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5G beam-steering 2×2 butler matrix with slotted waveguide antenna array

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Abstract

In this research paper, substrate integrated waveguide (SIW) was proposed as a technique by realizing bilateral edge walls to produce a compact 5G beam-steering antenna at 24 GHz. The beam forming network is produced using SIW directional coupler perform as 2×2 Butler Matrix (BM) fed with SIW slotted waveguide antenna array. The output signal is steered from -29 degrees and +29 degrees when the signal is fed to the respective input ports. If one of the input ports is fed, the signal is evenly distributed between the adjacent output ports with 90 degree constant phase shift. The compact size of directional coupler was designed by longitude slots on the surface of SIW substrate with bandwith of 16.85% at the operating frequency. The proposed antenna produce gain of 6.34 dB at operating frequency and the promising outcome of the beam steering make proposed design suitable for 5G communications especially with tracking capabilities.

Keywords: *2×2 butler matrix, 5G, directional coupler, slotted waveguide antenna array, substrate integrated waveguide*

1. Introduction

Antenna with tracking capabilities became tremendous importance in many applications especially for 5G wireless connectivity. Scaling to a higher frequency operation contribute to smaller wavelength, in which limiting the applications especially using microstrip device due to very tight tolerance. As a solution, Substrate Integrated Waveguide (SIW) techniques are preferred especially to be used in beamforming and Multiple-Input Multiple-Output (MIMO) 5G system applications [1-3]. Beamforming identified as the most efficient data-delivery to a desired user, and it automatically reduces interference to nearby users. In addition, it can assist MIMO arrays by the usage of the spectrum around them and with base stations arrayed with hundreds of individual antennas in beam tracking capabilities [4-6]. One of the preferred antenna include slotted waveguide antenna due to small size, low cost, high gain and easy integration in the front end circuits. In 5G band, series-fed method has been widely adopted in simple feeding network antenna due to low insertion loss and relatively high gain [7, 8].

Among the new generation of high frequency integrated circuits, substrate integrated waveguide (SIW) technology is introduced in the beamformer Butler Matrix which consist of rectangular dielectric-filled waveguide synthesized with a planar substrate with arrays. Waveguide microstrip series fed patch antenna slot arrays are integrated with the beamformer for low sidelobe applications due to their high gain, high efficiency, and low radiation loss to both planar transmission line and non planar waveguide [9]. Butler Matrix has the ability to form orthogonal beams, lossless property and high beam crossover level [10-13]. Due to these extraordinary properties, four ports beam-steering Butler Matrix with slotted waveguide antenna array are identified as a breakthrough for 5G communication networks as they can enable beam switching to the targeted users while suppressing unwanted signal [14, 15] without having to compromise in the size limitation and diversify application.

Prior to this paper and to the authors' knowledge, the approach presented in this work has not been investigated earlier. In this paper, two ports substrate integrated waveguide directional coupler is developed into 2×2 Butler Matrix towards high performance, low cost and simplified 5G multibeam array antenna at 24 GHz. In half wavelength, the slotted waveguide

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antenna array has two slot elements that are longitudinally staggered with respect to one another which consecutively fed by 2×2 Butler Matrix without having to utilize phase shifter and crossover. Using the proposed approach design, the 2×2 Butler matrix beamforming antenna network simulation presented 90±5° output phase difference thus exhibit two beam direction steerable radiations at 30±1°.

2. Beam Steering Antenna

2.1. SIW Design

Substrate integrated waveguide is made of a rectangular waveguide with arrays of hole vias and has ability to create bilateral side walls due to transition within structures. These vias act as walls of the waveguide supporting current flow, thus allowing for waveguide mode propagation. Substrate integrated waveguide is preferred in high frequency design due to high density integration applications with low loss. Figure 1 illustrates the SIW topology with via hole of diameter, ***d***, horizontal spacing between two holes pitch, ***p*** and vertical spacing between holes, ***a***. In order to provide vertical current paths, via hole is shorted to both planes. The propagating modes of SIW can be analogous as in rectangular waveguide [16-18] since the vertical metal walls are replaced by via holes. With the optimized dimensions, an equivalent waveguide of dimension equal to ***a*** can provide a promising operational bandwidth at 24 GHz.

