# Designing and Analyzing a Planer Butler Matrix for Phased Array Antenna for Future 5G Applications

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## ABSTRACT

Future 5G (Fifth Generation) wireless communication claims for many fold increase in data rates, quality of service and connectivity. This gaga bits per second data rate is made possible by steerable antennas and mm-wave spectrum. This paper presents a design consists of 4-elements linear phased array feed by 4x4 Butler matrix for future 5G wireless communication networks. However, the Building block of Butler matrix are hybrid couple, crossover, and phase shifter. Both the Butler matrix and micro strip antenna array are designed on a single layer Roger RT5880 substrate having dielectric constant is 2.2 (r=2.2) and thickness 0.254mm. The dimensions of Butler matrix, its components and micro strip antenna are designed and optimized in CST (Computer Simulated Technology) microwave studio. The area of Butler matrix is 30x17mm$^2$ and the overall area is. The reflection from each input port and its coupling with other input ports are investigated and they are below -10dB in the whole band. The $S_{11}$ parameters of array shows a wide BW (Band Width) having frequency band from 26.3-29.55GHz. The insertion loss on average equal to 6.9dB. The radiation pattern for different input port excitation shows that beams are pointing at +10, -38, +38 and -10$^o$, from broad-side and their corresponding gains are 12, 10.4, 10.4 and 12dB respectively. The side lobe level are -11.5, -6.2, -6.3 and -11.6 while half power beam width are 29.2$^o$, 30.4$^o$, 30.2$^o$ and 29.3$^o$ respectively. Apart from this array pattern synthesis and analysis are discussed which conform simulated results.

**Key Words:** Fifth Generation, Hybrid Coupler, Crossover, Phase Shifter, Butler Matrix, Microstrip Antenna, Array Factor.

## 1. INTRODUCTION

Future 5G wireless communication will enhance data rates, QoS (Quality of Service) and connectivity. This amazing technology will support IoT (Internet of Things), IoV (Internet of Vehicle) and smart grid [1]. This gaga bits per second data rate is made possible by steerable antennas and mm-wave spectrum [2]. Apart from this, as the number of users increase, co-channel interference increases and hence degrade the QoS; which is also controlled by beam steerable antennas [3]. Beam steerable antenna is an antenna which transmit signal in desired direction and stop transmitting in undesired direction. Thus, a beam steerable antenna provide a significant improvement in system performance and system capacity [4-5]. This new technology will use the unused BW ranging from 3-300GHz [1]. There are different mm-wave bands proposed for 5G wireless network. The 28 and 38 GHz bands are completely discussed in [2]. In this paper building penetration, reflection, propagation, path loss, angle of arrival, angle of departure and RMS (Root Mean Square) delay spread both for rural and urban environment are analyzed and discussed. Furthermore a statistical model for urban environment is also developed.

There are different techniques used for beam steering like mechanical steering, integrated lens antennas, switched beam antennas, traveling wave antennas, reflect-array antennas, retro-directive antennas, beam-forming antennas and meta-material antennas [6]. But here in this work, analog multi-beam antenna which is a type of beam-forming antenna is used. The multi-beam antenna have many applications: in satellite communication, electronic counter measure, radar and cellular networks, for instance. The feed to multi-beam antenna comes from beam-former which is either network or lens. The lens may be Rotman Lens, Dome Lenses, Bootlace Lenses or some other lenses. While network may be Power Divider BFN, Blass and Nolen Matrices, Butler Matrix, the 2D (Two-Dimensional) BFN, or McFarland 2D Matrix [7]. In this work the Butler matrix was proposed because of its simple structure, low insertion loss, wider BW, orthogonal beam generation and easy realization [3,8].

Butler matrix is passive NxN beam forming network for uniform array, having N input ports and N output ports [9-10]. These N output ports have excitation signals that have same amplitude and progressive phase shift for each input port excitation [10-12]. These N output ports are connected with1xN linear array, which results in N orthogonal beams formation [12]. The Butler matrix along with array act as a reciprocal network that can be use either in a transmitter or in a receiver [12-13].

The Butler matrix for beam steering applications was investigated in literature [3-4,8,12,14-26]. In these designs the Butler matrix was designed for lower frequencies, mostly 2.4GHz, while [27-34] for higher frequencies. Apart from this, the technologies used for higher frequency bands are either SIW (Substrate Integrated Waveguide), multi-layer or semiconductors. Several research articles target 5G application [8,31-36]. But they are either on SIW technology or multi-layer technology. The author in [32] has used single layer micro-strip technology but has not discussed all the individual components and integration of Butler matrix with antenna. In general, the microstrip planer single layer structure has is very attractive due to its numerous advantages like compact size, simple structure, low cost and easy fabrication.

In this work, the Butler matrix was designed on a single layer microstrip technology as shown in the Fig. 1, which consists of four Hybrid couplers, two crossovers and two 45 degree phase shifters [27]. The design uses 50Ω line width, which is too wide at the designed frequency, and will overlap [14,27]. Thus, a low dielectric constant thin material is used. Therefore, Rogers RT5880 has dielectric constant 2.2 and thickness 0.254mm is used for effective designing. The performance of the BM is totally dependent upon these components and any error occurred in one of these components will be repeated as many times as the component is repeated and hence, the final output will degrade seriously [25]. Thus, good performance components should be designed and optimized in CST before the actual designing of the butler matrix [14]. Finally, Butler matrix is designed by combining these components. This optimized Butler matrix has net- area equal to 30x17mm$^2$. A micro-strip inset feed antenna is developed and integrated with the Butler matrix. This will result in 30x25mm$^2$ overall area. All the results of the simulation show good agreement with theory.

