Butler Matrix Miniaturization for 5G Communications and Beyond

Capstone Project Final Report

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Abstract:

This capstone project presents a miniaturized implementation of the Butler's beamforming array on microstrip technology. Firstly, basis size reduction is obtained by the development of structure that behaves exactly as the quarter-wave transmission line segment at the operation frequency. Secondly, this structure is applied to reduce the area of higher order components such as 3dB hybrid coupler and crossover. Then, the components are assembled into the layout of Butler Matrix where several components are reduced in size further. The obtained final structure takes up approximately two times lesser area at the cost of 20% theoretical bandwidth reduction. 4-by-4 experimental setup is developed for validation at 2.5 GHz which corresponds to the lower 5G frequency band.

Contents

Preface

The main beneficiaries of the project's development are the users of the next generation communication network. Because, the reduction in size of the Butler matrix is one of the crucial factors which influence the final price of the 5G establishment and commercial use. Additionally, the manufacturers that focus their business on the production of components needed for the 5G's frontend part benefit from the size reduction because it lowers the prices of transportation, thus decreasing the final cost.

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Chapter 1

Introduction

5G is the latest communication systems' generation which allows new different concepts to be implemented such as IoT, cloud computing and etc. These opportunities of implementation mainly come from its core principles such as beamforming, edge computing and application of mm-wave frequencies. The first concept is likely to be implemented by the circuit-type beamforming networks. The communication technology which is responsible for beamforming implementation is called massive Multiple-Input-Multiple-Output (MIMO) and one of its realizations includes combination of analog and digital circuits, where digital part is responsible for control and analog part is needed for beam steering using phase shifting. This technique is named as hybrid beamforming (HPF) and it has a great potential to become a massive and cost-effective solution for 5G.

There is a great motivation supporting this project's aim, because circuit-type beamforming might be the greatest solution due to low cost and power consumption which is necessary for 5G's development all over the world [1]-[2]. Specifically, Butler configuration is theoretically lossless and applies lesser number of components to realize compared to other beamforming matrices. Reduction of its size may decrease its cost, weight, and fit the space constraints of the system in which it is applied [1]-[2]. This solution is possible in the frames of HBF under massive MIMO, the technique which combines analog and digital beamforming for the sake of reduced power consumption and network complexity [3]-[4]. Furthermore, evaluation and detection accuracy for Butler matrix based massive MIMO is one of the most promising methods in achieving higher efficiency, robustness and adaptivity under different values of signal-to-noise ratio (SNR) [5].

Chapter 2

Background

There are different approaches taken to reduce the size of the Butler network such as:

1. The replacement of the quarter wavelength transmission line segments with the stepped impedance lowpass filters with approximately the same frequency behavior but significantly lower physical dimensions [6]. According to the authors, the reduction of 60.6% is achieved in terms of layout's area in exchange for the 5% of the operation bandwidth. The analysis of the circuit is based on the equivalence of the transmission matrices of both networks. As the analysis is performed, needed parameters of stepped impedance filter's parameters are obtained and substitution is examined for similarity of the frequency responses. The measured and simulated values of insertion and return losses correspond to each other within slight errors range.

2. Combination of the filtering and phase distribution stages of the system's frontend within the Butler matrix itself using the filtering 180 degrees hybrid couplers [7]. The structure of the Butler matrix is preserved in general, but new filtering hybrid couplers are substituted instead of the conventional couplers. The structure of the filtering coupler consists of 4 resonators which provide phase shift, power split and bandpass response. The theoretical analysis is done on equivalent lumped circuit representation from the input admittance point of view. The simulated and practical results agree with each other well in range of permissible manufacturing errors.

3. Reducing the dimensions of each separate components of Butler matrix such as branch line couplers, phase shifters and crossovers [8]-[9]. Some authors applied the concept of artificial transmission line to decrease the area occupied by the branch line couplers, so the overall dimensions of the Butler matrix reduce [3]. The concept of artificial transmission line is similar to the stepped impedance realization of the network; however, the transmission line segments are connected in parallel to the line connecting two ports, not in series as in the first case. Al-

though overall length of lines is higher, it can be intelligently folded into sections which occupy less area. Furthermore, the application of phase shifters in Butler matrix can be unnecessary if the branch line couplers applied in construction provide 45-degree phase shift instead of 90 or 180 [10]. The authors developed such kind of phase shifter and reduced the size of the matrix layout. Additionally, the phase shifting is implemented using Schiffman's phase shifter, the coupled line configuration which is an all-pass filter which provides phase shift at the end of the network and has a lower main length [9].

Reduction of components' size is in a particular interest here. There are three main microwave components which are applied in Butler Matrix design: crossovers, branch line couplers, and phase shifters

In [11], authors developed complex structure to decrease the size of the 4-port crossover. Obtained structure consists of open-ended and cascaded transmission lines which align the area evenly over given space. Authors of [12] proposed S-type structure to replicate the behavior of crossover, Designed architecture is less complex, however it inherits the issues of the previous structure with reduced bandwidth. Crossover in [13] is the simplest in connections and essentially repeats the scheme of conventional one. Area is decreased by the means of intelligent allocation of vertical transmission line segments.

