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A Simple 2 × 3 Beam-Forming Network with a 2-Bit Phase Shifter for Four-Beam Reconfiguration

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Abstract—A simple 2×3 reconfigurable beam-forming network (R-BFN) for four-beam reconfiguration application is designed and implemented. The proposed R-BFN with two input ports and three output ports consists of a 2:1 power divider, a 90° hybrid, a 180° hybrid and a 2-bit phase shifter. The 2-bit phase shifter has two states: one is a 180° phase shifter (State 1); the other is a 0°/360° phase shifter (State 2). By introducing the 2-bit phase shifter, the constant phase differences of three output ports can be reconfigured. When the proposed R-BFN is connected to an antenna array, a four-beam reconfiguration is obtained. Simulated and measured results show that good impedance matching, high port isolation, equal power division, and constant phase difference have been achieved simultaneously within the operation band of 2.4–2.6 GHz. The capability of the proposed R-BFN to reconfigure beams is also verified experimentally by using a 2.5 GHz dipole array.

1. INTRODUCTION

With the explosive development of wireless communication system in recent decades, high throughput and improved transmission quality are extremely demanded. A self-organizing and self-optimizing beam-forming network with reliable property becomes of great interest to increase the system capacity [1]. Phased array antennas [2–5] that use digital beam-forming network with the abilities of steering its beam toward desired directions and placing nulls toward undesired directions can achieve these tasks perfectly. However, the high cost and complexity prohibit the phased array antenna from commercial wireless communication system.

To compromise the performance and price, multiple beam-forming networks (M-BFN) are good choices. Well-known examples of the M-BFN are the Butler [6–9], Blass [10, 11] and Nolen [12, 13] matrices, which are characterized by multiple inputs feeding multiple outputs. They are usually consists of directional couplers, power dividers/combiners and phase-shifters with specific associating. However, all these M-BFN have the disadvantages of fixed beams and large size, especially when the input and output ports are increased.

On the other hand, developing intelligent-like wireless communication systems is the future trend, when there are more serious wireless propagation issues in modern wireless communication systems such as energy waste, interference and so on. In order to mitigate these propagation phenomena, an adaptive M-BFN with the ability to steer its main beams towards desired directions could be a good choice [14]. Besides, reconfigurable beam-forming network (R-BFN) also has the capability to provide different functionality using the same antenna systems.

Motivated by the challenging task above, we introduce a 2×3 R-BFN for four-beam reconfiguration to increase flexibility and decrease complexity of the M-BFN. One can switch the directions of the two radiation main beams by changing the two states of a 2-bit phase shifter simultaneously. The R-FBN can

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be utilized to provide four-beam switching capability with fewer components and simpler structure than the 4×4 butler matrix. Experimental results show that a return loss of better than 16.5 dB, an isolation of higher than 16.3 dB, a power distribution imbalance of less than 1.4 dB, and a phase imbalance of less than 15° are accomplished across the operation frequency band of 2.4–2.6 GHz. The capability of the R-BFN to form reconfigurable beams is also verified by using an antenna array prototype working at 2.5 GHz.

2. RECONFIGURABLE BEAM-FORMING NETWORK DESIGN

The schematic diagram of the proposed R-BFN is shown in Fig. 1. It consists of a 2:1 power divider, a 90° hybrid, a 180° hybrid and a 2-bit phase shifter. The 2-bit phase shifter has two states: one is a 180° phase shifter (State 1); the other is a 0°/360° phase (State 2). That is to say, the 2-bit phase shifter can be obtained by a SPDT (single-pole double-throw) and double phase shifters which have 180 and 360 phase lags, respectively. Output port A of the 90° hybrid is connected to port Δ of the 180° hybrid, while output Port B of the 90° hybrid is connected to the input port of the 2:1 power divider. The power ratio of the power divider output Port D and Port C is 2:1. The output Port D is connected to the 2-bit phase shifter while the output port C is connected to port $\sum$ of the 180° hybrid. For obtaining a constant phase difference among three output ports of the R-BFN, the input ports are designated as Port 1 and Port 2, and the output ports as Port 3, Port 4 and Port 5, which are shown in Fig. 1.