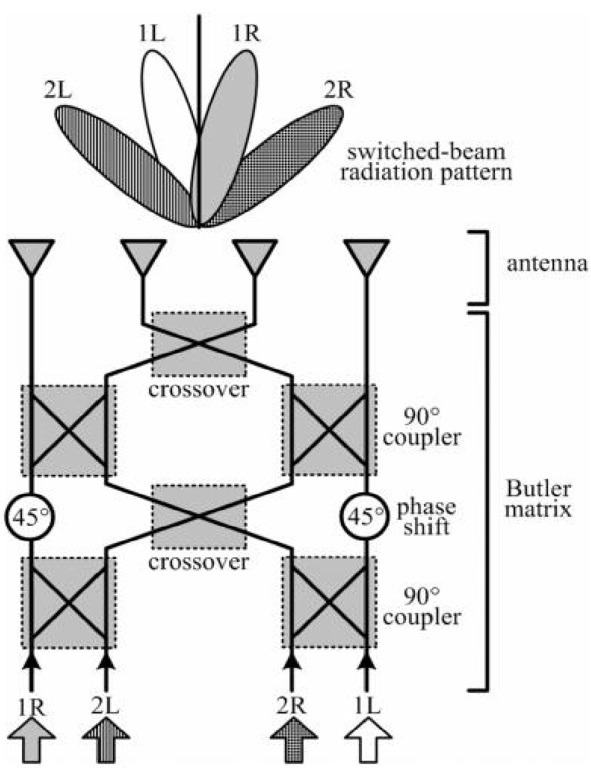



FIG. 1. BLOCK DIAGRAM OF BUTLER MATRIX

The work is organized as follows. In section-1 introduction is given. In section-2 the detail design of Butler matrix and its individual components are presented. In sections 3-5 the design of micro-strip antenna, array and array factor synthesis and analysis, designing and simulation results are discussed respectively. Finally, in section-6 concluded remarks are given.

## 2. DESIGNING OF BUTLER MATRIX AND ITS INDIVIDUAL COMPONENTS

In this section Butler matrix and its individual components designing is presented. For optimal Butler matrix the individual components are designed and optimized first. These components are then combined to make optimal Butler matrix. The individual components designing is discussed below.

### 2.1 Hybrid Coupler Designing

Hybrid coupler is a symmetric four port network. Any port can be taken as input port whose adjacent port will be isolated and it is opposite two ports will be consider as output ports. This can also be evident from the scattering matrix [37].

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

The Hybrid coupler is composed of two primary and two secondary transmission line, the secondary transmission line are connected in shunt and are quarter wavelength apart [23,28]. The impedance between two shunt lines is $Z_o/2$; where $Z_o$ is the impedance of primary and secondary transmission lines [37].

This circuit was designed and optimized using CST microwave studio as shown in Fig. 2. The detail dimensions are given in Table 1.The magnitude and phases are plotted in Fig. 3(a-b) respectively. Reflection coefficient ($S_{11}$) and isolation level ($S_{41}$) both are below -20dB. The power is equally divide between port-2 and port-3 i.e. $S_{21}$is nearly equal to$S_{31}$. The insertion loss on average is 3.35dB. The phase difference between port-2 and port-3 is 89$^o$.

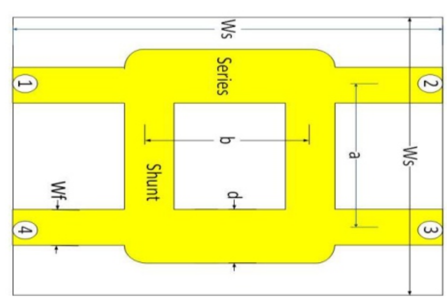



FIG. 2. HYBRID COUPLER FOR 5G APPLICATIONS

### 2.2 Crossover

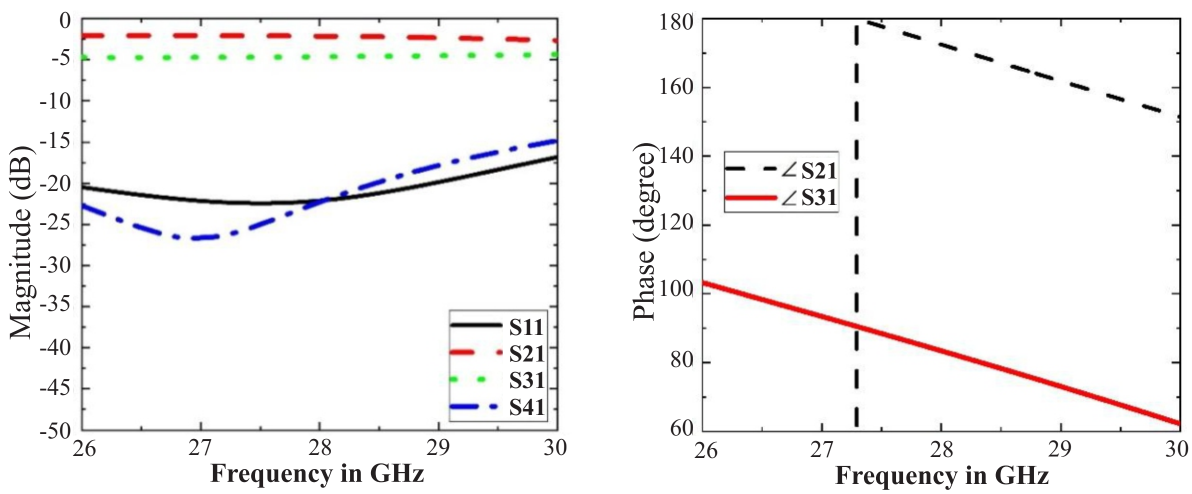
Crossover is used for crossing two transmission lines and prevent coupling between them [15]. The optimal crossover designing is very challenging task in the designing of butler matrix [14]. It is a symmetrical network having two ports on either side [14]. Itis designed to pass the power to the port diagonally opposite to the input port [25]. Crossover is designed on micro-strip [38-41] and is used in many microwave circuits like butler matrix etc. In this paper a two section crossover is used as shown in Fig. 4(a). The ideal crossover is designed using Equations (1-2) [41].

