Hindawi Publishing Corporation
International Journal of Antennas and Propagation
Volume 2014, Article ID 583903, 7 pages
http://dx.doi.org/10.1155/2014/583903

Research Article

Miniaturization Design for 8 × 8 Butler Matrix Based on Back-to-Back Bilayer Microstrip

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Received 27 January 2014; Accepted 23 February 2014; Published 30 March 2014

Academic Editor: Xiang Zhang

A low-cost, compact 8 × 8 Butler matrix based on a novel bilayer microstrip configuration is presented and implemented for 4.3 GHz telecommunication application. A back-to-back placed bilayer microstrip structure has been proposed to avoid using crossover. To expand operational bandwidth of the Butler matrix, a three-branch line directional coupler has been employed as 3 dB/90° bridge, and a kind of improved two-order Schiffman phase shifter has been adopted as fixed phase shifter. For application of indoor wireless communication, a compact broadband 8 × 8 Butler matrix has been designed and fabricated. The measured results show that the return loss of the matrix is lower than −10 dB, the isolation is better than 17 dB, the power distribution error is less than ±2.0 dB, the phase error is less than ±15°, and the relative bandwidth is more than 23%.

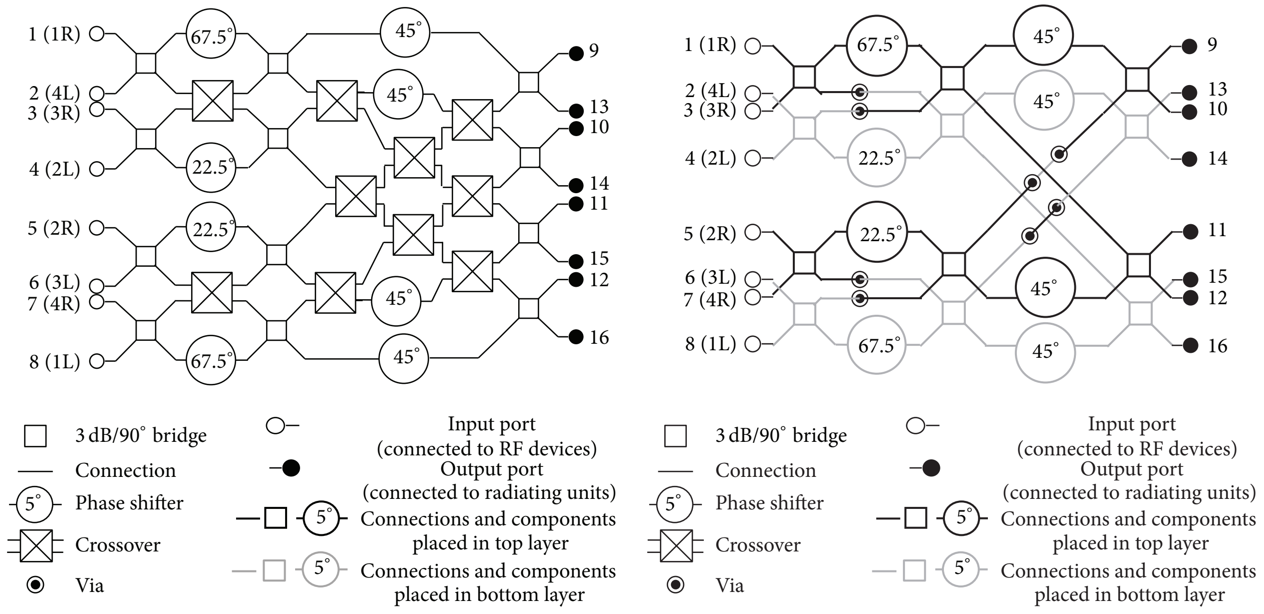
1. Introduction

MULTIBEAM antennas (MBA) have been wildly used in wireless communication to increase channel capacity and to improve transmission quality [1, 2]. One way to implement MBA is using an antenna array fed by a multiple beam forming network such as Blass matrix [3], Nolen matrix [4], Rotman lens [5], and Butler matrix [6]. The most important beams forming network for multiple beams with linear array is based on Butler matrix. Indeed, it seems to be the most attractive option due to its ability to form orthogonal beams and its design simplicity [7].

