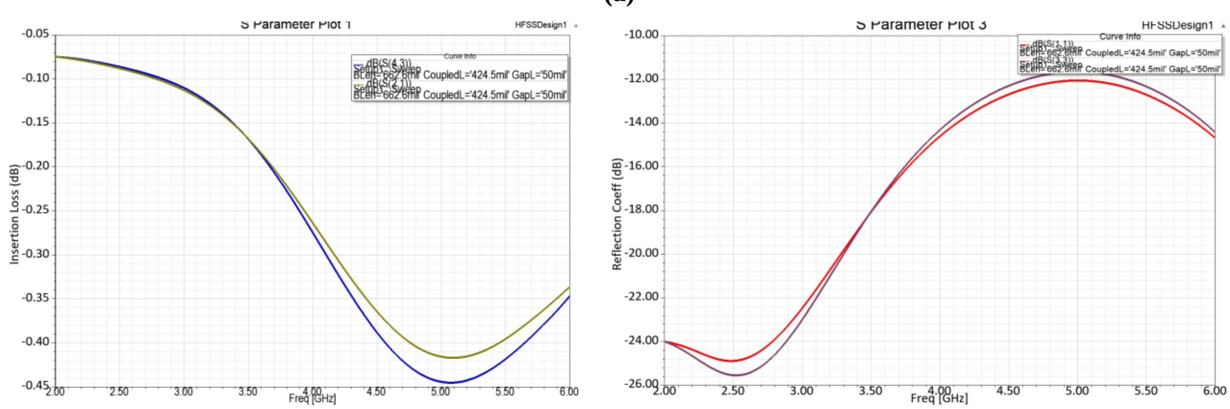


Figure 12: Layout of a 0deg phase shifter

The performance of this 0º phase shifter is shown below. This layout has the capability of providing 0deg phase shift across the band of interest. The reflection coefficient for this design is better than -10dB and the insertion loss is less than 0.5dB. The performance is shown in Fig. 13. This completes the design for a 0 deg phase shifter.



(a)



(b)

Figure 13: (a) Phase performance and (b) Insertion loss and reflection loss across band of operation

Up to this point, we have described in detail the steps taken to design both of the 90deg and the 0 deg phase shifter. As discussed in Ref [1], both of these phase shifters are needed to design the 4×4 Butler matrix. Remembering that the phase shifters that we have designed are differential phase shifters, both the reference line length as well as the coupled line lengths have to be included in the overall design. This is discussed in the next section

2.3 Building a 4×4 Butler Matrix

Using the 0deg and 90deg differential phase shifters the 4×4 Bulter matrix can be assembled as shown in Figure 14. The ports on the left-hand side are the input ports where the circular array elements will be fed into the matrix while the ports on the right-hand side are the outputs and will have phase modes as output. Only one of the lines sees a relative phase shift of 90deg, the other three lines all have a relative phase shift of 0deg. The final phase shifts for the phase modes that are generated from a 4-element circular array are at +90°, 0°, -90° and -180°.

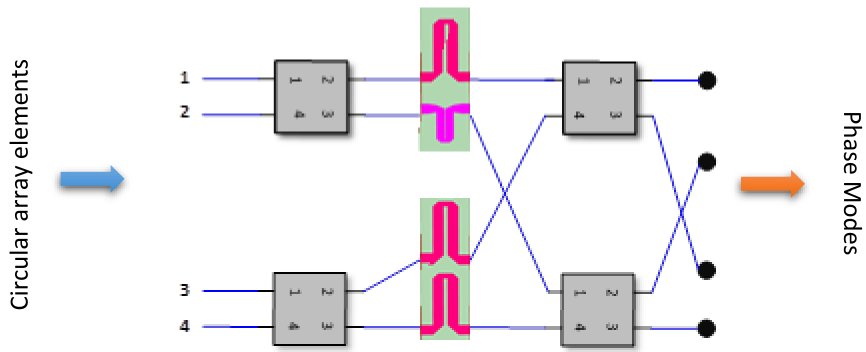


Figure 14: Layout of 4×4 Butler matrix using designed 0deg and 90deg phase shifters

Finally, we used GENESYS® to simulate the entire 4×4 Butler matrix by replacing the ideal phase shifters with the designed phase shifters and the 180° hybrid couplers with the Welatone hybrids. The overall performance from each the input port 2 to each of the output ports of the Butler Matrix is shown in Figure 15. The phase values show to have a deviation of about $\pm 5^o$ over the required phase values of +90°, 0°, -90° and -180° over a 2GHz bandwidth for each of the phase mode outputs. This shows that the phase mode for a 4-element array can be formed over a 50% bandwidth.

