

# A Novel Tri-Beam Antenna System Based on U-Shaped Dipole

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**Abstract.** Consisting of 6 radiating elements and a  $3 \times 3$  Butler matrix, a novel tri-beam antenna system is proposed in this paper. The radiating element consists of two U-shaped arms and coupled strips, which shows a wide impedance characteristic. Three branch line couplers and four  $-90^\circ$  phase shifters are combined into  $3 \times 3$  Butler matrix as a beam-forming network (BFN). In order to avoid the crossover of transmission lines, one main line of a 1.76 dB coupler is designed and located between two 3 dB couplers. With this arrangement, the signal from one input port can be divided into three output signals with equal amplitude and specified phase differences of  $0^\circ$ ,  $+120^\circ$  and  $-120^\circ$ . Furthermore, a  $2 \times 3$  antenna array is connected with this BFN for three orthogonal beams. Measured results show that three beams at  $\theta = 0^\circ$ ,  $40^\circ$  and  $-40^\circ$  are produced when different input ports are excited.

## Keywords

U-shaped arm, Butler matrix, tri-beam antenna

## 1. Introduction

Multi-beam antenna can form several narrow beams to cover specific area for the signal transmission in wireless communication system [1–3]. Comparing with the single beam antenna, multiple-beam antenna can have a higher gain and a better signal to noise ratio, which leads to the increased coverage for rejecting interference from co-channel reuse cells in mobile communication system [4]. As one of well-known beam-forming network, Butler matrix is a passive element with  $N$  input ports and can divide an input signal into  $N$  output ports [5], [6]. The low power loss and the simplicity in structure of the Butler matrix guarantee its prevalence in design of multiple-beam antenna [7–12]. However, the number of input/output ports of conventional Butler matrix is equal to  $2^m$  ( $m$  represents a positive integer) [8]. Therefore, the symmetrical beams formed by the Butler matrix are located on both sides of the

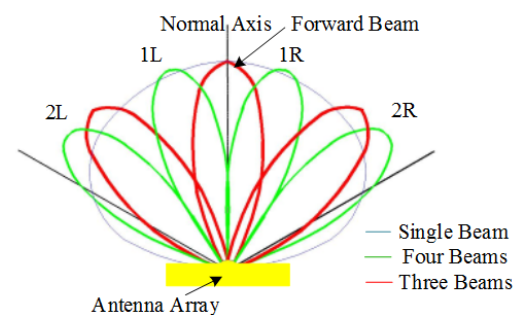


Fig. 1. Signal coverage with different-beam antenna.

antenna's normal axis, shown in Fig. 1. This restriction of a traditional Butler matrix greatly limits the flexibility of the design and leads to a high cost.

In order to improve the signal transmission and reduce mutual interference, a forward beam along the antenna's normal axis is preferred to be created. With the same signal coverage area, multi-beam antenna can have larger system capacity and better signal level, shown in Fig. 1. Several methods have been proposed to improve the Butler matrix for better signal coverage [10–16]. Without using any crossovers, a  $4 \times 4$  Butler matrix with broadband characteristic and CPW technology is proposed in [13]. As a key component, two-layer slot-coupled directional coupler is adopted to reduce the circuit size and the loss. A compact Butler matrix without phase shifter is introduced in [14]. By employing planar couplers with different phase differences, the Butler matrix avoids the interconnecting mismatch loss and imbalanced amplitude. Thus the circuit has a wide working frequency band of 20.1% and a small imbalance less than 0.4 dB. An asymmetric Butler matrix with 3 input ports and 4 output ports is proposed in [15]. With Wilkinson divider, the asymmetric structure allows to create a forward beam along the array's normal axis. In order to suppress spurious frequencies and provide near-band rejection, a novel Butler matrix with inherent bandpass filter transfer functions is presented in [16]. The new circuit has advantages of size and mass reduction due to its coupled resonators with characteristics of the power division, phase distribution, and filtering transfer function.

In [17], the authors analyzed different multibeam network with odd number of inputs or non-orthogonal pattern. Three-way directional coupler for orthogonal three-beam antenna array is proposed in [18]. However, dual micro-strip layer are needed for the cross connect, which increase the cost and reduce design flexibility. Based on the SIW and multifolded structure, a  $4 \times 8$  Butler matrix with working frequency of 38 GHz is designed for 5G applications [19]. A low-complexity beam-switching array using a standard  $4 \times 4$  Butler matrix and the phase reconfigurable synthesized transmission line (PRSTL) is demonstrated in [20]. With the help of 1-bit phase shifter function of PRSTL, the array has enhanced beam controllability and widened spatial coverage.

