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Design of 4x4 Butler Matrix for 5G Cellular Network

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***Abstract*—In this paper a new design model for 4x4 Butler Matrix is proposed to form a packet-switched network operating at 28 GHz. This transducer generates 4 perpendicular beams. The 4x4 Butler Matrix includes 4 directional couplers, two phase shifters and two transmissions. Directional couplers were used to divide the power evenly with a displacement of 90°, and phase modulators perform phase delays in the design and junction work for insulation. The paper simulation results for these components are consistent with the theory. The model is designed using Advanced Design System(ADS) software to simulate the real physical implementation. The overall size of the butler matrix is 22.7121mm x 24.18516mm.**
The obtained results for return loss of less than -11.845 dB and the output power distribution was in the range of -5 to -8 dB at the design frequency of 28 GHz. The four beams were obtained in the directions 147.5°, 101.3°, 54.8° and 10.5° when the port 1 is excited.

Keywords—Butter Matrix, Phase shifter, Directional coupler

I. Introduction

Millimeter waves are found in the spectrum between microwaves and infrared. In the past, this part of the spectrum was essentially unused since decades. Nowadays, millimeter wave's devices are practical, and they are finding all sorts of new uses, millimeter waves also allow high digital data rates [1]. The small size of these devices is another major advantage of millimeter-wave equipment, while ICs keep the circuitry small, and the high frequency makes very small antennas.

Microstrip patch antennas are widely used, they are utilized in many application such as satellite communications, GPS and mobile communications. This variety of applications is due to their compact shape, light weight, less complexity and easy implementation. Also, microstrip patch antennas are efficient radiators which have a support for both linear and circular polarizations [2]. Phased array devises are a multiple antennas system in which the radiation pattern can be directed in a certain direction [3]-[8]. The direction of phased array radiation can be electronically steered without any need for mechanical rotation. Nowadays, phased arrays can play a significant role in the success of mm-wave frequency band systems. Spatial selectivity of phased array beams can increase capacities of the wireless channels. A more efficient power management is also expected [1].

Butler matrix is a radio frequency beam forming network. Butler matrix is widely used for beam forming application because of its less power loss characteristic and simplicity. The beam forming network the output of the butler matrix is fed as input to the microstrip patch antenna, where the patch antenna acts as beam forming device and the butler matrix acts as a beam forming network[4]. However, This will introduce a finite insertion of losses, because of the inherent losses in phase shifters, directional couplers and in transmission lines based network. The number of coupling level needed for the butler matrix depends on the size of the entire structure and is given by formula N=2n , where 'N' denotes the size of the butler matrix and 'n' presents the Number of levels[9]-[12].

Butler matrix network is easy to construct and implement on printed circuit boards. By varying the input current amplitude and input phase to the Butler matrix, the beam can be scanned to the required direction. This paper is aimed to design Beamforming networks (4x4 Butler matrix) operating at 28GHZ by using Advanced Design System (ADS) software. The ADS software was used because it is an implementation package for manufactures after simulation tests.

II. DESIGN AND SIMUATION OF BUTLER MATRIX

A. Design of ButlerMatrix

In this section we will show the process of designing hybrid coupler, crossover and phase shifter. In 4x4 Butler Matrix all these microwave components (in copper microstrip) will use the RT-Duroid5880 which has a dielectric substrate with 0.254mm height and dielectric constant of 2.2, these components will operate at 28GHZ.
Finally the integration and simulation of stated microwave components will be carried out to form the 4x4 Butler Matrix. The simulation results of important parameters will be illustrated.

1) Simulation of 90° Hybrid Coupler

In this design, the basic schematic circuit operating at 28 GHz is simulated using S-parameters simulation engine after terminating the four ports with 50 Ω termination and swept the frequency from 10GHz to 46GHz in steps of 1GHz are carried out . The Dimensions of the hybrid (Calculated and Optimized) values are listed in Table: I. With these optimized values all simulated parameters (S-Parameters and Phases) are satisfied the required designed parameters.