The 90° hybrid equally divides one input port incident power between the two opposite output ports, with a constant phase difference of −90°, keeping the contiguous port isolated. The 180° hybrid consists of a sum input port $\sum$, a difference input port Δ and two output ports. When the power is fed into port $\sum$, it is split equally and in phase between Port 3 and Port 5, and port Δ is isolated. On the country, when the power is fed into port Δ, it is split equally and with a 180° phase difference between Port 3 and Port 5, and port $\sum$ is isolated. Because of the 2-bit phase shifter not changing the magnitude of the signal, the signal injected into the input port going through a 90° hybrid, a 2:1 power divider and a 180° hybrid is equally distributed into the three output ports, namely, the power of each output port is one third of input port. Considering the effect of the 2-bit phase shifter, as input Port 1 is excited, the relative phase of Port 4 is 0° or 180° by changing the two states of the 2-bit phase shifter, while the relative phases of Port 3 and Port 5 are 60° and −60°, respectively. Thus, a constant phase difference of 60° or 120° from Port 3 to Port 5 is obtained with the 2-bit phase shifter at State

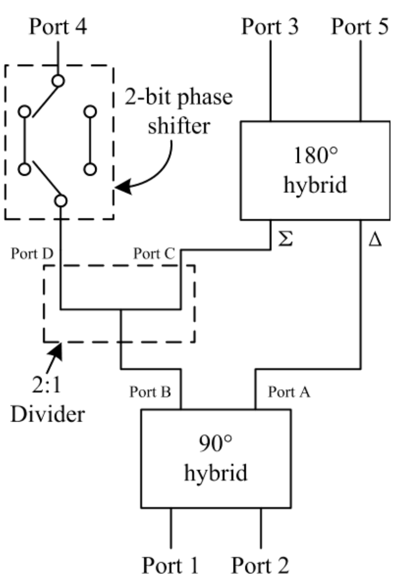


Figure 1. Schematic diagram of the proposed R-BFN.

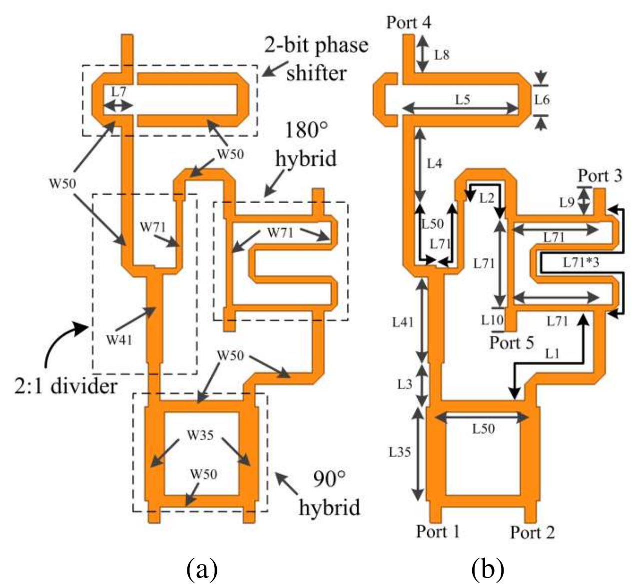


Figure 2. Layout of the proposed R-FBN. (a) State 1. (b) State 2.

1 or State 2, respectively. On the other hand, as input Port 2 is excited, the relative phase of Port 4 is -90° or 90° by changing the two states of the 2-bit phase shifter, while the relative phases of Port 3 and Port 5 are -30° and -150°, respectively. Therefore, a constant phase difference of -60° or -120° from Port 3 to Port 5 is obtained with the 2-bit phase shifter at State 1 or State 2, respectively.

With the help of the commercial software Advanced Design System (ADS), the ideal components are connected as shown in Fig. 1. The 2-bit phase shifter is achieved by changing phase of the ideal phase shifter between 180° and 0°. Tables 1(a) and 1(b) show the simulated output amplitude and phase characteristics of the ideal R-BFN at State 1 and State 2, respectively. It is obvious that when the 2-bit phase shifter is at State 1 (180° phase shifter), the R-FBN provides three output signals with equal power levels and the progressive phases of -120° and $+120^\circ$, respectively. On the other hand, when the 2-bit phase shifter is at State 2 ($0^\circ/360^\circ$ phase shifter), the R-FBN provides three output signals with equal power levels and the progressive phases of $+60^\circ$ and -60°, respectively.

Table 1. Simulated output amplitude and phase characteristics of the ideal R-BFN at State 1 and State 2, respectively.