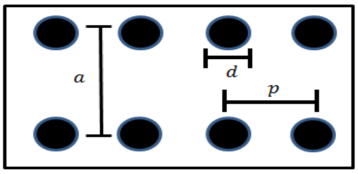


Figure 1. SIW topology

In (1-3), resonance frequency, f_r is determined and the size of SIW cavity is optimized in order to support TE_{10} mode as discussed in [19]. In analysis, w_{eff} and l_{eff} represent width and length of the SIW cavity dimesion. In order to minimize the leakage loss between nearby hole, pitch, ***p*** needs to be kept small based on (4)-(5).

$$f_r = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{\pi}{w_{eff}}\right)^2 + \left(\frac{\pi}{l_{ff}}\right)^2} \quad (1)$$

$$w_{eff} = w - \frac{d^2}{0.95\, p} \quad (2)$$

$$l_{eff} = l - \frac{d^2}{0.95\, p} \quad (3)$$

$$d < \frac{\lambda_g}{5} \quad (4)$$

$$p \leq 2d \quad (5)$$

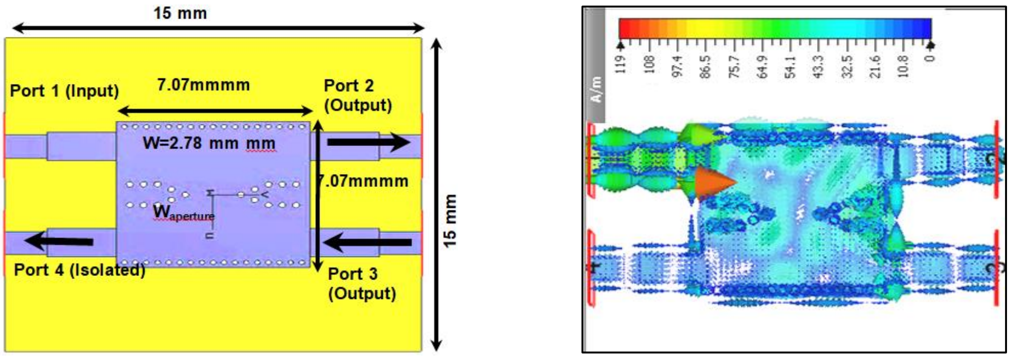
2.2. SIW Directional Coupler

Directional coupler is a four port microwave network which delivers power from any port to the other three output port. SIW directional coupler support TE_{10} mode where the signal fed to the coupler transfer power from input port to the other output ports. Due to quarter wavelength transmission, the reference signal line lead phase shift of the coupler signal with 90° phase. The design of proposed coupler is shown in Figure 2 (a) with two perpendicular rectangular waveguide while Figure 2 (b) illustrates the signal flow through SIW via hole when signal was fed from input 1 with value of 119 A/m. From the analysis, aperture dimension width, $W_{aperture}$

controls the coupling value to be ±3 dB. 90° directional coupler is realized by two pairs of 50 Ω and 35.35 Ω quarter wavelength microstrip line. When the signal fed at Port 1, the signal equally distributed to port 2 and port 3, while port 4 is isolated since there is no power reaching it.

Line impedance between these outputs port is matched at 50 Ω to maximize the power transfer and minimize the reflection from the load. With all ports matched, power entering port 1 is evenly divided between ports 2 and 3, with a 90° phase shift between these outputs [20]. This scattering matrix indicates that the 90 degree hybrid has the property of delivering two output signals with same magnitude and implies that it has a high degree of symmetry. The signal arrive at Port 4 is out of phase, thus no power is coupled to this port. The coupling factor can be determined from (6) where the $W_{aperture}$ dimension, optimized to be 4 mm, while pitch, p is given as 1 mm and diameter, d of air hole is 0.4 mm.

$$Coupling = 10\log\frac{P_1}{P_3} = -20\log\frac{1}{\sqrt{2}}dB \quad (6)$$



(a) (b)

Figure 2. Configuration of (a) SIW directional coupler (b) amplitude of the surface current

2.3. 2×2 Butler Matrix using Directional Coupler

The Butler Matrix has N inputs×N outputs ($N=2^n$) of where n is the matrix order. The switched beam Butler Matrix system has the ability to increase the channel capacity limited by interference. As shown in Figure 3, 2×2 Butler matrix input beam ports equals to the number of output elements ports. When the signal is fed in the input port, two output signals with the same magnitude but a phase shift of ± 90° will be generated. When RF signal excites each of the input ports, signal is distributed equally with a constant phase between them.

