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A Compact Design of 4×4 Butler Matrix with Four Linear Array Antenna at 38 GHz

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Abstract**—*****This paper creates a compact design of a 4×4 butler matrix integrated with an array of antenna elements at 38 GHz frequency. The antenna simulation performance is acceptable, approaching the ideal one. The butler matrix can generate four beams through the output port directly. Each input port 1, 2, 3, and 4 has beam direction, which is 42°, -19°, 19°, and -42°, respectively. The phase difference between output ports of the butler matrix is approaching 45° and 135°. Besides, antenna patch simulation has a good performance. The results are still acceptable after combining the butler matrix and four linear array antenna.***

Keywords**—*****Beam Forming Network, Butler matrix, Five Generation (5G) antenna.***

I. Introduction

Mobile and wireless connectivity is hugely needed and has become an issue in telecommunication systems. Therefore, the newest communication system, such as the 5G antenna, has been developed. The 5G antenna system requires more capacity, higher data rate, and beamforming capability to overcome telecommunication issues [1,2]. A new design of wideband dual-polarized multiple beamforming array antennas was studied for overcoming heavy traffic in the 4G LTE base station [1]. Higher data rates and gain can be obtained by designing a compact 38 GHz multi-beam patch antenna array with a multi-folded butler matrix [2].

Beam Forming Network (BFN) is a feeding line technique aiming to feed radiating elements to generate many radiation patterns in distinct directions and angles [3]. Antenna beamforming can increase power in a specific direction while declining power in undesired directions [4,5]. The butler matrix creates one beamforming network to produce many beam directions [6,7].

Based on [3], the Butler Matrix is a feeding line technique with many inputs and outputs that are useful for beamforming and switched beams in many forms, such as linear array and circular array [8]. Furthermore, Butler Matrix is a feeding line for the antenna, which generates many beam directions [9], where the main component in the structure is a 3dB coupler. This feeding line circuit is very familiar and is often used as a beamforming technique for 5G antenna applications [10-15].

Some research about BFM, such as in [10], has been studied. As a result, a Multiple Input Multiple Output (MIMO) antenna was built to work at 3.5–4.2 GHz that used a 4x4 butler matrix circuit. The material used Rogers 3003 as the substrate with a thickness of 0.508 mm and a dielectric constant of 3. As a result, the simulation performance has been optimum, where the amplitude was between -6 dB and -8 dB at the outputs. Furthermore, the main beam directions were 15° and 35°.

In another research [16], an antenna for a 5G application was created to operate at a 28 GHz frequency. The radiating element was fed by creating a 4x4 butler matrix as the feed line to generate beamforming ability. The antenna structure was created using the material of roger RT5880, which had a thickness of 0.25 mm, a dielectric constant of 2.2, and a loss tan is 0.001. As a result, the simulation performance is optimum, indicated by the resulting amplitude of around -6 dB at the central frequency. In addition, the butler matrix had phase differences of -45°, 135 -135°, and 45° in each output port.

A 4x8 butler matrix was created to apply System on Chip (SoC) at 38 GHz has been studied in [17]. In this study, the 8x8 butler matrix has been developed to become a 4x8 butler matrix by reducing some components but adding switches. Although, the additional switches caused relatively significant losses higher than 4.2 dB. As a result, the simulation performances were not optimum since the insertion losses in output ports were approximately 8 dB.

This research proposes an original 4x4 Butler Matrix combined with a four-linear array antenna that works at 38 GHz for 5G. The butler matrix structure is created in this work by three main components: coupler, crossover, and phase shifter. These three components provide a good agreement with prediction at high frequency, although those generate acceptable amplitude and phase imbalance. The return losses and isolation losses are lower than -15 dB, while insertion losses are around 7 – 11 dB. Phase differences between output

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ports are 45° and 135°, with an average phase imbalance of 5.6°. Moreover, the overall design has a simple and compact structure for future 5G antennae. The structure of this paper is as follows: Section II presents the butler matrix and antenna configuration, section III presents the result and discussion, and section IV presents the conclusion.

