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Implementation of a Miniaturized Planar 4-Port Microstrip Butler Matrix for Broadband Applications

M. Maleki[1], T. Aribi[2], A. Shadmand[3]
[1]*Department of Electrical Engineering, Urmia University, Urmia, IRAN*
[2]*Department of Electrical Engineering, Miandoab Branch, Islamic Azad University, Miandoab, Iran*
[3]*Department of Electrical and Computer Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran*
m.maleki@urmia.ac.ir, tohidaribi@gmail.com, shadmand.ali@gmail.com
Corresponding author: M. Maleki

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***Abstract*- In this paper, a miniaturized and broadband 4 × 4 Butler matrix is presented. All components of the presented matrix are designed in a way that, have the broadband impedance bandwidth and compact electrical size as much as possible. Traditional previous Butler matrix composed of phase shifters, while in the presented feeding network dummy crossover role this act, which results to enhance the phase difference bandwidth. The compactness of the optimized and proposed coupler is related to inserting the S-shaped arms instead of ordinary parts. The modified dummy crossover is used to overcome the mismatch phase difference among phase shifter and crossover. Design procedure of miniaturized broadband components such as 3-branch-line coupler, crossover, phase shifter and final design are presented step by step. The results of the simulation and measurement of the desired Butler matrix makes it suitable for the applications of planar multi-beam antennas. The extracted results determine that the bandwidth of the presented network is from 4.5 ~ 6 GHz, that is a good candidate for WLAN applications. The whole size of network is 71.5 × 38.3 mm^2.**

Index Terms- Butler matrix, microstrip, broadband, planar, miniaturized.

I. INTRODUCTION

N × N Butler matrix (N input ports and N output ports) is a passive microwave network. If this matrix is used to feed an N-element array antenna, a set of N orthogonal beams will be generated. Also, this network in sequentially rotated scheme is a good candidate to achieve circular polarization feature in antenna arrays. Butler matrix networks are the fundumental components of the switched beam networks, which are widely used in smart antennas [1]. Various techniques have been used to implement Butler matrix, such as suspended strip lines [2], single layer [3], and multilayer microstrip [4] lines, waveguides [5], [6], coplanar waveguide (CPW) [7], etc. Due to compact size and simple

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fabrication process, microstrip technique is used as a popular approach in realization of beam switching networks. In the study of microstrip method, 3dB couplers and crossovers should be investigated. To enhance the total impedance matching of the feeding network, all of components must be designed as broadly as possible. Inherent feature of broad banding is increase of the dimensions; hence miniaturization should not be neglected. Couplers are fundamental components of Butler matrices, inserted stubs results to have a compact size and stable impedance matching with frequency variations. The Butler matrix at [8] is made of modified 3 dB branch-line couplers for 5G applications, which has broadband operation. Introduced couplers at [9, 10] have compact size and wide band feature. Since attached arms acts as distributed capacitance, they are capable to minimize the physical size of coupler while the electrical length is preserved. The interaction between arms (role as capacitors) among other current paths (role as inductors) leads to produce new resonate frequency and results to improvement of impedance matching. The broadband performance of any feed network such as Butler matrix means that they can produce equal phase difference and coupling on output ports throughout the operating band. In order to obtain optimal values of physical dimentions and scattering parameters, mixed and lumped distributed elements [11]-[14] are embeded at conventional 3 dB branch-line couplers. Using crossover for planar layouts is necessary. Traditional structers at this filed have narrow bandwidth and relativly large electrical size [15]. Due to overcome the mentioned defects, using multi box topology was investigated. The minimization process is exactly similar to hybrid compression. In this paper, a compact and broadband microstrip Butler matrix with a center frequency at 5.25 GHz, i.e., 4.5 ~ 6 GHz is presented.