Microstrip technology is widely used for implementation of antenna arrays [8, 9], feeding networks [10] such as Butler matrices [11, 12], because it has advantage of low cost, low profile, and convenience for manufacture. However, 8 × 8 or higher order microstrip-line matrices have seldom been reported due to their complexity, increased dissipation, and difficulty in design [13]. Consequently, some multilayer Butler matrix configurations have been reported emphasizing size reduction. Nedil adopted a coupler using coplanar waveguide (CPW) to avoid crossing line in a 4 × 4 Butler matrix [7]. Chang used a stripline configuration which consisted of three printed circuit boards for 8 × 8 Butler matrix [14]. Gruszezyński used CPW technology with the coupled-line coupler for 4×4 Butler matrix [15, 16]. However, compared to microstrip technology, the multilayer technology is difficult and expensive, because its performance is extremely sensitive to the distance between layers of substrate.

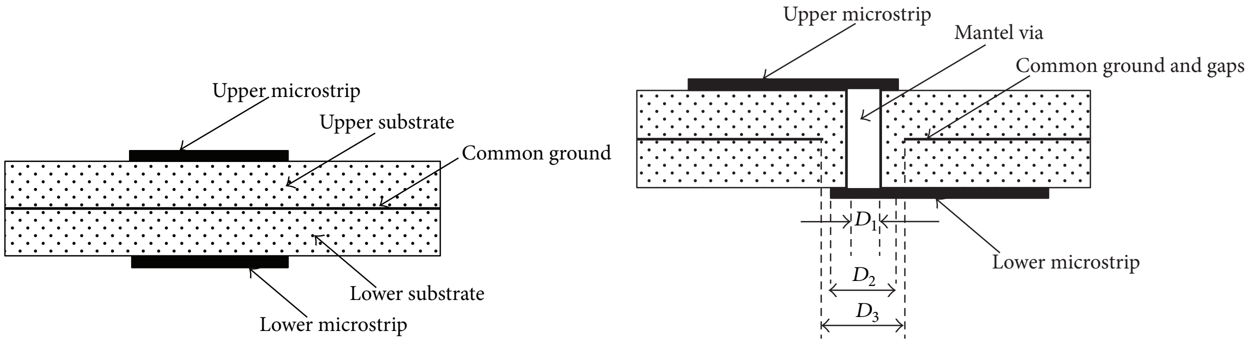
In this paper, a novel bilayer microstrip configuration for 8 × 8 Butler matrix has been proposed. The matrix is composed of bilayer microstrips which are placed back-to-back and fabricated independently; therefore its components have been placed in upper and lower layers, respectively. The proposed method avoids using crossover and then reduces dimension and transmission loss of the matrix. Meanwhile, the matrix has lower cost and lower installation and precision requirement than the Butler matrix employing CPW or BC-CPW transmission line. To expand the working bandwidth of the Butler matrix, a three-branch line directional coupler has been employed as 3 dB/90° bridge, and a kind of improved two-order Schiffman phase shifter has been adopted as fixed phase shifter.

For the application of 3.6 GHz–6 GHz indoor wireless communication system [17], a compact broadband 8 × 8 Butler matrix working at 4.3 GHz frequency has been designed



(a) (b)

Figure 1: The schematic diagram of classic 8 × 8 Butler matrix (a) and the schematic diagram of the 8 × 8 Butler matrix based on bilayer microstrip (b).



(a) (b)

Figure 2: Schematic diagram of the bilayer microstrip section (a) and the schematic diagram of the via section (b).