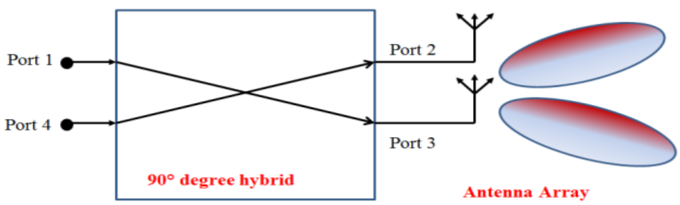


Figure 3. 2×2 Butler matrix schematic diagram

The proposed system has the element of transmitting signals at output ports when the signal is fed at the input ports. The separation between the SIW antenna arrays is controlled to achieve the desired beams and reduced Sidelobe Level (SL). N x N Butler Matrix can generate output signals with equal power and a section phase shift between adjacent output ports, δ_i [21].

$$\delta_i = 2\pi i/N \quad (7)$$

where i=± 1/2, ± 3/2, ± 5/2... ± (N-1) /2.

The phase shifts between two different adjacent ports, δ_i of the SIW directional coupler can be obtained according to (7) with N represent the number of input ports. As clearly tabulated, phase difference between outputs port are ± 90º as listed in Table 1.

Table 1. Phase Difference between Input and Output ports

	Port 1	Port 4
Port 2	0°	0°
Port 3	90°	-90°
Phase shift between adjacent port	+ 90°	- 90°

2.4. SIW Slotted Array Antenna with SIW Directional Coupler

Slotted waveguide series fed antenna array is used as the radiating patch to provide beamforming networks to enable communication and tracking functions. This proposed antenna array with λ_0 /2 spacing at 24 GHz was integrated with the SIW Butler Matrix using coupling fed technique. The two by two SIW symmetrical slotted array antennas with slot dimension of coupling aperture 1 mm×2.7 mm is illustrated in Figure 4 and detailed dimension is listed in Table 2. The SIW directional coupler Butler Matrix integrated with series connected patches antenna and fed with aperture couple is designed to produce narrow E-plane beamwidth with maximum gain and low mutual coupling when input signal is fed in input port, Port 1 and Port 2.

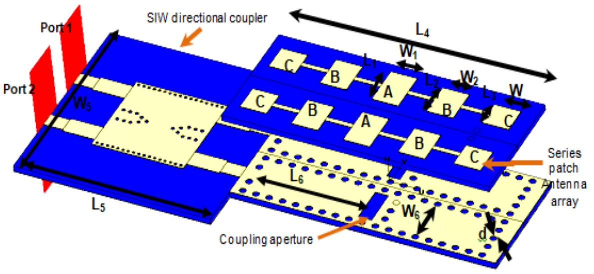


Figure 4. Exploded view of proposed steerable 2×2 butler matrix

Table 2. Dimension Details for Figure 4

Parameter	Dimension (mm)	Parameter	Dimension (mm)
W_1	2.00	W_4	4.50
L_1	3.06	L_4	20.00
W_2	2.00	W_5	15.00
L_2	2.06	L_5	15.00
W_3	2.00	d	0.45
L_3	2.00	W_6	3.60
		L_6	8.50

The amplitude and phase excitation of each elements of phase array antenna is individually controlled to form a radiated beam of desired shape. Hence, beam scanning is operated with the antenna aperture remaining fixed in space without involvement of mechanical motion in the scanning process. Array factor generally is a function of the number of elements, geometrical arrangement, relative magnitude, relative spacing and relative phase. The corresponding phase shift across element is given by (8) and beam direction of Butler Matrix is given by (9) [22], where λ represents the wavelength and d is the antenna element spacing. From the calculation, two beams generated with ± 30° beam direction respectively.

