A 4x4 Butler Matrix

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***Abstract*—This paper focuses on the design, simulation, and optimization of a 4x4 Butler Matrix, a critical component in beam-forming networks for wireless communication systems. Driven by the increasing demand for higher bandwidth and lower latency in technologies like 5G and potential 6G, multi-beam antenna systems have gained importance. The Butler Matrix is constructed using a hybrid 3dB coupler, a 0dB radiofrequency crossover, and controlled phase lines. Simulations conducted with Keysight ADS demonstrate satisfactory performance within a narrow bandwidth centered at 2.45 GHz. The paper discusses the design intricacies, highlighting challenges such as the impact of the lossy PCB and limited computational resources on the simulation results. Additionally, practical suggestions for further optimization are provided to improve the designed 4x4 Butler Matrix's implementation. This research contributes valuable insights to the development of efficient beam-forming networks for contemporary wireless communication requirements.**

***Index Terms*—Butler Matrix, Microwave Passive Circuit, Beam-forming,**

I. INTRODUCTION

Wireless communication is one of humanity's greatest achievements in the past century. With the increasing demand for higher bandwidths and lower latencies, 5G and future 6G technologies dictate the need to utilize signals in the millimeter-wave frequency bands (30-300 GHz). However, by nature, as the frequency of operation increases, the losses experienced by a traveling electromagnetic wave are increased to the extent that it quickly becomes impractical to either build more wireless base stations or to use more powerful power amplifiers at base stations.

To overcome this, multi-beam antenna technologies have become of great interest in wireless communication infrastructure. A multi-beam wireless communication system is one in which several independent wireless transmissions can be transmitted at once to different spatial locations. Hence, the electromagnetic radiation is focused on a specific location instead of utilizing a semi-isotropic antenna to greatly enhance the antenna's gain and create a spatially diverse wireless communication environment. A multi-beam antenna can be realized using multiple ways such as a phased array, in which the input signal passes through power division and phase-shifting microwave circuitry to feed antenna elements, or a Beam Forming Network (BFN) in which the signal radiated by N antenna elements is steered by changing the input excitation port. Some examples of BFNs are the Blass Matrix [1], the Nolen Matrix [2], and the Butler Matrix [3]. The Butler matrix is a good candidate for wireless communication applications as it has equal power division between the output ports.

The Butler matrix, a fundamental component in beam-forming networks, stands as a key player in steering radio transmission beams in a phased array of antenna elements. This matrix integrates hybrid couplers, RF Crossovers, and phase shifters into one passive microwave circuit. The Butler matrix is comprised of input ports, known as beam ports, where power is applied, and output ports, referred to as element ports, to which antenna elements are connected. The operational elegance of the Butler matrix lies in its ability to distribute power to antenna elements with a gradual phase progression and a constant magnitude, effectively steering the radio transmission beam in the desired direction by employing the effects of constructive and destructive interference. This directional control is executed by selectively switching power to the intended beam port, enabling the activation of one or multiple beams simultaneously.

The inception of the Butler matrix concept dates back to 1961 when Butler and Lowe [3] introduced the foundational principles, building upon Blass's work in 1960. An inherent advantage of the Butler matrix over alternative analog beam-forming methods is its hardware simplicity, requiring significantly fewer phase shifters, and its adaptability to microstrip implementation on cost-effective printed circuit boards (PCBs). Despite the cost-effectiveness of microstrip technology, practical constraints arise with a large number of antenna elements due to the cumulative insertion losses. In such cases, alternatives such as waveguide or substrate-integrated waveguide become viable options, albeit with specific trade-offs in terms of cost, bulkiness, and design complexity.

II. THE BUTLER MATRIX

One of the main advantages of a Butler Matrix is its design simplicity. A typical Butler Matrix requires designing 3 Microwave Passive circuits, namely a Hybrid 3dB coupler, a 0dB Radio-frequency (RF) crossover, and a delay line according to the size of the Butler matrix. In the scope of this work, we are interested in developing a 4x4 Butler Matrix, hence a delay line of an electric length of 45 degrees is appropriate for such a design.