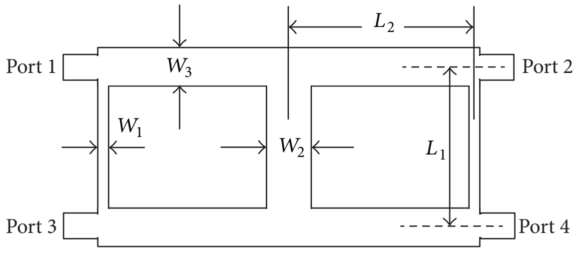


Figure 3: The upper circuit structure diagram of the three-branch line directional coupler, in which $W_1 = 0.4$ mm, $W_2 = 3.5$ mm, $W_3 = 3.5$ mm, $L_1 = 16.5$ mm, and $L_2 = 11.3$ mm.

and fabricated. The measured results show that the novel matrix has such performances in 23% relative bandwidth: the return loss is lower than −10 dB, the isolation is better than 17 dB, the power distribution error is less than ±2.0 dB, the phase difference error is less than ±15°, and the average measured insertion loss is about 2.5 dB.

2. Butler Matrix Design

2.1. Butler Matrix with Bilayer Structure. The schematic diagram of conventional 8 × 8 Butler matrix is shown in (Figure 1(a)), which indicates that ten crossovers should be used to realize the branch intersection except for twelve 3 dB/90° bridges and eight fixed phase shifters, which results in large dimension and increasing transmission loss of the circuit board.

The schematic diagram of the proposed 8 × 8 Butler matrix based on bilayer microstrip structure is shown in Figure 1(b). As it is seen, six bridges and four phase shifters are placed in upper and lower layers, respectively, the number of

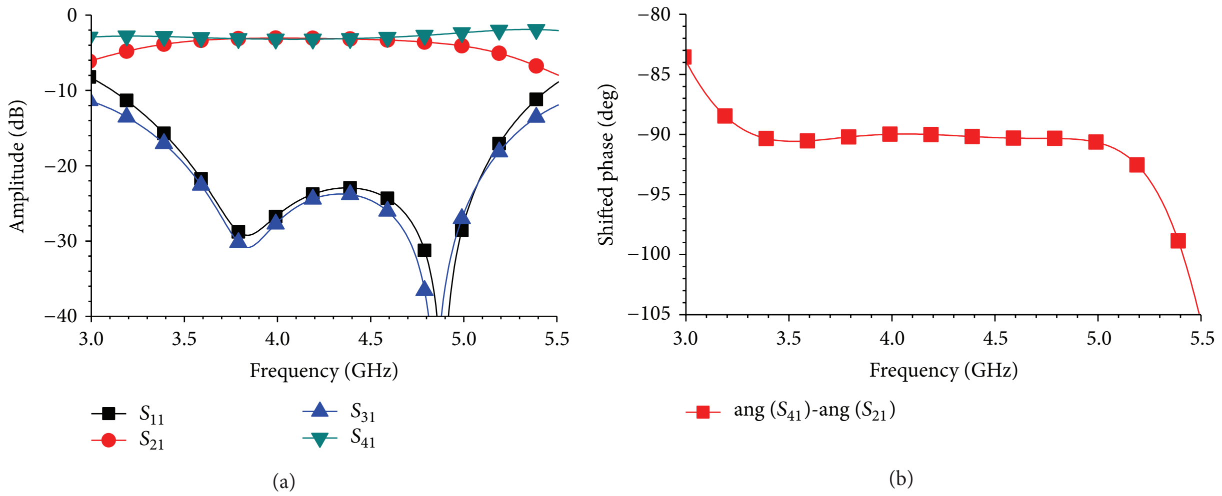


Figure 4: The simulated results of the three-branch line directional coupler: insertion loss and return loss (a) and phase difference performance (b).