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TABLE I. DIMENSIONS AND PARAMETERS OF THE 90° HYBRID COUPLER

Parameters	Calculated	Schematic	Optimize Real Simulation
ε_{eff} for (50 Ω)	1.872764		
ε_{eff} for (35.355)	2.67812		
Length for (50Ω)	1.95732 mm	1.940250 mm	1.8058576 mm
Length for (35.355 Ω)	1.636811 mm	1.809060 mm	1.6063799 mm
Width for (50 Ω)	0.781516 mm	0.787518 mm	0.4307581575 mm
Width for (35.355 Ω)	1.346262 mm	1.285800 mm	0.713131 mm

From the schematic circuit, 3D Layout of 90° Hybrid is generated using the tools available in ADS software. The layout of the 90° hybrid is important for its performance and it will be used as a part of in the Butler matrix. Fig.1, shows the 90° hybrid layout in 3-dimensions. Fig. 2, shows Layout results, The plot shows a deep null at 28GHz at m1= -14.036 dB Return Loss which indicates a good match at that frequency to 50Ω. This is very desirable, because there will be maximum power delivered to the load (device) at this frequency.

Fig. 3 shows, the Layout phases at port 2 and port 3. The phase difference between port 2 and port 1 which marketed by m4 at the frequency 28 GHz is 92.419° whereas the marker m5 gives the phase 1.823°, then the phase difference between ports 2 and 3 is Phase difference (m4-m5)=90.596°.

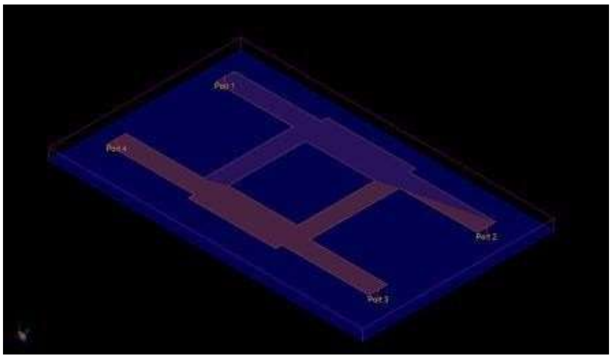

Fig. 1. Layout of a 90° Directional coupler

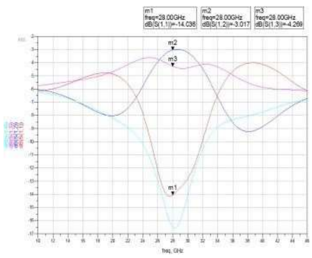

Fig. 2. S-Parameters of a 90˚ Hybrid Coupler in dB

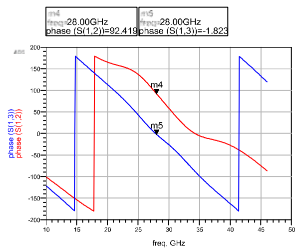

Fig. 3. Phase difference at outputs of 90° hybrid

Fig. 4 shows, the Layout phase of output ports where plot of phase difference between ports 2 and 3 just as divided the phase of S(2,1) by phase of S(3,1). The marker m13 gives directly the phase difference between ports 2 and 3 at designed frequency (m13 = 94.242°).

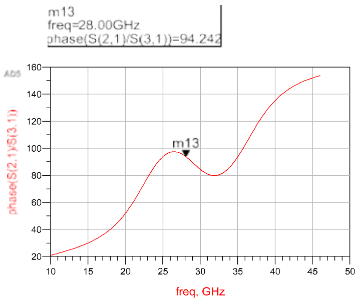

Fig. 4. Simulation phase of 90° hybrid

In the Fig. 4 shows phase difference between port 2 & 3. As was shown (the input signal applied to port 1) the results at 28 GHz frequency illustrate a good matching with the theory, as we know that we can use any port as port 1.

Any reflection from mismatches at the output port flow to the isolated port (port 4). This is one of the reasons hybrid couplers are used to split signals in applications where unwanted reflections can damage the circuit.