$$\phi_p = 2\pi d \sin\theta / \lambda \quad (8)$$

$$\sin\theta = \pm \frac{\lambda}{d} \frac{\phi_p}{360°} \quad (9)$$

3. Simulation Results

3.1. SIW Directional Coupler

A steerable SIW directional coupler has been designed and simulated using CST Microwave Studio on the 0.508 mm thickness Rogers RO4350 substrate with relative permittivity of 3.48. The dimension of the directional coupler is optimized to 15 mm×15 mm and connected to the serially patch antenna array. Figure 5 and Figure 6 illustrated the results of the directional coupler in terms of return loss, isolation, coupling and phase difference between the coupled ports. The simulation shows the return loss, S_{11} and isolation value S_{41} less than -10dB, which are -15.22 dB and -15.71 dB, indicated promising return loss value. The coupling factor shows average of -3±2 dB of transmission coupling power indicated the output signal is distributed equally between output ports. From the results, it is shown that S_{21} and S_{31}, which are -4.15 dB and -4.06 dB at 24 GHz while phase difference of 92° between two outputs ports. Detailed simulation results are tabulated in Table 3. Directional coupler impedance is designed to be matched to the transmission line delivering the energy for antenna radiating. From the simulated result showed that Voltage Standing Wave Ratio, VSWR shows compromising value of 1.11, indicates that the coupler has matched impedance to the transmission line.

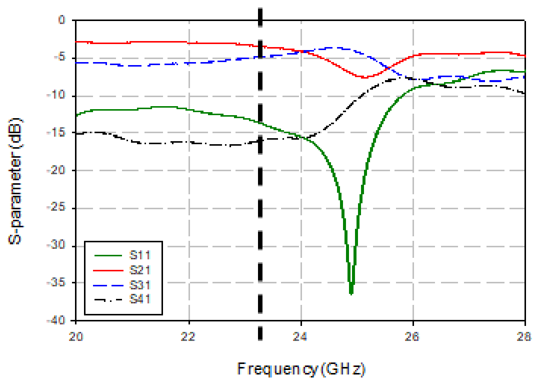


Figure 5. S-Parameter of SIW directional coupler

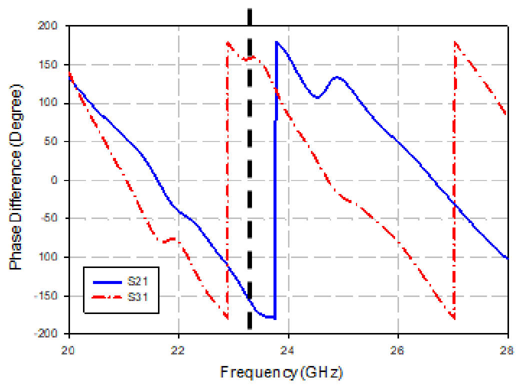


Figure 6. Phase difference between output ports

3.2. Steerable Antenna

The input return loss and isolation simulation results are shown in Figure 7. The return loss, S_{11} simulation value shown as -24.68 dB while isolation, S_{21} shows the value of -11 dB with fractional bandwidth of 1 GHz (f_1=23.7 GHz, f_2=24.7 GHz). The array generates two beams at different angles in its H-plane due to the phase progression in its individual elements. The H-plane radiation patterns are shown in Figure 8 which showed that two steered beams are formed when each of the two ports are fed individually with maximum gain of 6.34 dB. The beams are mirror images of each other where when the signal is fed to Port 1, the main lobe beam will direct to 29° while the signal will direct to -29° when the signal is fed to Port 2. Base on theoretical calculation, the beam angles are 30 ±1° from the perpendicular. The array exhibit angular width 3 dB of 27° when fed with Port 1 and Port 2 respectively as shown in Figure 9.

Table 3. The Performance of proposed SIW directional coupler

Coupler Performance	Results
S_{11}(dB)	-15.22
S_{21}(dB)	-4.15
S_{31}(dB)	-4.06
S_{41}(dB)	-15.71
VSWR	1.11
Phase Difference	(167-75)°=92°

