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DESIGN AND IMPLEMENTATION OF A COMPACT PLANAR 4 × 4 MICROSTRIP BUTLER MATRIX FOR WIDEBAND APPLICATION

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Abstract—A compact planar 4×4 microstrip Butler matrix is proposed in this paper. It is a wideband beam-forming network with the advantages of compact size, low cost and ease of fabrication. Three-branch line couplers with lumped-distributed elements are adopted to reduce the size, and multi-U-shaped coupled-line Schiffman phase shifters are designed to get good transmission and phase performances. The Butler matrix is fabricated and measured, and a good agreement is found between the simulated and measured results, which makes it very attractive for wideband multi-beam antenna applications.

1. INTRODUCTION

The Butler matrix is a beam-forming network of lossless property and able to form orthogonal beams, which is useful for the synthesis of a complex antenna's radiation pattern. The beam-forming networks based on Butler matrices can be used in either transmitting or receiving systems, and due to design simplicity as well as the ability of wideband implementation, the Butler matrix looks like a very attractive option for researchers.

In general, the $N \times N$ Butler matrix is a network with N input ports and N output ports and composed of microwave hybrids, crossovers and phase shifters. These days, there are two methods to obtain a wideband Butler matrix in general. One method is using multilayer technology, such as two-layer substrate integrated waveguide (SIW) [1], multilayer coplanar waveguide (CPW) [2] and stripline coupled line [3]. The other method is based on planar printed circuit technology such as SIW [4] and microstrip lines [5, 6].

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The Butler matrix based on multilayer technology can obtain wideband performances easily, whereas the structure is complex and costly. In addition, the processing requirements are more rigorous than the single-layer planar circuits. In the study of planar wideband matrices, some researchers adopted SIW technology to design a Butler matrix for wideband applications [4], and some other researchers use disk hybrids [5] or wideband branch-line couplers [6] to compose wideband Butler matrices. These Butler matrices own their superiorities in some aspects as well as some disadvantages in other aspects. For example, a SIW wideband Butler matrix which is proposed in [4] has low loss and can be fabricated easily, but the overall size is too large. In [5], disk hybrids are basically used as components of a Butler matrix, and half-wavelength open stubs are employed to generate phase differences among output ports. This structure needs smaller area because of few couplers. However, the Butler matrix needs extra coaxial transmission line to connect to antennas because the input and output ports of such a structure are arranged irregularly. Actually, the overall performance is not good owe to the big loss of disk couplers. The Butler matrix designed in [6] is composed of traditional microstrip three branch-line couplers and wideband phase shifters, has simple architecture and is easy to implement. The performances are excellent according to simulated results. We can also see obvious drawbacks such as that the Butler matrix has larger size because of three-line branch line coupler and needs coaxial transmission line connecting to linear arrays as it cuts down a crossover, so these planar structures need improvements.

A planar wideband 4×4 Butler matrix is proposed in this paper. The microstrip three branch-line 3 dB couplers with mixed distributed and lumped distributed elements [7–9] are adopted in order to obtain enough bandwidth with compact size. Besides, the wideband phase shifters based on original Schiffman line phase shifter [10, 11] are improved to get good performances. Finally, a microstrip Butler matrix is optimized, fabricated and measured. Measured and simulated results are in good agreement. Isolation characteristics close to 20 dB with input reflection levels lower than 18 dB are experimentally validated over 20% bandwidth centered at 5 GHz. Measured transmission magnitudes and phases exhibit good dispersive characteristics of 1.3 dB, around an average value of -7.5 dB and 10° with respect to the theoretical phase values, respectively, over the band of $4.5 \sim 5.5$ GHz.

Table 1. Phase distribution of outputs ports.

	5	6	7	8	$\Delta\varphi$
1	$-45°$	$-90°$	$-135°$	$-180°$	$-45°$
2	$-135°$	$0°$	$-225°$	$-90°$	$135°$
3	$-90°$	$-225°$	$0°$	$-135°$	$-135°$
4	$-180°$	$-135°$	$-90°$	$-45°$	$45°$

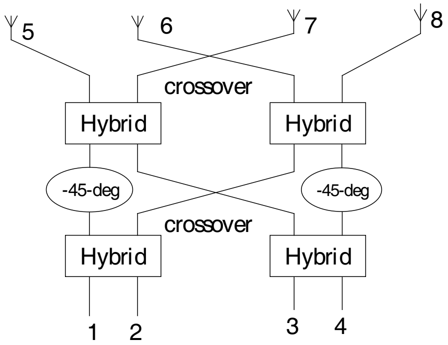


Figure 1. 4×4 Butler matrix.

