A Compact Broadband 16×16 Butler Matrix for Multibeam Antenna Array Applications

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***Abstract*-This paper presents a compact 16×16 Butler Matrix operated from 9 GHz - 11 GHz. Compared with the traditional structure, the presented network is much simpler and can be easily designed. The number of needed components in the design is only sixty, where the number of crossovers is four. In addition, the designed network can be fully realized in a single layer laminate with the size of 165 mm×165 mm ($5.5\lambda_0 \times 5.5\lambda_0$). It is shown that the maximum simulated output phase error at 10 GHz is only ±8° and the transmission coefficients are in the range of -14.5 ± 1.5dB over the bandwidth. The measured and simulated results agree well. The designed network can be a potential candidate for the one or two dimensional multibeam array antennas.**

I. INTRODUCTION

Butler Matrices are widely used in modern communication devices, because it can provide multiple orthogonal signal channels for antenna arrays to have multiple tilted radiating beams in space. In addition, they can also have important applications in generating orbital angular momentum waves (OAMWs) [1], tracking [2], QAM multiport modulators [3] and multiport amplifiers [4], etc. Many publications related to Butler Matrices mainly focus on the development of 4×4 and 8×8 Butler Matrices, which usually have relatively low complexity and can be easily realized [5] – [7]. In these designs, the striplines, defected ground structures (DGSs) and LTCCs are often used to improve the operating bandwidth.

Due to extremely high complexity, the 16×16 Butler Matrix has been seldom reported. A standard 16×16 Butler Matrix consists of three kinds of components, namely 3dB directional couplers, phase shifters and crossovers. The total number of these components is more than 116. Notably, the number of crossovers in the topology take the percentage of more than 50%. Thus, to realize such a network is very challenging and time-consuming.

In this paper, we present a simplified broadband 16×16 Butler Matrix designed with microstrip lines. The number of components in this design is significantly reduced from 116 to 60 where only four crossovers are required. The designed 16×16 Butler Matrix can be fully realized in a single laminate by using the standard PCB processing technique with very low cost. With advantages of broadband, low complexity and low cost, the designed 16×16 Butler Matrix is a very potential candidate in future wireless communication systems.

II. TRADITIONAL 16×16 BUTLER MATRIX

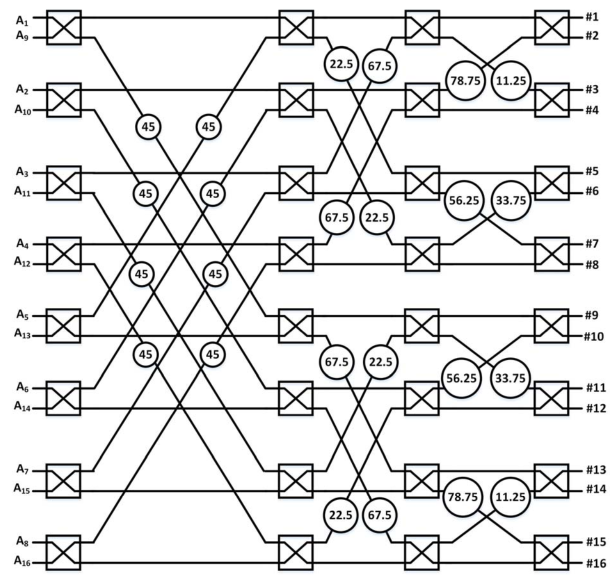


Fig. 1. Topology of the traditional 16×16 Butler Matrix.

Sharing some similarities with 4×4 and 8×8 Butler Matrices, the traditional 16×16 Butler Matrix can be viewed as multiple combinations of 3dB directional couplers, fixed phase shifters and crossovers [8]. As can be seen from Fig. 1, #1 – #16 are the input ports while the output ports A1 – A16 are located on the left. To design such a network, 32 3 dB directional couplers, 24 fixed phase shifters and 60 crossovers are needed. It should be noted that the crossovers take the percentage of more than 50%. The phase shift of each fixed phase shifter is evenly spanned from 11.25° to 78.75°. In the geometry, the existence of a large number of crossovers results in much difficult in designing such a network. In addition, in the 16×16 Butler Matrix, each input signal must travel through seven essential components before flowing out from an array port. The transmission loss and phase errors caused by these components will be progressively accumulated. Hence, regarding to its realization, another challenge is how to ensure good transmission performances and broadband operation.