A. Hybrid 3dB Coupler

A Hybrid 3dB coupler is a 4-port microwave Passive circuit. A Hybrid 3dB coupler can be realized using a Branched Line Coupler (BLC) topology. The 4 ports of a BLC are the input port, the through port, the coupled port, and the isolated port. The input port is the port at which the input signal is excited, whilst the through and coupled ports are the output ports. An ideal Hybrid 3dB coupler divides the input signal power by two and has a 90 degrees phase shift between the through and coupled output ports such that it has the following Scattering matrix:

$$\frac{-1}{\sqrt{2}}\begin{bmatrix}0 & j & 1 & 0\\ j & 0 & 0 & 1\\ 1 & 0 & 0 & j\\ 0 & 1 & j & 0\end{bmatrix} \tag{1}$$

It can be noted that the Hybrid 3dB coupler is a reciprocal passive circuit. Furthermore, a low-loss PCB dielectric material can ensure comparable performance to the ideal Hybrid 3dB coupler with minimal changes to the calculated widths and lengths for the line impedances as specified in Fig.1. However, the implementation of the circuit on a lossy PCB calls for further tuning as the equivalent circuit will not behave as idealized. Nevertheless, the Hybrid 3dB coupler plays the most crucial role in designing a Butler Matrix as it is integral to phase shifting and dividing the input signal, in addition to being the main building block in creating the 0dB Radio-Frequency (RF) Crossover.

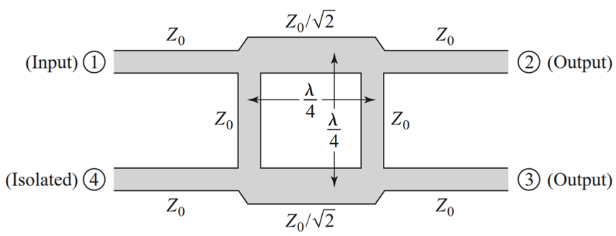


Fig. 1. Ideal Hybrid 3dB Coupler [4].

B. 0dB Crossover

A 0dB Crossover is a 4-port Microwave passive circuit that is utilized to isolate two signal paths whilst simultaneously crossing over the signal paths to alternate paths. The input signal from port 1 is transferred to port 3 and the input signal from port 4 is transferred to port 2 with no phase or amplitude change ideally to result in the following Scattering matrix:

$$\begin{bmatrix}0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\\ 1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\end{bmatrix} \tag{2}$$

Although the functionality of a 0dB Crossover can be achieved using numerous microwave circuits, the easiest way to realize a 0dB crossover is by cascading two hybrid 3dB couplers back-to-back. To complete the design of a 4x4 Butler Matrix, delay lines of an electric length equivalent to 0 degrees and 45 degrees are required. The designed lines must be of the same length as the 0dB Crossover to maintain continuity in the butler matrix layout.

C. 4x4 Butler Matrix

A 4x4 Butler Matrix has 4 input ports and 4 output ports. When one of the input ports is excited, the signal is divided into 4 equal parts with a gradual phase change according to which of the input ports is excited. Table 1 summarizes the ideal gradual phase progression experienced when each input port is excited. Some of the main parameters of interest when designing a butler matrix are the phase error, amplitude error, fractional bandwidth, and the isolation between input ports. For the purpose of this work, a 4x4 Butler Matrix will be designed and simulated using Keysight ADS with a center frequency of 2.45 GHz.

TABLE I
IDEAL 4X4 BUTLER MATRIX PHASE PROGRESSION.

	PORT 5	PORT 6	PORT 7	PORT 8	PHASE Progression
PORT I EXCITED	-90	-135	-180	-225	-45
PORT 2 EXCITED	-180	-45	90	225	135
PORT 3 EXCITED	225	90	-45	180	-135
PORT 4 EXCITED	-225	-180	-135	-90	45

III. ADS DESIGN SETUP

The 4x4 Butler Matrix centered at 2.45 GHz will be designed for a double-sided FR4 PCB with a dielectric constant =4.4, a dielectric thickness= 1.5 mm, a loss tangent= 0.03, and 1oz of copper. To Design the Butler Matrix, Keysight's ADS will be utilized. ADS allows for two types of simulations when designing microwave circuits. The first type of simulation engine is the Scattering Parameters engine in which the analysis is performed from a scattering parameters perspective which concerns currents and voltages. The second type of simulation engine is the electromagnetic-based simulation engine in which the analysis is performed by simulating how electromagnetic radiation interacts with the designed structure. The electromagnetic simulation engine solves Maxwell's equations in their different forms according to which simulation back-end is utilized.