In this paper, a novel tri-beam antenna system is proposed for wireless communication application. The element of  $2 \times 3$  antenna array is designed with two U-shaped arms and coupled patch for broadband operation. The Butler matrix is composited of three branch line couplers and four  $-90^\circ$  phase shifters. With the help of one non equilibrated coupler, the signals at three output ports can have the equal amplitude with accurate phase difference of  $0^\circ$ ,  $+120^\circ$  and  $-120^\circ$ . By connecting this circuit with the antenna array, three beams including one forward beam along the antenna's normal axis are obtained. It can split original 65 degree coverage into three sectors with separate narrow beams, which can reduce the overlap interference and improve efficient spectrum reuse. It has a potential application in the mobile communication systems.

## 2. Theoretical Analyses

### 2.1 Radiating Element

The modified dipole unit is chosen as the radiating element for tri-beam antenna system due to its broadband impedance characteristic and high gain performance. The element consists of two U-shaped arms and coupled strips, which shows a wide impedance bandwidth and vertical polarization characteristics. An integrated balun with  $\lambda/4$  height is located between U-shaped arms and metal reflector, which is shorted at the metal reflector and provides a balanced feed to the two U-shaped arms. In order to broad the working frequency band and improve the front to back ratio, several coupled strips printed on FR4 substrate are utilized. The geometry of radiating element is given in Fig. 2, and its main parameters are summarized in Tab. 1.

The antenna design procedures can be summarized as follows: Firstly, according to the resonant frequency, the height of dipole  $H_d$  can be determined,  $H_d = \lambda_0/4$ . Then the dimensions of U-shaped arms can be calculated. The length  $L_d$  is related with the resonant frequency, while the width  $W_d$  is related with the working frequency band. Next the triangular patch should be optimized due to its huge impact on the matching. Lastly, several coupled strips are added to improve its bandwidth and radiation performance.

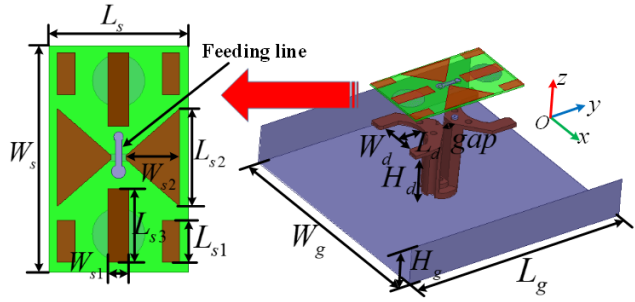


Fig. 2. Geometry of the proposed radiating element.

Parameter	Value (mm)	Parameter	Value (mm)
$W_g$	120	$L_g$	120
$W_s$	36	$L_s$	62
$W_{s1}$	5	$L_{s1}$	11
$W_{s2}$	15	$L_{s2}$	28
$W_d$	22.4	$L_d$	16
$H_g$	20	$L_{s3}$	21
$H_d$	34	gap	5

Tab. 1. Parameters of the radiating element.

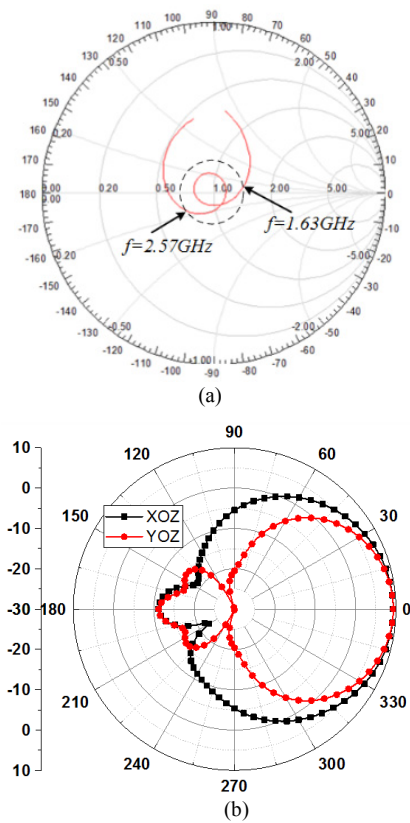


Fig. 3. Performance of the radiating element. (a) Smith chart, (b) radiation pattern.

