Compact Planar Design of 2-D Butler Matrix for Passive Beamforming of 2×2 Patch Array in D-Band

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***Abstract*—This paper presents a compact planar design of 2-D Butler matrix steering the beam of a 2×2 patch antenna array for D-band frequencies. The stripline Butler matrix feeding network is beneath the microstrip patch array with a similar size. The full-wave simulation results show an operating band wider than 125GHz – 150GHz for the butler matrix, and demonstrate the four beams of antenna array with 8.5dBi gain.**

Keywords—2-D antenna array; Butler matrix; passive beamforming; patch antenna

I. Introduction

The development towards next-generation (from 5G to 6G) wireless communications is expanding the new spectrum bands into sub-terahertz frequencies above 100GHz [1]. With the frequency increasing, common active beamforming of antenna arrays is facing challenges as the array size becomes smaller and active devices are less efficient. Passive beamforming can be advantageous, one option of which is the Butler matrix that provides multiple beams by selecting its input [2]. However, 2-D array beamforming requires two rows of 1-D Butler matrices perpendicularly connected, which becomes complicated and often results in a 3-D structure. With a small number of antenna elements and beams, say a 2-by-2 array, planar implementation of 2-D Butler matrices is feasible. In this paper, we present a compact planar design of 2-D Butler matrix that feeds a 2×2 patch antenna array, operating in D-band at nominal frequency of 140GHz, with a similar size to the array so that its stripline implementation fits beneath the microstrip patches. With further modification, the array can be used in a larger 2D array that provides the necessary gain and field of view [3].

II. 2-D Butler Matrix

A 1-D 2×2 Butler matrix (Fig. 1(a)) is simply a quadrature hybrid coupler that can be implemented as a planar branch-line coupler. It provides ±90° phase difference between two outputs to antenna elements, and thus forms two beams of the linear array, depending on the selection of input port. To steer the beam of a 2-D antenna array of 2×2 elements, we must create such phase differences in both directions using a 2-D Butler matrix consisting of four hybrid couplers, which gives four selectable beams. Fig. 1 (b) shows the configuration of these couplers with perpendicular connections, resulting in a 3-D structure. The two cascaded coupler arrays give phase differences between antenna rows and columns respectively. To implement this Butler matrix array on a planar structure, we modify it to an equivalent configuration shown in Fig. 1 (c) while maintaining the topology. However, as the circuitry becomes complex, the size of this implementation can be quite large. A few planar designs of 2-D Butler matrices in mm-wave have been previously reported [4][5], but these implementations of Butler matrix feeding networks have much larger physical sizes than the antenna array.

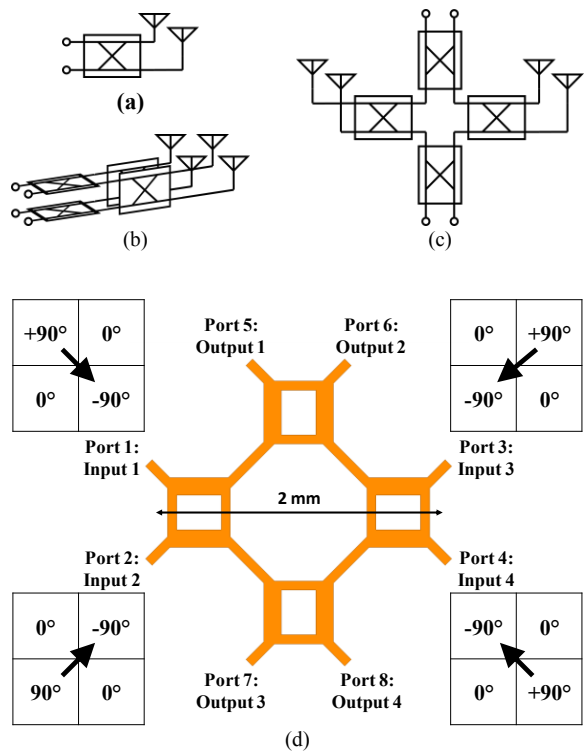

Fig. 1. (a) Schematic of a 1-D 2×2 Butler matrix. (b) Schematic of a 2-D Butler matrix and (c) its planar equivalent. (d) Lay-out of a D-band stripline 2-D Butler matrix and demonstration of its operation (arrows indicate the beam directions).

