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Printed 4x4 Butler Matrix for Beam-Steering and MIMO Applications in 2.4 GHz ISM Band

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***Abstract*— This paper focuses on simulation of the planar 4x4 butler matrix functioning at 2.4 GHz and then its implementation to an array of four slotted microstrip patch antennas resonating at 2.4 GHz. For that, we have simulated and implemented microwave devices such as 3 dB quadrature hybrid couplers and cross-couplers, newly proposed 45^0 phase shifters, microstrip patch antennas using an epoxy substrate (FR4) having a dielectric constant 4.4 and a thickness of 1.6 mm. Combining the above components presented, The butler matrix circuit with patch antennas as a load is designed and tested by using dual channel Rohde and Schwarz make 14 GHz VNA. All the simulations are done in HFSS.**

***Keywords*— Butler matrix, MIMO, beam forming, cognitive radio, coupler, microwave phase shifter;**

I. INTRODUCTION

With the development of multi-input and multi-output (MIMO) systems, beam forming networks have been widely studied and employed in the past decades. Butler Matrix, as one of the most famous beam forming networks, draws much attention due to its simple design and orthogonal beam providing [1] [2]. BUTLER matrices are commonly known microwave circuits developed primarily for application in feeding networks of multibeam antennas. Such circuits allow the generation of N independent beams when an $N \times N$ Butler matrix is applied in conjunction with N or more radiating elements. Among other applications of Butler matrices, one can mention direction finding systems [3], multichannel amplifiers [4], or multiport measurement systems [5], [6]. Another well-investigated application is the space division multiple access (SDMA). This application is based on a multiple beam antenna which electronically divide a given service area, increasing the capacity of the communication system. The most commonly utilized are 4 × 4 Butler matrices due to their relatively low complexity. Such networks allow the design of four-beam antenna arrays. Sivasun. S. in [7] has given the performance analysis of not only multiple Beamforming but multiband networks also using Butler matrix. The author presented only simulated result for butler matrix covering 2.8 GHz, 6.4 GHz, and 9 GHz frequencies from multiband. A multiband hybrid coupler, crossover coupler and multi band phase shifters are used to design such network. R. D. Cerna and M. A. Yarlequé in [8] have described the design and implementation process of 8×8 Butler Matrix in 1.65 GHz to 2.3 GHz and 2.4 GHz to 2.6 GHz AWS and PCS 1900 MHZ bands for beamforming networks. The paper describes the design and implementation of 8x8 Butler Matrix using compact wideband branchline hybrids, parallel Schiffman phase shifters but without using crossovers. An array of printed Quasi-Yagi antennas was used to verify the beamforming functionality of the 8×8 Butler Matrix.

This paper gives the correlation between simulated and tested results for multiple Beamforming network using 4x4 Butler Matrix in 2.4 GHz ISM band. An array of 2.4 GHz rectangular patch microstrip antenna was introduced in the system to verify the beamforming functionality of the 4×4 Butler Matrix.

II. ANALYSIS AND DESIGN OF INDIVIDUAL COMPONENTS USED IN BUTLER MATRIX

A. Phase Shifter

It requires two 45 degree phase shifters to implement a 4x4 butler matrix. The major novel contribution of this work relies on the new Three-array ‘T’ shaped Defected Microwave Structure (DMS) used in conventional micro strip line for implementing 45^0 phase shifter at 2.4 GHz design, as shown in figure 1. The working frequency and the phase of this structure can be controlled by changing the length of slots or by changing number of arrays. Theoretically, the phase difference of the new phase shifter can be calculated as

$$slow\ wave\ factor = \frac{\lambda_0}{\lambda_g} = \frac{\beta_0}{k_0} \qquad (1)$$

Where k_0 is wave number in free space and the β is propagation constant of the transmission line. The phase angle of a conventional 54 mm long and 3 mm width microstrip line gives 74.4^0 phase difference with a return loss of -22 dB. To make this phase angle equal to 45 degree, ‘T’ shaped slots as a slow wave structures are inserted in line to increase the electrical length line by keeping physical dimensions constant.

