Application of a two-dimensional Butler matrix antenna array for tile-based beamforming

Cheng-Hung Hsieh¹, Yi-Ting Lin¹, Hsaing-Chieh Jhan¹, and Zuo-Min Tsai²(a)

Abstract This paper proposes a new two-dimensional (2D) Butler matrix antenna array with 16 switching beams for tile-based beamforming. This study fabricated and assembled a 3.5-GHz Butler switching antenna array using multilayer Rogers printed circuit board technology. It adopted a new design concept and layer-by-layer vertical connection architecture. This 2D Butler matrix antenna array does not require long coaxial cables to connect functional circuit interfaces, which is an improvement over the traditional Butler matrix beamforming network (BFN) antenna array and may facilitate considerable reductions in circuit volume and complexity.

Key words: antenna array, antenna feeds, Butler matrices, multilayer printed circuit board technology, microwave, tile-based beamforming

1. Introduction

Because one-dimensional (1D) Butler beamforming techniques [1, 2, 3, 4, 5, 6, 7, 8, 9] have become inadequate for satisfying the requirements of modern communication systems. Research efforts have shifted to the design of two-dimensional (2D) Butler beamforming systems [10, 11, 12, 13, 14, 15, 16, 17, 18]. Studies have proposed a tile-based concept for beamforming elements to simplify the assembly of 2D beamforming systems [19, 20, 21, 22, 23, 24, 25], which is illustrated in Fig. 1(a). The beamforming elements, including the antenna array and circuits with beamforming function, are constructed in the shape of tiles. Therefore, the spatial resolution and antenna gain could be enhanced by increasing the tiles integrated on a large motherboard. This concept is efficient and convenient for a beamforming system with numerous elements.

To meet the requirement for use in a tile-based 2D Butler beamforming system, the size of circuits with beamforming function must be smaller than or similar to the size of the antenna array. For the design case in the present study, the size of the antenna array was estimated to be 2λ₀ × 2λ₀, where λ₀ is the wavelength in free space at the design frequency. Thus, the authors previously proposed a 2D Butler matrix in [26, 27], and this concept also appeared in [28, 29]. However, the integration of a 2D Butler matrix with an antenna array still must be verified.

The concept of a 2D Butler matrix entails directly extending the structural dimensions of the couplers from 2D to 3D and the connections of the components from a planer 1D Butler matrix to a traditional 2D Butler matrix BFN. The planer 1D Butler matrix can be directly extended to a 2D Butler matrix as shown in Fig. 1(b). In the different view directions, the signal paths are the same as those in a 1D Butler matrix except for the four phase shifters. However, all four paths have the same phase shifters, which would not contribute phase differences between output ports. Therefore, the function of 2D Butler matrix can be equal to that of a traditional 2D Butler matrix beamforming network (BFN).

This paper details the design and implementation of the aforementioned 2D Butler matrix. Measured normalized array factors indicated that the behaviors of beams were almost identical under all azimuth and elevation scanning conditions. To verify the functionality of the proposed 2D Butler matrix antenna array, the 2D Butler matrix was integrated into an inset feed microstrip patch...
antenna array, and the antenna radiation patterns were measured. Compared with the traditional 2D Butler matrix BFN antenna array, the proposed 2D Butler matrix antenna array possesses the advantages of a compact size and tile-based configurability.

2. Circuit design

Although the purposed configuration is 3D structural concept, it is more convenient to implement the configuration in planar structure which can be fabricated with multilayer PCB technology. The 2D Butler matrix antenna array is divided into several key components, including a 2D coupler, crossover, phase shifter, and antenna. In addition, due to multilayer structure, signals must pass vertically through various layers and from boards to connectors. Therefore, the vertical transition and connector transition must be designed.

2.1 Implementation of 2D Butler matrix antenna array using a multilayer PCB

Fig. 2 presents the assembly schematic and process information for the proposed 2D Butler matrix antenna array with multilayer PCB technology. The 2D Butler matrix antenna array is divided into several key components, including a 2D coupler, crossover, phase shifter, and antenna. In addition, due to multilayer structure, signals must pass vertically through various layers and from boards to connectors. Therefore, the vertical transition and connector transition must be designed.

Fig. 2. Implementation and assembly of the proposed 2D Butler matrix antenna array with multilayer PCB technology.

Fig. 3. Structure of (a) 2D coupler, and simulated results of (b)–(c). For (b), \( S_{11} = S_{22} = \ldots = S_{88}, S_{72} = S_{81} = \ldots = S_{54}, S_{62} = S_{51} = \ldots = S_{73}, S_{82} = S_{71} = \ldots = S_{53} \), and for (c) \( S_{12} = S_{34} = \ldots = S_{68}, S_{42} = S_{31} = \ldots = S_{87} \), and \( S_{32} = S_{41} = \ldots = S_{85} \) due to structure symmetry.
mation. The 2D Butler matrix was implemented and assembled using Board A, Board B, and commercial surface mount package (SMP) sets. Both the M1 and M4 layers contain four 2D couplers. The 2D couplers of M1 are vertically cascaded to 2D couplers of M4 by vias. In M1, connector transitions are used to connect the SMA connectors for signal input ports. In M4, connector transitions are used to connect SMP sets for connecting to Board B. Board B contains only crossovers and connection lines in M5 and M8. Subsequently, the 2D Butler matrix was integrated with the antenna array using subminiature version A (SMA) male-to-male adapters. All of the primary function circuits were located at M1, M4, M5, M8, and M10.