II. Butler Matrix and Antenna Configuration

This antenna uses a well-known beamforming network, the butler matrix. Butler matrix has three main components, i.e., coupler, crossover, and phase shifter. After the feeding network is designed, a radiation element (patch) is made, and both integrate into a complete antenna design. In this paper, the antenna is designed using the RT Duroid 5880 substrate with a thickness of 0.381 mm, a dielectric constant of 2.2, and a tangent loss of 0.0009. The material is used because it has a minimum loss.

A. Branch-line Coupler

This research shows the branch-line coupler's first significant component of the designed butler matrix. Branch-line coupler is often called a coupler 3 dB or hybrid 90°. This component is intended to divide the input power into two output powers at output ports equally. Theoretically, a coupler must transmit the half-power (-3 dB) into both output ports and generate a 90° phase difference [18, 19]. However, the simulation result is always more or less at -3 dB and not precisely at -3 dB due to some losses [20]. The structure of a branch-line coupler is shown in Fig. 1.

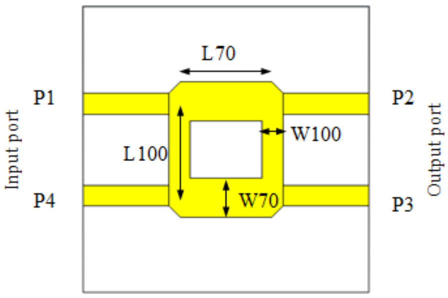

Fig. 1. Structure of branch-line coupler.

Fig. 1 shows the structure of the coupler 3 dB fed by four ports. Generally, port one (P1) and port four (P4) are the input ports, whereas the second port (P2) and third port (P3) are named as the output ports. When P1 is assumed as an input port, P4 becomes an isolation port and vice versa. If the input power is transmitted by P1, it will be evenly distributed across both outputs, P2 and P3, and low power will be distributed to P4. Table 1 shows the characteristic of the branch line coupler.

TABLE I. CHARACTERISTICS OF THE BRANCH-LINE COUPLER

Parameters	Dimension (mm)
L100	1.74
W100	0.38
L70	1.68
W70	0.7

B. Crossover

The second major component that has been created is crossover. This component is commonly created by combining two couplers of 3 dB [18]. This element avoids the affection of the coupling power of two 3 dB couplers. As a result, the performance of the crossover simulation generates 0 dB power in the crossing line port. The crossover is also designed to provide high isolation loss in another two crossing lines, ensuring both of the lines are not connected electrically [19]. Fig. 2 shows the structure of the crossover.

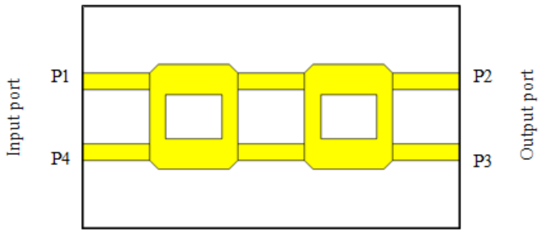

Fig. 2. Structure of crossover.

The crossover in Fig. 2 has an input port shown in P1 and a crossing output port in P3. In this case, P2 and P4 are called isolation ports.

C. Phase Shifter

The third principal component of the butler matrix is the phase shifter. This component is a section of a transmission line and has a particular length for adjusting the signal's phase shift [19]. This study designed two 45° phase shifters and two 0° phase shifters. The design and characteristics of a 45° phase shifter are shown in Fig. 3 and Table II.

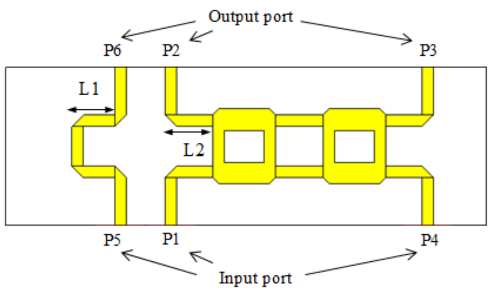

Fig. 3. Structure of 45° phase shifter.