The performance of radiating element is analyzed with EM software of ANSYS HFSS v15 and its performance is shown in Fig. 3. It can be seen that the return loss is lower than  $-15$  dB at 1.63~2.57 GHz, and the front to back ratios of XOZ- and YOZ-plane radiation patterns are better than 20 dB at the center frequency. The gain of the

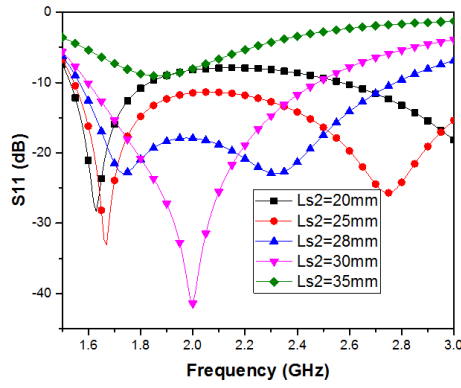


Fig. 4. Reflection coefficient varied with parameter  $L_{s2}$ .

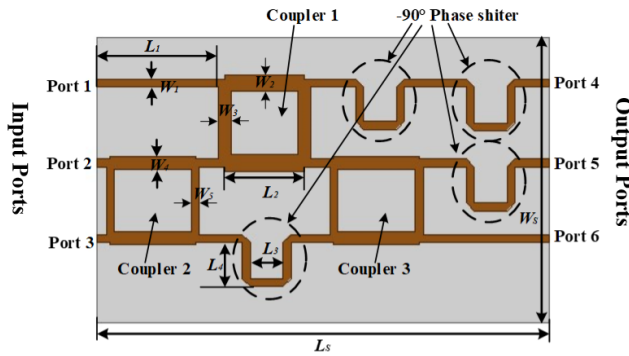


Fig. 5. Geometry of the proposed Butler matrix.

radiating element is varied from 8 to 10 dBi, while the half power bandwidth (HPBW) of XOZ-plane are round  $65^\circ$  over the whole working frequency band. In order to analyze the mechanism of radiating element, a parameter study is carried out. While the parameter  $L_{s2}$ , length of triangular coupled patch, varied from 20 mm to 40 mm, the reflection coefficient ( $S_{11}$ ) of the radiating element is shown in Fig. 4. It can be observed that the coupling patch has a great influence on the reflection coefficient. The value of  $L_{s2}$  is chosen as 28 mm for the appropriate bandwidth and good return loss.

## 2.2 $3 \times 3$ Butler Matrix

The geometry of the proposed  $3 \times 3$  Butler matrix is shown in Fig. 5. Three branch line couplers and four  $-90^\circ$  phase shifters consist the circuit. Coupler 1 is 1.74 dB coupler with  $90^\circ$  phase difference between two output ports, while Coupler 2 and Coupler 3 are 3 dB couplers. The  $-90^\circ$  phase shifter is formed by the meander line for its compact structure. When the signal is excited at port 1, the signals at three output ports with equal amplitude and a phase difference of  $0^\circ$  are obtained. A forward beam along the antenna normal axis can be formed when the signal is excited at port 1. Similar analysis can be made when port 2 and port 3 are excited, respectively. The signals at three output ports are shown in Fig. 6. With the help of one non equilibrated coupler, the signals at three output ports can have the equal amplitude with accurate phase difference of  $-120^\circ$  and  $+120^\circ$ . Thus, a right/left tilted

beam can be produced when port 2 or port 3 is connected with antenna elements, respectively.

Assuming that the circuit has perfect matching, infinite isolation and no loss, the scattering parameters of the proposed Butler matrix can be written as follows:

$$S = \frac{1}{\sqrt{3}} \begin{bmatrix} 0 & 0 & 0 & e^{j0} & e^{j0} & e^{j0} \\ 0 & 0 & 0 & e^{j\frac{\pi}{2}} & e^{-j\frac{\pi}{6}} & e^{-j\frac{5\pi}{6}} \\ 0 & 0 & 0 & e^{j0} & e^{j\frac{2\pi}{3}} & e^{-j\frac{2\pi}{3}} \\ e^{j0} & e^{j\frac{\pi}{2}} & e^{j0} & 0 & 0 & 0 \\ e^{j0} & e^{-j\frac{\pi}{6}} & e^{j\frac{2\pi}{3}} & 0 & 0 & 0 \\ e^{j0} & e^{-j\frac{5\pi}{6}} & e^{-j\frac{2\pi}{3}} & 0 & 0 & 0 \end{bmatrix}. \quad (1)$$