II. ELEMENTS OF MINIATURIZED BROADBAND BUTLER MATRIX

Fig. 1 depict the final structure of proposed feeding network. Due to approximately symmetric scheme and acceptable operation of each components of the network, uniform scattering parameter results are expected to perform similarly. Table 1 illustrates the conventional Butler matrix phase difference for each port excitation. The components of planner proposed matrix are: modified hybrids, phase shifters and crossovers. The design of broadband components leads to the broadband performance of the Butler matrix. In order to obtain the desired bandwidth with compact size, mixed distributed and lumped distributed elements are adopted in microstrip 3-branch-line 3 dB couplers. To design 4 × 4 Butler matrix, four 3-branch-line 3 dB couplers, one crossover, and two phase shifters are needed. By excitation any of the input ports, the equal phase differences between output ports occur. The accuracy of design process is directly associated to operation of each element, hence optimal design of mentioned components individually is very important.

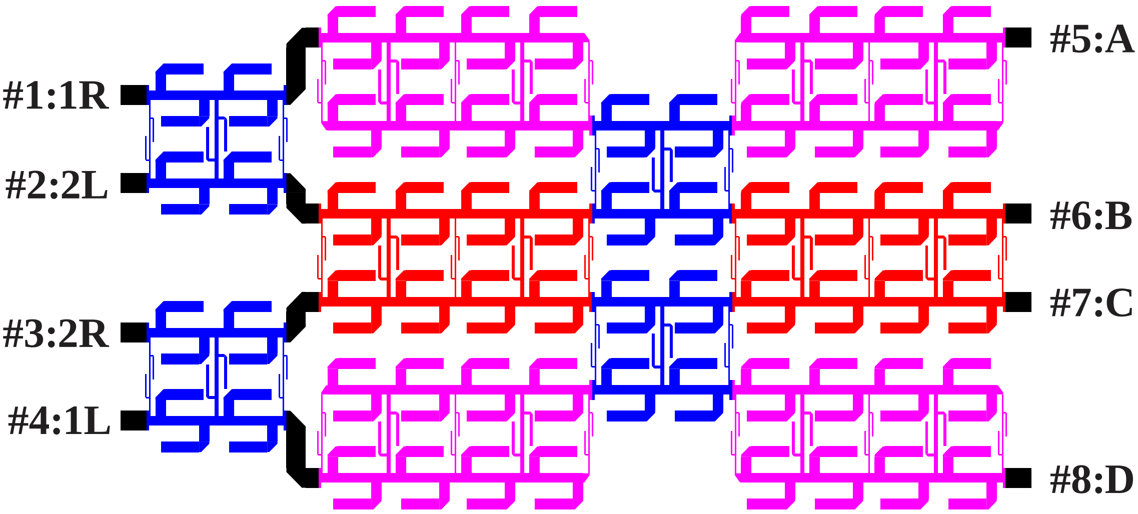

Fig. 1. Schematic of the proposed Butler matrix.

Table I. Phase distribution of output ports according to input ports.

-----Output Input------	A	B	C	D	Δφ
1R	-45°	-90°	-135°	-180°	-45°
2L	-135°	0°	-225°	-90°	135°
2R	-90°	-225°	0°	-135°	-135°
1L	-180°	-135°	-90°	-45°	45°

A. Design process

The design process of the proposed passive components was investigated in three iterations as follow:

- Step 1: Coupler 1; To improve the impedance matching, cascade configuration is used as a double box. Fig. 2 depicts the extracted curves of this coupler.
- Step 2: Coupler 2; For minimizing the physical size, S-shaped arms are added to the previous step.
- Step 3: Crossover; two S-shaped hybrids are attached consecutively. The performance of the proposed crossover can be achieved by adjusting the size of the interconnections.

