

# Design of Butler Matrix Integrated with Antenna Array for Beam Forming

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**Abstract**—This paper presents a 4x4 Butler matrix as a beamforming network that is combined with a 4-elements linear aperture coupled antenna arrays to produce four narrow steerable beams. The designed array is aimed to obtain a operating frequency at 2350 MHz for LTE applications by using the Advance Design System (ADS) and CST Microwave Studio. The measurement result shows that the bandwidth for each port is more than 100 MHz. the isolation between ports in the range frequency 2.3 – 2.4 GHz is more than 20 dB. When port 1, 2, 3, or 4 is activated, the beamwidth of the array is 33.8°, 39.8°, 40.3° and 35.6° with the gain is about 6.11 dBi, 3.94 dBi, 4 dBi, and 6.05 dBi, respectively. The main beam of the array in azimuth direction is tilted to -20°, 40°, -40°, and 20° for respective input port.

**Keywords:** Antenna array, Butler matrix, beam forming, switched beam system

## I. INTRODUCTION

Smart antenna is one of the most potential technologies that will enable a higher capacity in wireless networks by effectively reducing multipath and co-channel interference. This is achieved by focusing the radiation only to the desired direction and adjusting itself to changing traffic conditions or signal environments. Smart antennas employ a set of radiating elements arranged in the form of an array. Basically, there are two types of smart antenna system, the switched beam system and adaptive array system [1].

The topic of switched beam antenna as a smart antenna has been discussed because it is easy to be implemented and low cost compared to adaptive antenna array. Unlike the adaptive antenna, switched beam antenna only constructed by a number of radiating elements, a beam forming network and RF switches [2] while adaptive array systems offer more intelligent operation and require advanced signals processing [3]. Switched beam systems are antenna-array systems that form multiple-fixed beams with enhanced sensitivity in a specific area. This antenna system detects signal strength, selects one of the several fixed beams, and switches from one beam to another as the user moves [4].

In the switched beam system, there are some techniques to constructed analog beam forming network, such as Blas matrix, Rotmans lens, Nolen matrix, and Butler matrix [5]. One of the most common technique used in switched beam system with linear array antenna is the Butler matrix because it is simple, able to generate high directivity orthogonal narrow beamwidth [6] and it can achieve continuous beam scanning without any mechanical motion [7]. It also does not utilize any

active devices such as PIN diodes to maintain low cost. The Butler matrix is a passive feed network which utilizes hybrid couplers, phase shifters and crossovers to provide differential phase shifts at the input of antenna elements in the array [1].

There are some researches about smart antenna system. In [8], a smart antenna system with 4x4 Butler matrix that has coverage area 120° and microstrip patch antenna array is designed for 5.25 GHz Wi-Fi band with sidelobe level -10 dB and return loss below -20 dB. In [9], a smart antenna array with its similar design to [8] worked in 2.4 GHz ISM band and obtained an array gain of ~11dB and return loss of -33dB. Meanwhile, in [10] a 60 GHz patch antenna array for WiGig application is demonstrated with gain between 7-9dB and return loss better than -10dB. All designs proposed in [8–10] have 4 input ports and generate 4 different beam orientations with coverage area 120°.

In Indonesia, 4G TDD – LTE is allocated in 40 and 41 band at frequency range of 2300 – 2400 MHz and 2496 – 2690 MHz. Both bands are also covering 2.4 GHz ISM band for Wi – Fi application.

In this paper, a beam forming network using Butler matrix is designed to operate at 2.35 GHz and integrated to an aperture coupled antenna array. The design is conducted using Advance Design System (ADS) simulator and CST Microwave Studio Simulator 2014.

## II. BUTLER MATRIX INTEGRATED WITH ANTENNA ARRAY

For design of the Butler matrix, the major components, such as, hybrid coupler, crossover, and phase shifter, needs to be designed and analyzed separately.

### A. 4x4 Butler Matrix Design

The designed 3-dB hybrid coupler, crossover, and phase shifter are combined together to achieve a 4x4 Butler matrix using single-layer microstrip line, as shown in Fig. 1, with a total area of 16×28 cm. This structure was implemented and simulated using ADS software. The distance between output ports is arranged to qualify as the effective distance of antenna, for this case the distance is  $0.5\lambda$  between outputs.