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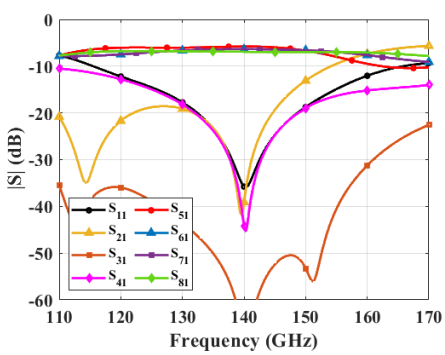
We have proposed a compact, planar design of 2-D Butler matrix that fits the array-scale area, as shown in Fig. 1(d), which is approximately 2.2mm × 2.2mm for the 2-by-2 array with a spacing of λ/2 (~1.1mm at 140GHz) between elements. This design is based on a stack-up with three 63.5-µm layers of Astra MT77 (ε_r=3.0, tanδ=0.0017) using striplines on the lower inner layer as an example. This Butler matrix structure is geometrically symmetrical, although we use four of the ports as inputs (from switch) and the other four as outputs (to antenna elements). By switching the inputs, the 2-D Butler matrix steers the array beam towards one of four diagonal directions. Fig. 1(d) also demonstrates the respective phase differences among output port and beam directions with respect to each input.

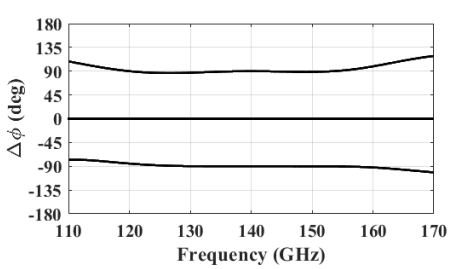
We simulate the design in ANSYS HFSS. The simulation results of the S-parameters and phase differences are shown in Fig. 2 (a) and (b), respectively. Within a bandwidth of approximately 125GHz – 150GHz, the input ports have sufficient matching/isolation, whereas the output ports deliver flat and uniform power with regular 0°, ±90° phase differences.

III. Passive Beforming of Patch Antenna Array

To use the designed 2-D Butler matrix for passive beamforming, we connect the stripline structures to a 2-by-2 array of microstrip patch antennas on the top layer, as shown in Fig. 3(a). Designed for 140GHz in D-band, the rectangular patch elements have the size of 580µm × 870µm, and are placed 1.1mm (λ/2) apart. The stripline feeding network including the Butler matrix occupies an area of approximately 2.5mm × 2.5mm, slightly larger than the array size.

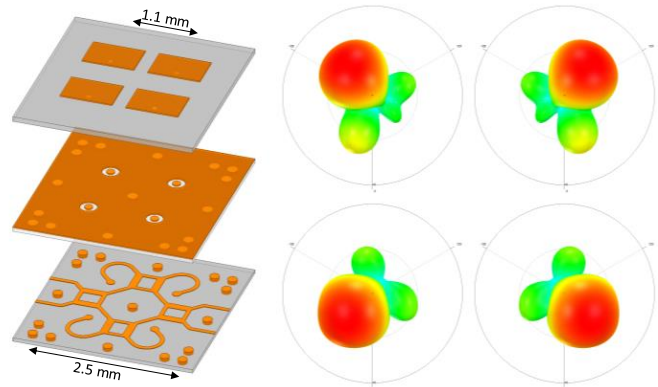


(a)



(b)

Fig. 2. Simulation results of (a) S-parameters and (b) output phase differences for the 2-D Butler matrix design.



(a) (b)

Fig. 3. (a) Structure of a 2×2 patch antenna array fed through vias using the designed 2-D Butler matrix. Note that the bottom most layer, which is a solid ground plane, is not shown. (b) Simulation results of the four radiation beams at 140GHz, switchable by selecting the input ports.

Switching among the input ports, the 2-D Butler matrix steers the radiation beam of the patch array towards one of four directions. We simulated the patch array with Butler matrix in HFSS. The simulation results of four beams at 140GHz are demonstrated in Fig. 3(b), with a peak gain of approximately 8.5dBi. The simulation also indicates the 10-dB return-loss bandwidth covering at least 125GHz – 150GHz for all ports.

IV. Conclusions

We have introduced the planar structure of a 2-D Butler matrix for beamforming of a 2-by-2 antenna array, and proposed a stripline implementation for D-band antenna array. Full-wave simulation results of S-parameters and output phase differences of the design show desired properties within 125GHz – 150GHz. We have also demonstrated the passive beamforming of a 2-by-2 patch antenna array using the designed Butler matrix. Four beams selected by the input ports are simulated, providing a gain of approximately 8.5dBi. The Butler matrix feeding network is beneath the patch array, with a compact size that is close to the array size.

References

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