2. DESIGN CONCEPT

2.1. Building Blocks Design Description

Figure 1 shows the scheme of a 4×4 Butler matrix designed in this paper, and Table 1 shows the phase distribution of outputs ports according to the input ports. We can see that the Butler matrix is composed of four 3 dB hybrid couplers, two crossovers and four phase shifters. When any input port is driven, the phase differences between output ports are equal. If we add more 3 dB hybrid couplers and phase shifters, we can get 8×8 or 16×16 and even more complex Butler matrix. The wideband performance of the Butler matrix is due to the wideband design of its components, next sub-sections will describe the design process of these different components.

2.2. Hybrid Couplers

The desired 90° hybrid should have a good performance such as return loss and isolation better than 20 dB over 30% or wider bandwidth, and a small size on a single-layer circuit without using any air-bridges.

The branch line coupler is popular as a hybrid in microwave circuits especially in planar circuits, while has narrow-band characteristics. To enhance the bandwidth, we choose cascaded branch line as a quadrature hybrid circuit. However, it requires a large circuit area. The loaded line is a popular method to reduce the size of transmission-line circuits such as branch-line and ring hybrids [7–9], which is important for planar integrated circuits. The results using a loaded line show good efficiency with regard to size reduction.

Figure 2 shows a transmission line and its equivalent circuit with lumped-distributed elements. Actually, the lumped-distributed elements are microstrip open stubs in our design. And the design equations can be defined as follows [9]:

$$jB_{01} = j\tan\theta_{01}/Z_{01} \tag{1}$$

$$B_{01} = \frac{\cos\theta_s - \cos\theta}{Z_c \sin\theta} \tag{2}$$

$$Z_s = \frac{Z_c \sin\theta}{\sin\theta_s} \tag{3}$$

where $0 \leq \theta_s \leq \theta \leq 90°$.

In [8, 9], the approach based on circuit models was used, and the consideration of analysis and design for wide-band applications was given. From [9], we know that the cutoff frequency of the equivalent circuit depends on not only the ratio θ_s/θ for given values of Z_c and θ, but also the dimension parameters of open stubs.

For demonstration, we select a transmission line of Fig. 2(a) with the characteristic impedance $Z_c = 46.33\,\Omega$ and electrical length $\theta = 45°$ as a unit line section, and it can be replaced by an equivalent distributed lumped element circuit in Fig. 2(b). Fig. 3 plots the cutoff frequency and the required characteristic impedance of series transmission line Z_s against the ratio of the electrical length θ_s and θ for given values of Z_c and θ. The ratio of θ_s and θ represents

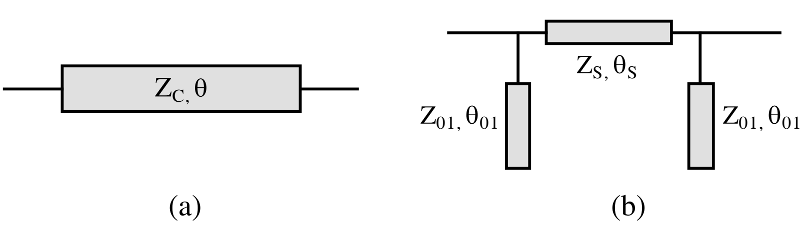


Figure 2. Size reduction scheme using lumped distributed elements. (a) Conventional transmission line. (b) Equivalent transmission line with a series transmission line and two open stubs.

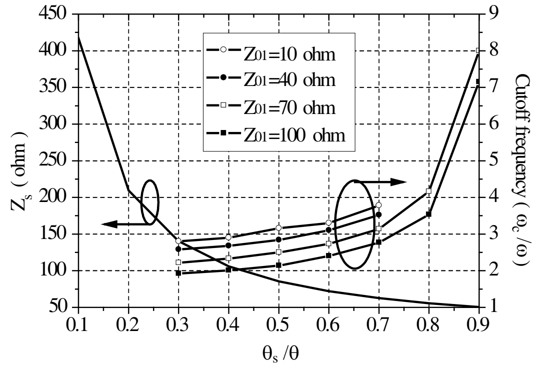


Figure 3. Z_s and the normalized cutoff frequency variations as a function of θ_s/θ.

the size reduction of the transmission line. Its lower value ensures the compact design area, while the cutoff frequency is also low. For a broad-band circuit, we should choose a unit section with higher cutoff frequency, which, however, will be a tradeoff with size reduction. Furthermore, the cutoff frequency increases as the impedance of an open stub decreases. Fig. 3 indicates a guideline to choose a unit section.