TABLE II. CHARACTERISTICS OF THE BRANCH-LINE COUPLER

Parameters	Dimension (mm)
L1	1.4
L2	1.55

The 45° phase shifter is established with a crossover, as can be seen in Fig. 3. The component is made beside the crossover, and the phase distinction can be measured by subtracting port 3 (S31) and port 6 (S65) to obtain the 45° phase distinction between S3,1 and S6,5 [18]. Besides, the 0° phase shifter is presented in Fig. 4.

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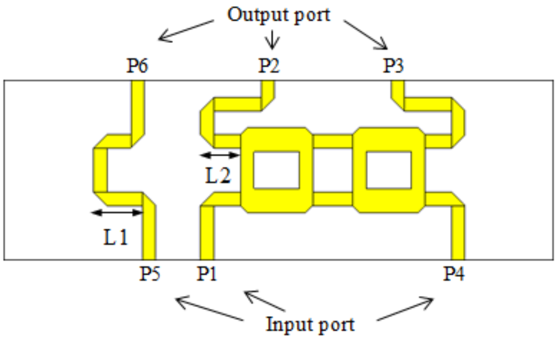

Fig. 4. Structure of 0° phase shifter.

After some optimization, a combination of the 0° phase shifter and crossover structure can be seen in Fig. 4. The characteristic of the 0° phase shifter is shown in Table III.

TABLE III. CHARACTERISTICS OF THE BRANCH-LINE COUPLER

Parameters	Dimension (mm)
L1	1.4
L2	1.15

D. Butler matrix

The Butler Matrix is designed after the three major components: coupler, crossover, and phase shifter. The ideal 4x4 Butler Matrix used in this study consists of four couplers, two crossovers, and four phase shifters. Fig. 5 shows the structure of the 4x4 Butler matrix.

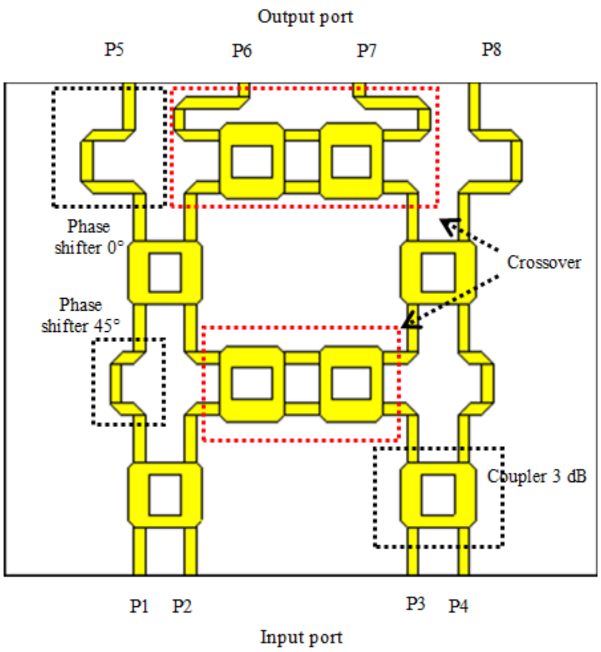

Fig. 5. Structure of 4×4 butler matrix.

The structure of the 4x4 butler matrix after combining couplers, crossovers, and phase shifters with four input and output ports is shown in Fig. 5.

E. Patch Antenna

This paper creates four radiating elements (patches) for optimal performance. The patch element aims to transmit the signal power to the atmosphere. Patch antenna design characteristics can be seen in Fig 6 and table IV.

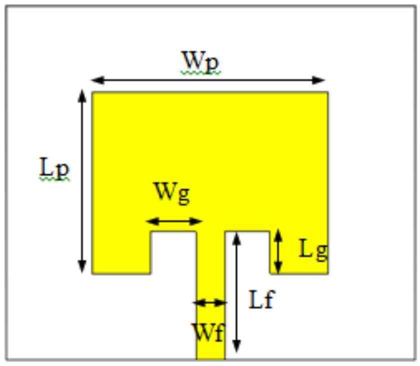

Fig. 6. Structure of patch antenna.