B. 3-Branch-line 3 dB Couplers

Due to bandwidth improvement, cascade configuration is used as double box coupler (hybrids), while it suffers from its double size (see Fig. 2(a)). The S-parameters of the double box hybrid are illustrated in Fig. 2(b, c) (step 1). In order to obtain a miniaturized size, S-shaped 3-branch-line 3 dB couplers, which is a broadband structure, is replaced by conventional 90° hybrids [16]. The characteristics of desired 3-branch-line 3 dB couplers such as return loss and isolation should be better than 15 dB over 80% or wider bandwidth, and a small size on a single-layer circuit without using any air-bridges in

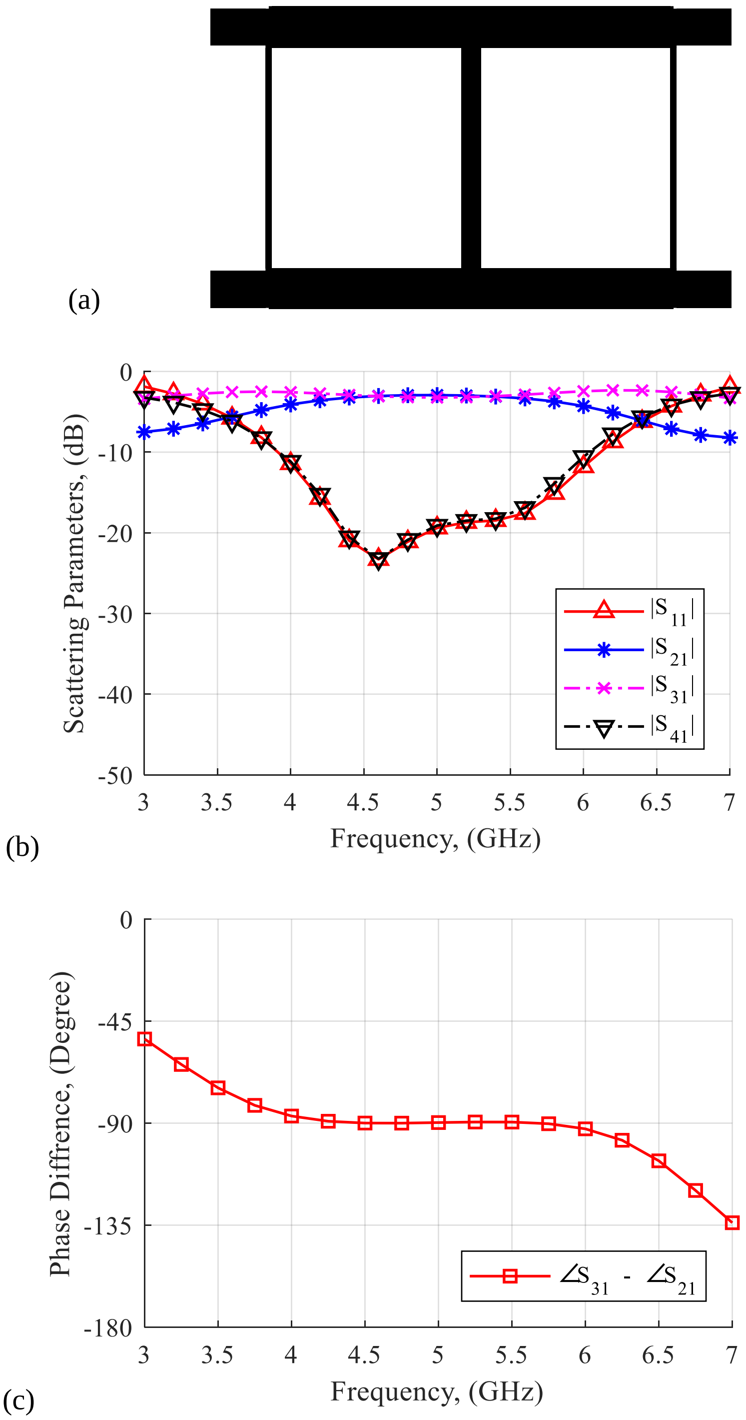

Fig. 2. (a) The layout and (b, c) S-parameters of the conventional broadband hybrid.