Initially, we followed a design method described in [12] and designed a cascaded branch-line coupler, which has three branch lines to achieve a fractional bandwidth of 35%, as shown in Fig. 4(a). The design parameters can be found as follows:

$$Z_{c1}=46.33\,\Omega,\ Z_{c2}=110.01\,\Omega,\ Z_{c3}=71.43\,\Omega,\ \theta_1=\theta_2=\theta_3=90^\circ$$

where Z_{c1}, Z_{c2}, Z_{c3} are the impedances of the branch lines, θ_1 ,θ_2, θ_3 are electrical lengths of them.

We know that 3-branch line coupler can easily enhance the bandwidth, but the cascaded structure nearly doubles the size. Because lumped or lumped-distributed elements give us a chance to have a small design area, we add mixed lumped-distributed elements to the 3-branch coupler prototype as in [8]. In this paper, lumped-distributed elements are added into the wider branch lines in Fig. 4(a), to decrease the size. Now the parameter is selected as $Z_c = Z_{c1} = 46.33\,\Omega$. In order to ensure high enough cutoff frequency and appropriate size reduction, a 90° microstrip line is divided into two equal lines for loading, that means $\theta = 45^\circ$. Then making $\theta_s = 22.5^\circ$, we can reduce about half of the length along the branch line c_1, as well as ensure the necessary distance between c_2 and c_3. According to Formulas (1)∼(3), we can get $Z_s = 85.6\,\Omega$, $B_{01} = 0.0066\,\mathrm{S}$. From

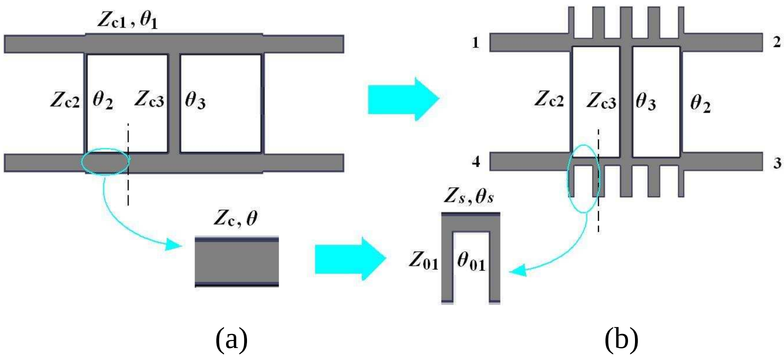
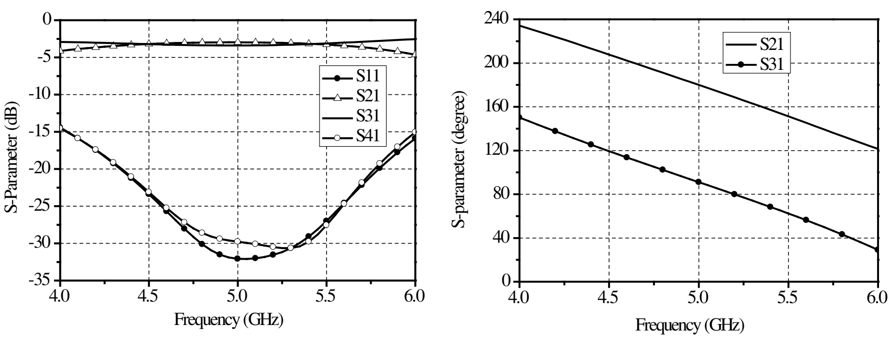


Figure 4. Branch-line hybrids with three branch lines. (a) Conventional 3-branch line coupler. (b) 3-branch line coupler using lumped distributed elements.



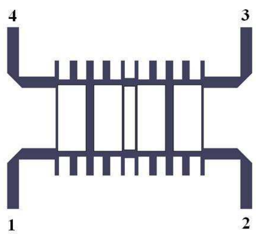
(a) Amplitude responses

(b) Phase responses

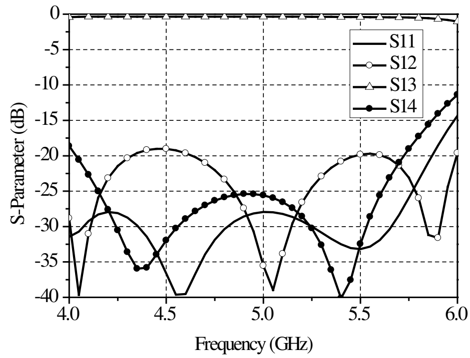
Figure 5. Simulated results of S-Parameters.