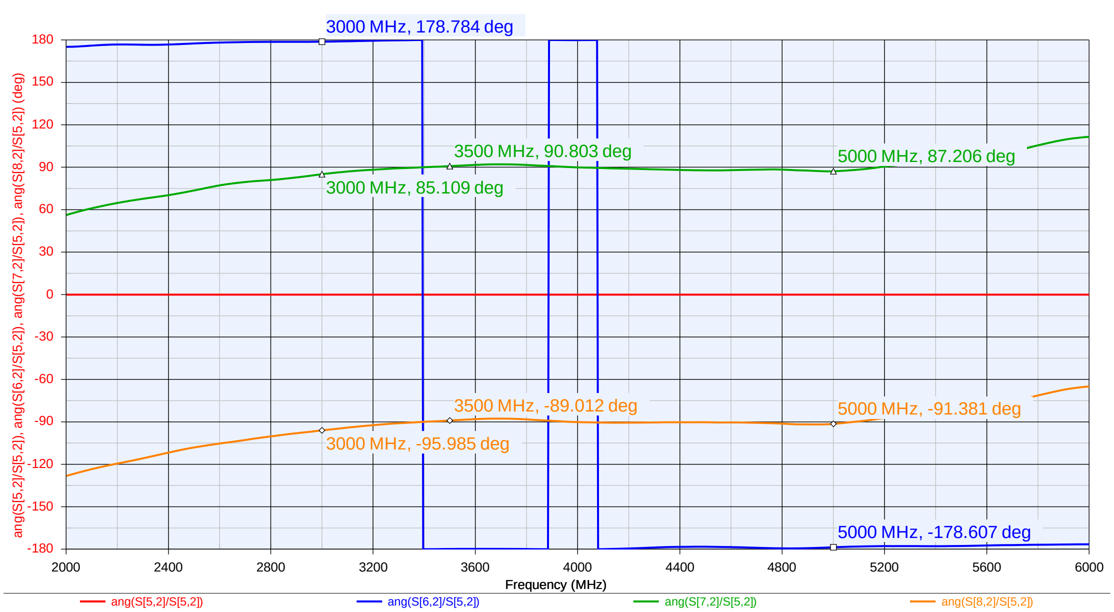


Figure 15: Phase performance from input port 2 to each of the output ports (5 to 8)

So far, all the presented designs were made using a 60mil thick substrate (RO4350). However, as the hybrids are all surface mounted components which need a 20mil thick board, using a 60mil board will mean using boards of two different thicknesses. This will require additional connecters and boards of different thicknesses. This will just result in additional [undesired] losses into the design. To alleviate this, the phase shifters were re-designed on a 20mil substrate. Using a thinner substrate means the need for thinner microstrip lines and thinner gaps in the coupled lines. Thinner microstrip lines usually result in a higher loss in the overall design, but easier manipulation of the layout of the design. The final designs are shown in the next section.

3. FINAL DESIGN

In this section, we will present the final designs for the 4×4 and 8×8 Butler matrices. These designs are all built on a 20mil Rodgers® 4350 substrate. This substrate has a permittivity coefficient of 3.38.

3.1 4-element Butler Matrix

Figure 16 shows the updated design for the 90deg phase shifter for a 20mil substrate. The 50Ω matched line needs to be about 44.5mil thick. The coupled line length is about 436.6 mil with a gap of 5mil. This gap is made to be greater than 4mil for practicality. A gap narrower than 4mil is hard to build. The short is emulated by a thin microstrip line (7.6mil). As this line is made thicker, the bandwidth over which the phase remains flat gets narrower. The reference line length is about 636.6mil. The thickness of the microstrip in the bend is made to be less than 44.5mil to reduce transmission loss and to reduce reflections. The miters at the line bends for both lines were optimized to improve overall performance such as S_{11} and S_{12}. In comparing with the earlier design, this phase shifter has higher loss and a worse S_{11} performance compared to the design on the 60mil board.

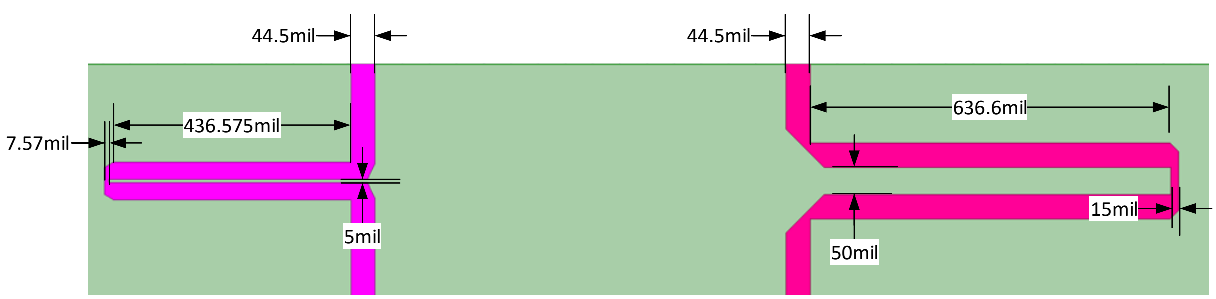
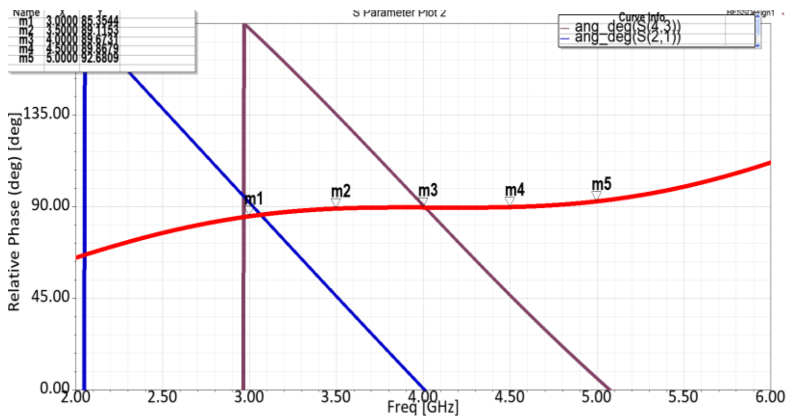
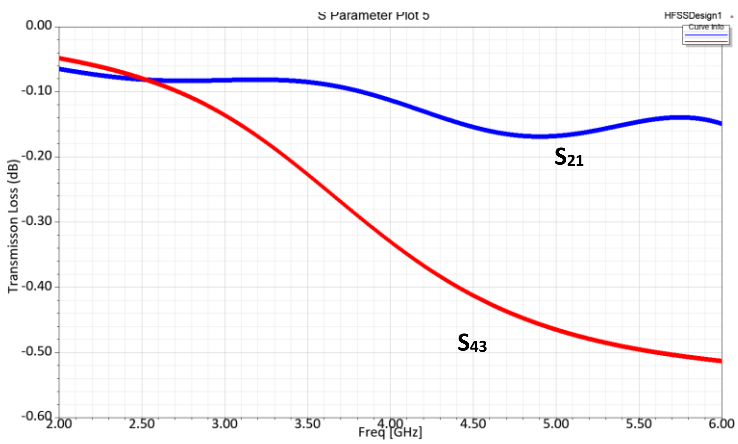