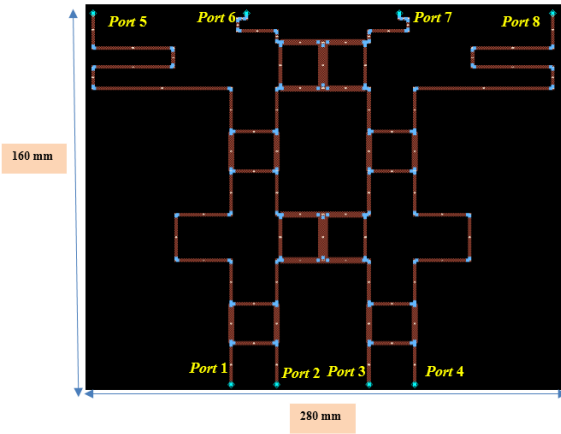


Figure 1. Layout 4x4 Butler matrix

From Fig. 1, the design of the Butler matrix, which provides the phase differences, is given in Table I.

TABLE I. PHASE RELATION BETWEEN PORTS AT OUTPUT OF BUTLER FEED

Output	Input			
	Port 1	Port 2	Port 3	Port 4
Port 5	-45°	-135°	-90°	-180°
Port 6	-90°	0°	-225°	-135°
Port 7	-135°	-225°	0°	-90°
Port 8	-180°	-90°	-135°	-45°
Phase difference between output ports	-45°	135°	-135°	45°

Fig. 2(a) shows the reflection coefficient and transmission coefficient of port 1 that represent the value of the other ports because its similarity for respective input port. From this result, it can be concluded that the bandwidth is about 500 MHz at the central frequency 2.35 GHz.

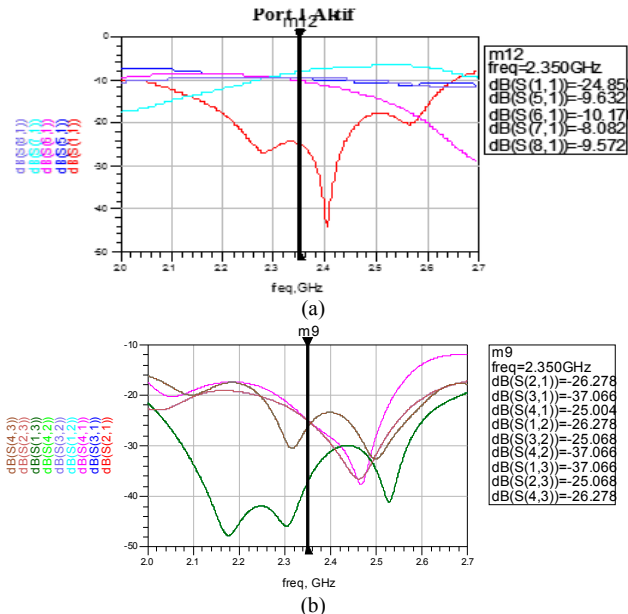


Figure 2. S-Parameter of 4x4 Butler matrix (a) Insertion loss and return loss for port 1 (b) isolation of the input port

The simulated transmission coefficients are around -9 dB. The value of 9 dB means that the power of the port 1 has been divided equally between the four output ports. The isolation of port 1 when the other input ports are matched with a resistance of 50  $\Omega$ , is shown in Fig. 2(b). It can be noted that the isolation losses between input ports is better than -25 dB from 2.3 GHz to 2.5 GHz.

### B. Butler matrix integrated with Antenna Array Design

The single element of the aperture coupled antenna has been designed in [11] with the dielectric constant is 4 and 0.2 for loss tangent. The antenna design using FR4 substrate consists of 2 layers with different thickness of 1.6 mm and 0.8 mm. The Butler matrix that has been designed in section A is integrated with the antenna array that has inter-element spacing about half wavelength to achieve maximum gain and low mutual coupling. Fig. 3 shows the exploded view of the Butler matrix integrated with the antenna array. From Figure 3(a) the upper layer shows the patch antenna without conductor behind the layer. The thickness of this layer is 1.6 mm. The top of the second layer is the ground plane of the with dumbbell shape slots. This dumbbell shape slot or coupling aperture is used for medium propagation of the electromagnetic wave from feed line to the patch. From Figure 3(b) the back view of the design can be seen and shows the second layer with 0.8 mm thickness. The backside of this layer contains the design of Butler matrix.