Fig. 3, we know that the cutoff frequency is high enough regardless of the value of Z_{01}.

At last, the 3-branch line coupler with lumped-distributed elements is shown in Fig. 4(b), and Fig. 5 gives the simulated S-parameters. We can see that in the required frequency range of $4.5 \sim 5.5$ GHz, the return loss and isolation are below -23 dB. And the area is greatly reduced, which is important for a compact Butler matrix.



(a) Crossover



(b) Simulated results of S-Parameters

Figure 6. The crossover and the simulated results.

2.3. Crossovers

In a planar single-layer implementation of Butler matrix, crossovers are necessary components and can be obtained by cascading two hybrids, as shown in Fig. 6(a). Adjusting the width and length of interconnection can get the best performance. Fig. 6(b) gives the S-parameters after optimization.

2.4. Wideband Phase Shifters

To satisfy the phase requirement, the wideband phase shifters are necessary in the design process. It is appropriate for the wideband application to adopt Schiffman phase shifter [10], which has a simple structure. The mature theoretical analysis and calculation formulas are presented in [11]. And some improved broadband Schifman phase shifters have been proposed [13, 14].

For a conventional Schiffman phase shifter, a U-shaped coupled-line is used to achieve additional phase. The Schiffman phase shifter is a broadband phase shifter where the phase shift $\Delta\varphi$ is obtained as a subtraction of the phase response of a coupled section with adjacent ports interconnected and the phase response of a uniform line. i.e., [11]:

$$\Delta\varphi = K\theta - \cos^{-1}\left(\frac{\rho - \tan^2\theta}{\rho + \tan^2\theta}\right) \tag{4}$$

where θ is the electrical length of the coupled section, and ρ is its impedance ratio defined as

$$\rho = Z_{0e}/Z_{0o} \tag{5}$$

Z_{0e} and Z_{0o} are the even and odd mode impedances of the coupled section respectively.

The coupling C and impedance ratio are related by:

$$C = -20 \log \frac{\rho - 1}{\rho + 1} \tag{6}$$

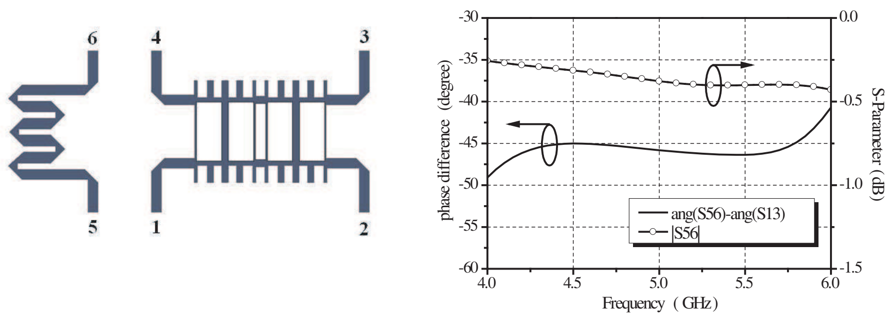
And the maximum bandwidth, B, can be defined as

$$B = \frac{180^\circ - 2\theta}{90^\circ} \tag{7}$$

From (4) and (6), we know that $\Delta\varphi$ increases as C increases. However, it is difficult to realize a narrow gap, especially for very strong coupling. On the assumption that a U-shaped coupled-line with weak coupling has the phase shift $\Delta\varphi_1$, n U-shaped coupled-lines with weak coupling have the phase shift $n\Delta\varphi_1$. So we can use multi-U-shaped coupled-lines instead of single U-shaped coupled-line, and each U-shaped coupled-line has the weak coupling, then the gaps of coupled-lines become wider while the total phase shift remains unchanged.