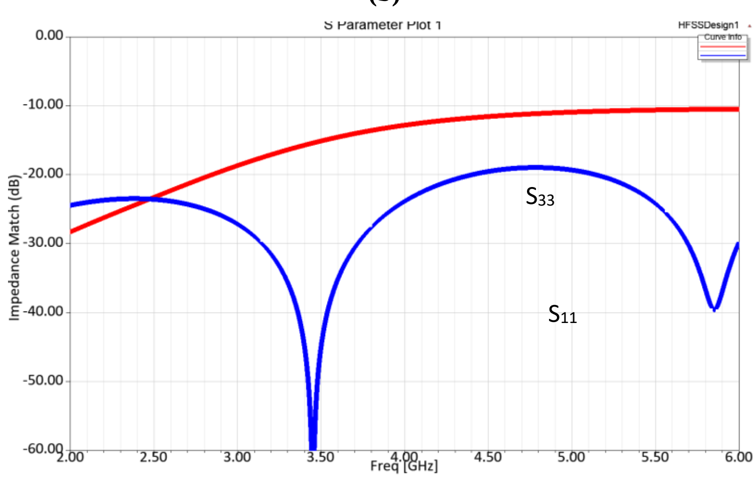
Figure 16: 90deg phase shifter



(a)



(b)



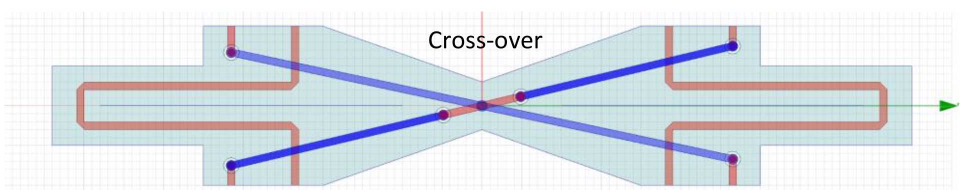
(c)

Figure 17: (a) Phase performance of 90deg phase shifter (b) insertion loss across the band and (c) reflection loss of the differential phase shifter

In a similar vein, the 0deg phase shifter design is as shown in Fig. 18. The reason to design a 0deg phase shifter is to ensure that the paths that do not need a phase shift see a similar delay and loss as the paths that require a phase shifter in them, so that the relative phase shift between the multiple paths is maintained. For example if no phase shift is added in the paths that don't require a phase then because of the reference line in the other paths, the paths with no phase shift will see a -270deg phase shift. The 0deg phase shift is made of two reference lines – each providing the same phase shift across the ports.

Figure 18: Layout of the 0deg phase shifter

The final piece in this 4×4 Butler matrix is the cross-over. The cross-over design cannot be made on a two-layer board because of the overlap or cross-over needed between the lines. Thus, the cross-over requires a three-layer board to build. The layout of this board is shown in the figure below. There are two vias in the center which are used to take the microstrip line to the bottom layer and then brings it back to the top layer. In Fig. 19 the "red" line is on the top layer while the "blue" line is on the bottom layer. When designing this, it is important to ensure that the delay between the two lines is about the same so that dispersion in the signal is low. The results are shown in Figure 20. The overall reflection loss of this cross-over is better than -10dB across the band of 2 – 6 GHz while the insertion loss stays within 0.5 dB. From the plots, the transmission loss increases as the frequency of simulation increases. The group delay between the lines is within ±1 ps.



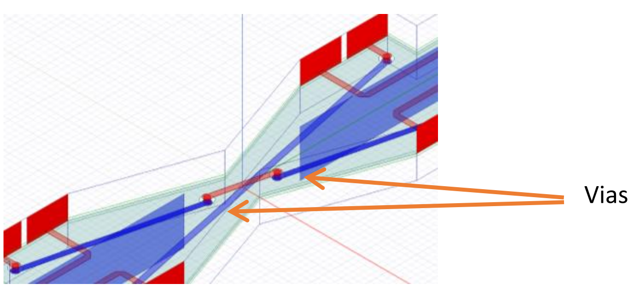
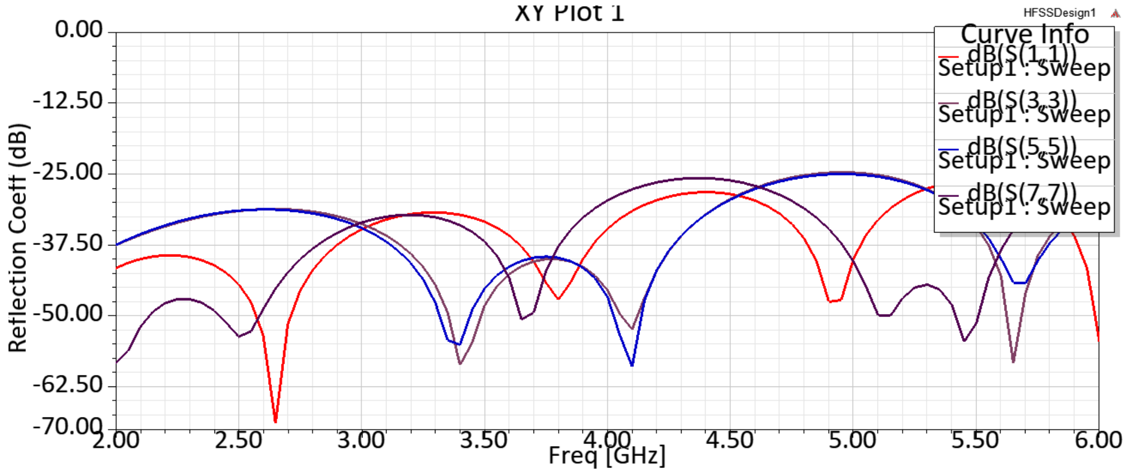
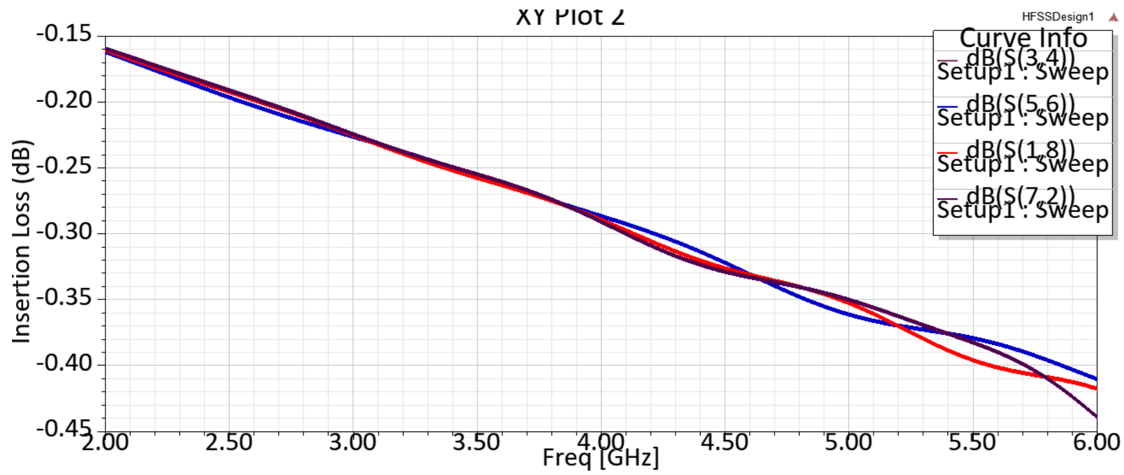