The electromagnetic simulation engine allows for performing Method of Moments (MoM) based simulations and Finite Element Method (FEM) simulations. FEM-based simulators allow for simulating 3D structures with high accuracy, but to get accurate results, high-density meshes are required to divide the 3D structure into the polygons of choice. On the other hand, MoM-based simulators are considered 2.5D simulators as they utilize planar current simulations to extract the electromagnetic characteristics of a simulated structure. For microstrip line-based circuits, MoM simulations are ideal to use due to the planar nature of the circuits. Hence, a momentum microwave simulation will be utilized to design the 4x4 Butler Matrix. The performance of the Scattering Matrix and Electromagnetic Simulation will be compared to identify the differences between the results. The momentum microwave simulator was set up with 100 cells per the smallest wavelength in the simulation. All simulations were performed over a frequency range between 2-3 GHz to minimize the computational resources required to carry out the electromagnetic-based simulations. Of course, this inherently limits the accuracy of the simulation results compared to utilizing 100 cells per wavelength at higher frequencies. However, covering a larger frequency range increases the computational resources required to perform the simulations.

IV. ADS Design Simulations

A. Hybrid 3dB Coupler

The first passive circuit which was designed is the Hybrid 3dB coupler as the Butler Matrix is essentially based on its design. The Hybrid 3dB coupler requires microstrip lines of 90 degrees electric length with characteristic impedances of 50 ohms and 35.3 ohms respectively. The ADS tool LineCalc was utilized to calculate the respective Widths and lengths as seen in Table 2.

TABLE II
LineCalc Hybrid 3dB Coupler circuit Parameters.

Parameter	Value (mm)
Width for Z0=50	2.864
L90 for Z0=50	16.84
Width for Z0=35.3	4.917
L90 for Z0=35.3	16.39

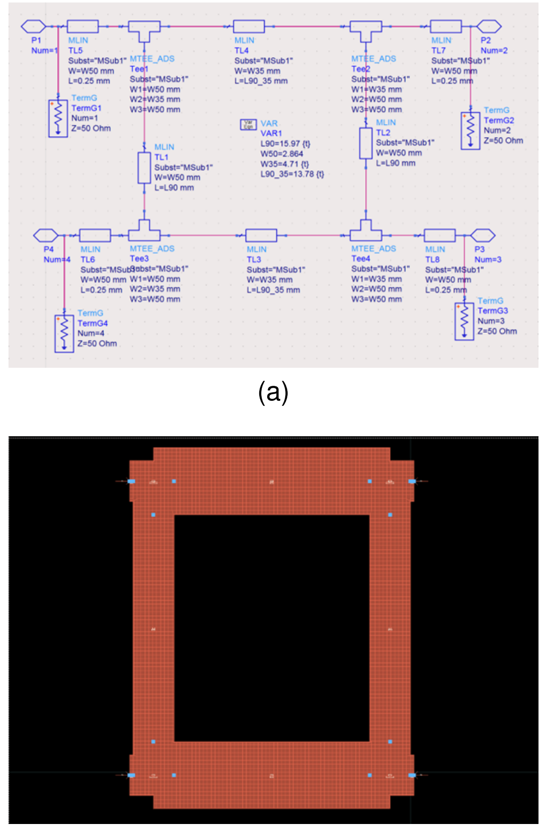
As the utilized PCB is relatively lossy, the calculated values function as rough estimates which can be used as a starting point to optimize the Hybrid 3dB coupler's performance. Hence, the calculated values were further optimized using the momentum microwave simulation results to give rise to the new values shown in Table 3. Although ADS has built-in optimization features that can be utilized to optimize a circuit for a specified performance, the optimization can only be performed for scattering parameters-based simulations. Hence, manual tuning was required to optimize the circuit design to meet the desired performance when simulated using the momentum microwave simulator.