(a)

State 1	Amplitude (dB)			Phase differential (degree)		
Fed by	Port 3	Port 4	Port 5	Port 3	Port 4	Port 5
Port 1	−4.77	−4.77	−4.77	0	−120	−240
Port 2	−4.77	−4.77	−4.77	0	120	240

(b)

State 2	Amplitude (dB)			Phase differential (degree)		
Fed by	Port 3	Port 4	Port 5	Port 3	Port 4	Port 5
Port 1	−4.77	−4.77	−4.77	0	60	120
Port 2	−4.77	−4.77	−4.77	0	−60	−120

3. SIMULATED AND MEASURED RESULTS

Based on the above-mentioned theoretical analysis and results, the proposed R-BFN is designed by using microstrip technology with the help of the electromagnetic simulator Ansoft high-frequency structure simulator (HFSS). Figs. 2 and 3 show the layout and photograph of the proposed R-FBN at State 1 and State 2, respectively. The input ports are designated as Port 1 and Port 2, while the output ports as Port 3, Port 4, and Port 5. The substrate of the microstrip is PTFE with $\varepsilon_r = 2.65$ and thickness

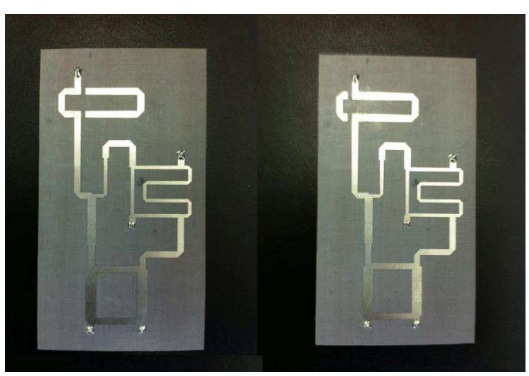
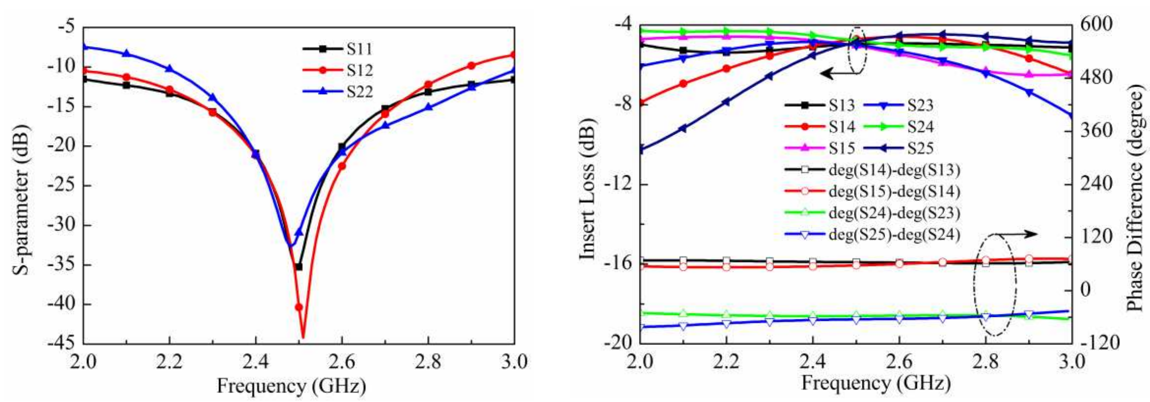


Figure 3. Photograph of the proposed R-FBN.

$h = 1$ mm. The proposed R-BFN is operated at a center frequency of 2.5 GHz. Hybrid couplers, unequal divider with 2:1 power ratio, and a 2-bit phase shifter are studied and optimized separately, and then connected by microstrip lines with the characteristic impedance of 50 Ω according to the design presented in Fig. 2. Additional microstrip lines are adopted to compensate the absolute phase difference caused by the components. It is worth mentioning that the MEMS will be introduced to control the state of the 2-bit phase shifter in the future, and here we just adopt soldering technology for convenient. The 2-bit phase shifter is obtained by the 50 Ω microstrip lines with different lengths. The basic structural parameters are listed in Table 2.