$$Z_3 = \frac{50 \times Z_2}{Z_C^2} \quad (1)$$

$$Z_1 = \frac{Z_C^2}{50} \quad (2)$$

This crossover was designed in CST as shown in Fig. 4(b) and its dimensions are given in Table 2. The scattering parameters are shown in Fig. 5. Its isolation loss is below -25 dB while its insertion loss, return loss and $S_{41}$ is 0.52, 26 and -17.8dB respectively.

| TABLE 1. DESIGN DIMENSION OF HYBRID COUPLER | | | | | | |
|---|---|---|---|---|---|---|
| $W_s$ | $L_s$ | $h_s$ | $W_f$ | a | b | d |
| 6 | 4 | 0.254 | 0.8 | 3 | 1.7 | 1.216 |




(a) MAGNITUDE PLOT (b) PHASE PLOT

FIG. 3. SIMULATED S-PARAMETERS OF HYBRIDCOUPLER FOR 5G APPLICATIONS

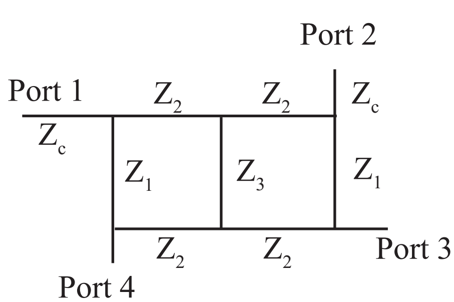



FIG. 4 (a). BLOCK DIAGRAM OF CROSSOVER

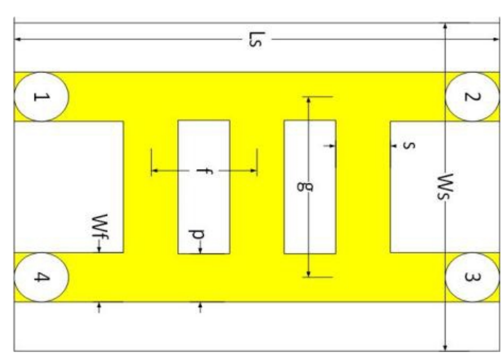



FIG. 4 (b). CROSSOVER FOR 5G APPLICATIONS

| TABLE 2. DESIGN DIMENSION OF CROSSOVER FOR 5G PPLICATIONS | | | | | | | |
|---|---|---|---|---|---|---|---|
| $W_s$ | $L_s$ | $h_s$ | $W_f$ | f | g | p | s |
| 6.85 | 8 | 0.254 | 0.8 | 2 | 2.75 | 0.769 | 0.8 |

### 2.3 Phase Shifter

A transmission line delays signal and acts as a phase shifting network and the phase shift relation with length is given by Equation (3)

$$\varphi = \left(\frac{2\pi}{\lambda_g}\right)\Delta \qquad (3)$$

Where

$$\lambda_g = \frac{\lambda_o}{\sqrt{\in_e}}$$

Where $_{e}$ is effective dielectric constant.

The phase shifter is designed as shown in Fig. 6. The $\Delta_l$ between straight and u shaped part is equal to 45°.

### 2.4 Final Design

All the individual components that were designed and optimized are combined on a single layer Rogers RT5880 substrate to make Butler matrix. The final Butler matrix is shown in Fig. 7. The total area of the Butler matrix is 30x17mm$^2$. The simulated magnitude are shown in Fig. 8(a-d) for all input port excitation. The magnitude plot shows that the return losses i.e. $S_{11}$, $S_{22}$, $S_{33}$, and $S_{44}$ are below -10dB in an entire bandwidth. The transmission coefficient on average is equal to 6.89 dB for port-1 and port-4 and 6.98 dB for port-2 and port-3, as shown in Table 3. The coupling with other input ports are below -10 dB in the whole range.