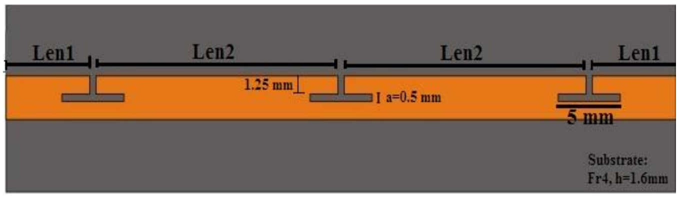


Fig. 1. 45^0 Phase Shifter using 'T' shaped Defected Microwave Structure

After performing several simulations in HFSS, the optimized dimensions for designed structure are given in figure 1.The simulated Phase difference between two ports is observed as 43.13^0 at 2.4 GHz when DMS slot size a=0.5 mm, len1= 6.75 mm , len2= 19.5 mm at array size =3. Figure 2 shows the simulation result angle(S12) for designed phase shifter.

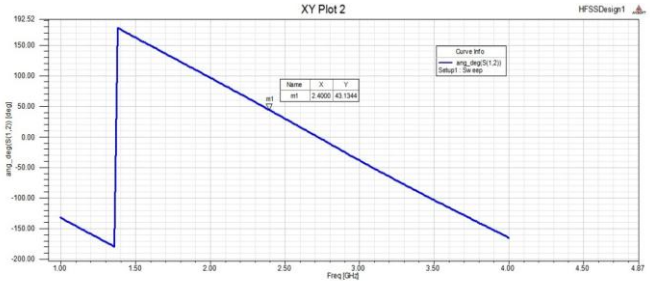


Fig. 2. Phase shifting: 43.13^0 at 2.4 GHz.

B. Directional Coupler:

Quadrature hybrids are 3dB directional couplers with 90° phase difference in the outputs of the through and coupled arms. The geometry of directional coupler is shown in figure 3. With all ports matched, power entering port 1 is evenly divided between port 2 and 3 with a 90° phase shift between these outputs. No power is coupled to port 4. Through even-odd made analysis, it can be shown [9] that the S-matrix is giving as follows.

$$s = \frac{-1}{\sqrt{2}}\begin{bmatrix} 0 & j & 1 & 0 \\ j & 0 & 0 & 1 \\ 1 & 0 & 0 & j \\ 0 & 1 & j & 0 \end{bmatrix} \qquad (2)$$

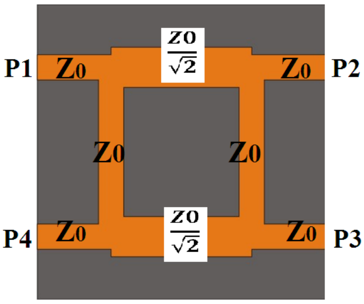


Fig. 3. Design of 3 dB Quadrature hybrids

Dimensions of Quadrature hybrid are calculated as per [9] at 2.40 GHz frequency. In simulation we got perfect isolation between port 1 & port 4 and good return loss at the designed frequency.

C. Cross-Coupler

This component ensures the crossing of two transmission lines. It is also called 0 dB coupling. Reference [10] [11] mentioned that the coupling between the two transmission lines constituting the cross-coupling is relatively low. Furthermore, it is stated that the combination of two hybrid couplers allows to obtain a cross-coupling.

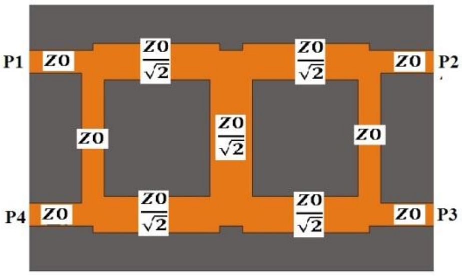


Fig. 4. Design of 0 dB Cross-Coupler

Figure 4 shows the geometry adopted for the achievement of this device whose corresponding S matrix [9] [10] can be written as follows:

$$s = \frac{-1}{\sqrt{2}}\begin{bmatrix} 0 & 0 & j & 0 \\ 0 & 0 & 0 & j \\ j & 0 & 0 & 0 \\ 0 & j & 0 & 0 \end{bmatrix} \qquad (3)$$

Simulation results carried out at 2.40 GHz frequency for above shown design exhibit a good isolation between the cross lines.