2.2 Key components and transitions

All simulations in this study were completed using a circuit design simulator (advanced design system [ADS]), a 2.5-D EM simulator (Sonnet), and a 3-D EM simulator (high-frequency structure simulator [HFSS]). The ADS is used to validate the performance of array factor and S-parameters. All transitions and key components can be designed as individual cells and can be simulated individually by Sonnet, and the performance of antenna array is evaluated by HFSS.

1) Key components: Fig. 3 presents implementation of a 2D coupler and simulated insertion and return losses. A traditional branch-line coupler structure was adopted. The impedance levels of wide and narrow branches were determined to be 35.4 and 50Ω, respectively, and the lengths of all wide and narrow branches were determined to be 1/4λg, where λg is the guided wavelength in substrate at a design frequency. The diameter was set to 0.2 mm for all vias used as well as for other transitions and key components. The via walls surround the structure to prevent interference from other circuits. The spacing between the walls of the vias was set to 0.1 mm. The simulated insertion and return losses are illustrated in Fig. 3(b). The return losses were greater than 20 dB at 3.5 GHz, and the insertion losses were approximately 6.5 dB. The isolations were greater than 20 dB presented as shown in Fig. 3(c). The delay lines are used to achieve a 45° phase shift at 3.5 GHz for phase shifters.

To quickly evaluate the function of the proposed 2D Butler matrix antenna array, a simple inset feed microstrip patch antenna structure was adopted [30].

2) Transitions in the PCB: Fig. 4(a) illustrates the structure for connecting the top and bottom circuits (M1 to M4 and M5 to M8) and the simulated performance. This transition structure involves all crossovers (azimuth, elevation, and hybrid). Primary design parameters were the number and position of signal vias, spacing (SLT) between the circuit metal and GND metal, and size of the signal sheet. Favorable return and insertion losses can be obtained when the two signal vias are positioned at the center with a spacing of 0.1 mm. Simulation shows the return loss was greater than 60 dB at 3.5 GHz and the insertion loss was about 0.025 dB. Fig. 4(b) illustrates the connector-to-circuit transition. This transition connects SMA connectors or SMP sets. The interface between the connector and circuit is similar to a coplanar waveguide with a ground structure, and the inside circuits have a microstrip line formation. The return loss was determined to be greater than 40 dB at 3.5 GHz.

3) Layouts of separate circuit sheets: Figs. 5(a)–5(c) show detailed layout allocations for the three functional circuit sheets. The inner ground layers are not shown in these figures for the sake of simplification. For layout allocations, the first task is to determine the position of the antenna array, and the second task is to determine the
position of the 2D couplers according to the position of the antenna array, then the phase shifters, crossovers, and connection lines can be allocated to the corresponding positions. P1 to P16 are the signal input ports of Board A (on M1), and P17 to P32 are the signal output ports of Board B (on M8). The output ports were designed to have a distance of \( \frac{1}{2} \lambda_0 \) to ensure that the size of the BFN was similar to that of the antenna array. All sheets were determined to measure 200 mm x 200 mm.

Finally, according to the simulated results of the 2D Butler matrix, the average insertion losses are 13.5 dB, and return losses are better than 20 dB.

3. Measurement

Figs. 6–7 display the measurement setup for the 32-port S-parameter and radiation pattern, and the measurement results. The return loss was greater than 20 dB for both input ports. The average insertion loss was 14.5 dB. The normalized array factors of beams were almost identical. The strongest beams were determined to be located in the middle, and the peak gain was 11.1 dBi.

The compared results are presented in Table I. An index, namely the percentage of the extension area, was also proposed to help evaluate the degree of compactness of works. Only the purposed work is suitable for tile-based systems, and has lowest extension area (2.7%).
Table I. State-of-the-art PCB 2D 16-beam switching antenna array

|                | [16] EuRaC 2012 | [17] TMIT2017 | [18] TAP 2018 | This work |
|----------------|-----------------|---------------|---------------|-----------|
| Operation Frequency $f_0$ (GHz) | 2.45            | 60            | 30            | 3.5       |
| Peak Gain (dBi)              | 13.7            | 14.7          | 15.9          | 11.1      |
| Tile-based configurability   | NO              | NO            | NO            | YES       |
| Electrical Size $L \times W \times H$ (λ0) | $2.2 \times 2.2 \times 4.1 \lambda_0$ | $3.0 \times 3.0 \times \text{n.a.}$ | $4.5 \times 16.5 \times \text{n.a.}$ | $2.33 \times 2.33 \times 0.62\lambda_0$ |
| Percentage of extension area ($A_\text{ext}/A_\text{norm}$) | $2.2 \times 4.14 \times 100\%$ | $28 \times 28 \times 100\%$ | $4.5 \times 24 \times 100\%$ | $0.33 \times 0.33 \times 4 \times 100\%$ |

† Estimated by paper info.
‡ Include all integration loss.
§ Only simulation result is available.
¶ n.a.: not available.
*Extra extension area must be occupied due to circuit design or integration issue, lower % is better.

Fig. 7. Measurement results of S-parameters and gain patterns in dBi.
4. Conclusion

This 2D Butler matrix antenna array has the advantage of compact volume and can compete with previous designs. The measured radiation patterns were provided to validate the beamforming functions of the proposed antenna array. Two key features necessary for this compact and tile-based 2D Butler matrix antenna array were the 2D coupler concept and layout allocation. With these, all of the functional circuits of traditional 2D Butler matrix BFN antenna array could be distributed to the multilayer PCB structure. The distributed circuits could be connected by transmission lines and layer transition structures of PCBs and assembled using compact connectors and adapters.

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