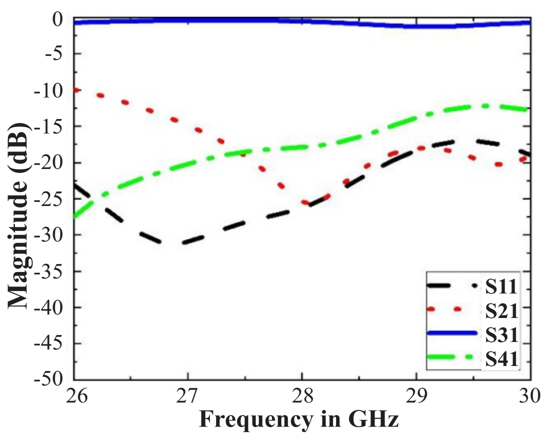



FIG. 5. SIMULATED S-PARAMETERS OF CROSSOVER FOR 5G APPLICATIONS

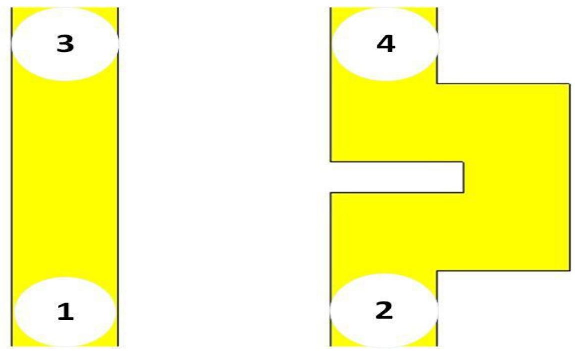



FIG. 6. PHASE SHIFTER FOR 5G APPLICATIONS

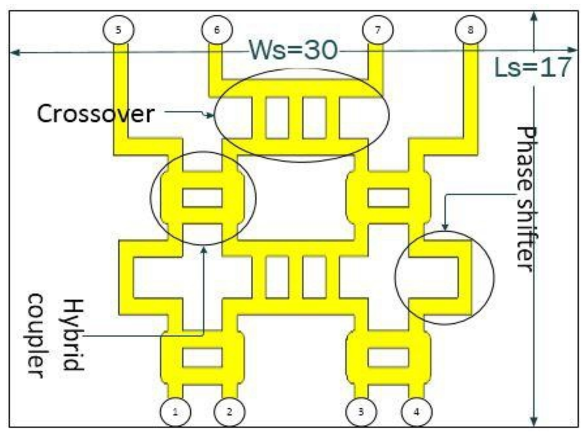
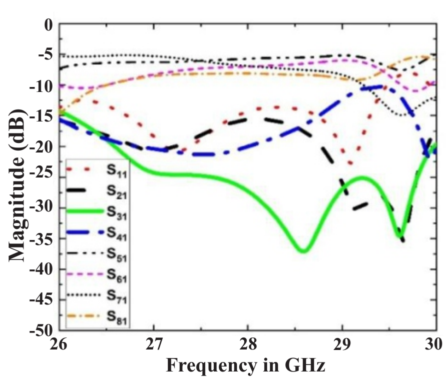
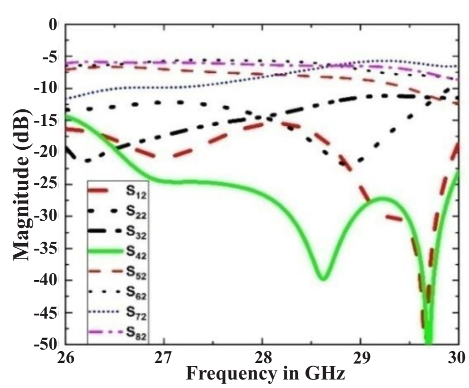


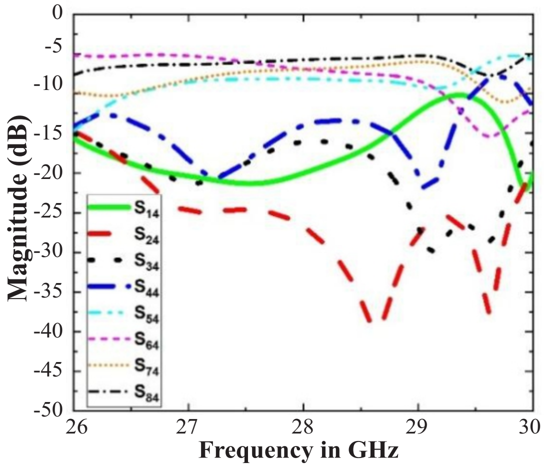

FIG. 7. BUTLER MATRIX FOR 5G APPLICATION



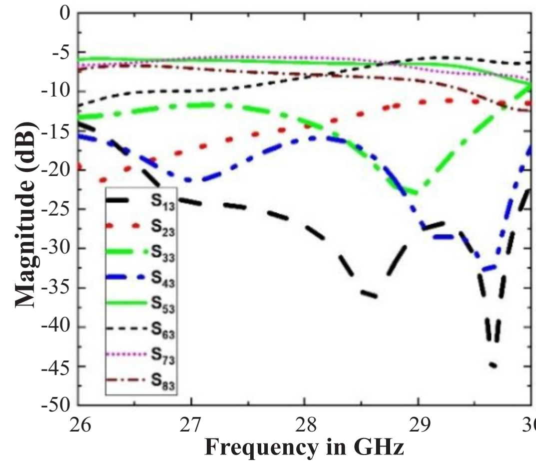

(a) MAGNITUDE PLOT WHEN PORT 1 IS EXITED




(b) MAGNITUDE PLOT WHEN PORT 2 IS EXITED




( c ) MAGNITUDE PLOT WHEN PORT 3 IS EXITED



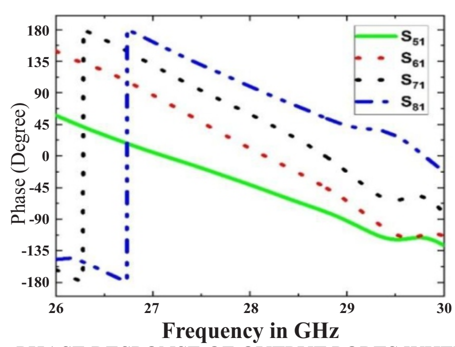

( d ) MAGNITUDE PLOT WHEN PORT 4 IS EXITED

FIG. 8. SIMULATED S-PARAMETERS OF BUTLER MATRIX FOR 5G APPLICATIONS

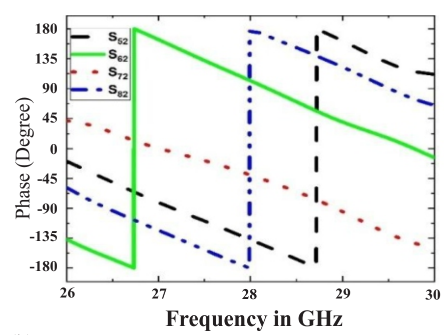
TABLE 3. TRANSMISSION COEFFICIENT OF BUTLER MATRIX

| Ports | Port-5 | Port-6 | Port-7 | Port-8 |
|---|---|---|---|---|
| Port-1 | -5.54 | -6.65 | -7.44 | -8.03 |
| Port-2 | -7.78 | -6.89 | -6.9 | -5.70 |
| Port-3 | -6.32 | -8.18 | -5.69 | -7.81 |
| Port-4 | -6.32 | -8.18 | -5.69 | -7.81 |