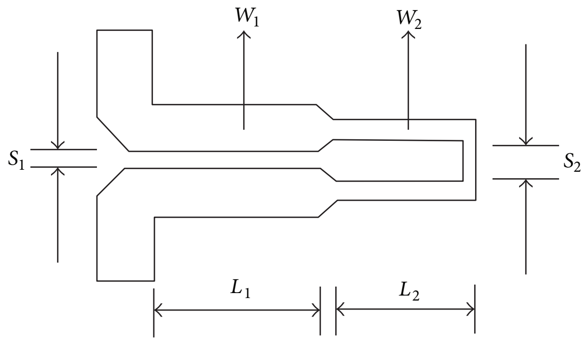


Figure 5: The structure of the Schiffman differential phase shifter.

intersection point has been reduced, and via has been adopted other than crossover. The connection relationship between components is concise and the number of the components is reduced.

The schematic diagram of the bilayer microstrip section structure of the Butler matrix is shown in Figure 2(a). As it is seen, two independent monolayer microstrip circuits are placed back-to-back with common ground to combine bilayer microstrip circuit.

In bilayer microstrip, via has been adopted to connect the upper and lower transmission line. Its structure is shown in Figure 2(b). The parameters of the via have been diligently designed to ensure good impedance matching. In the proposed design, the upper and lower layers both adopt microwave substrate having thickness of 0.8 mm and dielectric constant of 2.55. When $D_1 = 1.1$ mm, $D_2 = 1.4$ mm, and $D_3 = 1.8$ mm, a good matching with the microstrip line having a 50 Ω characteristic impedance could be obtained.

2.2. Three-Branch Line Coupler. A three-branch line directional coupler has been employed as 3 dB/90° bridge, which has proper performance of power distribution, port isolation, and 90° phase shift in wider bandwidth. For an application of indoor communication, the structural parameters of three-branch line directional coupler have been shown in Figure 3.

Table 1: The structural parameters of phase shifters with different shifted phase.

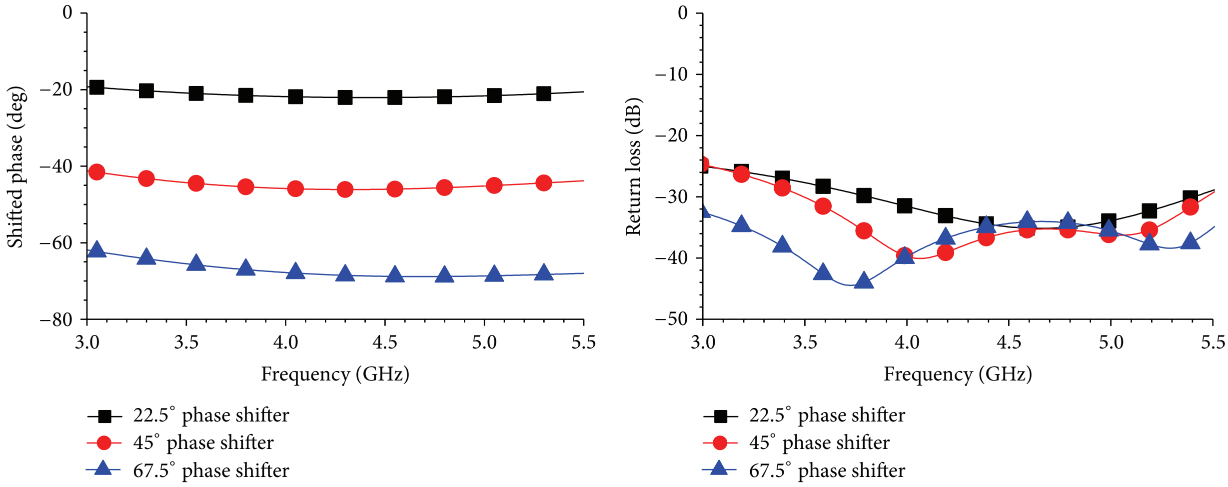
Shifted phase	W_1	W_2	S_1	S_2	L_1	L_2
22.5°	2.30	1.63	0.60	0.67	3.80	2.50
45°	2.30	1.71	0.22	0.32	4.20	4.20
67.5°	2.00	1.40	0.20	0.20	3.90	3.90

Unit: mm.