In view of the above mentioned problems, the objectives of our work are very clear: 1) simplify the traditional 16×16 Butler Matrix of Fig. 1. 2) realize the simplified 16×16 Butler Matrix with broadband operation and good transmission characteristics. The simplified topology of the 16×16 Butler Matrix will be presented in the following section. In our design, the compensated 3dB directional coupler, phase shifter

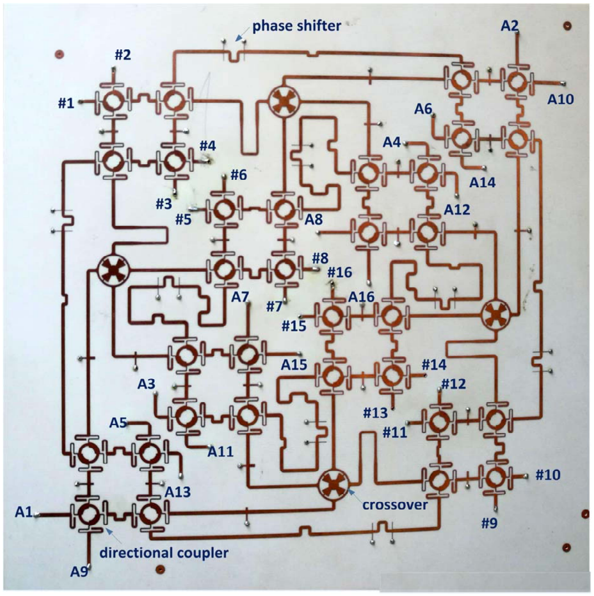


Fig. 2. The prototype of the designed 16×16 Butler Matrix.

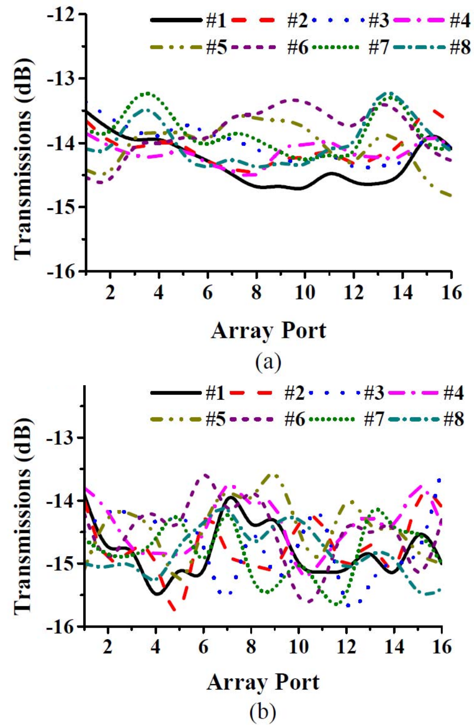


Fig. 3. Transmission coefficients at 10 GHz. (a) simulated. (b) measured.

with an open- and short-stub, crossover based on the ring-shaped structure and radial resonating patch are designed to ensure the proposed Butler Matrix operated in the broad bandwidth.

III. The Proposed 16×16 Butler Matrix

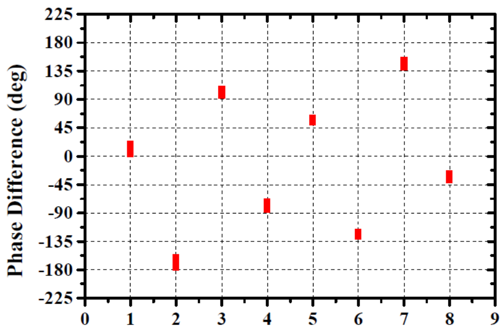
The prototype of the proposed 16×16 Butler Matrix working from 9 GHz to 11 GHz is shown in Fig. 2. It is realized with a single RO4003C laminate, which has thickness of 0.508 mm, a relative dielectric constant of 3.55, and loss tangent of 0.0027. The fabricated prototype has a compact size of 165 mm × 165 mm ($5.5\lambda_0 \times 5.5\lambda_0$). As shown in Fig. 2, at least three advantages are highlighted: 1) the crossovers needed are reduced significantly, from sixty to only four. 2) the proposed network has eight submatrices which are either duplicate or symmetrical. 3) the design can be fully realized in a single layer laminate with microstrip structures by using the standard PCB processing technology.