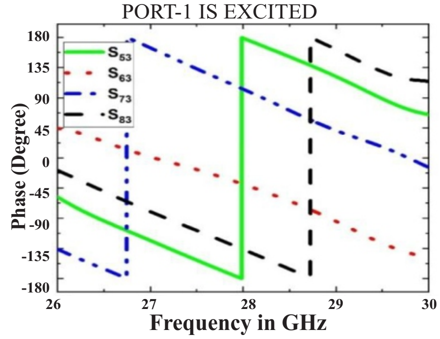
The phase response is plotted in Fig. 9(a-d). The average progressive phase shift between output ports, i.e. $S_{6i}$, $S_{5i}$ = - $S_{6i}$ = $S_{8i}$ - $S_{7i}$, for each input port i are 46.75, -134.3, 134.8 and 46.24 respectively. These phase differences are plotted in Fig. 10(a-d). The respective phases are shown in Table 4. A minute phase difference occur due to coupling with isolated ports and among different sections of butler matrix. The reflection from other ports, bends and junctions also degrade the performance. Furthermore, at higher frequencies there ismutual coupling between different sections of Butler matrix.



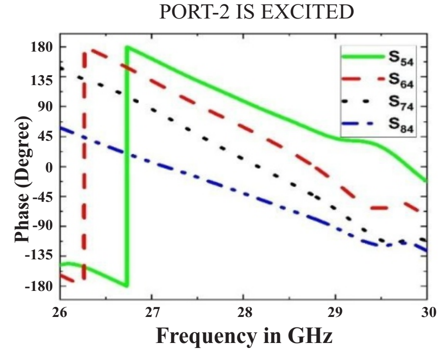

(a) PHASE RESPONSE OF OUTPUT PORTS WHEN PORT-1 IS EXCITED




(b) PHASE RESPONSE OF OUTPUT PORTS WHEN PORT-2 IS EXCITED

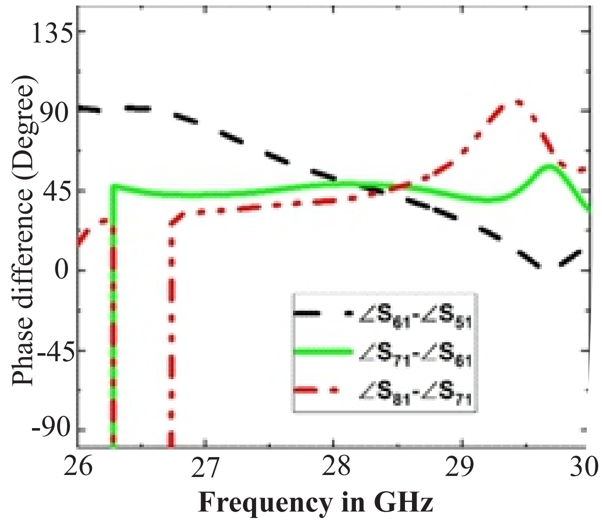



( c ) PHASE RESPONSE OF OUTPUT PORTS WHEN PORT-3 IS EXCITED

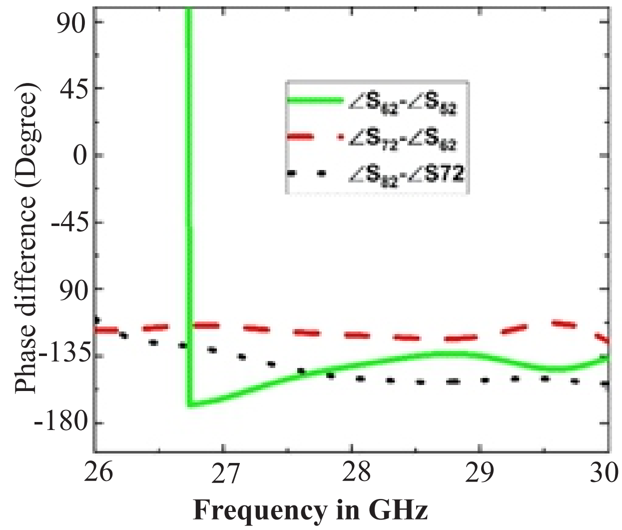



(d) PHASE RESPONSE OF OUTPUT PORTS WHEN PORT-4 IS EXCITED

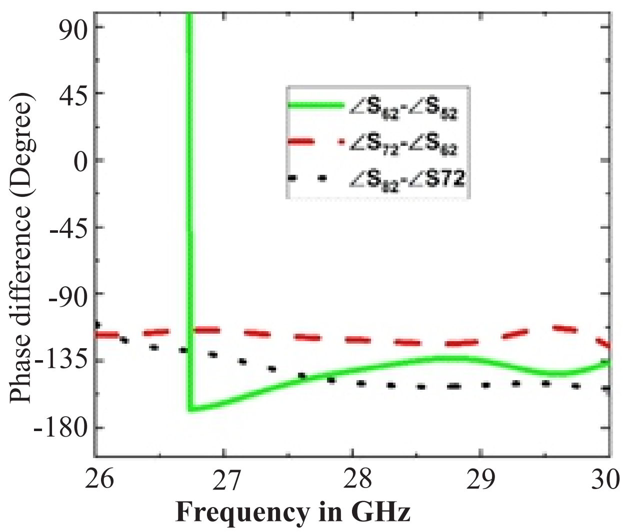
FIG. 9. SIMULATED PHASE RESPONSE OF THE OUTPUT PORTS OF BUTLER MATRIX FOR 5G APPLICATION