TABLE IV. CHARACTERISTICS OF THE PATCH ELEMENT

Parameters	Dimension (mm)
Length of a patch (Lp)	2.41
Width of a patch (Wp)	3.12
Length of gap (Lg)	0.557
Width of gap (Wg)	0.6
Length of feed (Lf)	1.7
Width of feed (Wf)	0.38

F. The 4×4 butler matrix integrated with four linear array antenna

The 4x4 butler matrix layout has been well constructed using couplers, crossovers, and phase shifters. A 4x4 butler matrix and radiating element make a precise beam direction antenna. The 4×4 butler matrix integrated with four linear array antenna patches has been studied in this research. The structure of the 4×4 Butler Matrix with four linear array antenna patches is shown in Fig. 7.

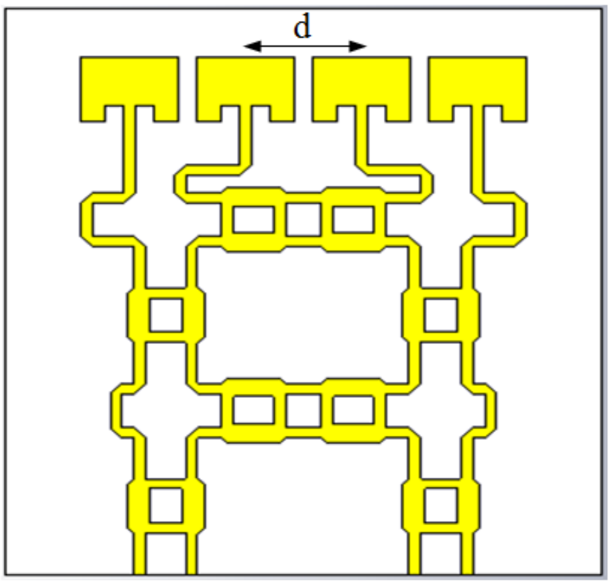

Fig. 7. Structure of 4×4 butler matrix integrated with antenna patch.

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Fig. 7 shows the complete layout of the 4×4 butler matrix integrated with four linear array antenna for the 5G application. The distance between each element is symbolized by d, and the value is 3.73 mm

III. Result And Discussion

This butler matrix works at 38 GHz for 5G technology implementation. The overall dimensions of the 4x4 butler matrix and array antenna are 19.21 mm × 21.322 mm × 0.451 mm. The design and simulation use Computer Simulation Technology (CST) Microwave Studio Suite.

A. *Branch-line coupler*

This optimized branch line coupler obtained a satisfying performance at 38 GHz. The simulation result of the branch line coupler is shown in Fig. 8.

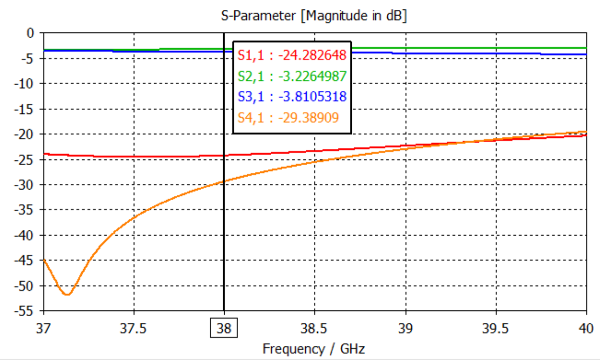

Fig. 8. S-Parameter (magnitude) of the branch-line coupler.

In Fig. 8 can be seen the result of the S-Parameter (magnitude in dB). The figure shows that return loss in port 1 (S11) is around -24 dB at 38 GHz, which indicates good input impedance matching. The insertion loss in the second and third ports (S21 and S31) is almost equal to -3 dB at 38 GHz, meaning input power is equally divided to both the second and third output ports. And isolation loss in port 4 (S41) is around -29 dB at 38 GHz, which means there is optimum isolation between port 1 and port 4. Finally, the phase result is shown in Fig. 9.