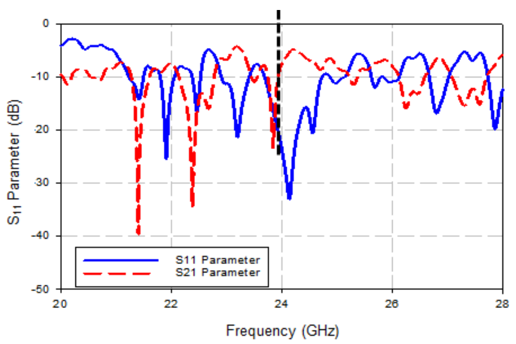
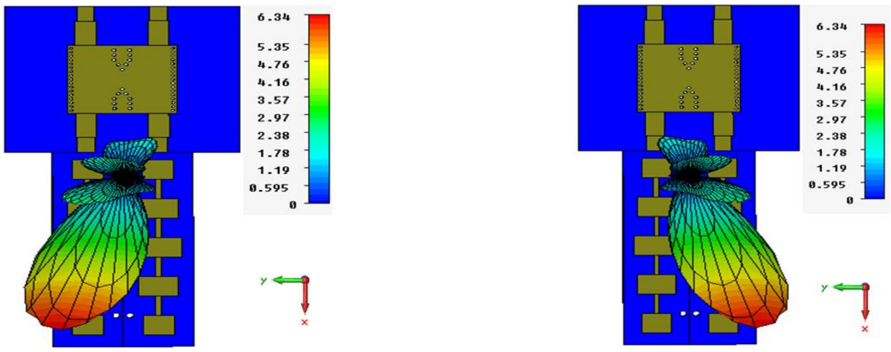


Figure 7. Simulated S_{11} and S_{21} between the ports



(a) (b)

Figure 8. Simulations of radiation pattern from (a) port 1 and (b) port 2

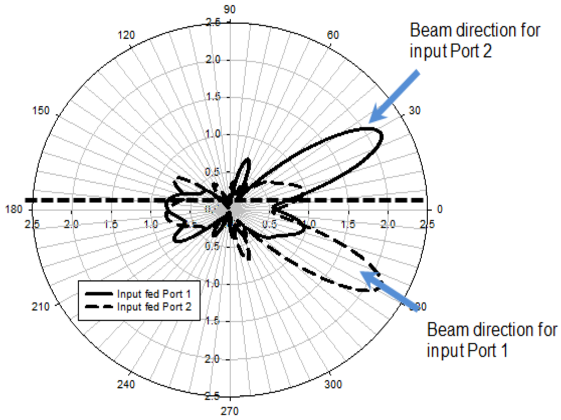


Figure 9. Simulated polar plot radiation patterns at 24 GHz when fed from port 1 and port 2

Comparison between the proposed approach is been performed with previous literature review. From Table 4, it can be seen that the performance of the proposed method of SIW with slotted antenna 2×2 beamformer is comparable with the result obtained in those reported in the previous work. The SIW technique by having via hole which create bilateral waveguide wall made it possible for development of high performance millimeter wave and sub-millimeter wave components in 5G wireless communication at 24 GHz without compromising the performance of the proposed beamforming performance.

Table 4. Proposed Butler Matrix Performance Comparison from Previous Literatures

Ref.	Freq (GHz)	S_{11} (dB)	S_{21} (dB)	S_{31} (dB)	S_{41} (dB)	BW	Phase Difference (°)	Gain (dB)	Size (mm^2)	Material
[23]	60	>-13.5	-2.5	-2.5	>-13.5		90			Rogers RT5880
[24]	270	>-30	–3	–3	-22.35	0.05	90			SU-8 wafer
[25]	29.2 - 32	-18.8	-6.3	-6.3	-18.9	9.3%	90	9.7~12	110.28 × 42.5	Rogers 5880
[26]	28	37.8	3.53	3.72	-22	6.8GHz	89	14.5	35 × 20	Rogers duroid
This work	24	-15.22	-4.15	-4.06	-15.71	1GHz	92	6.34	35 × 15	Rogers RO4350

4. Conclusion

In this paper, a SIW 2×2 directional coupler as Butler Matrix integrated with slotted waveguide antenna array for future 5G communications is designed and simulated. At 24 GHz, proposed design achieves promising results of return loss, transmission, coupling, isolation and phase difference which generate two beams with direction coverage of 30±1°, maximum beam direction of 29° and maximum gain of 6.34 dBi. The total area of proposed beamforming network Butler Matrix with antenna array is (35×15) mm^2 area dimensions. The proposed network is preferred for 5G communication networks as the system can enable beam switching to the targeted users while suppressing unwanted signal. In addition the proposed system has shown desirable gain, good steerable radiation and compact size that can well satisfy the general requirements in 5G communication system.

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