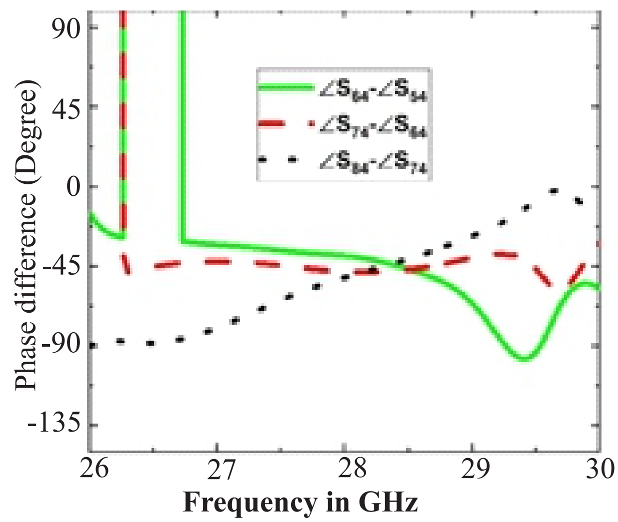

(a) PHASE DIFFERENCE BETWEEN OUTPUT PORTS WHEN PORT-1 IS EXCITED




(b) PHASE DIFFERENCE BETWEEN OUTPUT PORTS WHEN PORT-2 IS EXCITED




( c) PHASE DIFFERENCE BETWEEN OUTPUT PORTS WHEN PORT-3 IS EXCITED




(d) PHASE DIFFERENCE BETWEEN OUTPUT PORTS WHEN PORT-4 IS EXCITED

FIG. 10. SIMULATED PHASE DIFFERENCE BETWEEN THE OUTPUT PORTS OF BUTLER MATRIX FOR 5G APPLICATIONS

TABLE 4. PHASE SHIFT BETWEEN ADJACENT PORTS FOR EACH INPUT PORT EXCITATION

| Ports | Port-5 | Port-6 | Port-7 | Port-8 |
|---|---|---|---|---|
| Port-1 | -64.95 | -22.92 | 24.67 | 71.25 |
| Port-2 | -137.3 | 101.83 | -40.04 | 179.25 |
| Port-3 | 178.33 | -39.97 | 101.88 | -137.3 |
| Port-4 | 98.31 | 59.05 | 10.89 | -40.46 |

## 3. MICROSTRIP ANTENNA DESIGNING

The unit cell (microstrip patch antenna) of 1x4 phased array is shown in Fig. 11and its dimensions are shown in Table 5.Its return loss at 28GHz is -31dB and has a bandwidth of 833 MHz as shown in Fig. 12. The 3D radiation pattern is shown in Fig. 13. The peak gain at operating frequency is 7.47 dB, the HPBW is 79.3° and side lobe level is -17dB.

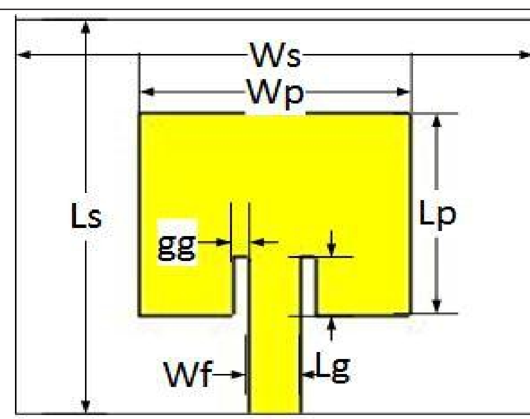



FIG. 11. DESIGN MICRO-STRIP ANTENNA

TABLE 5. DESIGN DIMENSION OF MICROSTRIP ANTENNA

| $W_s$ | $L_s$ | $h_s$ | $W_p$ | $L_p$ | $W_f$ | $L_g$ | $g_g$ |
|---|---|---|---|---|---|---|---|
| 6.485 | 6.88786 | 0.254 | 4.2425 | 3.44393 | 0.8 | 1 | 0.25 |

## 4. ARRAY AND ARRAY FACTOR SYNTHESIS AND ANALYSIS

Let us consider four microstrip antennas placed along z-axis to make a linear array of four elements. The distance between two adjacent elements is d and p(x,y,z) is the point of observation of fields at distance r from the origin as shown in the Fig. 14. In order to avoid grating lobe in scanning array, the distance between antenna elements is taken $0.5\lambda_o$ [10,24].