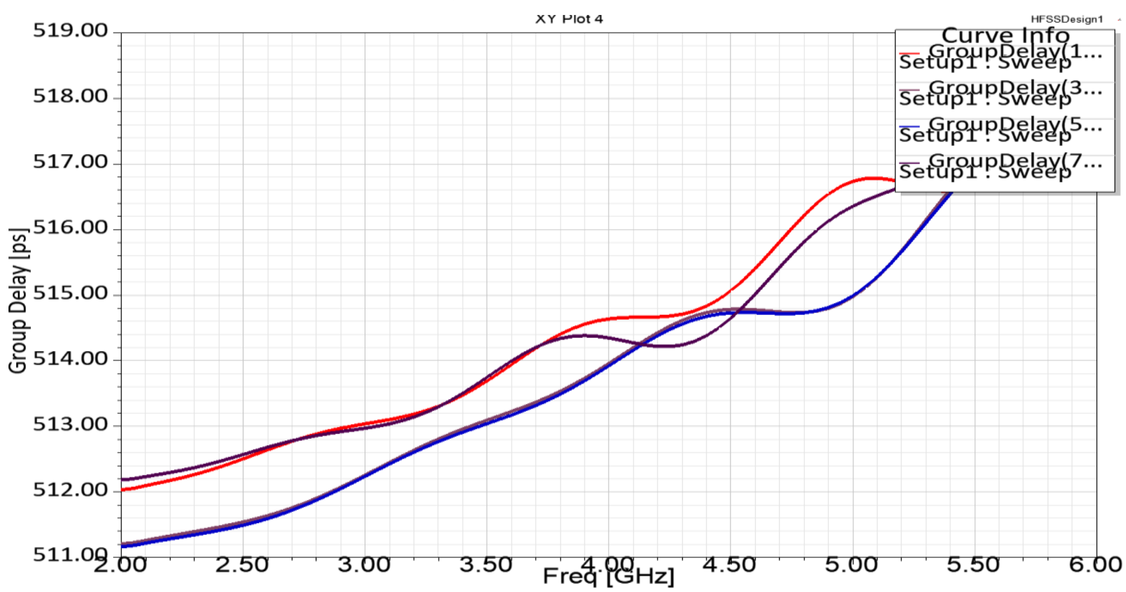
Figure 19: Layout of cross-over for 4×4 Butler matrix



(a): Reflection Loss



(b): Transmission loss



(c): Group Delay

Figure 20: Performance of the cross-over across the band of interest

With the completion of the cross-over design, the overall layout of the 4×4 Butler Matrix is shown in Fig. 21 below. The measurements from this design will be presented in a future report.