D. 4 X 4 Butler Matrix:

As can be seen in figure 5, the 4x4 Butler matrix used includes two crossover couplers, 4 blocks of hybrid couplers (-3dB / 90 °) and finally 2 Phase shifters (45°).

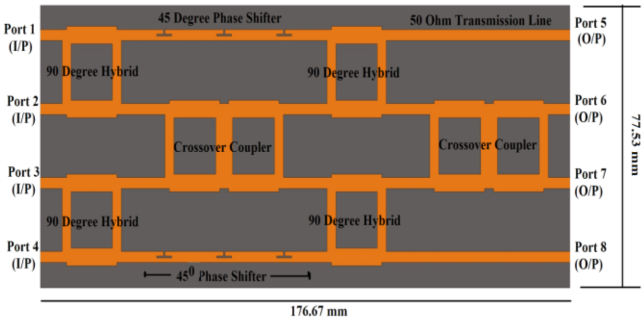


Fig. 5. Design of 4x4 Butler matrix by combining individual microwave blocks

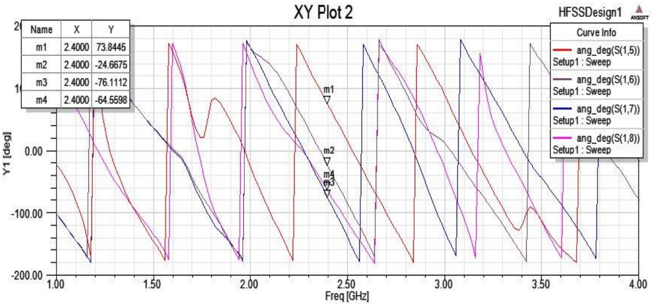


Fig. 6. The simulated phase responses when port 1 is excited and phase difference is measured at port 5, 6, 7 and 8.

Figure 6 gives the phase shift measured when input port 1 is excited with microwave source and phase shift is measured at port 5, 6, 7 and 8.

E. 2.4 GHz Microstrip Patch Antenna

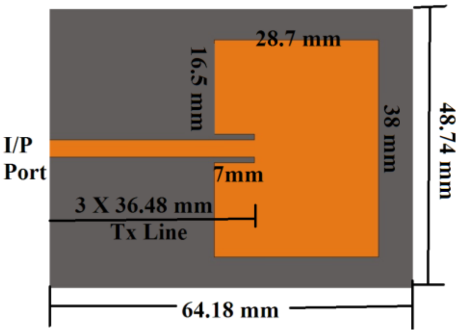


Fig. 7. 2.4 GHz Microstrip Patch Antenna

In order to verify the beamforming functionality of designed 4×4 Butler Matrix, a microstrip patch antenna with operating frequency 2.4 GHz is designed. The optimized dimensions of designed antenna are shown in figure 7.

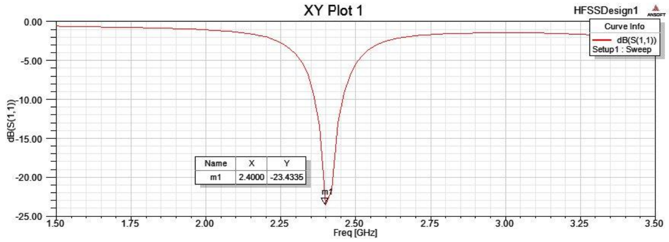


Fig. 8. S_{11} of Microstrip Patch Antenna

Figure 8 shows the simulation result of return loss (S_{11}) which is observed as -23.43 dB at 2.4 GHz frequency.