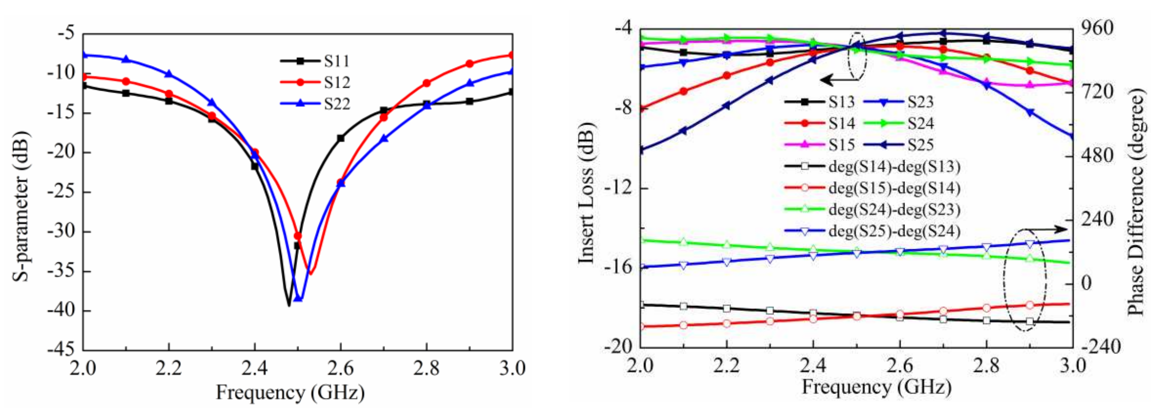
Table 2. Principal structural parameters of the R-BFN.

Parameters	*W50*	*W71*	*W35*	*W41*	*L50*	*L71*
Values/mm	2.7	1.5	4.5	3.7	19.1	20.6
Parameters	*L35*	*L41*	*L1*	*L2*	*L3*	*L4*
Values/mm	21.9	19.9	34.0	22.4	10.0	19.3
Parameters	*L5*	*L6*	*L7*	*L8*	*L9*	*L10*
Values/mm	26.9	7.0	6.9	8.8	6.2	5.6



(a) (b)

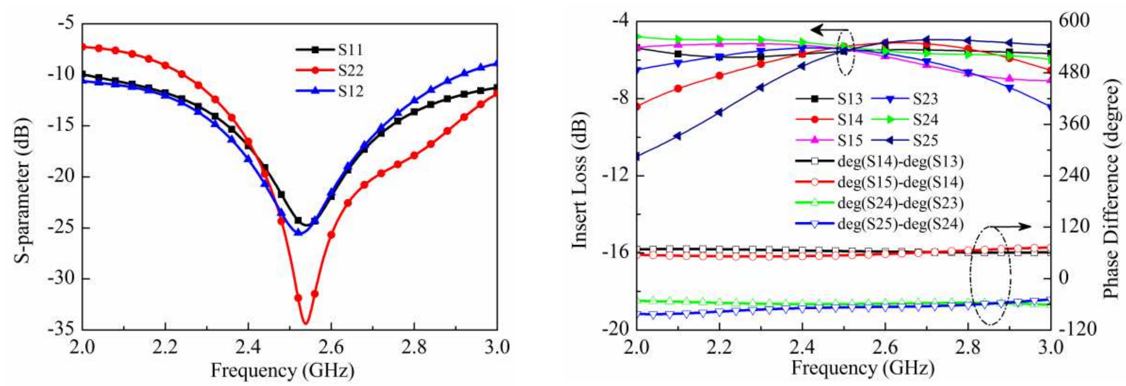
Figure 4. Simulated results at State 1. (a) Return loss and isolation. (b) Insertion loss and phase difference.



(a) (b)

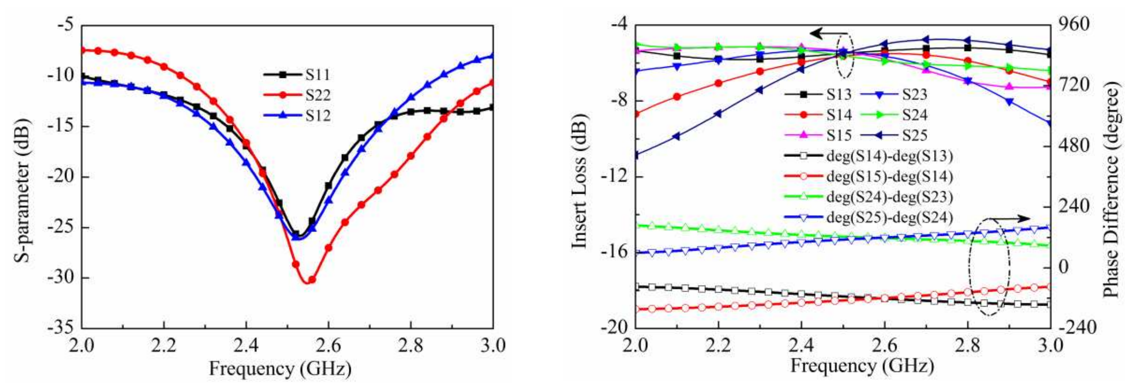
Figure 5. Simulated results at State 2. (a) Return loss and isolation. (b) Insertion loss and phase difference.