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In accordance with the previous results, we can say that a 90° hybrid coupler has been successfully designed to operate at the frequency of 28 GHz.

2) Crossover

After designing a 90° hybrid coupler, the design of the crossover (schematic circuit) will be easy because it is a cascading of two quadrature couplers, using the microstrip equations. We can obtain all dimensions (Calculated and Optimized), that will be used in the design of the crossover, which are listed in Table II

TABLE II. DIMENSIONS AND PARAMETERS OF THE A CROSSOVER

Parameters	**Calculated**	**Schematic**	**Optimize Layout Simulation**
ε_{reff} for (50 Ω)	1.872764		
ε_{reff} for (35.355)	2.67812		
Length for (50Ω)	1.95732 mm	1.940250 mm	1.8058576 mm
Length for (35.355 Ω)	1.636811 mm	1.909060 mm	1.6063799 mm
Width for (50 Ω)	0.781516 mm	0.787518 mm	0.4307581575 mm
Width for (35.355 Ω)	1.346262 mm	1.285800 mm	0.713131 mm

From the schematic circuit, 3D Layout of the crossover is generated. The layout of the crossover is important for its performance and it will be used as a part of in the Butler matrix. Fig. 5. Shows the crossover layout in 3-dimensions.
S(1,2), S(1,3) and S(1,4) are shown in Fig. 6. The Simulation results carried out at 28 GHz frequency, it exhibit a good isolation between the cross lines. So the results demonstrate that the designed crossover works with good performance and with a high level of isolation.

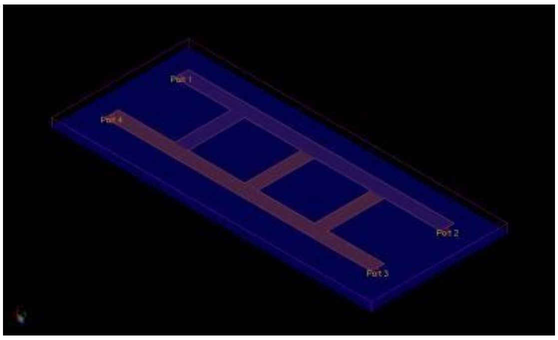

Fig. 5. Layout of a Crossover

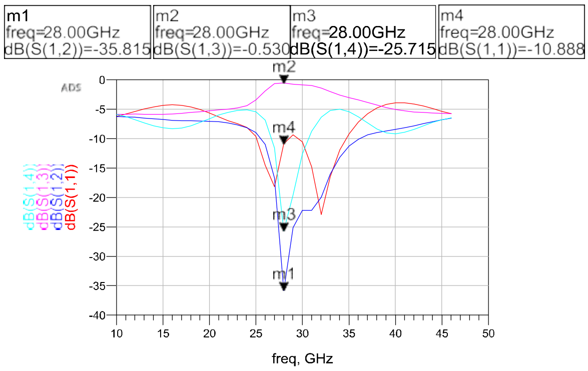

Fig. 6. S-Parameters of a 0 dB Crossover

3) Phase Shifter

Phase shift is a phenomenon that occurs when a signal is delayed or advanced in time relative to another signal.
The schematic circuit of the phase shifter is performed using, the length of the 45° phase shifter is 2.4246 mm using the same substrate materials, then the 3D layout circuit is generated as shown in Fig, 7. The layout dimensions are optimized using optimization process in ADS software. Fig.8. shows, the Simulated results of the phase shift at 28 GHz frequency on m1=44.817°.