The simulated results of the three-branch line directional coupler are shown in Figure 4. It could be seen that, in frequency between 3.5 GHz and 5.0 GHz, the directional coupler could realize equal power distribution, the error is less than ±1 dB, the return loss and isolation are better than −15 dB, and the phase difference in within 90° ± 5°.

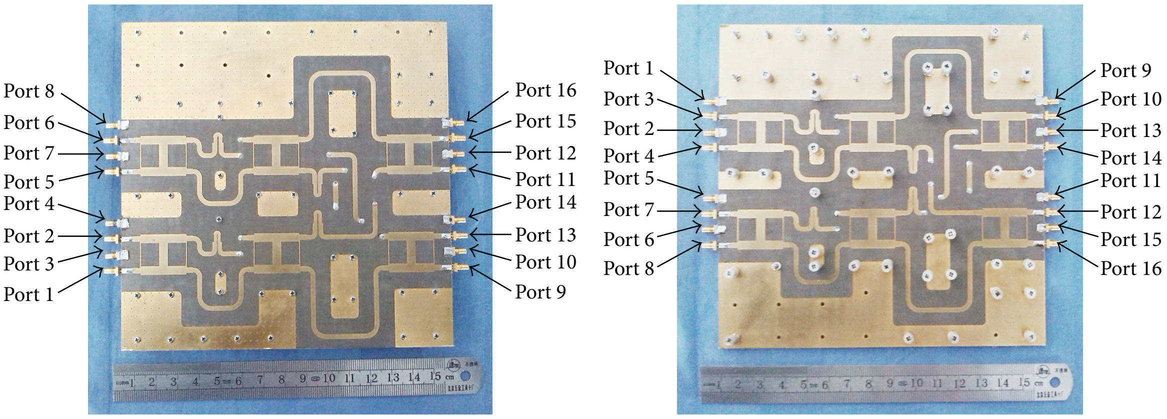
2.3. Schiffman Phase Shifter. Schiffman differential phase shifter is a common used fixed phase shifter form in Butler matrix. In classic Schiffman differential phase shifter, the phase velocity of odd mode and even mode of the couple transmission line is not equal. Although the phase shift performance is proper, the broadband matching feature is not good enough. In the proposed design, an improved two-order couple transmission line structure is adopted to compensate the phase velocity of odd mode and even mode and then optimize its performance. The structure of the Schiffman differential phase shifter is shown in Figure 5.

The shifted phases required in 8 × 8 Butler matrix are 22.5°, 45°, and 67.5°, respectively. Table 1 shows the structure parameters of each phase shifter. Figure 6 shows the simulated results of principal performance of each improved Schiffman phase shifters.