Figures 4 and 5 show the simulated results, including the return losses and port isolation in Figs. 4(a) and 5(a), and the insert loss and output port phase difference in Figs. 4(b) and 5(b) for the 2-bit phase shifter at State 1 and State 2, respectively. As can be seen, within the frequency range of 2.4–2.6 GHz, the return losses of input ports of the R-FBN is better than 18.2 dB and 20 dB, while the input ports isolation is higher than 20 dB and 21.1 dB at State 1 and State 2, respectively. The output power division errors are less than 1.3 dB and 1 dB, and the phase imbalances are less than 5° and 11° when



(a) (b)

Figure 6. Measured results at State 1. (a) Return loss and isolation. (b) Insertion loss and phase difference.



(a) (b)

Figure 7. Measured results at State 2. (a) Return loss and isolation. (b) Insertion loss and phase difference.

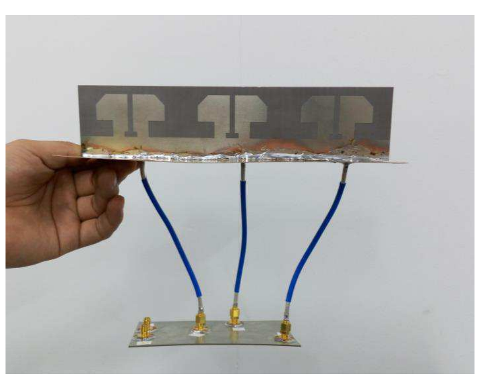


Figure 8. Prototype of an R-BFN antenna array.

the 2-bit phase shifter is at State 1 and State 2, respectively.

Measured results are shown in Figs. 6 and 7, of which the return losses and isolation are sketched in Figs. 6(a) and 7(a), and the insert loss and output port phase difference in Figs. 6(b) and 7(b) for the 2-bit phase shifter at State 1 and State 2, respectively. It is obvious that the measured results are in good agreement with the simulated results. As can be seen, within the frequency range of 2.4–2.6 GHz, the return losses of input ports of the R-FBN are better than 16.5 dB and 17 dB, while the isolation between the two input ports is higher than 18.3 dB and 18.6 dB at State 1 and State 2, respectively. The output power division errors are less than 1.4 dB and 1.1 dB, and the phase imbalances are less than 7° and 15° when the 2-bit phase shifter is at State 1 and State 2, respectively.

To verify the characteristic of beam-forming reconfiguration of the proposed R-FBN, a three-element antenna array working at 2.5 GHz beam-forming reconfiguration application is designed and fabricated. As shown in Fig. 8, printed dipole array is chosen as the radiating element due to its