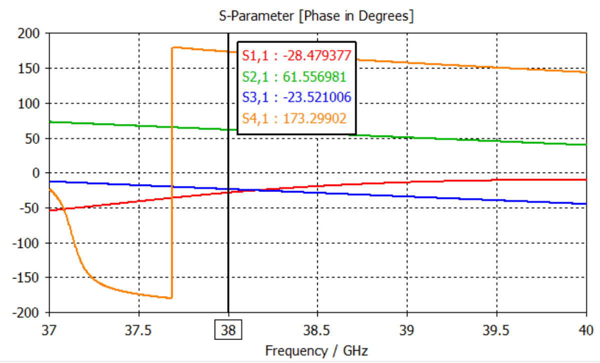

Fig. 9. S-Parameter (phase) of the branch-line coupler.

From Fig. 9, the phase difference between the second and third output ports (S21 and S31) is approximately 85° with a phase error of 5°. The result of the phase difference is approaching 90°, which is good theoretically.

B. *Crossover*

This component allows the input power to be distributed through two crossing ports. Fig. 10 shows the performance of the crossover.

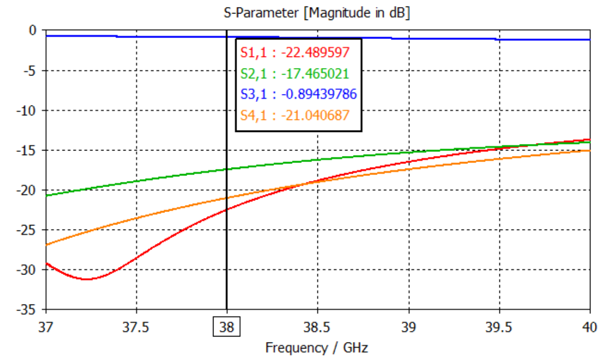

Fig. 10. S-Parameter (magnitude) of the crossover.

According to Fig. 10, the amplitude of the crossing line port 3 (S31) is around -0.89 dB, which is good theoretically compared to 0 dB. It means there are minimum losses produced at crossing line port 3. In addition, the coefficient reflection of S11, S12, and S14 are below -15 dB.

C. *Phase shifter*

The 4×4 butler matrix has four phase shifters, two of the 45° phase shifter and two of the 0° phase shifter. Fig. 11 shows the 45° phase shifter simulation.

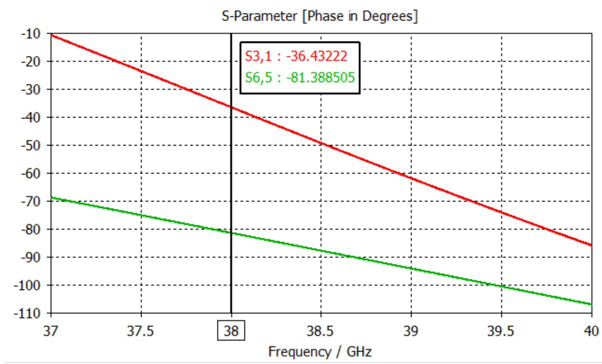

Fig. 11. S-Parameter (phase) of the 45° phase shifter.

The phase shift of the 45° phase shifter is presented in Fig. 11. The result of the phase difference between port 6 (S65) and port 3 (S31) is around 44° with a phase imbalance of 1°.

The performance of 0° phase shifter is shown in Fig. 12.

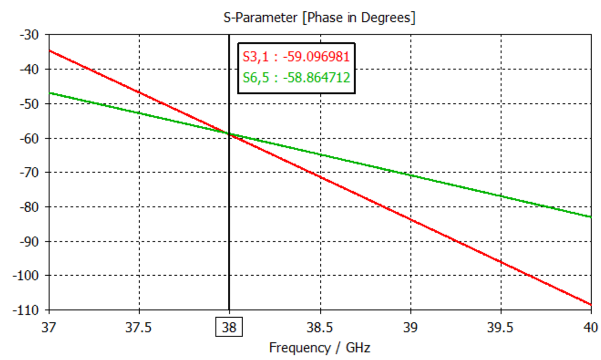

Fig. 12. S-Parameter (phase) of the 0° phase shifter.