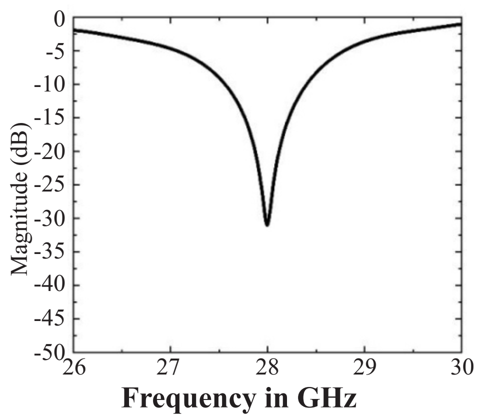



FIG. 12. S-PARAMETERS OF MICRO-STRIP ANTENNA

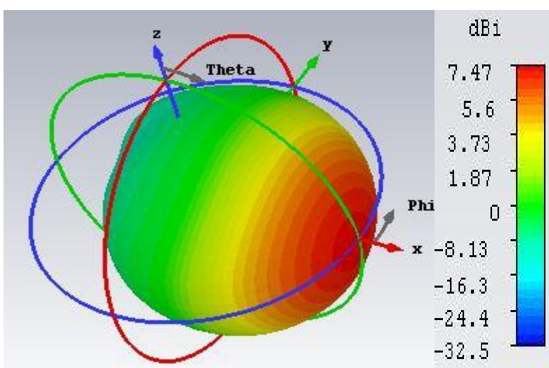



FIG. 13. 3D RADIATION PATTERN OF PATCH ANTENNA

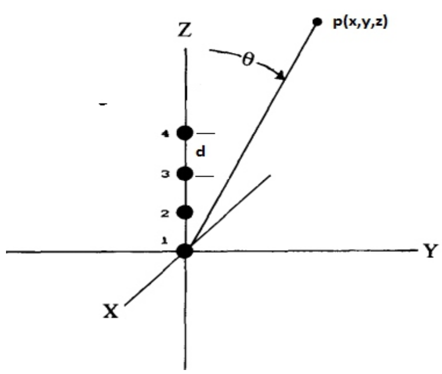



FIG. 14. GEOMETRY OF 4 ELEMENT LINEAR ARRAY PLACE ALONG Z-AXIS

### 4.1 Array Factor Synthesis and Analysis

The electric field for $n^{th}$ element is given by Equation (4).

$$E_n(x,y,z) = \frac{e^{-jkr}}{r} A_{mn} I_{en} e^{j(n-1)[kd\cos\theta+\beta]} \tag{4}$$

Where k is wave number, d is the distance between adjacent element, (n-1)d is the distance of $n^{th}$ element from the origin, $A_{mn}$ is the behavior of individual microstrip antenna in term of orientation and polarization of electric fields, θ is the angle from source axes to field point position vector (as in spherical coordinate system), $I_{en}$ is the excitation current amplitude of $n^{th}$ element, (n-1) kd cosθ is the spatial phase shift and (n-1)β is the electrical phase shift to $n^{th}$ element. Also note that β is the electrical phase shift between two adjacent elements and (n-1)[kd cos θ + β] is the total phase shift.

The field at point p is the superposition of all the fields radiated by all antenna elements is given by Equation (5).

$$E_n(x,y,z) = \sum_{n=1}^{4} E_n(x,y,z) \tag{5}$$

$$E_n(x,y,z) = \frac{e^{-jkr}}{r} A_m \sum_{n=1}^{4} I_{en} e^{j(n-1)[kd\cos\theta+\beta]}$$

$$E_n(x,y,z) = \frac{e^{-jkr}}{r} A_m \times AF$$

Where AF is called array factor which is given by Equation (6).

$$AF = \sum_{n=1}^{4} I_{en} e^{j(n-1)[kd\cos\theta+\beta]} \tag{6}$$

Let us consider all the elementshave excitation amplitude equal to 1 for the sake of easy visualization of the array pattern. The simplified array factor is given by Equation (7).

$$AF = \sum_{n=1}^{4} e^{j(n-1)[kd\cos\theta+\beta]} \tag{7}$$

To simplify the analysis of pattern, put$\Psi$=kd cos θ + β. Now the array factor will look like

$$AF = \sum_{n=1}^{4} e^{j(n-1)\psi}$$

Here inside the summation is complex exponential which will be maximum at ψ = 0. Let θ corresponding to maximum amplitude is $\theta_o$ which is calculated as follow:

$$kd\cos\theta_o + \beta = 0$$

$$\cos\theta_o = \frac{-\beta}{kd}$$

$$\theta_o = \cos^{-1}\left(\frac{-\beta}{kd}\right) \tag{8}$$

After simplification

$$\theta_o = \cos^{-1}\left(\frac{-\beta}{\pi}\right) \quad (9)$$

The Equation(8-9) gives the beam direction from z-axis. The beam direction is usually measured from broadside or from xy-plane which is given Equation (10).

$$\theta_o = \cos^{-1}\left(\frac{-\beta}{\pi}\right) - 90^o \quad (10)$$

The beam direction corresponding to Butler matrix progressive phase shift are calculated and given in Table 6

## 4.2 Half Power Beam Width

The half power beam width for scanning array is given by Equation (11) [42].

$$HPBW = \cos^{-1}\left(\cos\theta_o - \frac{2.782}{N\pi}\right) - \cos^{-1}\left(\cos\theta_o + \frac{2.782}{N\pi}\right) \quad (11)$$

The calculated beam width is given in Table 7. The error occurs because the Butler matrix does not provide uniform phase shift and the calculation involves approximation.

## 5. ARRAY DESIGNING AND SIMULATION RESULTS

The direction of main beam from z-axis for port-1 to port-4 excitation are 100, 52, 128 and 80$^o$ respectively as shown in Fig. 15(a), while the direction of main beam from broadside were 10, -38, 38 and -10$^o$ respectively as shown in Fig. 15(b), which are summarized and compared with calculation in Table 6. Half power beam width are 29.2, 30.4, 30.2 and 29.3$^o$ respectively, they are also summarized and compared with calculation in Table 7. The side lobe level were -11.5, -6.2, -6.3 and -11.6dB. The gains of this array are 12, 10.4, 10.4 and 12dBi respectively.