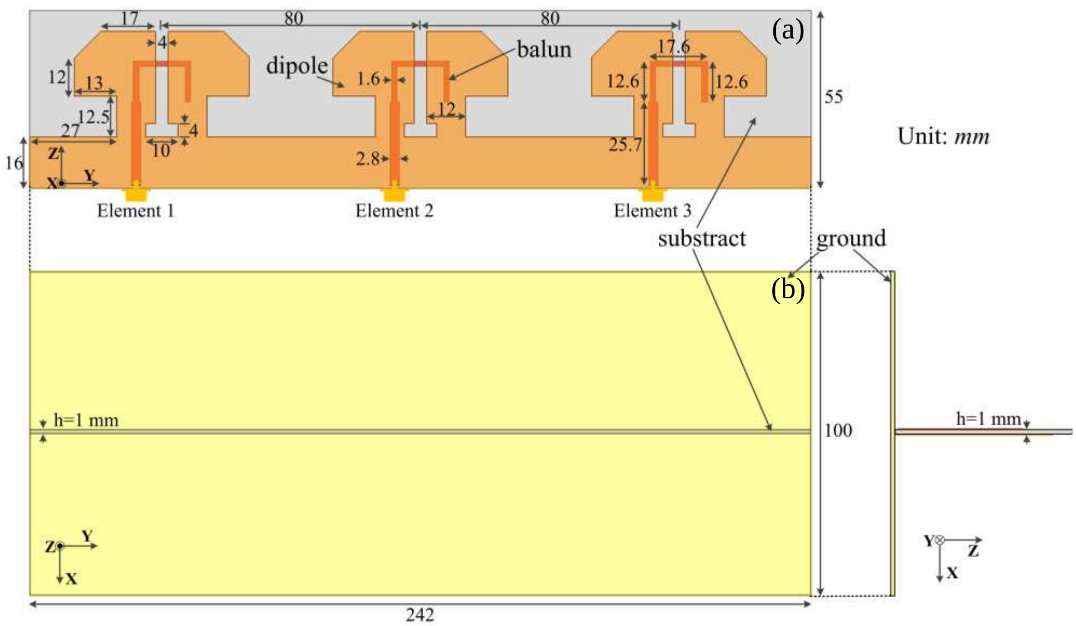


Figure 9. Geometry and the main parameters of the printed dipole antenna array. (a) Top view. (b) Bottom view.

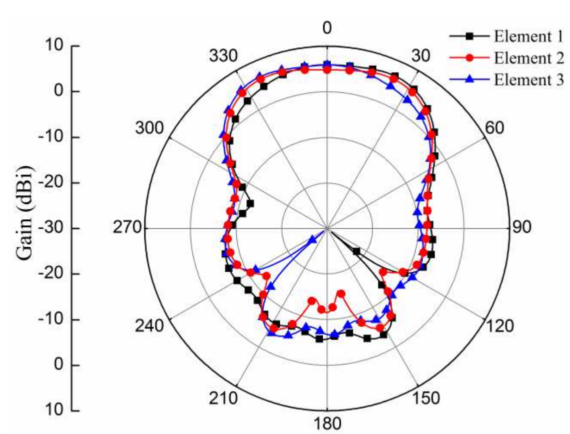


Figure 10. Without the proposed R-FBN, the measured radiation patterns of each printed dipole antenna.

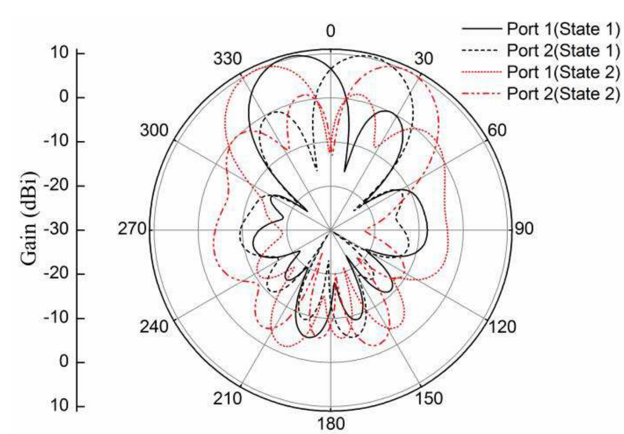


Figure 11. With the proposed R-FBN, the measured radiation patterns of the three-element array.

simplicity and versatility, which are fed by the R-BFN. The geometry and main parameters of the array are shown in Fig. 9. The spacing between two adjacent radiating elements is $\lambda/2$ (80 mm), where λ is the air wavelength at 2.5 GHz. In contrast, the measured radiation patterns of each printed dipole antenna without the proposed R-FBN are shown in Fig. 10. With the proposed R-FBN, the measured radiation patterns of the three-element array are presented in Fig. 11 when the 2-bit phase shifter is at State 1 or State 2, respectively. The array can be excited by different input ports, and two symmetrical patterns are obtained. By switching the two states of the 2-bit phase shifter, two different symmetrical patterns are achieved. When the 2-bit phase shifter is at State 1, the main beam points to the 14° or −14° as Port 1 or Port 2 is excited. When the 2-bit phase shifter is at State 2, the main beam points to the 26° or −26° as Port 1 or Port 2 is excited.

4. CONCLUSION

In this paper, a simple 2×3 reconfigurable beam-forming network (R-FBN) with 2-bit phase shifter for four-beam reconfiguration has been designed and realized. The simulated and measured results show that the proposed R-FBN has good performances of impedance matching, port isolation, equal power division, and constant phase difference at the three outputs within the frequency band of 2.4–2.6 GHz. By switching the two states of the 2-bit phase shifter, constant phase differences among the three outputs are changed simultaneously. The R-FBN has the advantages of lossless, simple fabrication, reconfigurable beams forming, and minimum number of components. Based on the R-FBN presented in this letter, the capability of the proposed R-BFN to reconfigure beams is also verified experimentally by using a 2.5 GHz dipole array.

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