Fig. 12 shows the phase difference of approximately 0° obtained in the simulation. The result was simulated similarly with the 45° phase shifter.

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D. The 4×4 butler matrix

The ideal 4×4 butler matrix is produced by designing and combining the branch line coupler, crossover, and phase shifter. The 4×4 butler matrix has four input ports, from port 1 to port 4, and four output ports, port 5 to port 8. After simulation, the result of the butler matrix is presented in Fig. 13 and Table V.

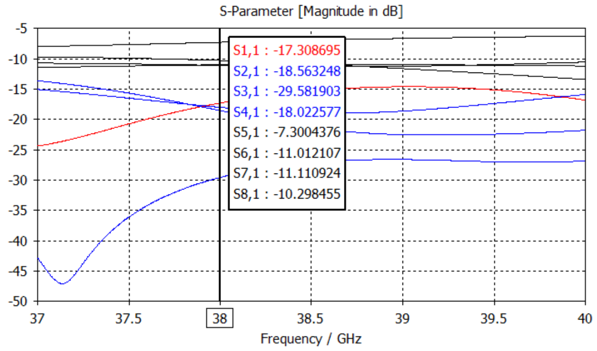

Fig. 13. S-Parameter (magnitude) port 1 of the 4×4 butler matrix

Amplitudes at port 1 of the butler matrix are shown in Fig. 13. The return loss and isolation loss values are lower than -17 dB, while the insertion losses are around 7 to 11 dB. It is proven that the performance of the 4×4 butler matrix is acceptable based on return loss and isolation loss but has a few more losses compared to the ideal butler matrix.

TABLE V. PHASE DIFFERENCE CHARACTERISTIC OF 4×4 BUTLER MATRIX

	P5	P6	P7	P8	Phase Difference
P1	-42°	-83°	-126°	-178°	-45°
error	3°	7°	9°	2°	
P2	-138°	-9°	145°	-94°	135°
error	3°	9°	10°	4°	
P3	-94°	145°	-9°	-138°	-135°
error	4°	10°	9°	3°	
P4	-178°	-126°	-83°	-42°	45°
error	2°	9°	7°	3°	

The performance of phase shifts and errors are presented in Table V. The average phase difference between P1 and P4 is 45°, whereas the average phase difference between P2 and P3 is 135°. The average phase imbalance of the 4×4 butler matrix is 5.6°. This paper's butler matrix simulation results are acceptable compared to other similar research.

E. Patch antenna

The patch antenna has been designed and simulated at 38 GHz. As a result, this component obtained an excellent performance after optimization. The result of the patch antenna simulation is presented in Fig. 14.

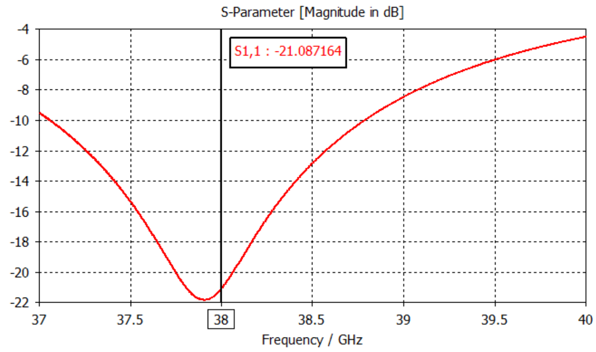

Fig. 14. S-Parameter (phase) of the 0° phase shifter.

In Fig. 13 can be seen that the coefficient reflection of antenna S11 is around -21 dB. Therefore, it means the antenna can generate a minimum return loss.

F. Butler matrix integrated with antenna

In this case, the simulation result is focused on the radiation pattern. The radiation pattern of the butler matrix integrated with the array antenna is plotted on a sigma plot graph. It is shown in Fig. 15.