According to the above analysis, the proposed Butler matrix is designed and simulated at 2.0 GHz, whose geometry is depicted in Fig. 5. The circuit is designed on AD300 substrate with a dielectric constant of 3.0, a thickness of 0.8 mm and a loss tangent of 0.002. The branch lines of Coupler 2 and Coupler 3 have the same dimensions, a width of 2.75 mm and a length of 28 mm, while the main line has a width of 4.4 mm and the same length. Coupler 1 is an unequal coupler with different widths for branch line and main line. Four phase shifters are the same with its 2.75 mm width and 31 mm length. The geometric parameters for the tri-beam Butler matrix are listed in Tab. 2. The structure is simulated by using ANSYS HFSS software based on the finite element method.

With the characteristic of branch line coupler, high isolation between input ports is achieved for this structure. Four phase shift of  $-90^\circ$  is designed by using a meander transmission line section. Even this structure is asymmetric,

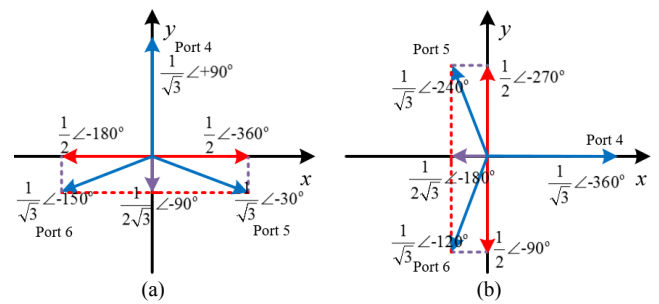
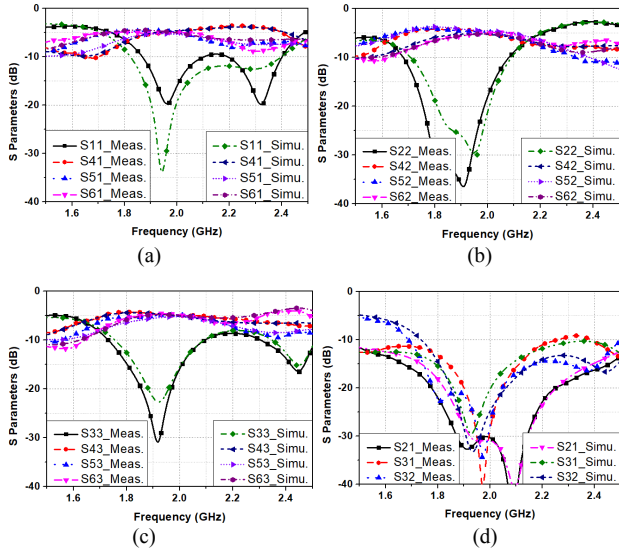


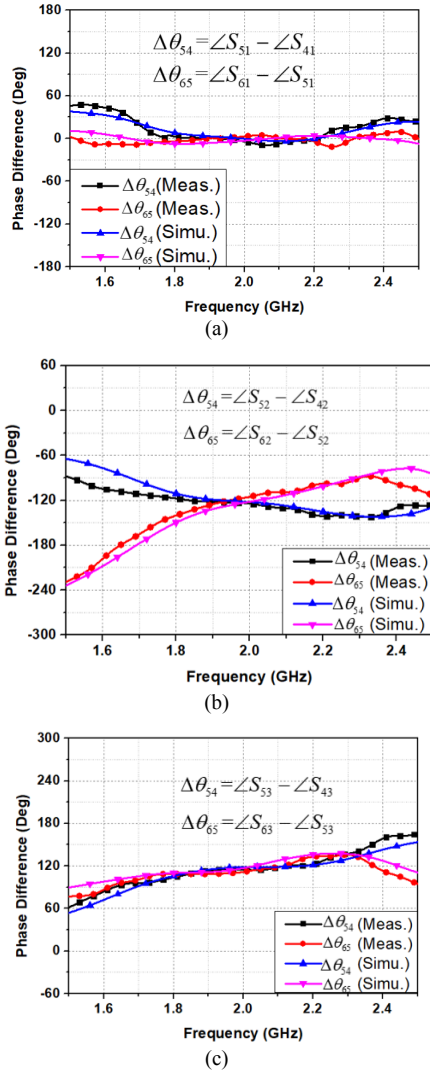
Fig. 6. Output signals at Port 4/5/6 when different ports are excited: (a) Port 2, (b) Port 3.