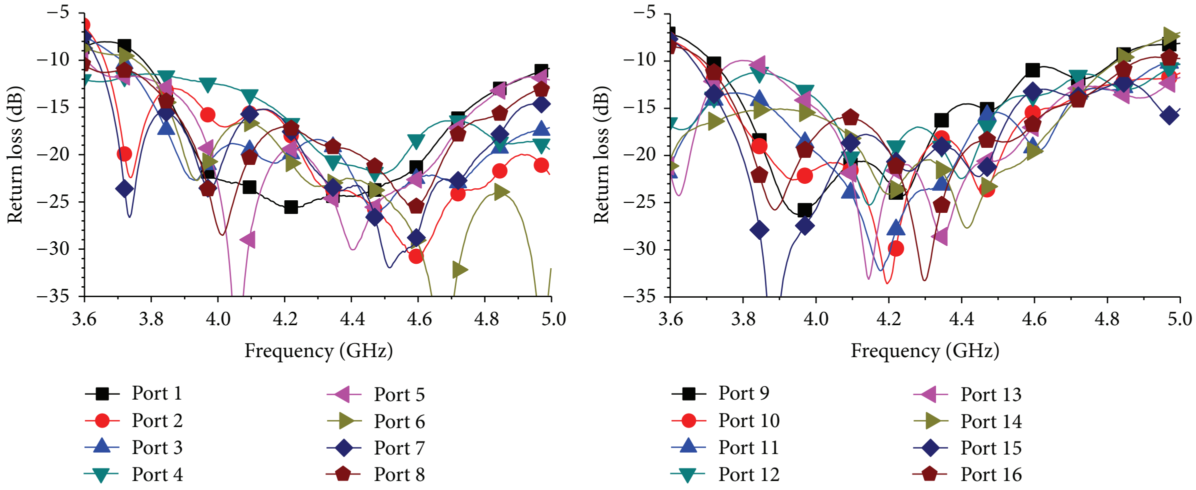
(a) (b)

Figure 6: The simulated results of matching and transmission performance of the improved Schiffman phase shifters.



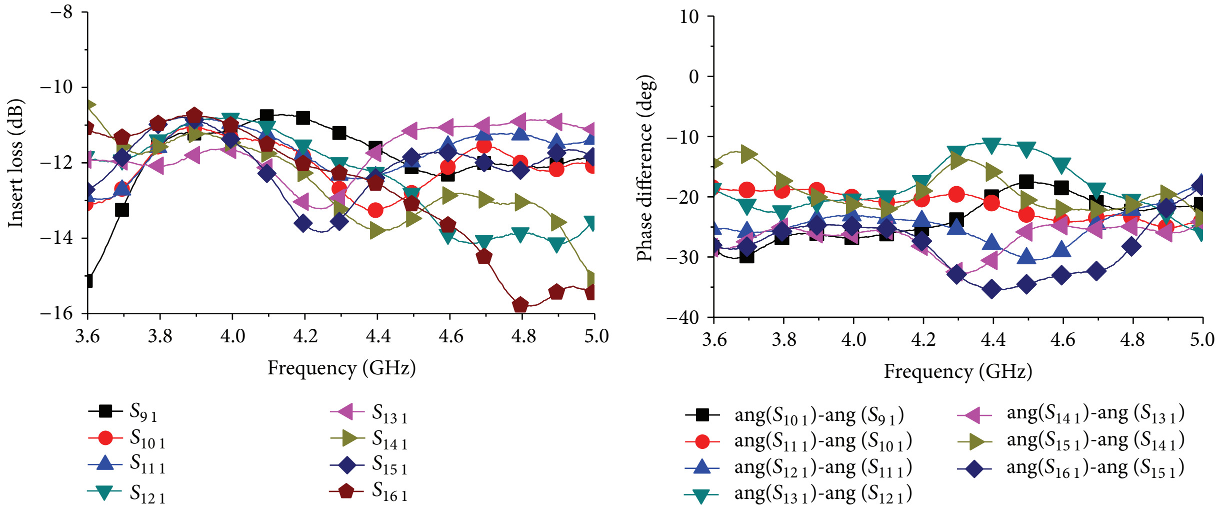
(a) (b)

Figure 7: Top (a) and bottom (b) view of the photographs of 8 × 8 Butler matrix sample.