TABLE III
Optimized Hybrid 3dB Coupler circuit Parameters.

Parameter	Value (mm)
Width for Z0=50	2.864
L90 for Z0=50	15.97
Width for Z0=35.3	4.71
L90 for Z0=35.3	13.78

The simulation circuit schematic and layout are shown in Fig.2. To enable the momentum microwave simulator to perform correct simulations, the ports of the hybrid 3dB Coupler were extended using 50-ohm microstrip lines of 0.25mm length.

The S21 and S31 simulation results of the momentum microwave and scattering parameters simulation are compared in Fig.3. It is clear that the results are affected by the type of simulation utilized. Thus, all of the reported results will be that of the momentum microwave simulations as an



(a)

(b)

Fig. 2. (a) ADS Hybrid 3dB Coupler schematic and (b) PCB Layout

electromagnetic-based simulation produces practical results. Fig.4 reports the results for the Hybrid 3dB coupler microwave momentum simulation. The simulation results are summarized in Table 4. The results indicate that the design is viable over a bandwidth of 400 MHz centered at 2.45 GHz. However, this does not reflect on the bandwidth of the final 4x4 Butler matrix. Nonetheless, the simulated hybrid 3dB coupler offers acceptable performance with a return loss as low as 39 dB and an isolation of 27 dB at the center frequency.

TABLE IV
Designed Hybrid 3dB Coupler Parameters.

Metric	Value
Center Frequency	2.45 GHz
Bandwidth	400 MHz
Insertion Loss	$<$ 4.1 dB
Return Loss	$>$16.5 dB
Isolation	$>$15.9 dB
Phase Shift between Port 2 and 3	90.97 +/- 2.7 degrees

B. 0dB Crossover

The 0dB crossover can be realized using multiple microwave circuits. The main requirement is to isolate two signals whilst simultaneously rerouting the signals' paths. Fig.5 shows the designed 0dB RF crossover schematic. An RF crossover would ideally have 0dB insertion Loss and no phase

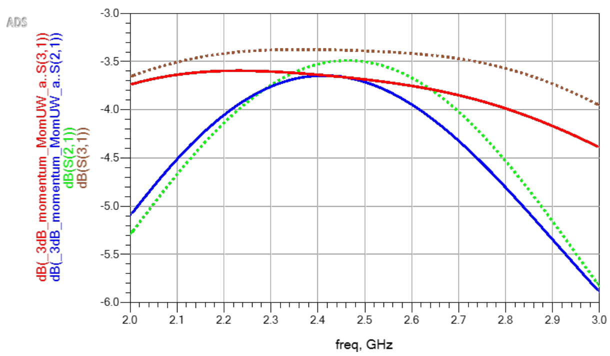


Fig. 3. Hybrid 3dB Coupler Simulation Comparison with the dotted line representing the scattering parameters based simulation and the solid line the momentum microwave simulation.

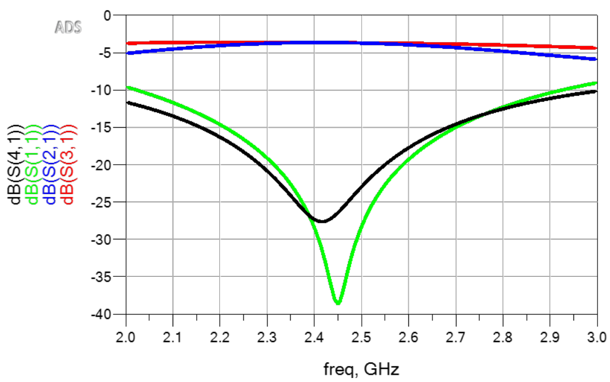


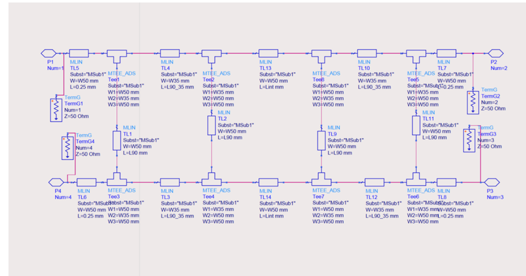
Fig. 4. Hybrid 3dB Coupler Scattering Parameters.