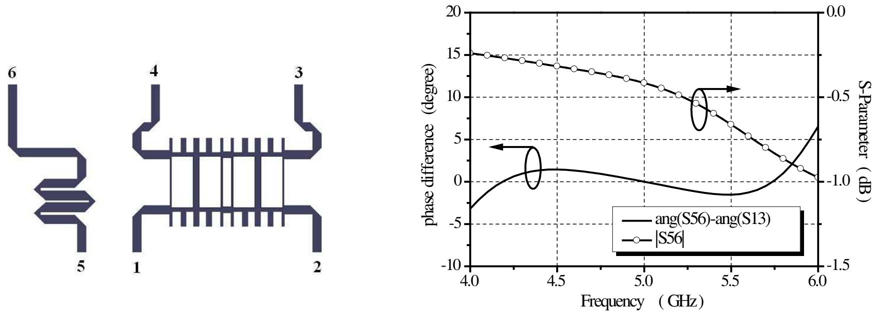
Figure 7 shows the -45° phase shifter and the simulated results. From Fig. 7(b), we can see that the insert loss of the coupled-line is less than 0.4 dB, and the difference between phase (S_{65}) and phase (S_{31} or S_{42}) is $-45.5 \pm 0.8^\circ$ in the band of $4.5 \sim 5.5$ GHz.

In the same way, we can design 0° phase shifter. Fig. 8 shows the 0° phase shifter and the simulated results. The insert loss of the coupled-line is less than 0.7 dB, and the difference between phase (S_{65}) and phase (S_{31} or S_{42}) is $0 \pm 1.3^\circ$ over the $4.5 \sim 5.5$ GHz frequency band.



(a) -45° phase shifter (b) Simulated results of S-Parameters

Figure 7. -45° phase shifter and the simulated results.



(a) 0 ° phase shifter (b) Simulated results of S-Parameters

Figure 8. 0° phase shifter and the simulated results.

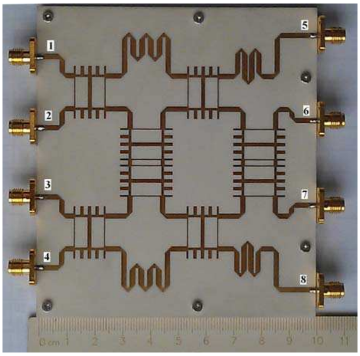
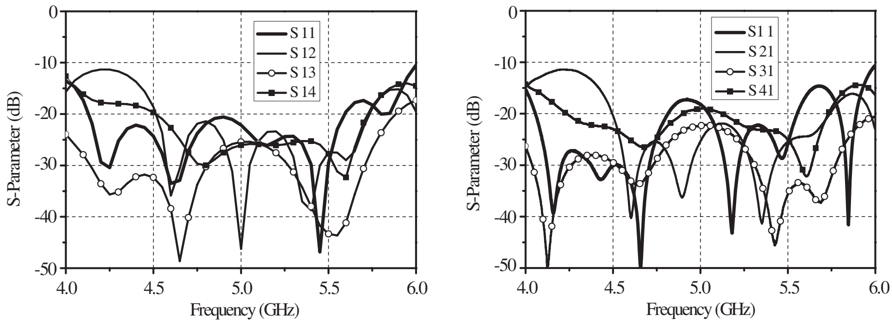


Figure 9. The proposed 4 × 4 wideband Butler matrix.

3. SIMULATION AND MEASUREMENT

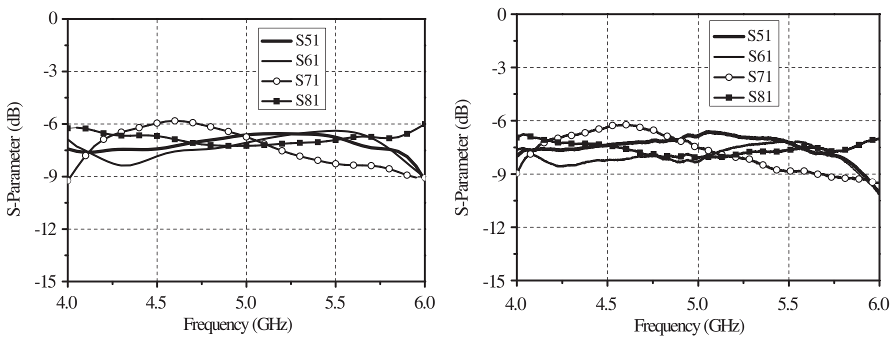
The proposed Butler matrix is designed on a Rogers RO4003 substrate with dielectric constant of 3.38 and substrate thickness of 0.813 mm. Fig. 9 shows the photograph of the proposed Butler matrix, and the total size is 109 mm × 99 mm including additional microstrip lines for input/output test. Every previously presented building block can be identified. No. 1 $\sim$ 4 ports are input ports, and No. 5 $\sim$ 8 ports are output ports. The distance between output ports is selected as half wavelength in free space of the center frequency for array antennas.