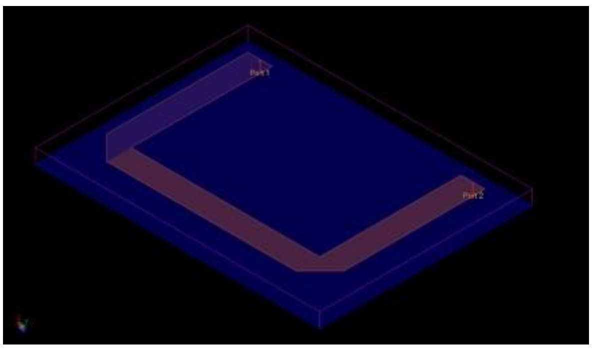

Fig. 7. Phase shift of the phase shifter

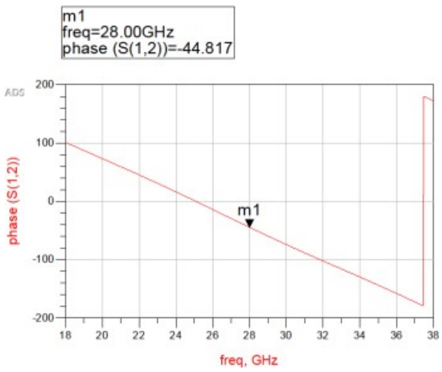

Fig.8. phase shift at 28 GHz

B. Implementation of Butler Matrix

In the previos part the main components of 4×4 Butler matrix such as a hybrid coupler, crossover and phase shifter will be designed and simulated separately. In this part all these components will be integrated together and simulated to form the final layout of the Butler matrix.

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Now all components which will be used to represent, the 4×4 Butler matrix are ready. Combining the above components presented to take shap the butler matrix. The circuit was designed to operate at 28 GHz using the same specification of substrate materials (RT-Duroid 5880). The Table III, lists the calculated parameters, and dimensions, with Optimized value at Layout.

TABLE III. DIMENSIONS AND PARAMETERS OF THE BLUTLER MATRIX

Parameters	**Calculated**	**Optimized**	**Optimize Real Simulation**
ε_{reff} for (50 Ω)	1.872764		
ε_{reff} for (35.355)	2.67812		
Length for (50Ω)	1.95732 mm	1.940250 mm	1.8058576 mm
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Let us consider that (P1, P2, P3, P4) and (P5, P6, P7, P8) are the input and the output ports of the Butler matrix respectively as shown in the Fig. 9.

Fig, 10, show layout results of the insertion loss and return loss for port 1 when the other ports are matched. These results illustrate that the return loss is better than -12 dB and the coupling to the output ports is well-equalized (around -5dB, -8 dB). It can be concluded that the obtained results are very promising.