microwave circuits especially in planar circuits. It's clear, the impedance bandwidth covers the frequency range of 4 ~ 6 GHz (40%), and the linear phase difference is achieved at the operational band. The desired 3-branch line 3 dB coupler (see Fig. 3(a)) has broadband characteristics and small

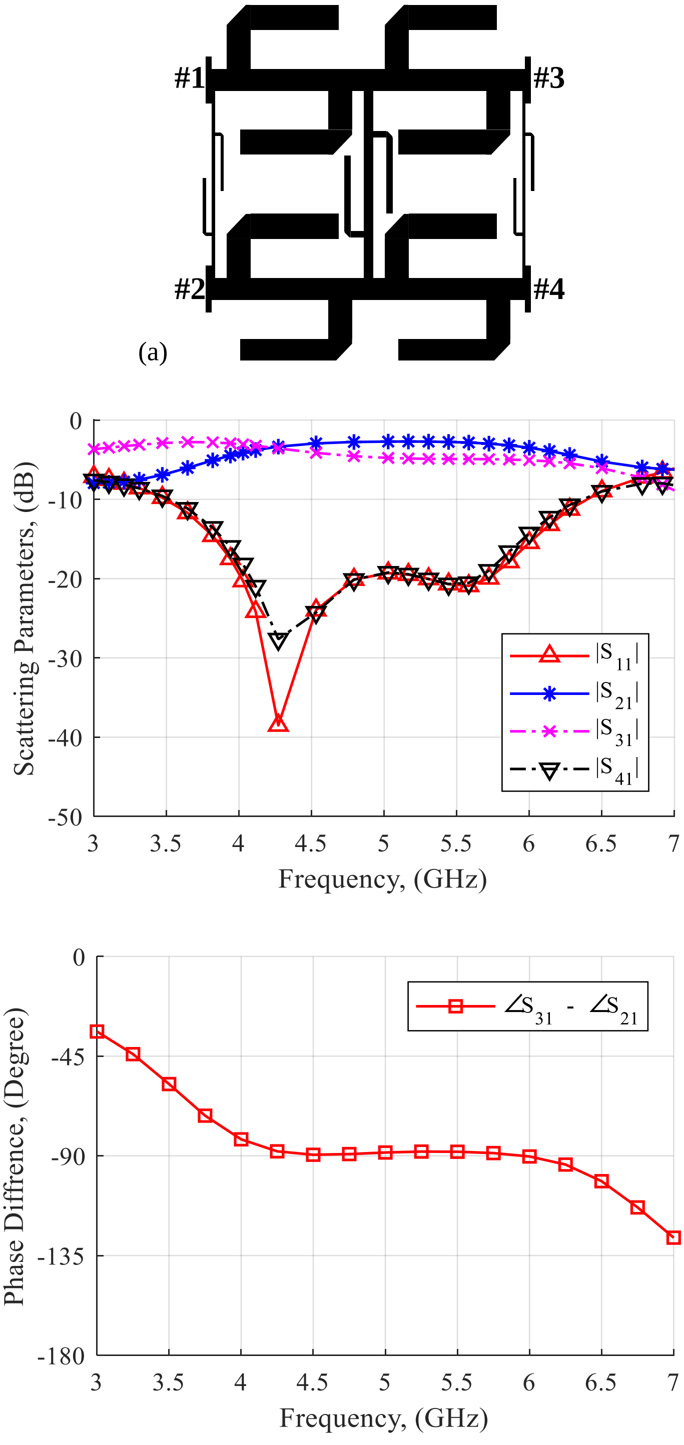

Fig. 3. (a) The layout and (b, c) S-parameters of the S-shaped 90° hybrid.

size respect to the conventional double box branch line hybrids (step 2). The S-parameters of the desired hybrid after optimization are shown in Fig. 3(b, c).