Figures 10(a) and (b) separately show the simulated and measured results of the return loss and isolations at the input port 1. In the band of 4.5 $\sim$ 5.5 GHz, the isolations are close to our goal of 20 dB, while the return loss is better than 18 dB. Fig. 11 presents simulated and



(a) Simulated results (b) Measured results

Figure 10. Return losses and isolations of the 4×4 Butler matrix fed at input port 1.



(a) Simulated results (b) Measured results

Figure 11. Amplitude distribution of the 4×4 Butler matrix when fed at Port-1.

measured transmission coefficients when the matrix is fed at port 1. We can see that the coupling factors are well equalized around -7 dB in the simulation and around -7.5 dB in the measurement over the frequency range of $4.5 \sim 5.5$ GHz. The theoretical relative phase between adjacent output ports is $-45°$, $+135°$, $-135°$, and $+45°$ when the signal is fed at input ports 1, 2, 3, and 4, respectively. Fig. 12 shows the simulated and measured phase differences for the 4 input ports. The phase differences between different output ports when the signal is fed at each input port are $-45° \pm 10°$, $+135° \pm 10°$, $-135° \pm 10°$ and $+45° \pm 10°$ over the frequency range of $4.5 \sim 5.5$ GHz. Good agreement is found for these parameters between simulations and measurements though the measurement results are a little worse than simulation.

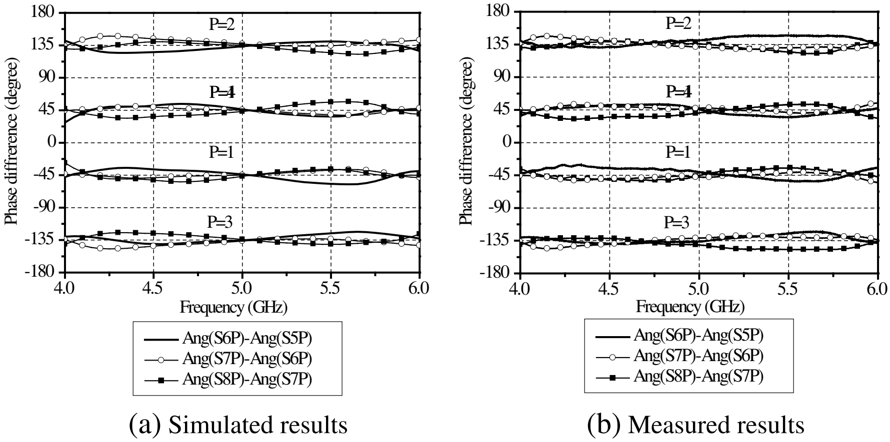


Figure 12. Output phase distributions per input port of the 4 × 4 Butler matrix.

Moreover, the proposed Butler matrix has a small size of $2.65\lambda_g \times 2.92\lambda_g$, including the transmission lines to the test ports, where λ_g is the waveguide wavelength at 5 GHz. As previously mentioned in the introduction, compared with the planar wideband Butler matrix in published literatures, this proposed Butler matrix is compact with good performances. Specifically, the performance in [4] is almost the same as that in this work while the size is about $8.64\lambda_g \times 8.76\lambda_g$, and [5] adopts fewer couplers which brings some problems when connecting to antennas and also occupies $2.49\lambda_g \times 2.49\lambda_g$. As a result, the performance is much worse. Reference [6] did not give any size parameters, but we can see that the size almost doubles that of this work due to the conventional 3-branch line coupler.

4. CONCLUSION

A compact microstrip 4 × 4 Butler matrix for wideband application is designed, fabricated, and tested. The wideband performance of the Butler matrix is due to the wideband design of its components including hybrid couplers, crossovers and phase shifters. A 3-branch line wideband coupler with lumped-distributed elements is adopted in the design, which can reduce almost half area of the conventional one. To get good phase and transmission performances during a wide band, an improved Schiffman phase shifter is designed, which uses multi-U-shaped coupled-line instead of single-U-shaped one.

Simulated and experimental results in terms of magnitude and phase shift demonstrate a good agreement over the band of 4.5 $\sim$ 5.5 GHz. The proposed Butler matrix could advantageously be used as a beam-forming network for a wide antenna array.

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