As to the component designs, the 3 dB directional couplers are realized by connecting a $\lambda/2$ series transmission line and a $\lambda/2$ shunt open-stub to each port of the conventional ring-shaped directional coupler. The performance of this coupler at the center frequency keeps unchanged. However, the impedance off the center frequency can be compensated. The simulated amplitude and phase variation of this designed 3 dB directional coupler is only –3.15±0.13 dB and 90.6±0.6° over the bandwidth, respectively. The fixed phase shifters are designed by taking the transmission line with an open- and short-stub as a reference, as shown in Fig. 2. The phase slope disparity between the phase shifting line and the reference path can be easily manipulated by resorting to this technique, which has already been demonstrated in [9]. The simulated phase responses for different phase shifters are 11.1±2.3°, 22.9±1.3°, 34.4±0.1°, 44.3±1.1°, 56±2.4°, 67.3°±0.9° and 78.7±1.5° over the operating bandwidth. The employed crossover combines a ring-shaped structure and a radial resonating patch providing multiple resonances. Hence, the designed crossover can be operated in broad bandwidth and have very low transmission loss. The simulated results show that the transmission loss at the center frequency 10 GHz is only 0.25 dB. The group delay introduced by the crossover are cancelled by referencing a transmission line with two shunt open- and short-stubs. Due to the page limitation, the design procedures of each components are not given.

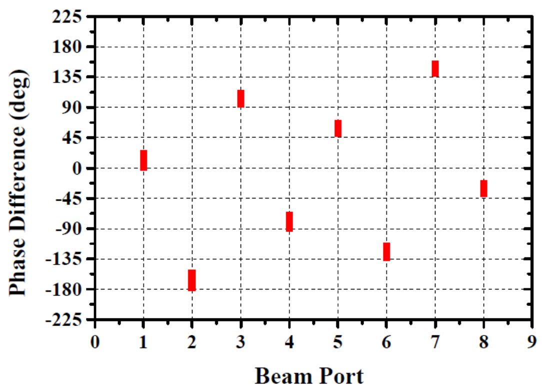
IV. Performance

One of important parameters in determining the performance of a Butler Matrix is the transmission coefficient. Excluding port mismatching, dielectric loss, parasitic loss, the ideal transmission coefficient is –12 dB. As can be seen from Fig. 3 the simulated coefficients at 10 GHz are –14 ± 0.6 dB, while the measured transmission coefficients can be, on average, 0.6 dB less than the simulated ones. Considering that each signal from a beam port to any array port must travel through seven components and dispersion is progressively accumulated, the transmission coefficient fluctuations are in a relatively low level.

As can be seen from Fig. 4, the simulated output phase differences for beam port #1 to # 8 excitation at 10 GHz are 11.5±8°, –168±8°, 101±4°, –78.5±6.5°, 57.4±3°, –123.9±3.2°, 145±4°, –32.5±4.8°, respectively. The simulated phase differences are very close to the theoretical values. Due to the existence of RF connectors, fabrication and measurement



(a)



(b)

Fig. 4. Simulated and measured phase differences between array ports at 10 GHz. (a) simulated. (b) measured.

errors, the dispersions of measured phase differences are higher than the simulated ones. For example, the measured phase differences at 10 GHz are 11.3±10.3°, –167.5±11.2°, 102.8±8.2°, –79.7±9.4°, 58.5±7.8°, –124.7±8.5°, 147.4±6.7°, –31.2±7.6°. The 2D radiation patterns of an antenna array fed by the designed Butler Matrix for different beam port excitation are calculated by using the measured *S*-parameters of the fabricated Butler Matrix. The arrangement of antenna elements follow (A1, A2, A3, A4), (A5, A6, A7, A8), (A9, A10, A11, A12), (A13, A14, A15, A16) while the antenna element spacing is 0.5 λ_0. As can be seen from Fig. 5, the titled beams of an antenna array fed by this network can occupies approximately 60% of the half space.

V. Conclusion

A simplified 16×16 Butler Matrix with super compact configuration is presented and its prototype is fabricated. In this design, the number of components of the proposed network is reduced significantly, from 116 to 60, where the

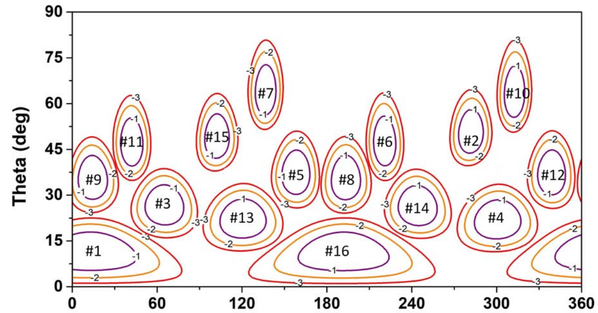


Fig. 5. 2D tilted radiation patterns of an antenna array fed by the designed Butler Matrix for different beam port excitation.

number of crossovers is only four. The proposed 16×16 Butler Matrix can be easily realized in a single layer laminate with the standard PCB processing technology. The maximum simulated output phase error is only ±0.8°, while the simulated transmission loss is only 2 dB in average over the operating bandwidth. The 16×16 Butler Matrix network can be served as the feeding network for antenna arrays to achieve beam switching in one or two dimensional space.

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