Branch line coupler design of lesser area consumption is developed in [14] and the architecture is novel in the sense that it applies slow wave structures which approximate the bahavior of the equivalent circuit, which is also reported. Similarly, in [15], authors came up with the structure which is more familiar in terms of transmission line representation, but with microstrip resonators acting as a capacitive elements ([16], [17], [18]).

Reduction of components' size is in a particular interest here. In [18], coupled-lines and open stubs based microstrip crossover is developed with reduced size based on second order even-odd mode analysis. The main feature of proposed architectures is that they use even-odd mode analysis - an essential tool in designing multiport networks ([19], [20]).

On top of that, there are many solutions which involve different realizations with substrate integrated waveguides, microstrip lines, etc. and each of them involve different type of analysis. Each realization type can find its need with respect to the conditions at which circuit is to be implemented, therefore research for each implementation is needed.

To sum up, there are many different ways and possibilities of matrix's size reduction and research is still being done, therefore further research is still needed.

Chapter 3

Methodology

3.1 Microwave Analysis Techniques

To reduce any circuitry in size, it is essential to preserve the behavior of circuit at the operation bandwidth. Approaches discussed in this document are mainly inspired by the approximation of either transmission or scattering parameters [8]-[15].

3.2 Simulation and Validation

To perform and optimize the behavior of proposed solutions, numerous software tools were applied, such as, Wolfram Mathematica, MATLAB, Desmos Graphs, and Keysight's Advanced Design System.

Chapter 4

Theoretical Analysis

4.1 Synthetic Transmission Line

Both Crossover and 3dB Hybrid Coupler require transmission line (TL) segments of quarter-wave length of different impedance. The figure below describes the architecture which is capable of behaving as the quarter-wave transmission line (QWTL) of $Z\Omega$ characteristic impedance:

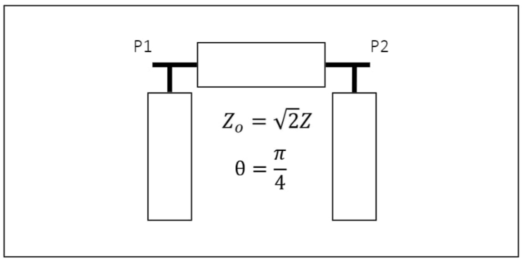

Figure 4.1: Synthetic QWTL

Considering the transmission parameters of the proposed network with each individual stub having characteristic of $\sqrt{2}Z$:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{1}{-j\sqrt{2}Z\cot(\theta)} & 1 \end{bmatrix} \begin{bmatrix} \cos(\theta) & j\sqrt{2}Z\sin(\theta) \\ \frac{j\sin(\theta)}{\sqrt{2}Z} & \cos(\theta) \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{1}{-j\sqrt{2}Z\cot(\theta)} & 1 \end{bmatrix} \tag{4.1}$$

After simplification process, it is apparent that:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = |\theta = \frac{\pi}{4}| = \begin{bmatrix} 0 & jZ \\ \frac{1}{jZ} & 0 \end{bmatrix} \tag{4.2}$$

From (4.2), it is apparent that architecture performs absolutely the same as a QWTL of Z characteristic impedance. Moreover, by analyzing ABCD parameters of

(4.2) and comparing them with transmission parameters of QWTL near frequency of operation, it can be seen that they are very close to each other. This gives a great degree of approximation which is implemented for size reduction.

4.2 Reduced-size 3dB Hybrid Coupler

3dB Hybrid Coupler for input impedance of 50Ω is shown in Fig.-4.2.

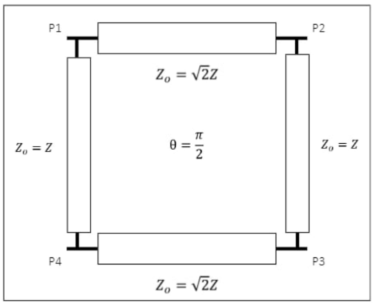

Figure 4.2: Classic 3dB hybrid coupler

After replacing the QW TL with their imitation, new network appears as described in Fig.-4.3.

Open-ended stubs at the port nodes can be combined according to their equivalent input impedance. This impedance can be described by the open-ended stub but with different characteristic impedance, specifically:

$$Z_{stub} = -j\frac{\sqrt{2}}{1+\sqrt{2}}Z\cot(\theta) \tag{4.3}$$

After replacing eight corner open stubs with the equivalent, following reduced-size network is obtained (Fig.-4.4).

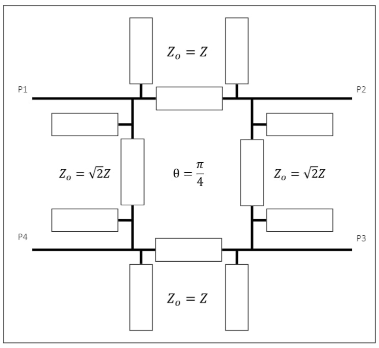

Figure 4.3: Reduced 3dB hybrid coupler

When it comes to the consumed area, reduced network saves 25% of the space occupied by the classic hybrid.