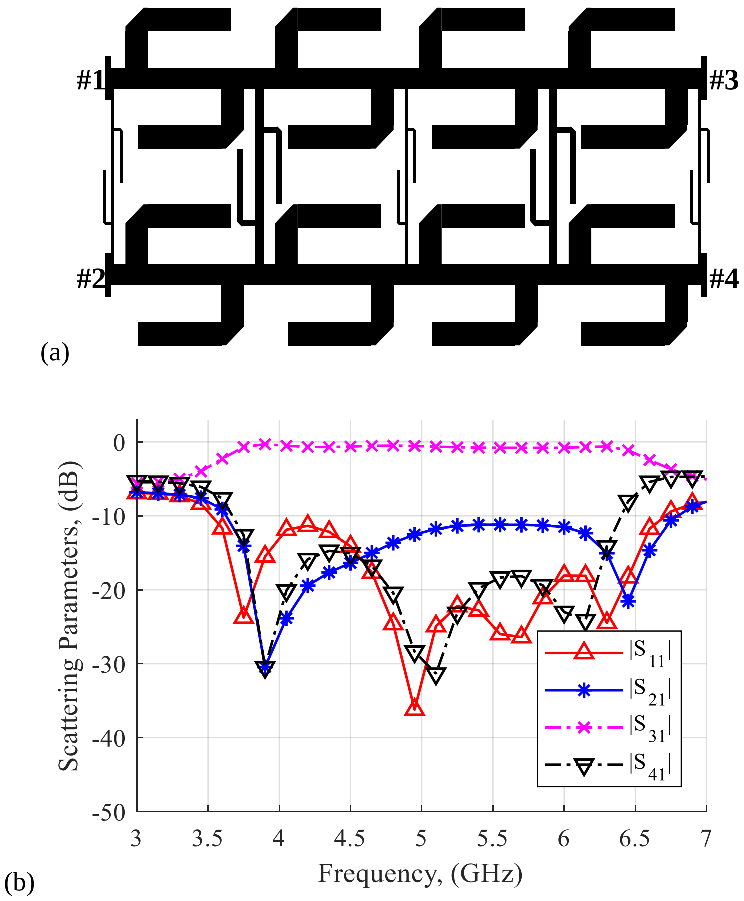

Fig. 4. (a) The layout and (b) S-parameters of the S-shaped crossover.

C. *Cossovers*

To implement a planar single-layer Butler matrix, crossovers are necessary components. By cascading two hybrids, crossovers can be obtained [17]. As shown in Fig. 4(a), two S-shaped hybrids are cascaded to generate proposed crossover. The optimal performance of the modified crossover can be obtained by adjusting the size of the interconnections. The S-parameters after optimization are shown in Fig. 4(b) (step 3).

D. *Phase Shifters*

Implementation of the differential phase shifter by a traditional transmission line results to a limited operational band. Using the principle of Schiffman line structure, the broadband phase shifter could be designed [17]. The existence of ordinary crossovers leads to produce unwanted phase difference (which is not completely linear as shown in Fig. 5(c)). Hence desire value of phase difference also can be obtained by dummy crossover as phase shifter. Fig. 5(b) illustrates, the broadband phase response of both dummy crossover and actual crossover are very close together. Realization of sufficient phase difference at the broadband frequency range by conventional delay line is not easily achievable. Thus,