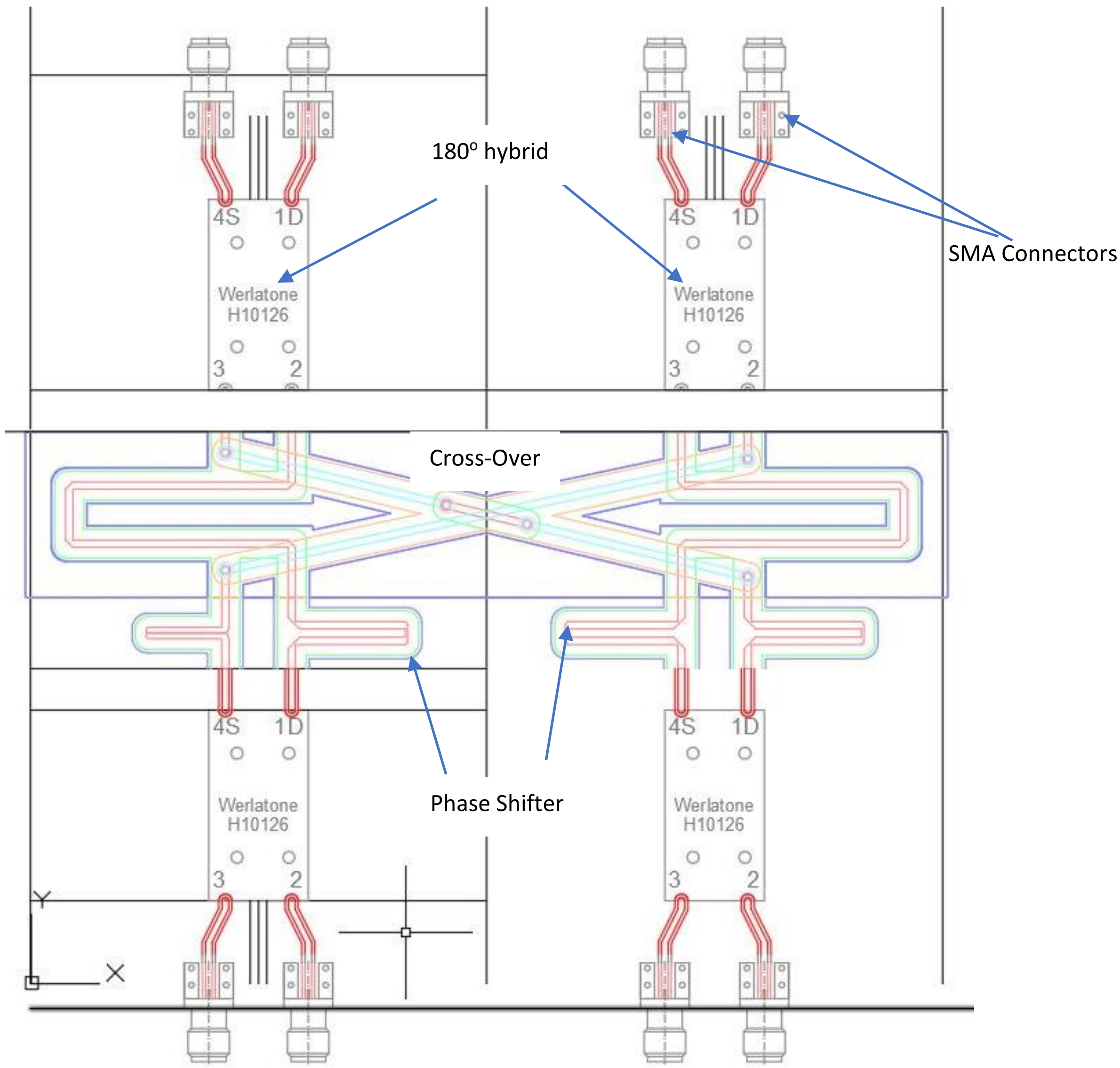


Figure 21: Complete layout of 4×4 Butler matrix on a circuit card

3.2 The 8×8 Butler Matrix

The design of the 8×8 Butler matrix follows the same methodology as the 4×4 design. The additional components that are needed is the 45deg phase shifter and a cross-over that interlaces 8 inputs and 8 outputs. This is a unique design that was developed using just a three-layer board.

3.2.1 Design of 45deg phase shifter

To design the 45deg phase shifter, the length of the coupled line was increased from the line length that was used for the 90deg phase shifter. By coupled lined length has to be increased such that the difference between the 270°

reference line and the coupled line is now only 45deg. In most differential phase shifter designs, both the length of the reference line as well as the phase line are optimized for best performance. However, here we have to optimize performance with a fixed reference line. Changing the reference line will result in non-zero phase shift for phase shift that need 0deg phase difference between them. The layout for the 45deg phase shifter is shown in Fig. 22.

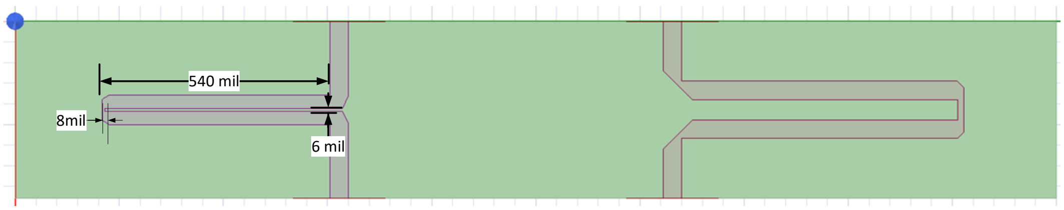
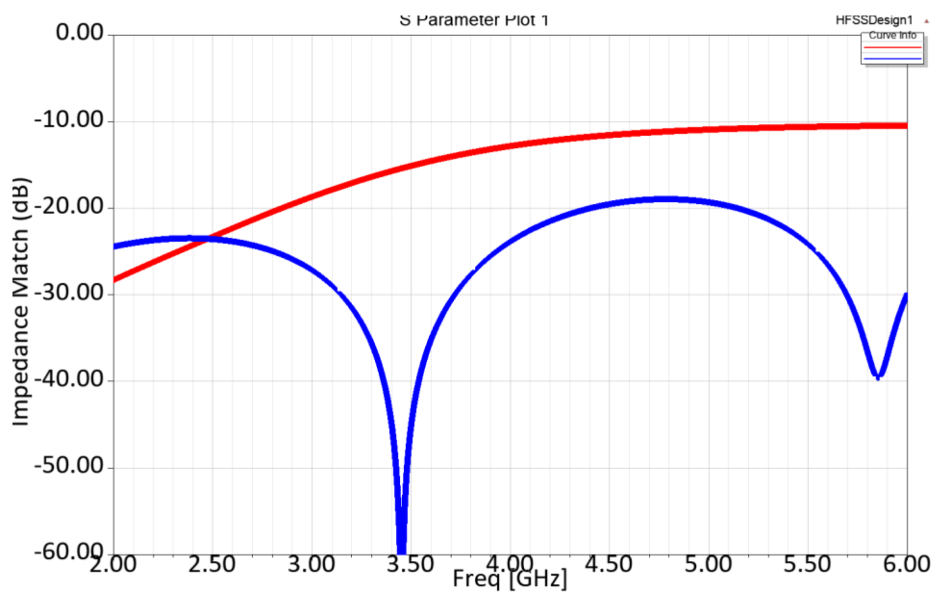
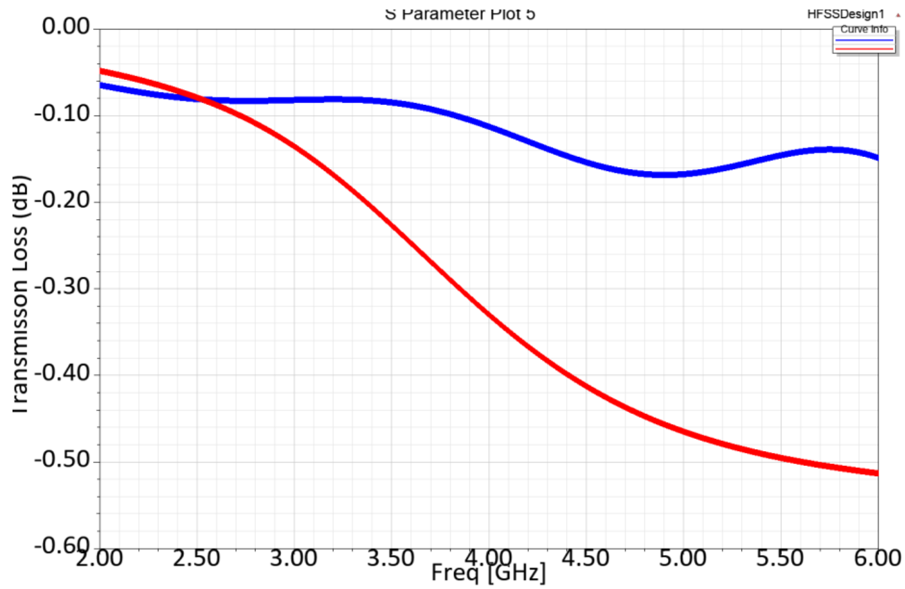