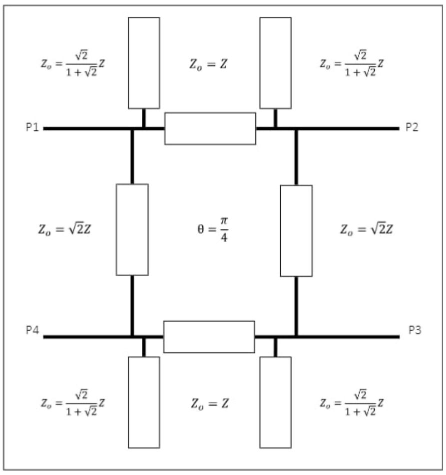

Figure 4.4: Further reduced 3dB hybrid coupler

4.3 Reduced-size Crossover

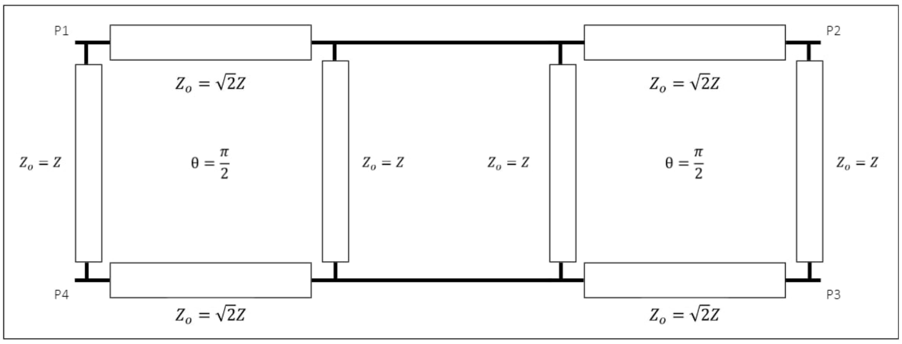

Figure 4.5: Classic crossover

Fig.-4.5 presents two hybrids cascaded which behaves the microwave crossover. The network can be reduced, because there are two identical transmission line segments in the middle. Specifically, transmission parameters of two such networks in parallel look as follows:

$$\begin{bmatrix} A_n & B_n \\ C_n & D_n \end{bmatrix} = \begin{bmatrix} A & \frac{B}{2} \\ 2C & D \end{bmatrix} \tag{4.4}$$

From (4), it is apparent that TLs in the middle can be replaced with one which has characteristic impedance of 25Ω (Fig.-4.6).

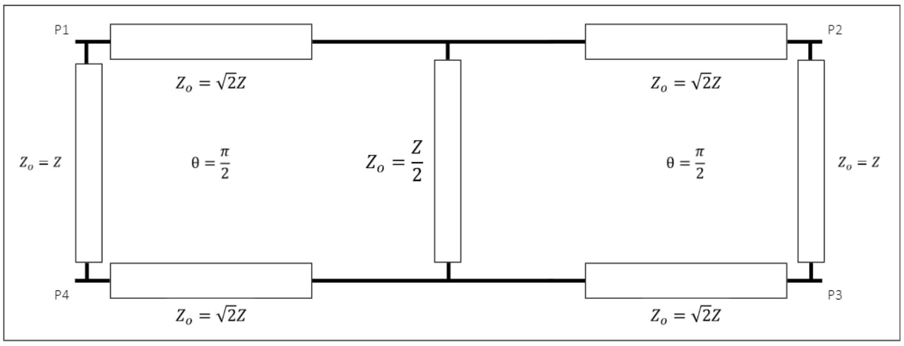

Figure 4.6: Reduced Classic crossover

After replacement of each QW TL with its imitation, network from Fig.-4.7 appears and it can be further reduced by replacing open-ended stubs with their input impedance equivalent.

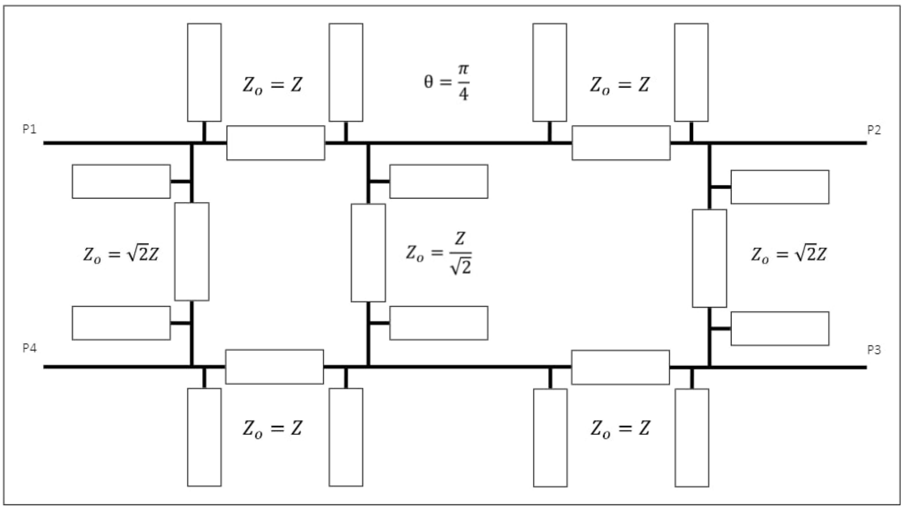

Figure 4.7: Reduced Classic crossover

Final reduced network is shown in Fig.-4.8 and consumed area reduced to about 75%.