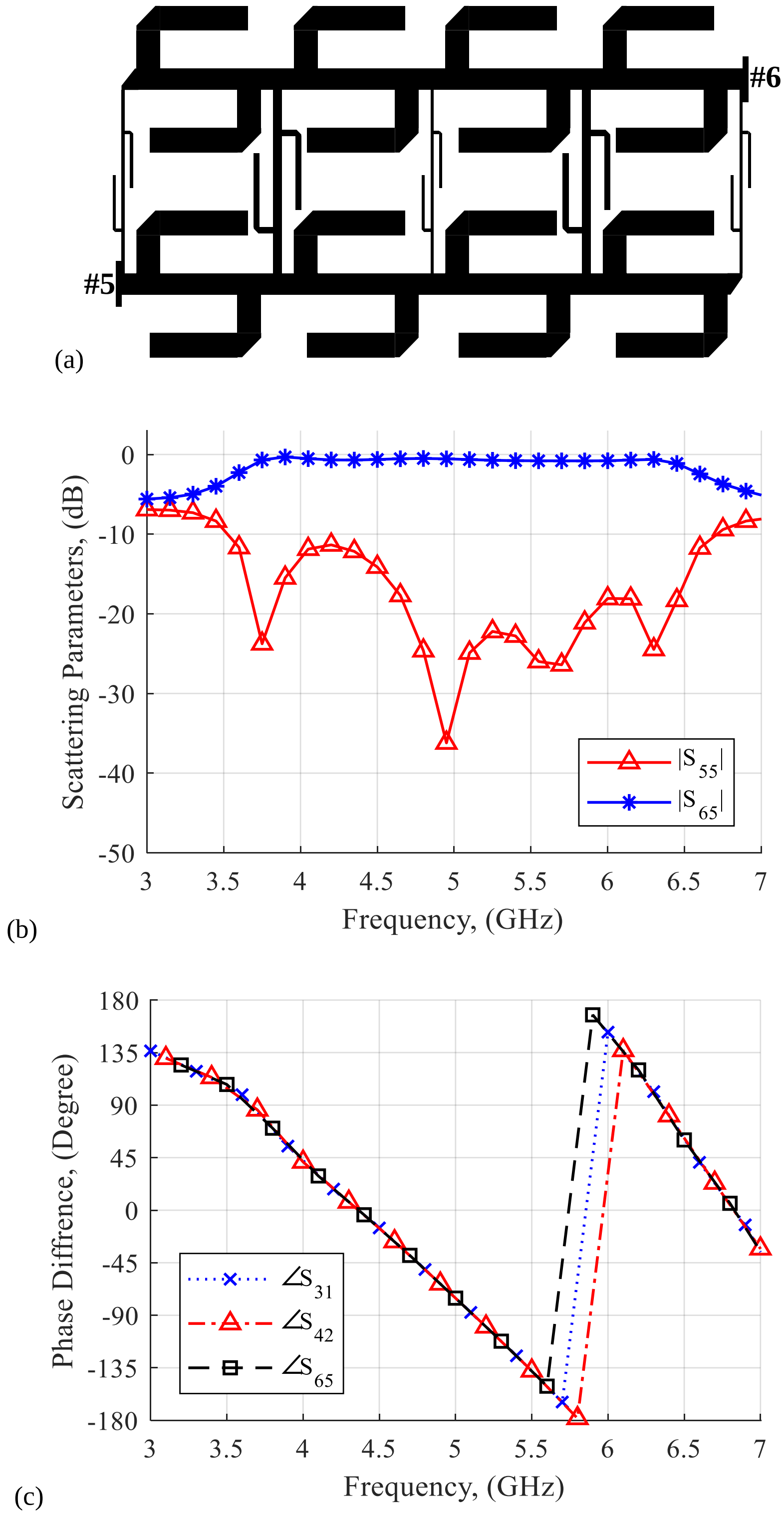

Fig. 5. (a) The layout of the S-shaped dummy crossover, (b) S-parameters of the dummy crossover and (c) phase difference compression of the crossover and dummy crossover

the dummy crossover with broadband property as shown in Fig. 5(b) is used at design process.