Figure 22: Layout and dimensioning of 45deg phase shifter

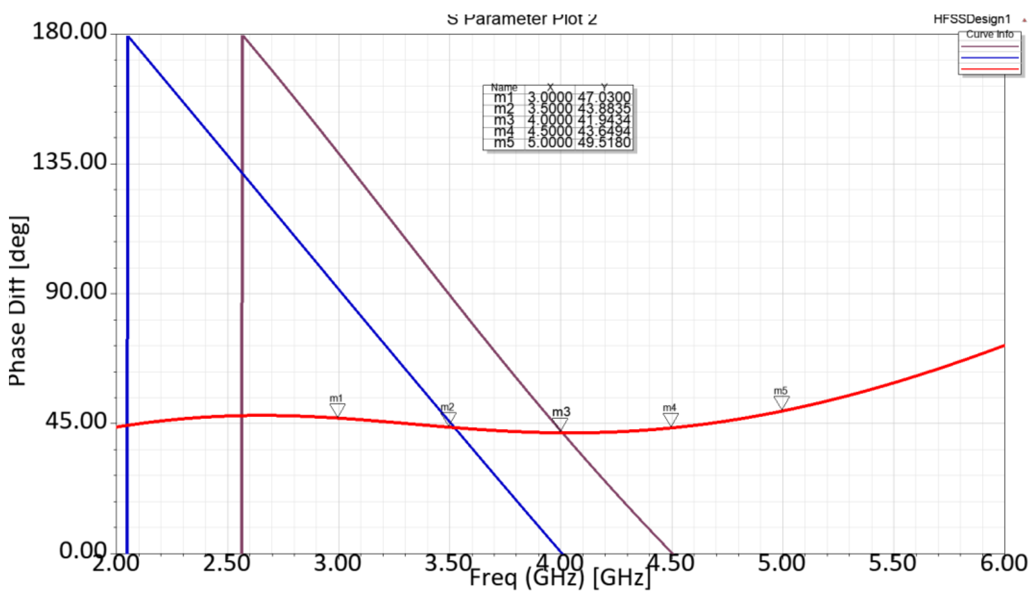
The reflection, transmission and phase performance of this device is shown in Fig. 23. Due to the small gaps in the coupled lines, the reflection performance in this device approaches the -10dB line which results in the insertion loss getting as high as -0.5dB at the higher end of the band. However when using a 20mil board, there is little flexibility in optimizing for better performance since the line widths and spacing are at limit for practical build. With this design, it is possible to get 45deg with ±5° deviation over a 3 – 5 GHz (50%) bandwidth.



(a)



(b)



(c)

Figure 23: (a) Reflection performance (b) Insertion loss and (c) phase performance of the device shown in Fig. 21

3.2.2 Cross-over design for 8-inputs

The final part for the 8×8 Butler matrix is the design for the cross-over that takes in 8 inputs and 8 outputs. A constrain of no more than three layers for this design was set. This constraint was added to minimize cost. A board with more than three layers gets expensive and is harder to obtain. The final design is shown in Fig. 24. At maximum two vias were used per line. The different colors on the lines indicate the different layers upon which the lines have been made. The performance of this board is shown in Fig. 25. The reflection for all the lines is better than -25dB with the lines 1-12 and 5-16 having the best match. Extra line lengths have been added onto some of the lines (see

Fig. 24) to ensure that the overall delay across the various paths is within ±2ps. The group delay in Fig. 25b shows the group delay performance.