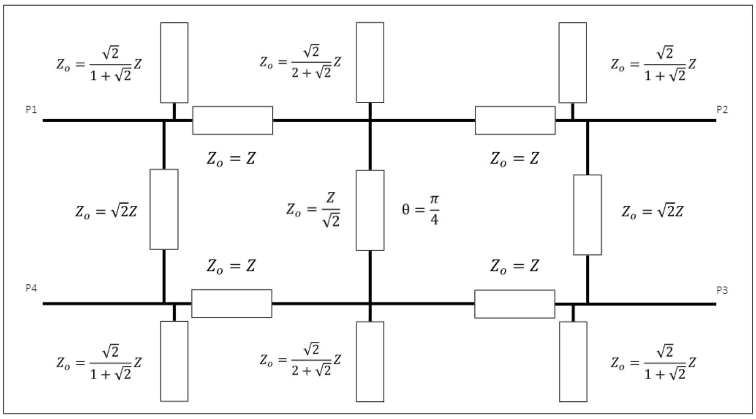

Figure 4.8: Reduced Classic crossover

4.4 Reduced-size Butler Matrix

Combining the reduced size hybrid and crossover, reduced size Butler Matrix is obtained and its size is compared to the classic butler matrix topology in Fig.-4.10. In that figure reduced Butler Matrix is not ensembled completely for easier observation purposes and it is possible to physically realize and push reduction further by clever microstrip design.

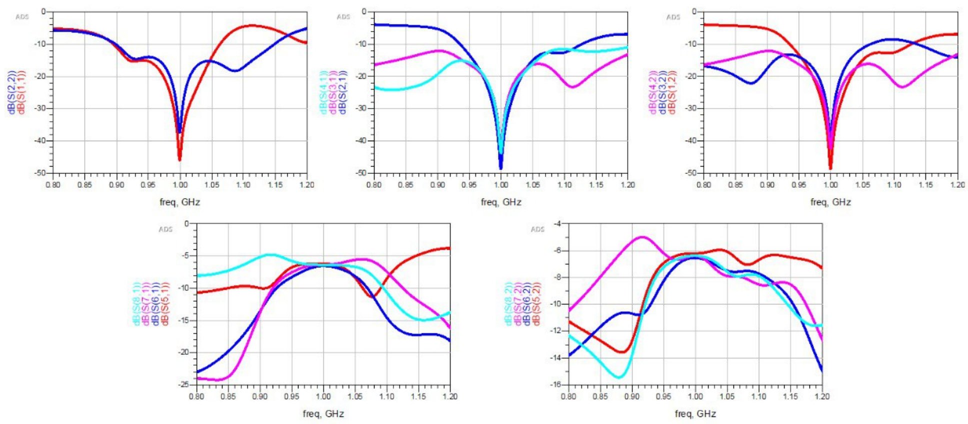

Figure 4.9: Theoretical Scattering Parameters of the Classic Butler Matrix Implementation vs. Frequency

Finally, Fig.-4.9 presents S-parameters of classic network from upper-left corner input port. It is apparent that reduced matrix performs very similar to the classic one but with reduced bandwidth. This tradeoff comes with possibility of maximum area reduction by 50% which can be accomplished with intelligent component placing during design implementation.