III. IMPLEMENTATION OF BUTLER MATRIX WITH AN ARRAY OF PATCH ANTENA: RESULT AND DISCUSSION

In order to verify the beamforming functionality of designed 4×4 Butler Matrix, it is fed with an array of four microstrip antenna operating at 2.4 GHz as shown in figure 9. Figure 10 gives the radiation pattern and 3D polar plot of a 2.4 GHz microstrip antenna which is having very large beam width. By using an array of antennas we can make the radiation pattern directional one. And by connecting the microwave source at different input port of a butler matrix, we can change the direction of radiation (beam steering). The same assembly when used at receiver side can be used for beam scanning.

Figure 11 gives the simulation result for radiation pattern obtained in HFSS. Inset a) of Fig. 11 gives the 3D radiation pattern and its cross sectional polar plot in the direction of radiation when microwave source is connected to port 1 of a BUTLER matrix. From inset b), c) and d) it is observed that the direction of beam can be changed by connecting the microwave source to different ports. When it is connected to port 1, the maximum radiations are in the direction $\theta=337^0$, whereas when connected to port-2 the maximum radiations are at $\theta=348^0$. When Port-3 is excited the maximum radiations are observed at $\theta=12^0$ and for Port-4 the maximum radiations are observed at $\theta=23^0$. One can further change the beam angle by exiting different ports with phase shifted microwave source.

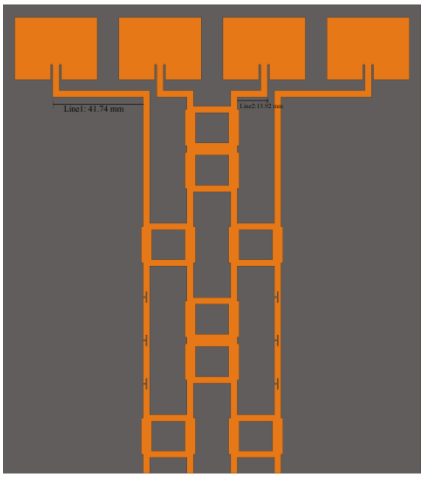


Fig. 9. Design of Butler Matrix feed network

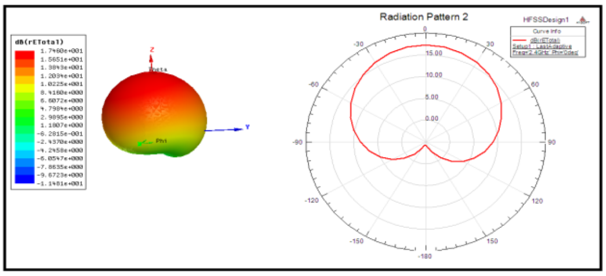
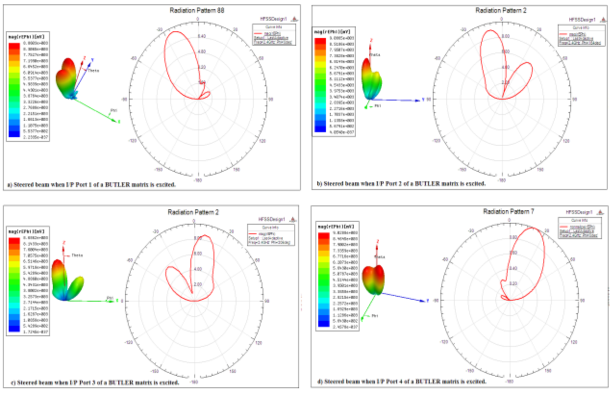


Fig. 10. Radiation pattern and 3D polar plot of a 2.4 GHz microstrip antenna



a) Steered beam when I/P Port 1 of a BUTLER matrix is excited.

b) Steered beam when I/P Port 2 of a BUTLER matrix is excited.

c) Steered beam when I/P Port 3 of a BUTLER matrix is excited.

d) Steered beam when I/P Port 4 of a BUTLER matrix is excited.

Fig. 11. Radiation pattern and 3D polar plot obtained when microwave source is connected at different input ports of BUTLER matrix.