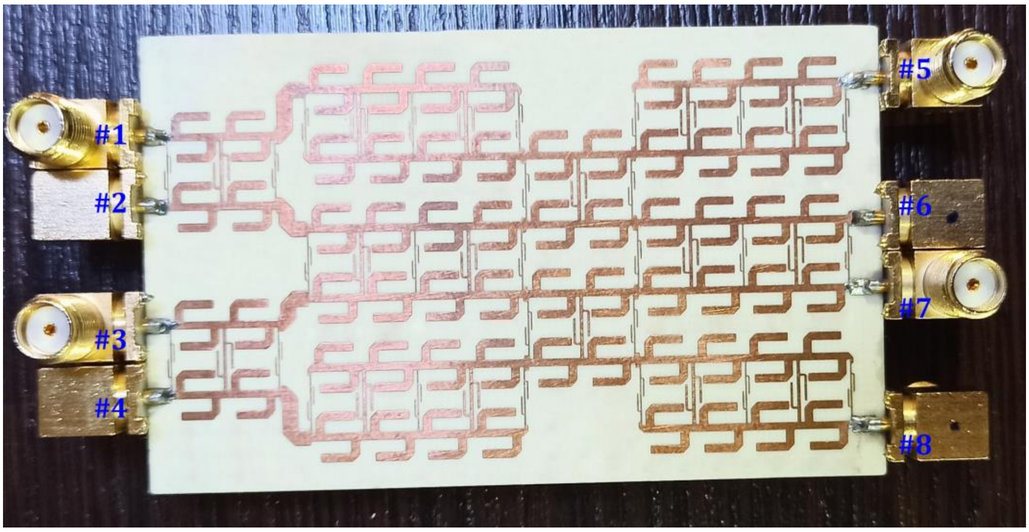

Fig. 6. The layout of the proposed 4 × 4 Butler matrix.

III. BROADBAND AND MINIATURIZED 4 × 4 BUTLER MATRIX

Simulated and measured scattering parameters are extracted from Agilent Advanced Design System software (ADS) and Agilent™ 8363C network analyzer, respectively. It is an electromagnetic wave simulator which provides an integrated design environment to RF electronic designers, and supports every step of the design process allowing the engineer to characterize and optimize an RF design without changing tools fully. Rogers RO4003 substrate with a thickness of 0.8 mm and a dielectric constant of 3.55 is used at design of proposed Butler matrix. The layout of the proposed Butler matrix with S-shaped elements is presented in Fig. 6, and its size is 71.50 mm × 38.30 mm. Port no. 1, 2, 3, and 4 are input ports, and ports no. 5, 6, 7, and 8 are output ports.

Measured S-parameters (the results of the return loss, isolations, and transmission coefficients) are presented in Fig. 7(a), (b), (c), and (d) at the input ports 1, 2, 3, and 4, respectively. At the frequency range of 4.5 ~ 6.0 GHz, the return loss and isolations are better than 15 dB, while the transmission factors are well equalized around 7 dB. The theoretical relative phase difference between two adjacent output ports are shown in Table 1. Mentioned values for the input ports are shown in Fig. 7(e). Measured results of proposed Butler operation matrix illustrate the tolerance less than 10° at operational band.