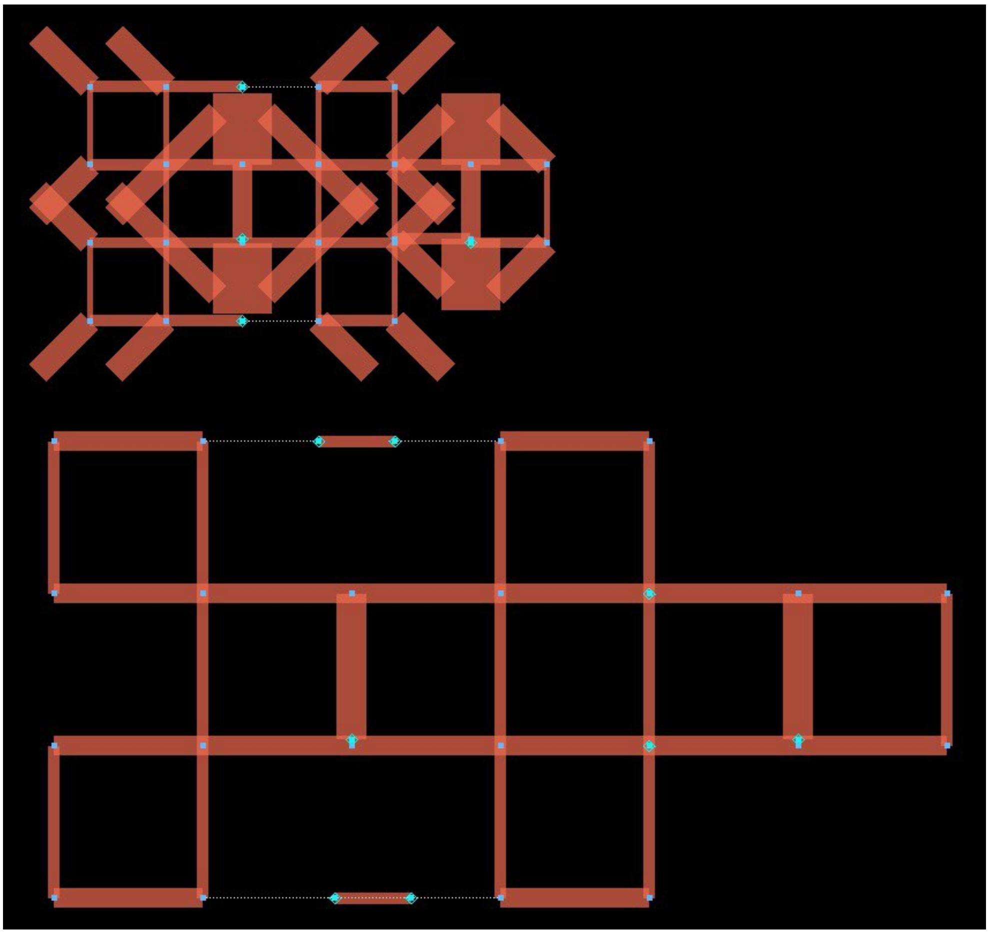

Figure 4.10: Layout representation of theoretical reduced-size Butler Matrix and its classical implementation

Chapter 5

Experimental Validation

5.1 Implementation of schematic

First of all, it is necessary define specification for the size-reduced Butler Matrix implementation to realize the design.

The operation frequency of 2.5 GHz was chosen since it corresponds to the upper bound for the 5G lower band. The substrate is implemented on FR4 substrate board using microstrip technology. The design impedance Z from the schematic is chosen to be standard 50Ω.

5.1.1 Approximation of the Open-Stub Impedance

Previously developed theoretical layout has physical limitations, specifically transmission lines cross each other. To overcome this issue, it is essential to substitute wide lines with more compact components which will be making slight impact on the practical performance.

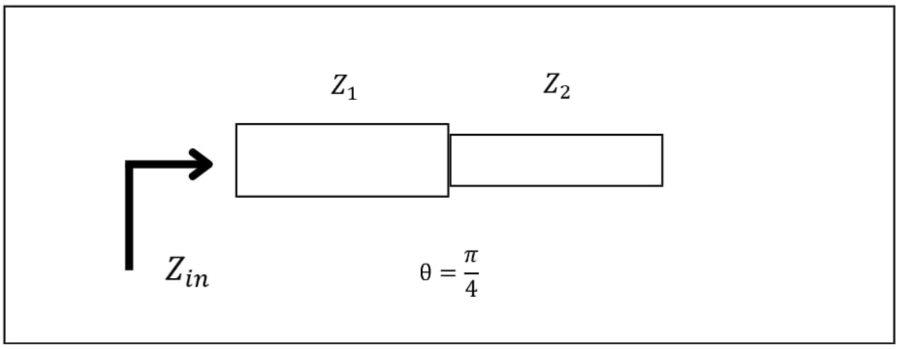

Figure 5.1: Open-stub equivalent

It is clear that the are still several open-ended stubs at the same node after connection of the reduced components. They are also combined before development of the physical layout to achieve lesser area consumption.

Great physical dimension of the transmission line is associated with its low characteristic impedance. To implement the layout, we need to find implementable change for 14Ω and 29Ω transmission lines. Input impedance of two cascaded and open-ended transmission lines from Fig.-5.1 at operation frequency can be represented as follows:

$$Z_{in} = Z_1 \frac{Z_1 - Z_2}{Z_1 + Z_2} \tag{5.1}$$

From (5.1), it is apparent that for 14Ω open-ended stubs can be replaced with the structure at Fig.-5.1 with Z_1 equal to 118Ω and Z_1 equal to 150Ω. The same substitution is applied for 29Ω with Z_1 equal to 66Ω and Z_2 equal to 150Ω.

5.1.2 Design Layout

Although substitutions have allowed transmission lines to be thinner, they increased in longitudinal dimension. However, this outcome does not make the implementation physically impossible, since the substitutions can be bent to fit within the open space areas of the matrix. To minimize the disturbance of physical layout's final performance, the following design rules are followed:

- The distance of separation between every pair of parallel lines is kept to be at least 5mm.
- Circular bending is preferred over right angle bend and mitered corner whenever it is possible to reduce reflections.
- Each miniaturized component like 3dB hybrid and crossover should be designed separately to improve the overall performance

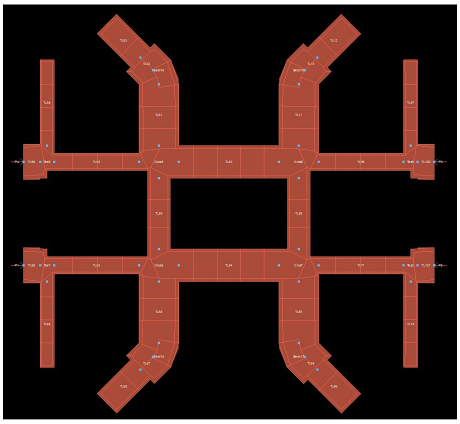

Figure 5.2: Reduced-size 3dB Hybrid

Thus, after optimization process the following components are obtained for miniaturized Butler Matrix assembly are reduced-size 3dB hybrid and crossover. Their estimated theoretical performance is also given at Fig.5.3 and Fig.5.5 respectively.