Figure 12 gives the return loss S_{11}, S_{22}, S_{33}, and S_{44} of four input ports of Butler Network at 2.4 GHz which is far less than -10dB implying that good VSWR close to one. Figure 13 and 14 shows the fabricated layout of designed network and its return loss measured by using dual channel 14 GHz Rohde and Schwarz make vector network analyzer (VNA). From the figure12 and figure 14 it is observed that measured return losses and simulated return losses shows good correlation.

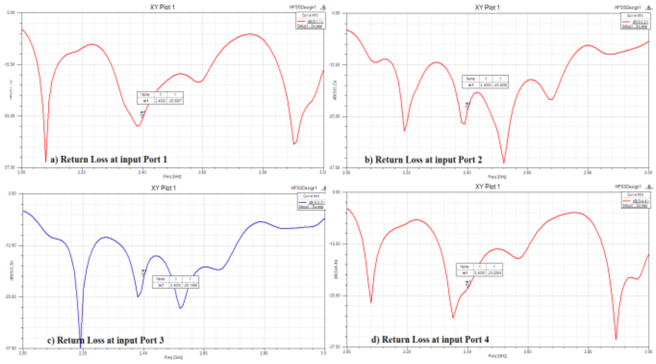


Fig. 12. Return Loss S_{11}, S_{22}, S_{33}, S_{44} at Port 1, 2, 3 and 4 respectively

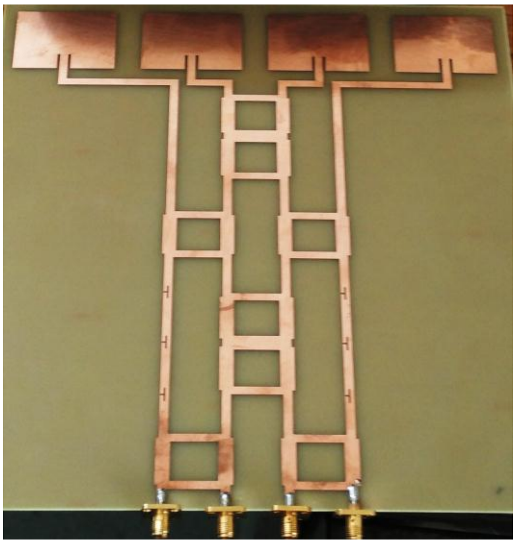


Fig. 13. Fabricated layout of designed network

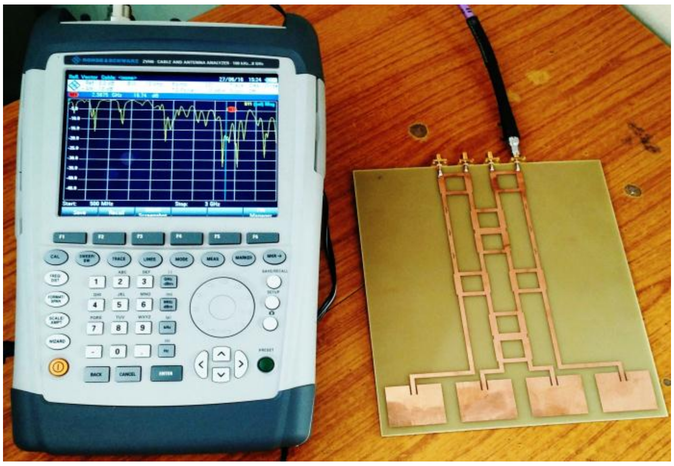


Fig. 14. Measured Return Loss of Fabricated network at port1

IV. CONCLUSIONS

This paper gives the correlation between simulated and tested results for multiple Beamforming network using 4x4 Butler Matrix in 2.4 GHz ISM band. An array of four 2.4 GHz rectangular patch microstrip antennas were introduced in the system to verify the beamforming functionality of the 4×4 Butler Matrix.

Measured return losses and simulated return losses shows good correlation. Simulated results of radiation patterns show that the 4×4 Butler Matrix is able to provide adequate phase difference and uniform amplitude to the antenna array in order to function as a beamforming network in the frequency range of interest.

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