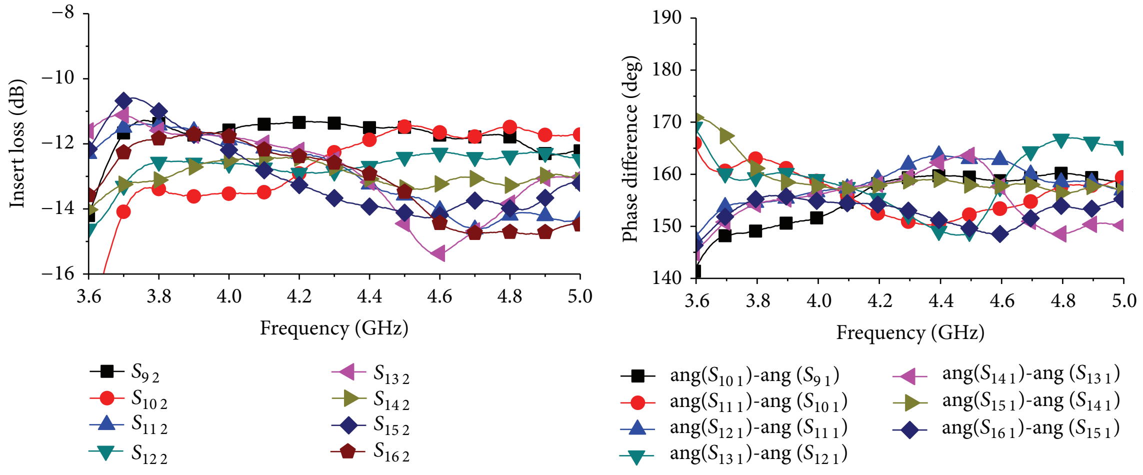
(a) (b)

Figure 8: The measured results of return loss at input ports (a) and output ports (b).



(a) (b)

FIGURE 9: The measured results of insertion loss (a) and phase difference (b) at Port 1. The phase difference at Port 1 is −22.5° theoretically.



(a) (b)

FIGURE 10: The measured results of insertion loss (a) and phase difference (b) at Port 2. The phase difference at Port 2 is 157.5° theoretically.

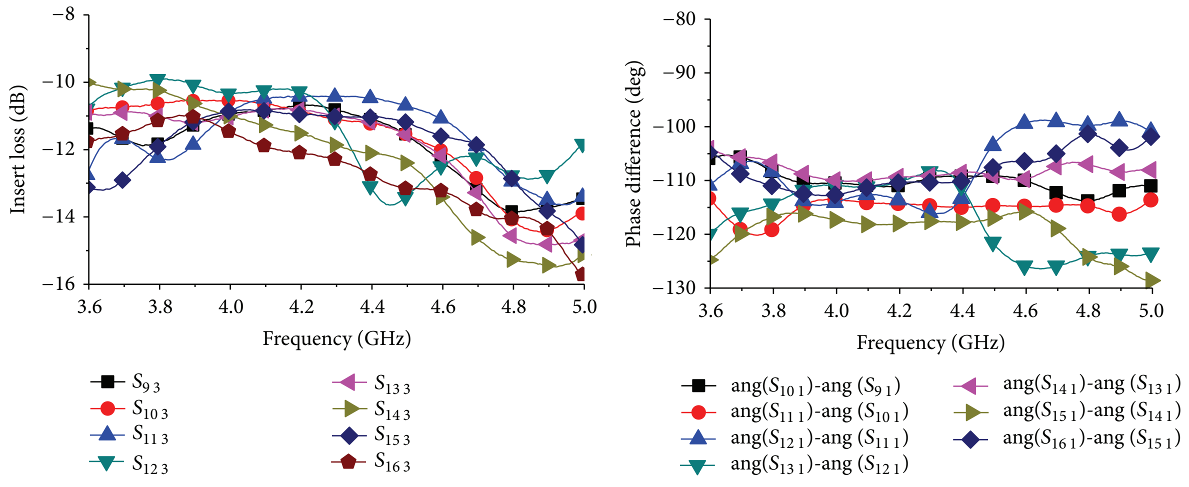
3. Experimental Results and Analysis

Based on the above-mentioned structure design results, a compact broadband 8 × 8 Butler matrix sample has been designed and fabricated, utilizing two substrates with a thickness of $h = 0.8$ mm and a dielectric constant of $\varepsilon_r = 2.55$. The photographs of the sample are shown in Figure 7, in which Port 1–Port 8, which are called input ports in this paper, are connected to RF device and Port 9–Port 16, which are called output ports, are connected to radiating units.