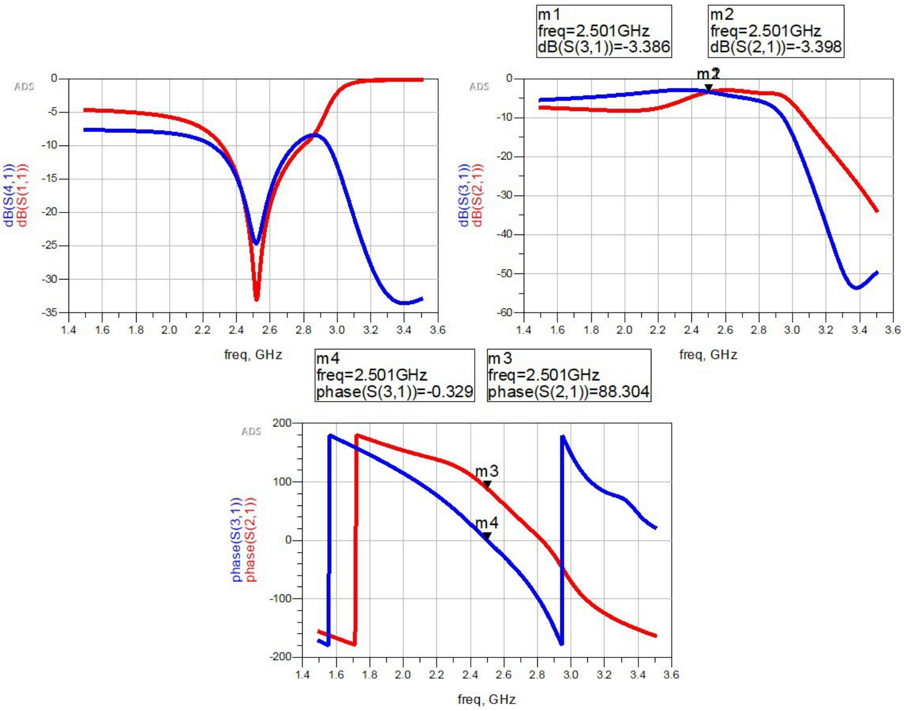

Figure 5.3: Theoretical performance of reduced-size 3dB hybrid

From Fig. 5.3, it is observed that isolation between the input ports has been reduced and reflection from each port minimized significantly. The respective phase response is also improved to the theoretical level.

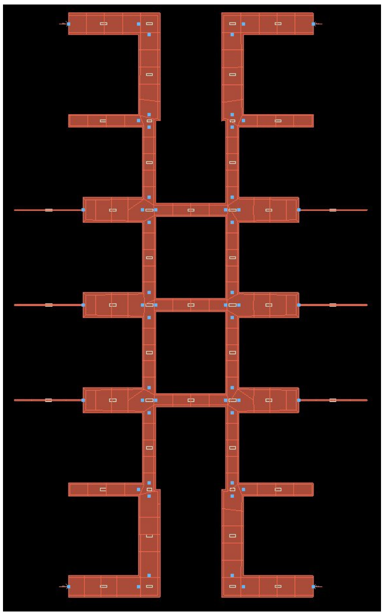

Figure 5.4: Reduced-size crossover

When it comes to the miniaturized crossover, the obtained performance turned out to be less isolated between non-output ports which results into lesser operation bandwidth. However, at the operation frequency (Fig.-5.5) the transmission between input port 1 and output port 3 is maximized.

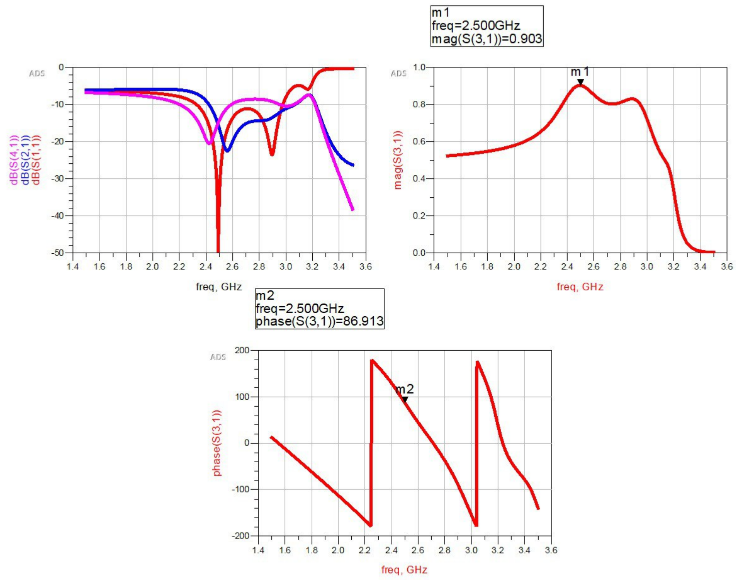

Figure 5.5: Theoretical performance of reduced-size crossover

Developed components are then assembled into the Butler Matrix architecture with standard 45 degree phase-shifter made with mitered corners:

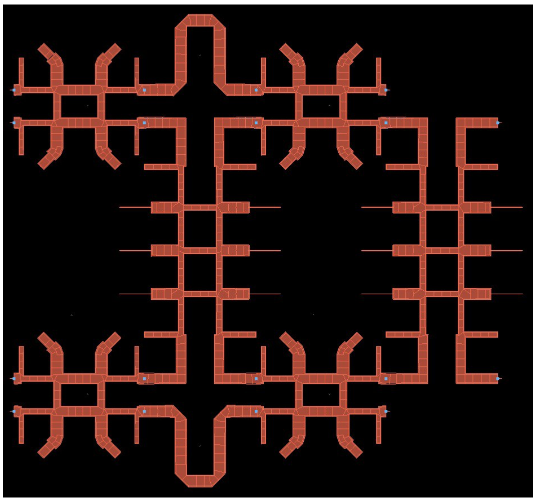

Figure 5.6: Layout of the reduced size Butler Matrix

The isolation between ports input-ports and return loss of each port achieve -20dB level at minimum.

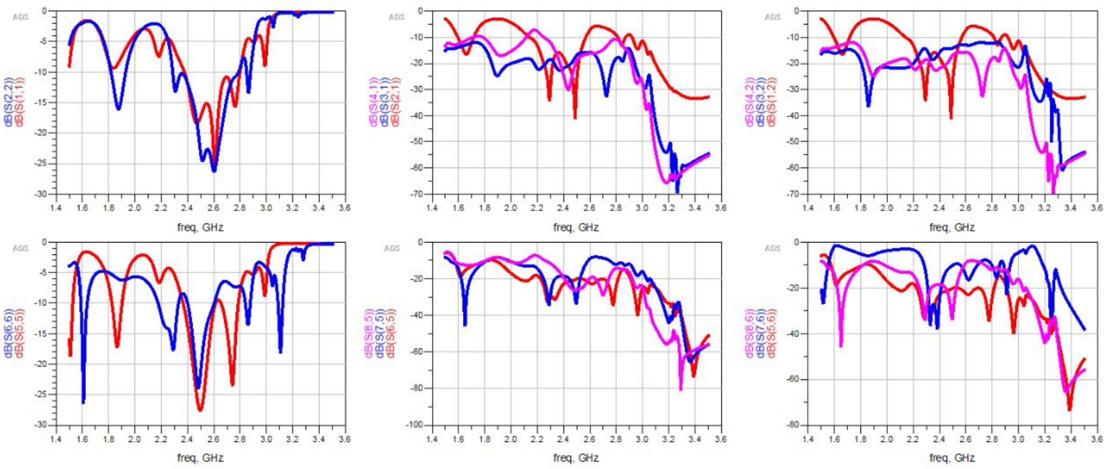

Figure 5.7: Theoretical isolation between input ports and return loss of the reduced size Butler Matrix

Since architecture has to split input power into 4 equal parts, the desired response at the output-ports ideally has to be -6dB. As can be seen from figures above, structure achieves slightly different values at the level the most practical simulation.

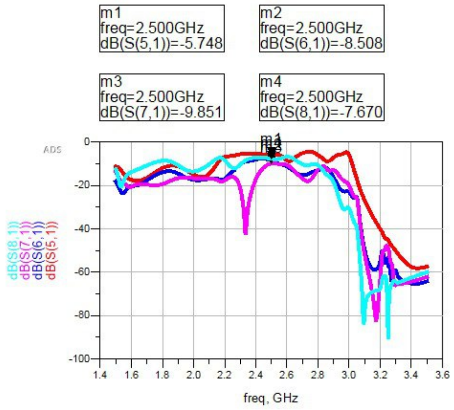

Figure 5.8: Theoretical return loss of the input ports

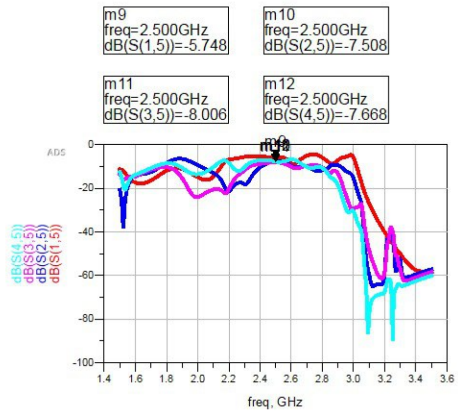

Figure 5.9: Theoretical return loss of the output ports

The S-parameters of the obtained network are very close to the behavior of the classic implementation of Butler Matrix. However, occupied area is reduced to 42%.

5.2 Experimental Results

From previously developed realizable layout, the practical setup has been implemented on the FR4 board as follows:

The structure then was tested with vector network analyzer (VNA) under 50Ω terminations at the ports which come from the special caps attached to SMA ports.