Parameter	Value (mm)	Parameter	Value (mm)
$W_5$	120	$L_5$	120
$W_1$	36	$L_1$	62
$W_2$	5	$L_2$	11
$W_3$	15	$L_3$	28
$W_4$	22.4	$L_3$	16
$W_5$	20		

Tab. 2. Parameters of the proposed Butler matrix.



**Fig. 7.** Measured and simulated S parameters of the proposed  $3 \times 3$  Butler matrix when different ports are excited. (a) Port 1, (b) Port 2, (c) Port 3, (d) Isolation.



**Fig. 8.** Phase differences between two adjacent outputs when different input ports are excited: (a) Port 1, (b) Port 2, (c) Port 3.

the input signal from port 1/2/3 can be divided into three output ports with equal amplitude and specific phase difference.

Figure 7 shows the simulated reflection and transmission characteristic of the proposed structure when different input port is excited and other ports are matched. It can be noticed that the transmission level for three output ports is around  $-4.9$  dB with a difference less than  $0.5$  dB at the working frequency of  $2.0$  GHz, meanwhile, the reflections of different input ports are less than  $-15$  dB.

Phase difference of adjacent output ports is an important factor for the Butler matrix. We define it in the following form,

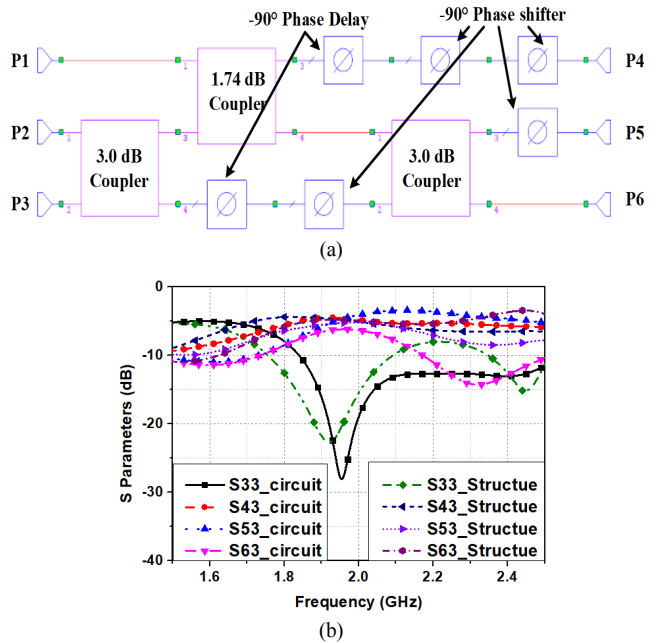
$$\Delta\theta_{54} = \angle S_{5i} - \angle S_{4i}, \quad (2)$$

$$\Delta\theta_{65} = \angle S_{6i} - \angle S_{5i} \quad (3)$$

where  $i$  represents the input port 1, 2, 3, respectively. The simulated phase differences of the proposed circuit are illustrated in Fig. 8. It can be seen that phase differences of  $0^\circ$ ,  $-120^\circ$  and  $+120^\circ$  are obtained when different input ports are excited, respectively. According to (4), beam scanning equation of planar antenna array, we can calculate the directions of beam with the phase differences. The phase differences on the output ports can produce three beams with the maximum radiation values in the directions of  $0^\circ$ ,  $+42^\circ$  and  $-42^\circ$ , respectively.

$$\theta_d = \arcsin\left(\frac{\lambda}{2\pi d} \Delta\theta_{ij}\right). \quad (4)$$

In order to validate the performance of the proposed structure, the equivalent circuit with ideal elements is given in Fig. 9(a). It can be noticed that two  $-90^\circ$  delay elements