Simulation result shows that the antenna works at 2.3 – 2.4 GHz ( $VSWR \leq 2$ ), with bandwidth more than 100 MHz. This antenna also has an isolation loss between ports below -20 dB and has gain from 4 to 6 dBi.

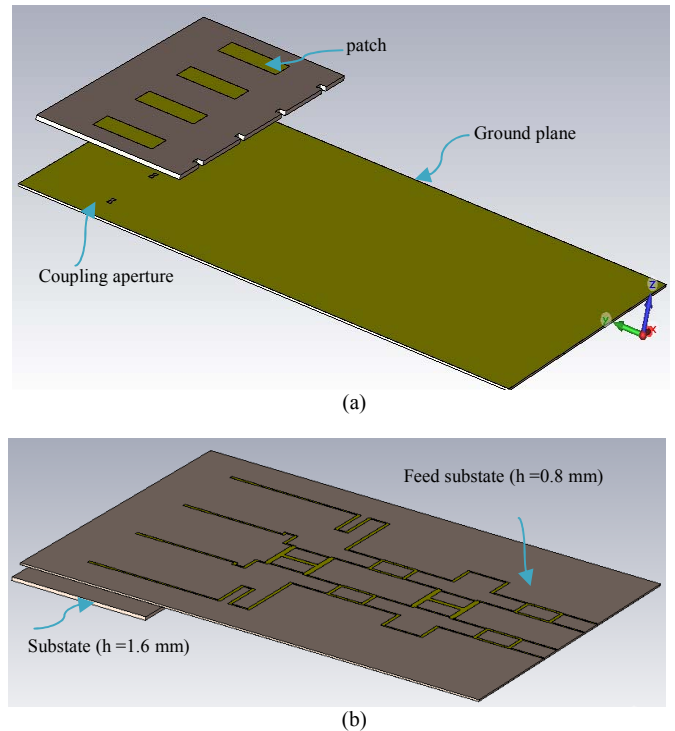


Figure 3. Exploded view of antenna design (a) front view (b) back view

### III. RESULTS AND DISCUSSION

The fabricated Butler matrix integrated with antenna array is shown in Fig 4. Its dimension is 280x260 mm.

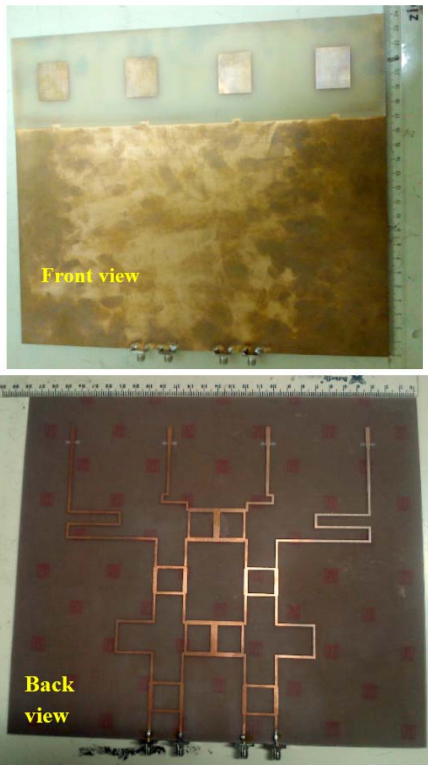


Figure 4. Fabricated Butler matrix integrated with antenna array

The measurement of the antenna was conducted in anechoic chamber at Department of Electrical Engineering, Faculty of Engineering, Universitas Indonesia.

#### A. Reflection Coefficient Measurement

The measurement result, which compared to simulation result of the reflection coefficient, is shown in Figure 5. The coefficient reflection when port 1 or 4 is activated is -26 dB, while when port 2 and 3 is activated is -15 dB. The frequency range for this design is 2.2 – 2.4 GHz with the impedance bandwidth of 200 MHz.