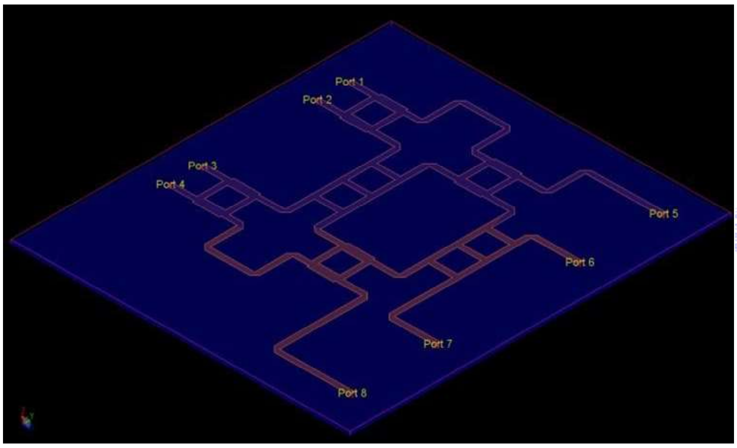

Fig.9. Structure of 4×4 Butler Matrix

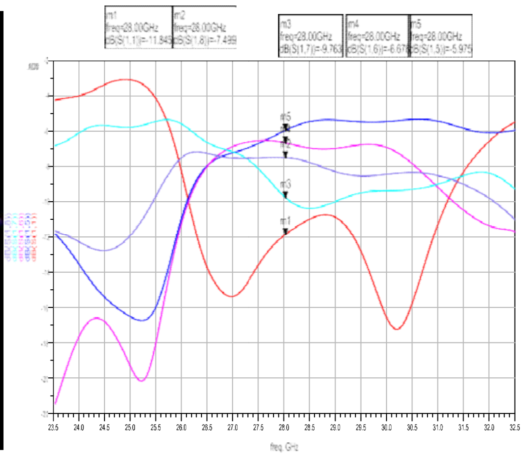

Fig.10. S-parameters of the Butler Matrix

Fig. 11, shows the simulated return losses at the resonant frequency of 28 GHz at m6= -11.845 dB of a hybrid.
With regard to the phase shifts between the output ports, It can be observed from Fig.12, that they are practically constant at the frequency 28 GHz. and we see in the Fig.12 , the gap between port 5 (m8) and port 6 (m9) is 46°

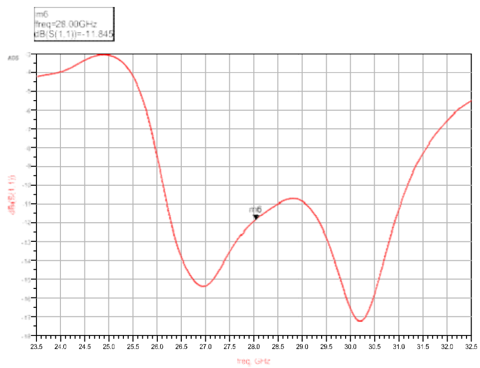

Fig.11. S11-Parameters of the Butler Matrix

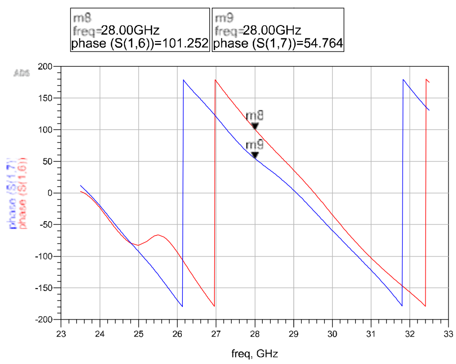

Fig.12. Simulated phase differences between port 5 and port 6

Fig. 13, shows the gap between port 7 (m10) and port 8 (m11) is 44° . According to Fig. 13, the overall results are quite satisfactory, it may be noted that the phase differences obtained at 28 GHz is closer to the theoretical model (±45°) with a quite tolerable phase error. These errors are due to the phase errors produced at the couplers.

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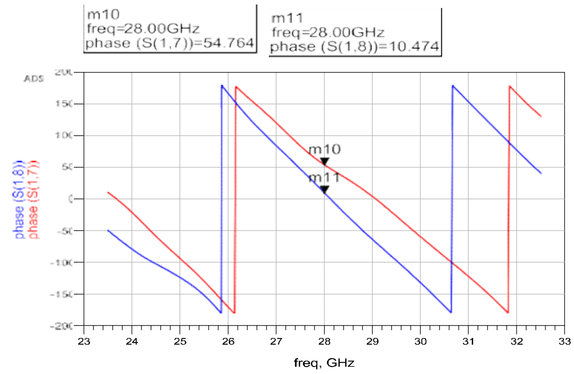

Fig. 13. Simulated phase differences between port 7 and 8

III. CONCLUSION

The proposed 4x4 Butler matrix system has the advantages of low cost, small volume, and light weight. These features make the proposed smart antenna suitable for beamforming applications at 28 GHz. For larger coverage, the design can be extended to 8x8 butler matrix.

A 4x4 Butler matrix based on microstrip technology is designed and optimized for better performance. We started by selecting a suitable substrate with low dielectric losses. The chosen substrate and its shape enables an operating frequency of 28 GHz. Later on, the characteristics of the Butler matrix are optimized, such as the phase shifter, the coupler and the crossing. Indeed, the obtained results of the Butler matrix shows high performances in terms of reflection coefficients and other related parameters.

Finally on the analysis it is observed that by using butler matrix, on excitation of each input port all output ports will give same signal at each output with different phase angle ..

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