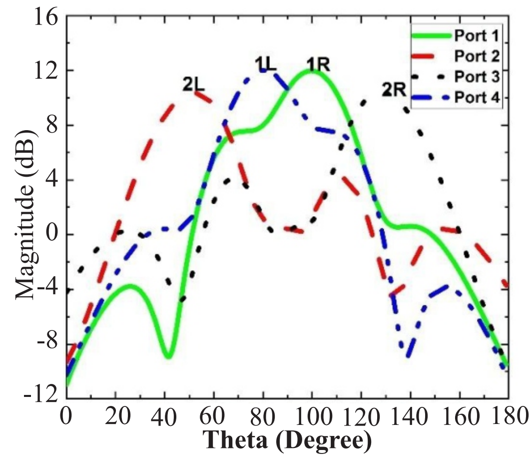
TABLE 6. COMPARISON BETWEEN SIMULATED AND CALCULATED BEAM STEERING ANGLE. C1: PORT NUMBER; C2: PROGRESSIVE PHASE SHIFT CORRESPONDING TO BM; C3: CALCULATED PHASE SCAN ANGLE FROM Z-AXIS; C3: CALCULATED PHASE SCAN ANGLE FROM BROADSIDE; C4: SIMULATED PHASE SCAN ANGLE FROM Z-AXIS C5: SIMULATED PHASE SCAN ANGLE FROM BROAD-SIDE

| C1 | C2 | C3 | C4 | C5 | C6 |
|---|---|---|---|---|---|
| 1 | 45.35 | 104 | 14 | 100 | 10 |
| 2 | -134.5 | 41.63 | -48.3 | 52 | -38 |
| 3 | 134.77 | 138.48 | 48.48 | 128 | 38 |
| 4 | -46.25 | 75 | -15 | 80 | -10 |

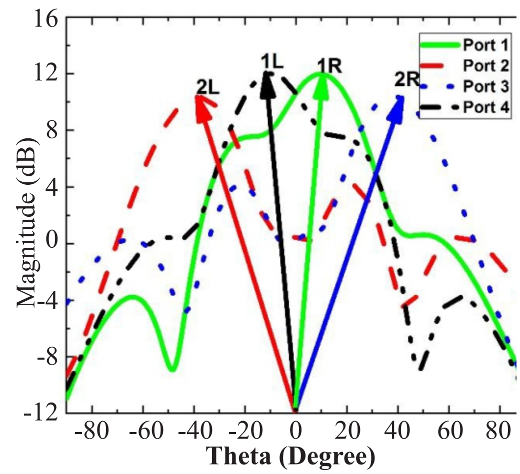
TABLE 1. COMPARISON BETWEEN SIMULATED AND CALCULATED HPBW. C1: PORT NUMBER; C2: PROGRESSIVE PHASE SHIFT CORRESPONDING TO BM; C3: CALCULATED PHASE SCAN ANGLE FROM Z-AXIS; C4: CALCULATED HPBW; C5: SIMULATED HPBW

| C1 | C2 | C3 | C4 | C5 |
|---|---|---|---|---|
| 1 | 45.35 | 104 | 26.4 | 29 |
| 2 | -134.53 | 41.63 | 43 | 30.4 |
| 3 | 134.77 | 138.48 | 44 | 30.5 |
| 4 | -46.25 | 75 | 27 | 29.3 |

The antenna system has a wide bandwidth from 26.3-29.55GHz as shown in Fig. 16.




(a) THETA FROM Z-AXIS




(b) THETA FROM BROADSIDE

FIG. 15. SIMULATED RADIATION PATTERN AT FOR DIFFERENT INPUT PORT EXCITATION

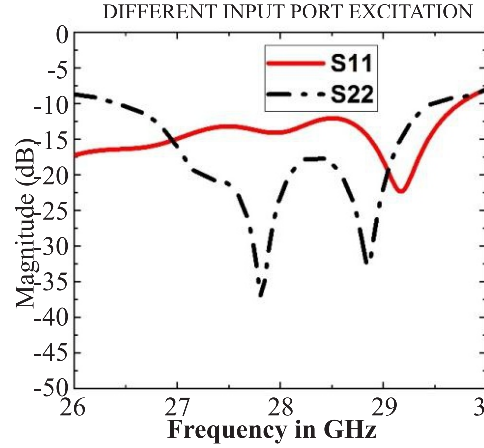



FIG. 16. S-PARAMETERS OF THE BEAM STEERING ANTENNA SYSTEM FOR 5

The 4 element linear array fed by 4x4 Butler matrix was designed in CST and all input ports were excited one by one as shown in Fig. 17. Here, in this designed both the array and Butler matrix are designed on the same substrate. The array elements are placed along z-axis above origin and keep the inter element spacing $0.5\lambda_o$. The total area of the Butler matrix is $30x25mm^2$. The detail parameters are given in Table 8.

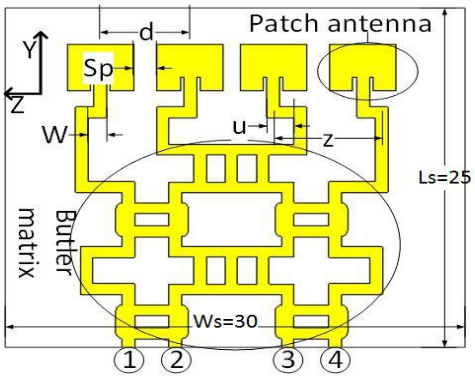



FIG. 17. 1X4 BEAM STEERING ARRAY SYSTEM FOR 5G APPLICATIONS

TABLE 8. PARAMETERS OF BEAM STEERABLE ANTENNA SYSTEM FOR 5G APPLICATIONS

| u | d | z | w | Sp |
|---|---|---|---|---|
| 1.32 | 5.357 | 5.75 | 0.39 | 1.1 |

## 6. CONCLUSION

In this paper, a 1x4 linear array of micro-strip antenna integrated with 4x4 Butler matrix is presented. Both the Butler matrix and micro-strip antenna are designed on a single layer Roger RT5880 substrate having $_r$ = 2.2 and thickness 0.254mm. This antenna cover 28GHz band for future 5G wireless communication networks. The beam is steered from broadside to +10 and +38 degrees. The gain for single element is 7.47dB while, for array the gain is 12, 10.4, 10.4 and 12dB for the respective input port. The half power beam width are $29.2^o$, $30.4^o$, $30.2^o$ and $29.3^o$ respectively. The side lobe level were -11.5, -6.2, -6.3 and -11.6 respectively.

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