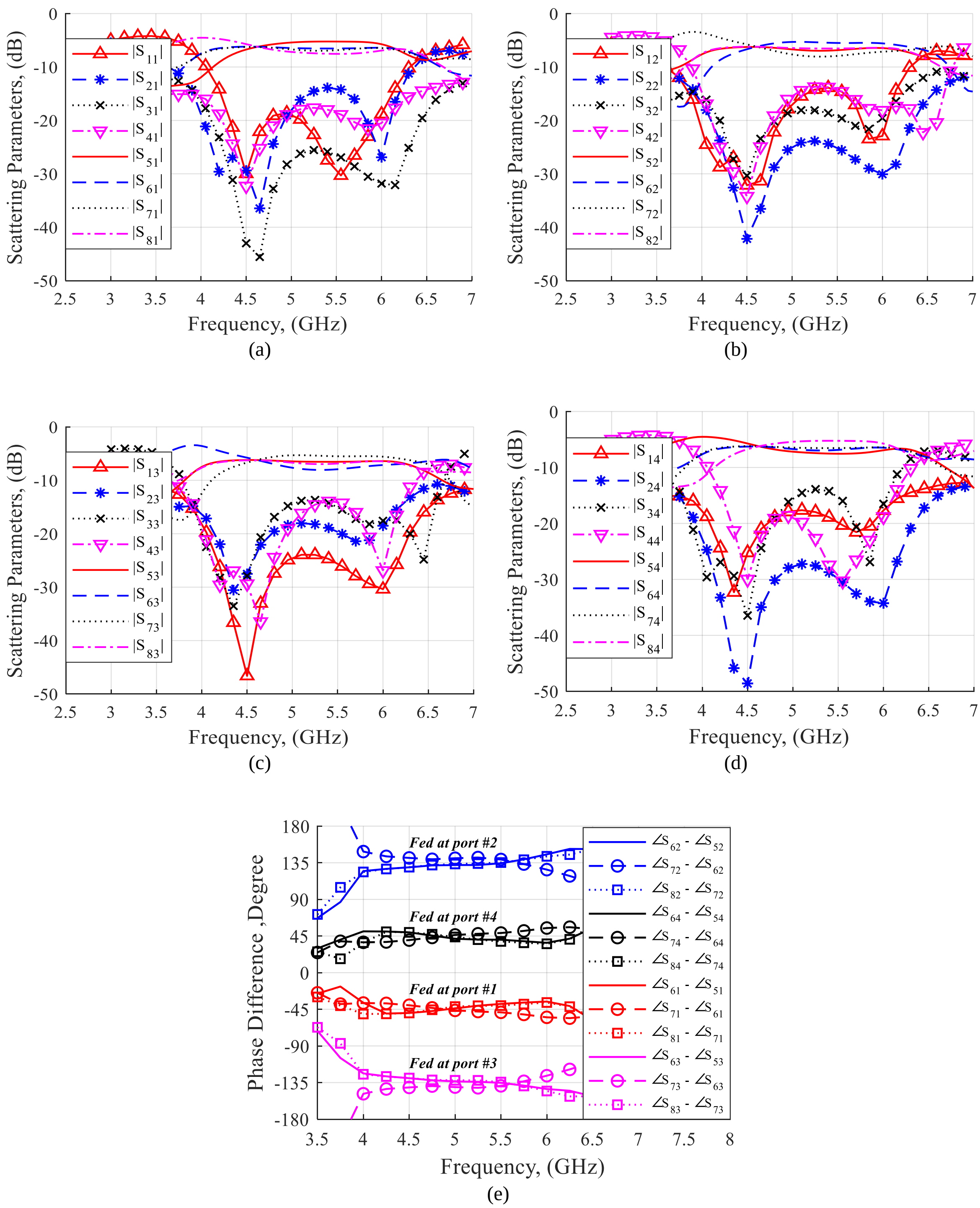

Fig. 7. Simulated scattering parameters and phase difference. (a), (b), (c), and (d) Return loss, isolations, and transmission factors to input port 1, 2, 3, and 4, respectively. (e) Phase differences for each input port 1, 2, 3, and 4.

IV. CONCLUSION

A microstrip 4 × 4 Butler matrix with miniaturized size for broadband applications is designed and fabricated. Using modified components such as S-shaped branch-line coupler and dummy crossover leads to have miniaturized and broadband scheme. In order to achieve desired phase and transmission performances, a dummy crossover is designed as phase shifters, which implies accurate phase shifts as crossovers. Experimental results in terms of magnitude and phase shift confirm a good agreement with theoretical values over the frequency range of 4.5 ~ 6.0 GHz. Isolation characteristics and input refection levels are lower than 15 dB, and goals are experimentally confirmed over all the bandwidth centered at 5.25 GHz. Extracted results of transmission magnitudes are approximately close to the value of 7 dB over the frequency range of 4.5 ~ 6.0 GHz, while differential phases have tolerance of ±10° respect to the theoretical result. The proposed Butler matrix is a good choice for broadband beam switching arrays.

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