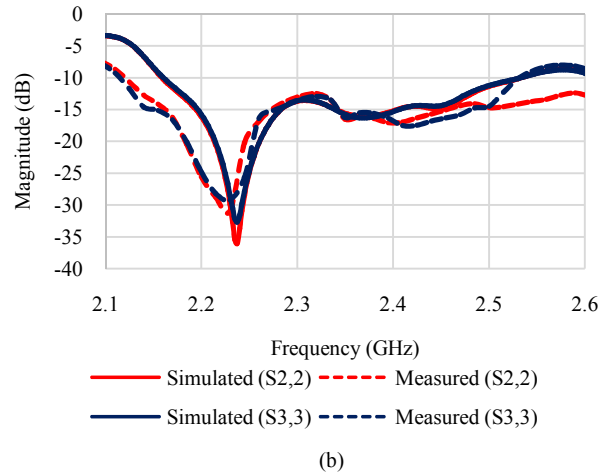
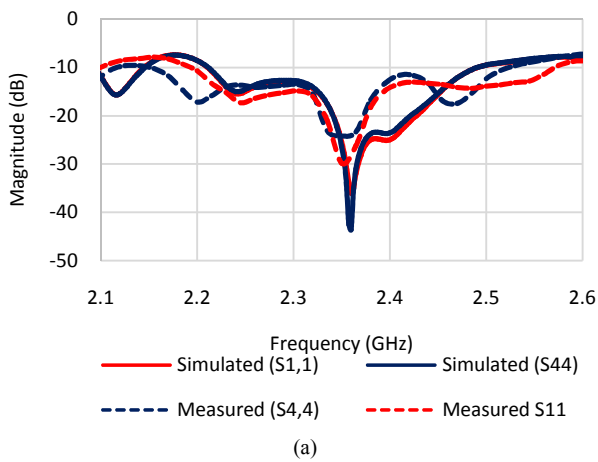


Figure 5. Return loss for respective port (a) when port 1 or 4 is activated (b) when port 2 or 3 is activated

#### B. Isolation Losses Measurement

Fig. 6 shows the measurement result of the isolation loss between ports in the range frequency 2.3 – 2.4 GHz. The result shows that the isolation loss for all ports is below -20 dB.

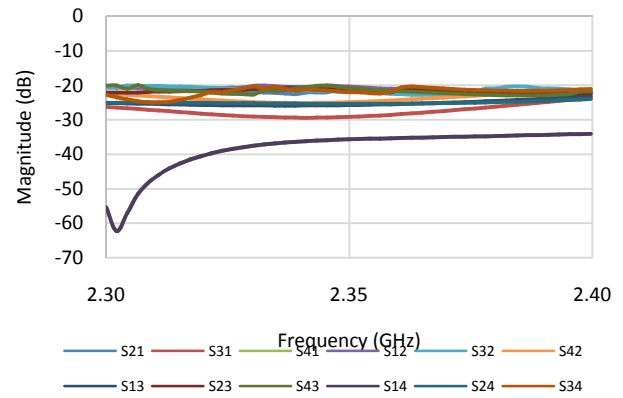
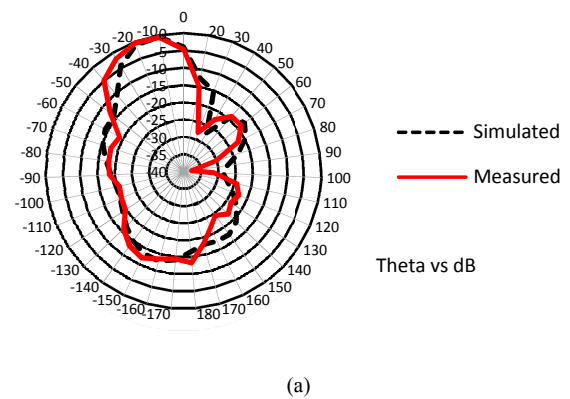
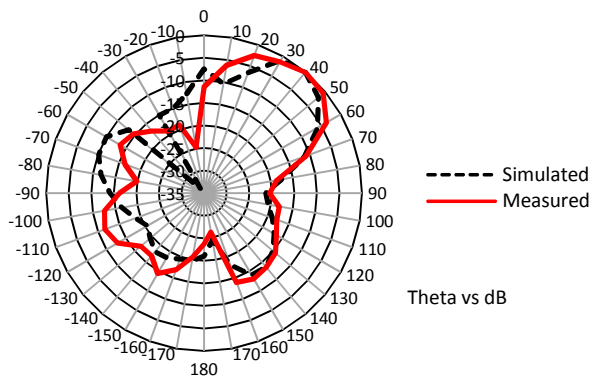