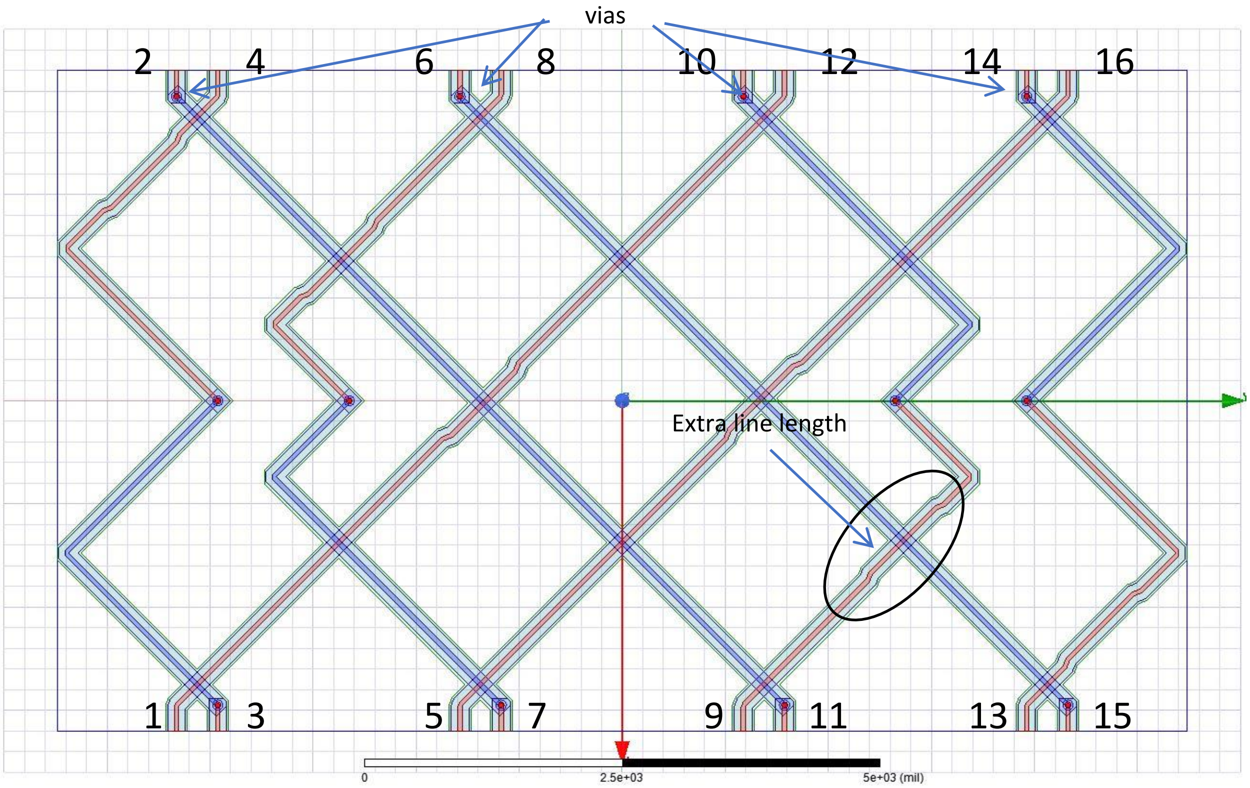
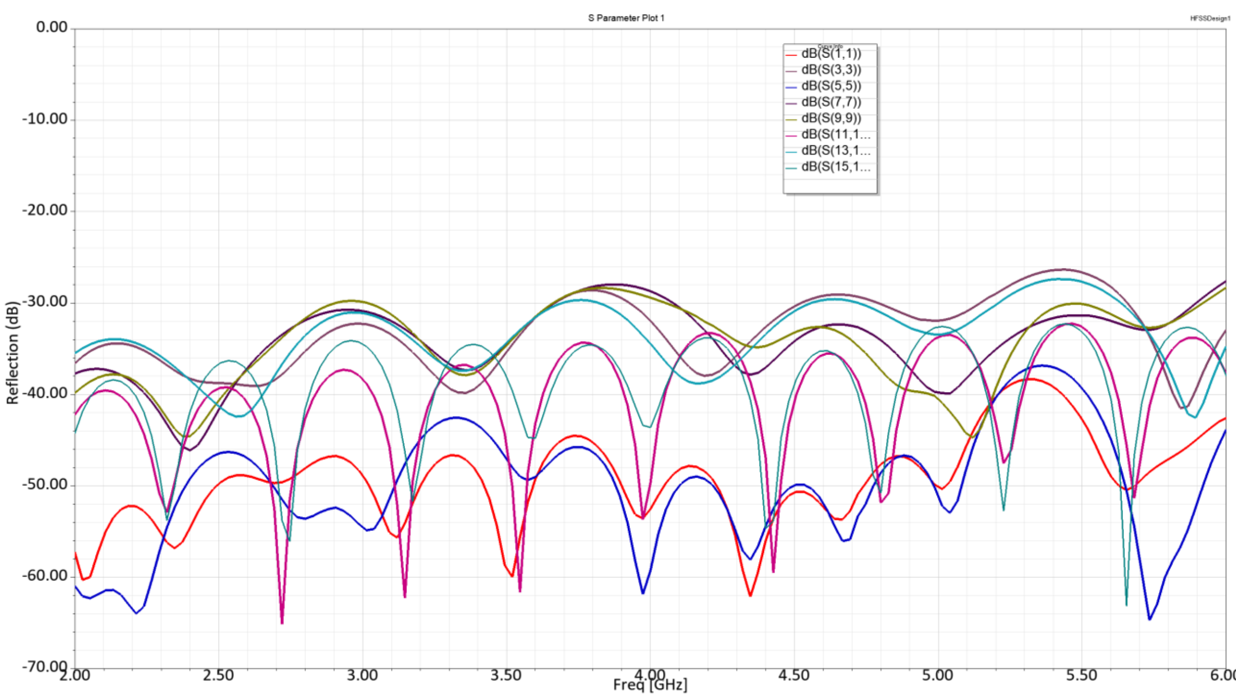
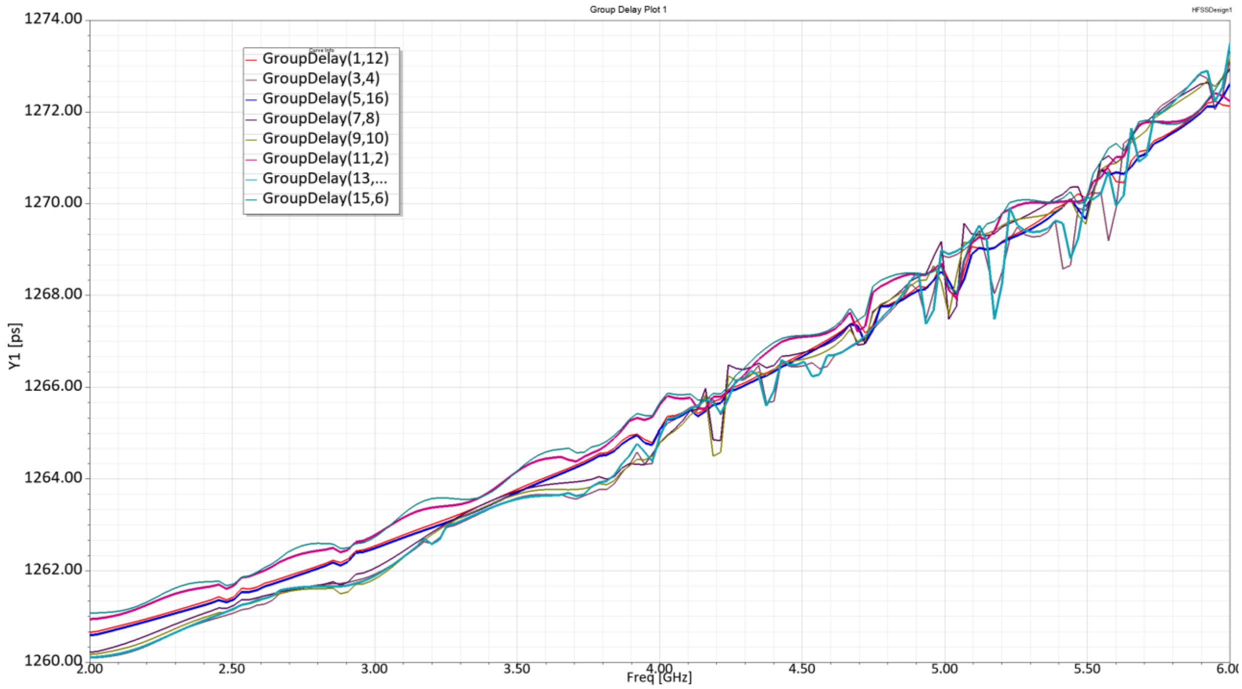