The measured results of performances of the 8 × 8 Butler matrix, such as matching, power distribution, and phase difference, are shown in Figures 8, 9, 10, 11, and 12. The measurement instrument is Agilent N5230A.

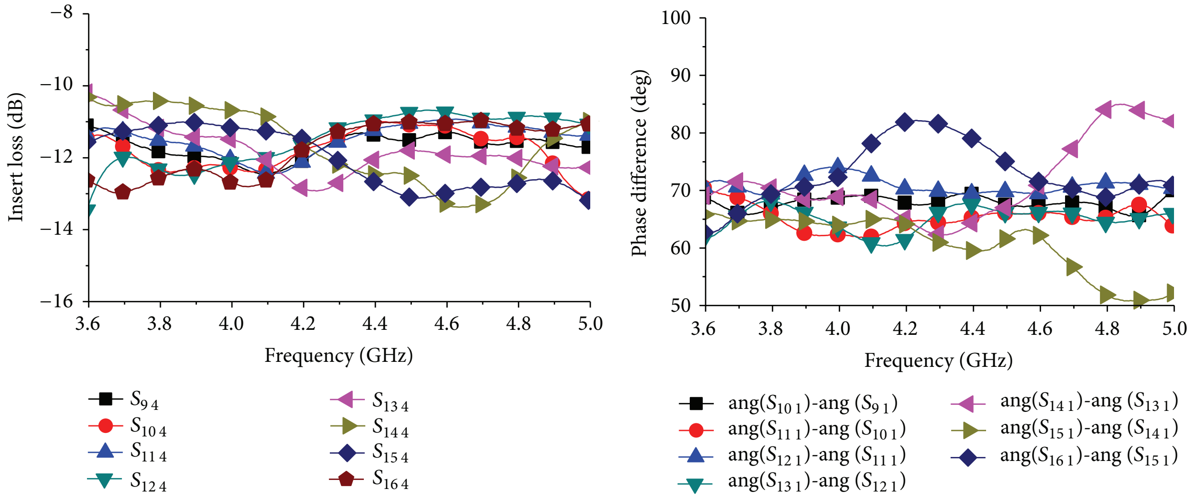
The match of input ports and output ports is shown in Figure 8, which shows that, in frequency between 3.7 GHz and 4.7 GHz, the return losses of each port are all lower than −10 dB.

The measured results of power distribution and phase difference performances of Port 1–Port 4 are shown in Figures 9, 10, 11, and 12. Due to the structural symmetry of Port 5–Port 8 and Port 1–Port 4 theoretically, the results of Port 5–Port 8 are not presented. The results show that, in frequency between 3.7 GHz and 4.7 GHz, the signals injected to the input ports could be distributed equally to each output port, the error is less than ±2.0 dB, the average measured insertion loss is about 2.5 dB, and the phase difference error is less than ±15°.



(a) (b)

Figure 11: The measured results of insertion loss (a) and phase difference (b) at Port 3. The phase difference at Port 3 is −112.5° theoretically.



(a) (b)

Figure 12: The measured results of insertion loss (a) and phase difference (b) at Port 4. The phase difference at Port 2 is 67.5° theoretically.

4. Conclusion

In this paper, a compact and broadband 8 × 8 Butler matrix based on bilayer microstrip structure has been designed and realized. By placing transmission line in the upper and lower layer, respectively, 0 dB crossover is avoided, the Butler matrix is simplified, and the transmission loss is reduced. Broadband component has been adopted to expand the matrix's bandwidth. The method has been validated to have good performance by measured results. The work will have proper adaptability to large scale multibeam forming network.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgment

This work was supported in part by the National Science Foundation of China (NSFC) under Grant no. F61301004.

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