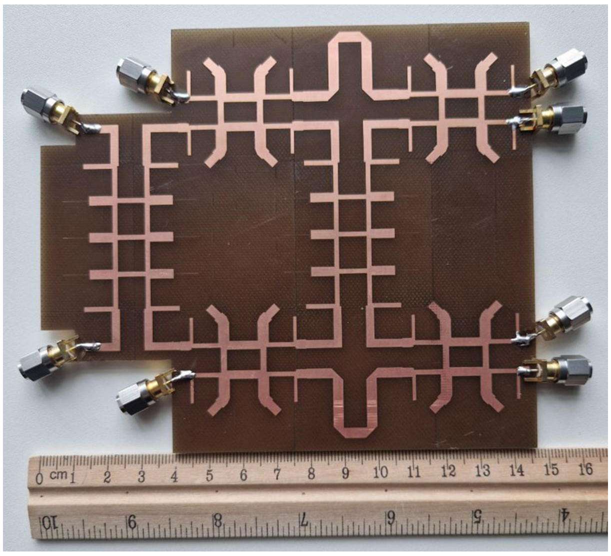

Figure 5.10: Physical realization of the reduced size Butler Matrix

5.2.1 Practical Scattering Parameters

The observed practical response has been collected from VNA and plotted using MATLAB software as follows:

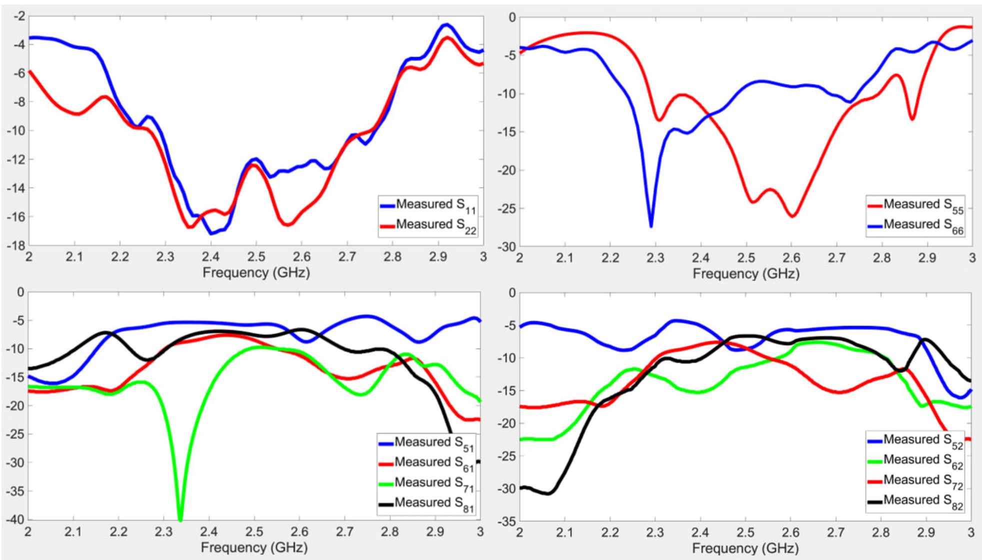

Figure 5.11: Practical S-parameters of the physically realized reduced-size Butler Matrix

Although experimental results diverge from the predicted results slightly, they agree within the general trends observed during theoretical simulation process.

Regarding the overall size reduction achieved by the practical setup, incomplete layout of classic Butler Matrix is created for the sake of comparison. The final area of the rectangle inscribing classic circuit is approximately 26000 mm^2 (184mm by 141mm), whereas the area of the developed implementation is about 15000 mm^2 (107mm by 140mm). Thus, the size reduction of almost 42% is achieved.

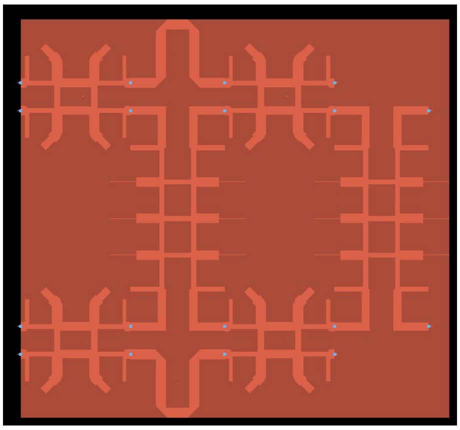

Figure 5.12: Microstrip layout of the reduced-size Butler Matrix

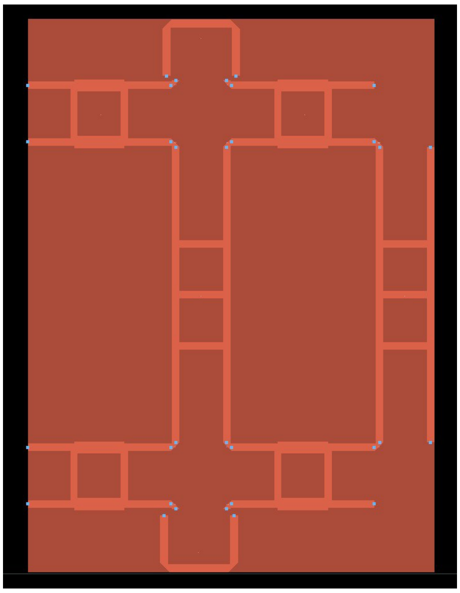

Figure 5.13: Microstrip layout of the incomplete classic Butler Matrix

Chapter 6

Conclusion

This project presented the technique for the miniaturization of classic Butler Matrix implementation. The theoretical derivation has been given and based on the presented reduced-size QW TL miniaturized 3dB hybrid and crossover were developed. Finally, these theoretical results have been verified through the practical implementation of the reduced size Butler Matrix. The experimental results reveal that the developed technique can be implemented and more accurate performance can be achieved through improving the layout design further.

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