Figure 24: Cross-over design for the 8×8 Butler matrix



(a)



(b)

Figure 25: (a) Reflection loss and (b) delay for the various paths of cross-over

The final layout of the 8×8 Butler matrix is shown in Fig. 26.

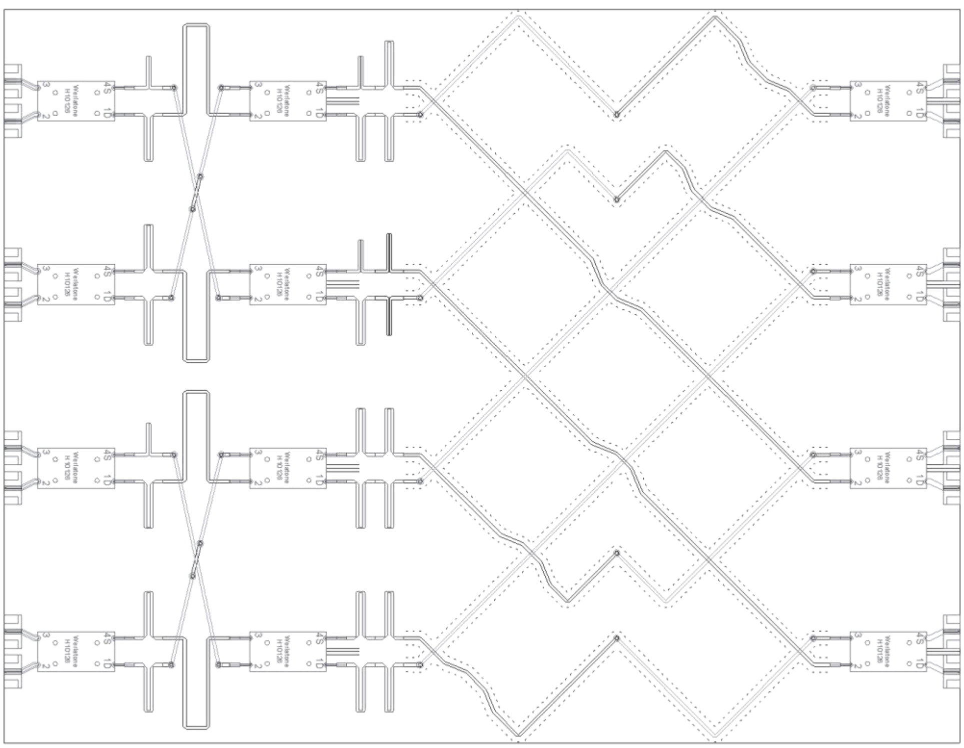


Figure 26: Final layout for the 8×8 Butler Matrix

4. CONCLUSION

The objective of this report was to discuss in detail the steps taken to design the components needed to build Butler matrices. These Butler matrices are necessary to build a passive network that can take as its input N circular array elements and output at most N phase modes. These phase modes are all orthogonal to each other with unit amplitudes and phases that cycle multiple times between 0 and 2π. In an earlier report [1], we had discussed in detail how the fixed-value phase shifters needed in the development of a Butler matrix can be calculated. Here in this report, we describe in detail the steps taken to design and build these phase shifters. We have designed differential phase shifters that can provide phases of 0deg, 45 deg and 90deg. These phase shifters have deviation of about $\pm$5 deg and can operate over a 50% bandwidth (3 – 5 GHz).

Additionally, we have also presented the designs of cross-overs needed to completely build 4×4 and 8×8 Butler matrices. The steps presented in this report can be used to build phase shifters and cross-overs that can be used for larger Butler matrices, with each larger Butler matrix getting more and more complex. For now, the plan is to build the presented designs and measure them to compare the overall simulation vs. measurement performance. The simulated and measured S-parameters will be used to feed a modeling and simulation tool which can be used to design phase modes of any size circular array and analyze beamforming performance. The details of the modeling and simulation tool will be presented in another report [13].

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