TABLE V
DESIGNED 0DB CROSSOVER PARAMETERS.

Metric	Value
Center Frequency	2.45 GHz
Bandwidth	400 MHz
Insertion Loss	<1.8 dB
Return Loss	>11.1 dB
Isolation	>17.7 dB

change between ports 1&3 and 4&2. However, the designed 0dB crossover has some insertion loss as summarized in Table 5. The RF crossover is centered at the design frequency 2.45 GHz with 0 degrees of phase change, but it exhibits a linear phase change for the frequency range between 2-3 GHz with an insertion loss of less than 1.8 dB for a bandwidth of 400 MHz centered at 2.45 GHz. The scattering parameters of the 0dB crossover are summarized in Fig.6.

The final components in the Butler Matrix are the Phase controlled lines. The construction of a 4x4 Butler Matrix requires the design of two phase controlled lines with the same length as the designed 0dB Crossover. The 0dB Crossover has a total length of 51.47mm which will also correspond to the length of the delay lines. The first delay line has an equivalent electric length of 0 degrees, whilst the second delay line has an equivalent electric length of 45 degrees. The two lines were designed and simulated using the momentum



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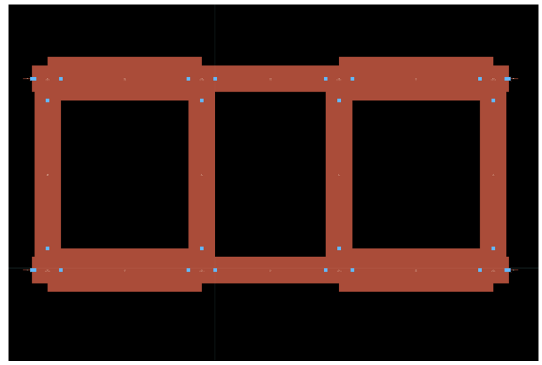

(b)

Fig. 5. (a) ADS 0dB Crossover schematic and (b) PCB Layout

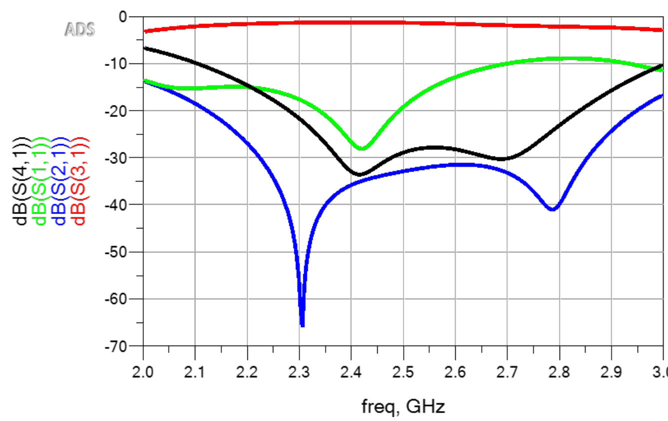

Fig. 6. 0dB Crossover Scattering Parameters.

microwave simulator and the results are summarized in Table 6. The results indicate good performance with a somewhat over-exaggerated insertion loss due to the lossy PCB.

TABLE VI
PHASED LINES PARAMETERS.

Metric	0 Degrees Line	45 Degrees Line
Center Frequency	2.45 GHz	2.45 GHz
Insertion Loss	0.95 dB	1.1 dB
Return Loss	22.8 dB	17.3 dB

V. Butler Matrix Simulation

The previous section discusses the design and simulation of each of the passive circuits required to build up a 4x4 butler matrix. Ideally, combining all of the aforementioned circuits would result in a 4x4 Butler matrix with -45, 135, -135, and 45 degrees of output phase progression when ports 1,2,3, and 4 are excited respectively. Fig.7 shows the final 4x4 Butler Matrix layout measuring 19x8 cm.