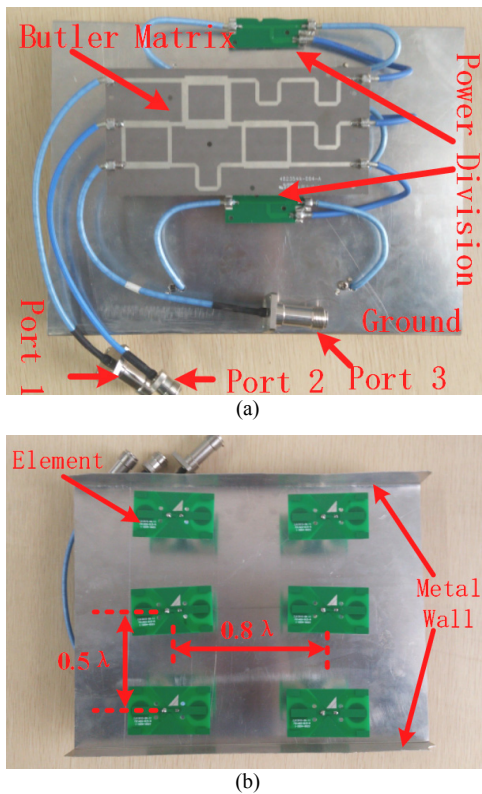


**Fig. 9.** The equivalent circuit and its performance. (a) The circuit, (b) frequency responses.

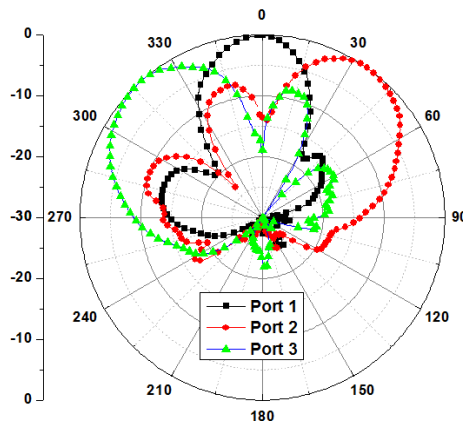


Ref.	Ports	Structure	Center frequency (GHz)	Amplitude imbalance (dB)	Phase error (degree)
[3]	$4 \times 4$	Lumped element	1.0	1.5	10
[5]	$4 \times 4$	SIW	9.5	0.6	5
[9]	$4 \times 4$	Slot line	5.8	3	-
[15]	$3 \times 4$	One layer	2.4	1.5	2.21
Our work	$3 \times 3$	One layer	2.0	0.5	2

**Tab. 3.** Comparison of the performance of the proposed Butler matrix with other Butler matrices.



**Fig. 10.** Photograph of the tri-beam antenna array. (a) Back view, (b) top view.



**Fig. 11.** Measured radiation patterns of the proposed tri-beam antenna array.

are added in the circuit, which are used to be equivalent to the phase delay induced by the couplers. The frequency responses of the circuit and the structure are given in Fig. 9(b). Only the performance of port 3 is given for the similarity of other two ports. It can be observed that the return loss of the circuit is better than that of the structure. The reason is good matching of the ideal elements in the circuit. In the whole, good agreement is achieved between the circuit and the structure.

Several recently published Butler matrices are selected to be compared with the proposed Butler matrix, which is given in Tab. 3. The proposed one can be designed with one layer substrate, and has a minimum amplitude imbalance and phase error. When connecting with the antenna array, the proposed Butler matrix can create three beams with one forward beam along the normal axis.

### 3. Experiment Results

As a tri-beam forming network, the proposed Butler matrix is connected to a  $2 \times 3$  antenna array, shown in Fig. 10. Each row has two dipole elements spaced by  $0.8\lambda_0$  at 2.0 GHz, and connected with equal power divider. In order to reduce the mutual coupling between elements, the distance between adjacent rows is designed to be  $0.5\lambda_0$ , which also guarantees the orthogonality between different beams. The antenna has a resonant frequency at 2.0 GHz with return loss less than  $-20$  dB. The minimum mutual coupling between elements is achieved due to its spacing, and the isolation is better than 25 dB.

Figure 11 shows the measured radiation patterns of this antenna array with the Butler matrix. It can be observed that three beams at  $\theta = 0^\circ, 40^\circ, -40^\circ$  are produced. When port 1 is excited, equal amplitude and  $0^\circ$  phase difference at three output ports create a forward beam along the antenna's normal axis. Similarly, a beam tilt to right/left direction can be created when port 2/3 is excited. The gains of three beams are 14.1, 13.2 and 13.3 dBi at 2.0 GHz, respectively.

### 4. Conclusions

A novel antenna array with three orthogonal beams is proposed for wireless communication system. This system is composed of broadband radiating elements and  $3 \times 3$  Butler matrix. Consisting of two U-shaped arms and several coupled strips, the radiating element has a broad impedance bandwidth characteristic. The proposed Butler matrix is consisted of three couplers and four  $-90^\circ$  phase shifters, which provides three output ports with equal amplitude and specific phase difference. A tri-beam antenna array is designed with this structure, resulting in three orthogonal beams at  $0^\circ, 40^\circ$  and  $-40^\circ$ . The proposed tri-beam antenna system has a good potential application for wireless communication.

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