Figure 6. Measured Isolation loss between port

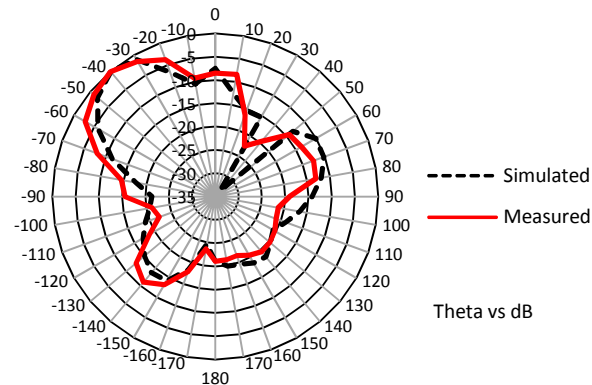
#### C. Radiation Pattern Measurement

The E-field radiation pattern comparison between measurement and simulation result of the Butler matrix integrated with antenna array is shown in Figure 7. The radiation pattern is measured at frequency of 2.35 GHz.

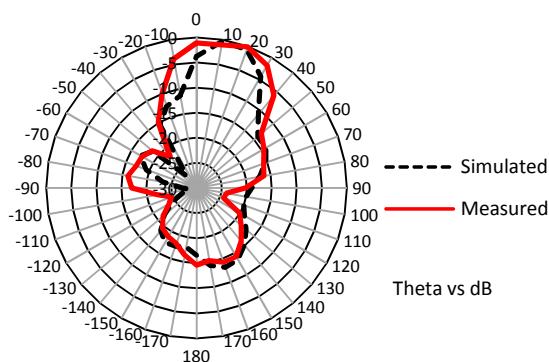




(b)



(c)



(d)

Figure 7. Measured and simulated results of radiation pattern (a) port 1 is fed (b) port 2 is fed (c) port 3 is fed (d) port 4 is fed

Figure 7. shows the main beam direction at port 1, 2, 3, and 4 is  $-20^\circ$ ,  $40^\circ$ ,  $-40^\circ$ , and  $20^\circ$ , respectively. The half power beamwidth is  $33.8^\circ$ ,  $39.8^\circ$ ,  $40.3^\circ$  and  $35.6^\circ$ , respectively.

In addition, the antenna gain was measured from 2.3 GHz until 2.4 GHz for all ports. From the measurement result at the center frequency 2.35 GHz, the gain of port 1, 2, 3, and 4 are 6.11 dB, 3.94 dB, 4.01 dB, and 6.04 dB, respectively.

All of the measurement results show similar results compared to the simulation result. The slight difference occurred due to imperfect fabrication of the antenna. The design can be further improved in terms of insertion losses and

efficiency by using a low loss substrate instead of FR4. Phase error can be mitigated by using tunable phase shifters.

#### IV. CONCLUSION

In this paper, the simulation and measurement result of a 4x4 Butler matrix integrated with antenna array for range frequency 2.3 – 2.4 GHz has been presented. The bandwidth for each port is more than 100 MHz. Isolation loss in that frequency range is from -20 dB until -62 dB. The measurement result at 2.35 GHz shows that when port 1, 2, 3, or 4 is activated, the beamwidth is  $33.8^\circ$ ,  $39.8^\circ$ ,  $40.3^\circ$  and  $35.6^\circ$  with gain 6.11 dB, 3.94 dB, 4 dB, and 6.05 dB, respectively.

#### ACKNOWLEDGMENT

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