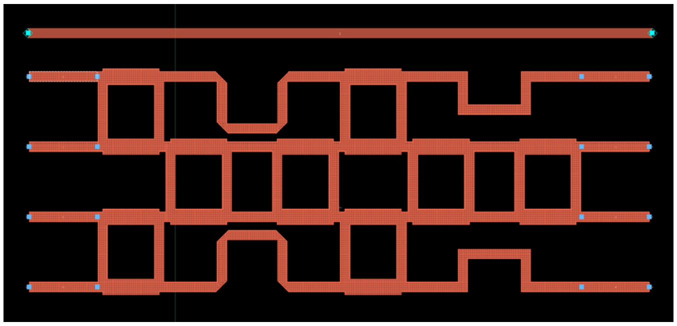

Fig. 7. Butler Matrix PCB Layout.

A momentum microwave simulation was performed on the full circuit to evaluate its performance. Table 7 shows the amplitude in dB of the output signal at each of the output ports from 5-8 when a signal is excited at any of the input ports 1-4. The results indicate a somewhat consistent amplitude with an amplitude imbalance of 0.3 dB at a maximum. Further, Table 8 reports the phase of each output port and the average phase progression between each consecutive output port. The results indicate that the average phase progression is somewhat consistent with the ideal phase progression and that the deviation from the ideal phase progression is less than 4 degrees for any given two ports.

TABLE VII
4x4 Butler Matrix output amplitude at 2.45 GHz (dB).

	PORT 5	PORT 6	PORT 7	PORT 8
PORT I EXCITED	-9.92	-10.2	-9.79	-10.13
PORT 2 EXCITED	-9.85	-10.1	-9.8	-10.23
PORT 3 EXCITED	-10.23	-9.8	-10.1	-9.85
PORT 4 EXCITED	-10.13	-9.79	-10.2	-9.92

TABLE VIII
4x4 Butler Matrix output phase at 2.45 GHz (degrees).

	PORT 5	PORT 6	PORT 7	PORT 8	Phase Progression
PORT 1 EXCITED	-102	-143.3	171.8	127.5	-43.5
PORT 2 EXCITED	167.9	-54.4	78.1	-143.8	136
PORT 3 EXCITED	-143.8	78.1	-54.4	167.9	-136
PORT 4 EXCITED	127.5	171.8	-143.2	-101.9	43.5

Furthermore, the results indicate acceptable performance over a frequency range between 2.36 GHz and 2.67 GHz with an insertion loss deviation of 1.5 dB across all output ports. Fig.8 shows the reported scattering parameters. It can be noted that due to the inherent symmetry of the 4x4 Butler Matrix, it is sufficient to report the insertion loss when the signal is excited at ports 1 and 2 only, and the return loss for ports 1 and 2 only. Moreover, Fig.9 shows the output ports' phase difference when ports 1 and 2 are excited vs frequency, and it indicates that the Butler matrix maintains acceptable performance over the claimed bandwidth. Lastly, the reported results are based on the momentum microwave simulations, and a simulation of the same circuit using the scattering parameters simulator results in an insertion loss drop of 1dB, and an increase in all phase progressions by 4 degrees. Consequently, the proposed 4x4 Butler matrix design can be utilized to achieve a beam-forming network operating at 2.45 GHz.

