Abstract—This paper describes the design and implementation of 4x4 Butler matrix. The design specification is at 3.5 GHz. Small and easy to fabricate microstrip layout topology for the 4x4 Butler matrix have been designed and constructed relying on a low cost dielectric material, the well-known FR4. The compactness of the system is depending on the design of Branch-line Coupler. Design of Branch-line coupler is discussed and simulation results are also presented. The simulation and fabrication results will be compared and discussed.

Index Terms—Butler matrix, Branch-line coupler.

I. INTRODUCTION

The Butler matrix is a type of beam-forming network. Depending on which of N inputs is accessed. The antenna beam is steered in a specific direction in one plane. It performs a similar function to a Rotman lens, or a phased array antenna system.

The Butler matrix was first described by Jesse Butler and Ralph Lowe in [1]. This is a passive reciprocal network, so it works the same when it transmits energy as when it receives energy. The basic properties of a butler matrix are isolation between input and output, linearity in phase with respect to the position of output and the increment in phase depending upon the selection of input. Another capability of a Butler matrix is it can steer a beam with magnitude and fixed phased. The ADS2009 is used to simulate the design. The material specification for FR4 board with the dielectric constant 4.4, substrate thickness 1.57mm and tangent loss is 0.023.

II. DESIGN PROCEDURE

The Butler matrix consists N input with N output port. The design of Butler matrix constructed by combined of hybrid coupler, phase shifter and crossover. The figure 1 illustrated diagram of Butler matrix.

The governing equations in the form of matrix for butler matrix shown in figure 1 are as follows:

\[
\begin{bmatrix}
2R \\
1R \\
1L \\
2L \\
\end{bmatrix} = \begin{bmatrix}
0 & -135 & 90 & -45 \\
0 & -45 & -90 & 135 \\
0 & 45 & 90 & -135 \\
0 & 135 & -90 & 45 \\
\end{bmatrix} \begin{bmatrix}
A_1 \\
A_2 \\
A_3 \\
A_4 \\
\end{bmatrix}
\]

Figure 1: 4x4 Butler Matrix block diagram

The hybrid coupler creates the 90° phase shift at the output port. The crossover is done by cutting the ground plane and taking the connection from there. This works as a jumper and provides required isolation between cross points.

Design of Branch-Line Coupler:

The T-model of a quarter wavelength transmission line can be given is shown in figure 2. Various impedances can be calculated by using following equations.

\[
Z_a = \frac{Z_0}{\tan \theta_a}
\]

\[
Y_{ab} \tan \theta_b = \frac{2}{Z_a \tan 2\theta_a}
\]
The branchline coupler or quadrature hybrids are well known device used to generate signals 90 degree out of phase at its output. The analytical S parameters of this quadrature hybrid are:

\[
S = \frac{-1}{\sqrt{2}} \begin{bmatrix}
0 & j & 1 & 0 \\
j & 0 & 0 & 1 \\
1 & 0 & 0 & j \\
0 & 1 & j & 0
\end{bmatrix}
\]

The power applied at a port is evenly distributed between the ports located on the opposite side of the coupler. There is a 90 degree phase difference between these two ports; the port closer to the input port is leading in phase by 90 degrees. The port located on the same side as the input port is isolated since there is no power reaching it.

In the designing of branch-line coupler each quarter wavelength transmission line is replaced with its equivalent T-model. Figure 3 shows the branch-line coupler design at the center frequency of 3.3 GHz. Choosing \( \theta_1 \) and \( \theta_2 \), \( Z_3 \) and \( Z_4 \) to be 30\(^\circ\), 35\(\Omega \) and 30\(\Omega \) respectively. Thus \( Z_1, Z_2, 03 \) and 04 can be derived by above shown equations. These come out to be 61.17\(\Omega \), 86.41\(\Omega \), 33.45\(\circ\) and 21.85\(\circ\) respectively.

**Design of crossover:**

Crossover is done by making a slot in the ground plane

In the simulation of crossover ground plane is taken as closed plane and a slot is drawn to differentiate the ground and conductor (providing connection between the cross points).

The 45\(^\circ\) phase shift is provided by a quarter wavelength transmission line. This makes the design simpler and easy to fabricate.

The complete layout of the 4x4 Butler matrix is shown in figure 5.

**Simulation Results**

Simulation results are shown in following figures. These results are extracted from the Agilent ADS 2009. During the simulation of cross the ground plane is kept closed and during branch-line coupler ground plane is kept open.
Following tables dictates the simulated results of Branch-line coupler and crossover.

**Table 1:**
**Branchline coupler:**
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Magnitude (dB)</th>
<th>Phase (Degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S11</td>
<td>-28.674</td>
<td>57.02</td>
</tr>
<tr>
<td>S12</td>
<td>-3.39</td>
<td>-162.027</td>
</tr>
<tr>
<td>S13</td>
<td>-3.79</td>
<td>110.64</td>
</tr>
<tr>
<td>S22</td>
<td>-29.067</td>
<td>57.519</td>
</tr>
</tbody>
</table>

**Table 2:**
**Crossover:**
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Magnitude (dB)</th>
<th>Phase (Degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S11</td>
<td>-26.567</td>
<td>-97.063</td>
</tr>
<tr>
<td>S12</td>
<td>-16.809</td>
<td>-66.171</td>
</tr>
<tr>
<td>S13</td>
<td>-0.256</td>
<td>-137.284</td>
</tr>
<tr>
<td>S14</td>
<td>-16.896</td>
<td>-58.394</td>
</tr>
<tr>
<td>S22</td>
<td>-39.558</td>
<td>-9.149</td>
</tr>
<tr>
<td>S23</td>
<td>-16.896</td>
<td>-54.952</td>
</tr>
<tr>
<td>S24</td>
<td>-0.59</td>
<td>-155.17</td>
</tr>
</tbody>
</table>

From the above results, 4x4 Butler matrix is fabricated in FR4 substrate and tested in Agilent N5230A Performance Network Analyzer.
**Measured Results:**
The available experimental data for the individual component is close to the simulated results but small errors were encountered. Unfortunately the accumulation of these little discrepancies between model and realization makes the whole matrix performance far from the predictions.

![Figure 8. Measured results of 4x4 Butler matrix (Magnitude plot)](image)

![Figure 9. Measured results of 4x4 Butler matrix (Phase plot)](image)

**Table 3:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Magnitude (dB)</th>
<th>Phase (Degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S11</td>
<td>-54</td>
<td>-60</td>
</tr>
<tr>
<td>S51</td>
<td>-8.40</td>
<td>-152</td>
</tr>
<tr>
<td>S61</td>
<td>-6.32</td>
<td>-138</td>
</tr>
<tr>
<td>S71</td>
<td>-7.86</td>
<td>-68</td>
</tr>
<tr>
<td>S81</td>
<td>-7.80</td>
<td>-30</td>
</tr>
</tbody>
</table>

**IV. Conclusion**
A laboratory project on 4x4 Butler Matrix was presented. It was designed, implemented, and measured at the Microwave Lab of Indian Institute of Science, Bangalore. The use of crossover by cutting the ground plane made the Butler matrix compact. In this work the size of 4x4 Butler matrix was found to be 40x40 mm, which is a large reduction from the structure of [3]. The reduction of area was around 94% for design A and 91% for the design B presented in [3].

**Acknowledgment**
I heartily thank Prof. K. J. Vinoy for all his guidance for the entire project.

**References**