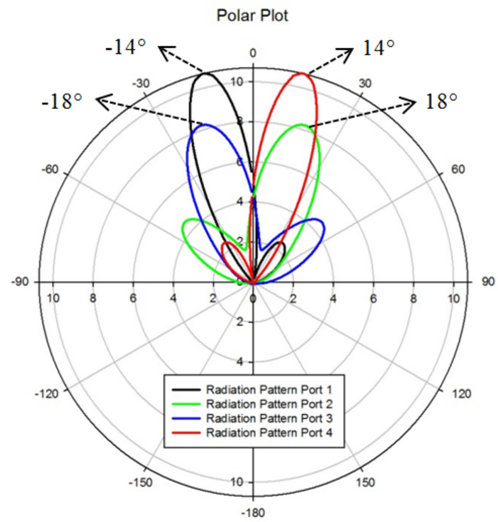

Fig. 15. S-Parameter (phase) of the 0° phase shifter.

Fig 15 shows the radiation patterns of the 4×4 butler matrix integrated with an array antenna produced by port 1 to port 4 and given in different colors. The beam directions of -14°, 18°, -18°, and 14° can be achieved at each input port. Moreover, the antenna gain is around 8 – 11 dB.

IV. CONCLUSION

The 4×4 butler matrix with four linear array antenna has been successfully designed in this study. This antenna operates at 38 GHz and can apply in a 5G antenna. The return loss and isolation loss of the butler matrix are less than -17 dB, while insertion loss is around -7 to -11 dB. Therefore, the butler matrix performs well based on the value of return loss and isolation loss. However, the insertion loss value is more than the ideal one since there are additional losses at crossovers and phase shifters. Furthermore, the beam direction of the 4×4 butler matrix is directed at four different angles, which are -14°, 18°, -18°, and 14°. Therefore, this

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antenna can produce beamforming ability and is appropriate to apply to 5G antenna technology.

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Yusnita Rahayu (M'76–SM'81–F'87) is a senior lecturer and researcher at the Faculty of Engineering, Universitas Riau (UR). She has been working for Universitas Riau since 2005 till now. She graduated with her B.Eng from Institute Science and Technology National (ISTN), Jakarta, in 1999. She finished her Ph.D. from Universiti Teknologi Malaysia (UTM) in 2009 and graduated with her Master of Engineering (M.Eng) in 2004 at the same university. She has experience of more than ten years in academic and research positions at various international and national universities. She has conducted various research projects with national and international grants. Her research interests include radio transceiver design, antenna design, sensor networks, controlling and monitoring systems, IoT, and wireless communication systems. She has published more than 30 papers for national and international conferences, 5 book chapters, 12 international journals. She is also active as a reviewer and technical program committee for various journals and conferences. She is a senior member of IEEE and a member of IEEE antenna & propagation society.

Jan R. M. Simanihuruk is a student at Universitas Riau since 2016 till now in the Department of Electrical Engineering. He graduated his senior high school at SMA N 2 Pangururan. His interests include antenna design and optical and wireless communication systems.

Yuyu Wahyu (M'10) was born in Bandung, Indonesia, on February, 1962. He received the Ir. (Insinyur) degree in 1990, the M.Eng (MT) degree in Telecommunication Information System from the electrical engineering study program in 2000, and the Ph.D. degree in Global Information and Telecommunication Studies from the school of electrical and informatics engineering, in 2010, all from Institut Teknologi Bandung, Bandung, Indonesia. He joined the Telecommunications Research Center, Strategic Electronics, Components, and Materials (Telkom) Indonesian Institute of Sciences (LIPI), now the Research Center for Electronics and Telecommunications, LIPI, since 1991. He served as the head of the Telecommunications and Radio Laboratory between 2000 and 2003. He served as the head of research facilities from 2010 to 2016. He has been the chair of the research group of Antennas and Propagation since 2014. Since 2019, he has been appointed the main researcher in telecommunications transmission. He followed some activities related to his field of competence, including Guest Research in Okayama, Japan, in 2003 for 1.5 months on Active Antenna and radar training in 2006 and 2007 at IRCTR-TU Delft Netherlands. He conducted FMCW radar research from 2006 to the present and electronic support measures (ESM) from 2015 to 2018. He participated in professional organizations, including the Head of West Java province for Himpenindo (Indonesian Researchers Union), from 2020 to 2024. Indonesian Radar Association since 2008, and IEEE Antenna and Propagation Society since 2010.