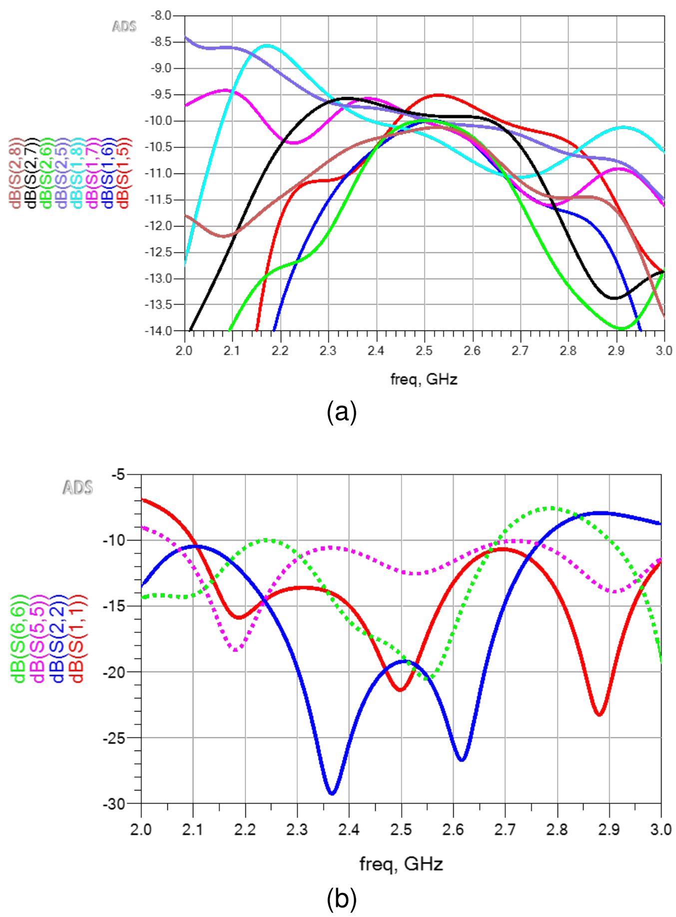

Fig. 8. (a) 4x4 Butler matrix Insertion losses and (b) Reflection Coefficients

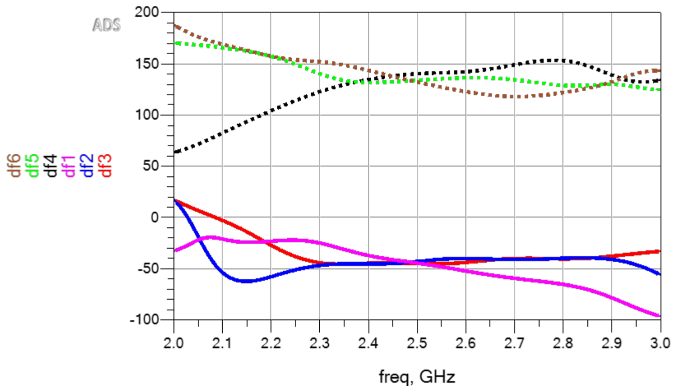

Fig. 9. Butler Matrix Phase difference with the dotted line representing the phase difference between the output ports when port 2 is excited, and the solid lines when port 1 is excited.

VI. Conclusion

The reported design performs relatively well over a narrow frequency bandwidth of 300 MHz as summarized in Table 9. Nonetheless, the designed butler matrix meets the minimum requirements to function as a beam-forming network with a linear amplitude and phase relationship. One of the main limiting factors that exponentially increases the complexity of the design is the utilization of a lossy PCB dielectric material. As a result of the high-loss tangent, the results of the scattering parameters simulation significantly deviate from that of the momentum microwave simulator. Hence, the design optimization procedure becomes much more complex. This could have been solved by creating an ADS schematic-based electromagnetic simulation, but this greatly increases the time required to optimize the design as the electromagnetic simulation is computationally expensive.

TABLE IX
(4x4 Butler Matrix Simulation Results

Metric	Value
Operating Frequency	2.36-2.67 GHz
Bandwidth	310 MHz
Insertion Loss	9.5-11 dB
Return Loss	>11 dB
Isolation	>14 dB

Furthermore, it is apparent from the results that the input and output impedances of the designed circuits are not 50 ohms as the loading effect of each circuit affects the overall Butler Matrix design. Hence, the design requires further optimization to accommodate this and ensure that the input and output impedances of each individual passive circuit of the Butler Matrix are close to 50 ohms at 2.45 GHz. Furthermore, one of the main limitations faced is that accurate simulations were not accessible during the simulation phase. To perform much more accurate FEM and momentum microwave simulation, the computational resource requirements and simulation time increase exponentially which renders such simulations inefficient when optimizing such a design. Nevertheless, the designed 4x4 Butler Matrix somewhat meets the desired performance, and the design only requires fabrication for physical testing using a vector network analyzer.

Acknowledgment

N/A

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