High-Efficiency All-Metal E-Plane Butler Matrix and Its Application to Millimeter-Wave Wide-Angle Multibeam Antenna

Chun Geng, *Student Member, IEEE*, Ji-Wei Lian, *Member, IEEE*

***Abstract*—In this report, a novel millimeter-wave highly-efficient E-plane Butler matrix (BM) utilizing the ridge gap waveguide (RGW) technology is proposed for the first time, which can promote the 3D integration of RGW beamforming network (BFN). To construct such an E-plane RGW BM, a new E-plane coupler structure which can achieve arbitrary coupling from 0 to 20 dB, an E-plane crossover and two types of ridge transitions are developed, respectively. A folded configuration is introduced to further improve the compactness. To realize wide-angle coverage utilizing the proposed BFN, a new end-fire antenna is derived from the traditional horn antenna, which features gain enhancement and wide half-power beamwidth (HPBW). By integrating the E-plane RGW 4 × 4 BM with the designed antenna array, a millimeter-wave highly-efficient wide-angle multibeam antenna is obtained, which achieves a wide HPBW coverage of ± 86°, a maximum efficiency of 84.1%, and a maximum gain of 14.3 dBi.**

***Index Terms*—E-plane Butler matrix (BM), ridge gap waveguide (RGW), wide-angle coverage, high-efficiency, multibeam antenna, millimeter-wave.**

I. Introduction

Millimeter-wave multibeam array antenna technology has undergone extensive research for its high gain and beam switching property [1]. Meanwhile, with communication systems advancing towards high integration, there is a growing demand for the three-dimensional (3D) integration of beam-forming networks (BFNs). Compared with other BFNs, Butler matrices (BMs) are preferable for its virtues of consistent amplitude and phase stability, inherent theoretical lossless [2]. A typical solution to constructing a 3D integrated BFN is resort to interconnecting H-plane and E-plane sub-BFNs. In the open literatures, the H-plane sub-BFNs have been extensively researched, including microstrip, hollow waveguide, substrate integrated waveguide and gap waveguide [3]-[4]. But the E-plane counterparts are rarely reported and investigated due to the constraint of the planar structure.

In this paper, a novel millimeter-wave highly-efficient E-plane 4 × 4 BM based on RGW technology is proposed for the first time. A novel E-plane 3-dB coupler, an E-plane crossover and two types of ridge transitions are developed to construct such an E-plane BM. A gain-enhanced antenna with wide beamwidth is designed for wide-angle coverage. By integrating the proposed E-plane BM with the antenna array, a wide-angle highly-efficient multibeam antenna is implemented.

II. E-Plane RGW Butler Matrix

Configuration of the proposed E-plane RGW 3-dB coupler based on coupling slots and parallel line technology is displayed

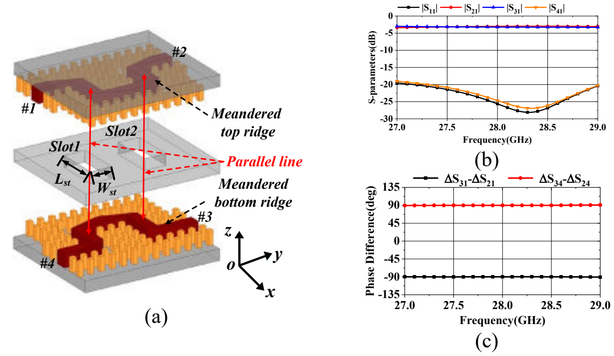

Fig. 1. Geometry of the proposed E-plane RGW 3-dB coupler. (a) Explosion view. (b) Simulated *S*-parameters. (c) Simulated phase differences.

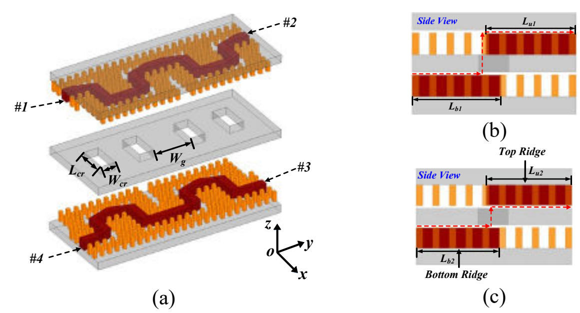

Fig. 2. Geometry of the proposed (a) E-plane RGW crossover, (b) E-plane ridge transition Type I and (c) Type II.

in Fig. 1(a). The employment of coupling slots and parallel line allows for the overlap of top ridge and bottom ridge. The size and location of the rectangular slots, size of the corners will mainly affect the coupling coefficient of the designed E-plane coupler. By adjusting the aforementioned parameters, arbitrary coupling coefficients from 0 dB to 20 dB can be achieved. By cascading two E-plane RGW 3-dB couplers together, an E-plane RGW crossover can be realized, as shown in Fig. 2(a). To solve the mismatch of RGW type between components, two types of E-plane ridge transitions are designed for integration, which are displayed in Fig. 3. The required −45° and 0° phase shifters can be realized through RGW delay line. To further increase the compactness and tackle hurdles in practical employment, a triple-folded topology is adopted in this design. The total configuration and simulated results of the triple-folded E-plane 4 × 4 BM is exhibited in Fig. 4.

III. RGW End-Fire Antenna

The development of the proposed RGW end-fire antenna is decomposed into stages 1−3, as displayed in Fig. 5(a). At stage

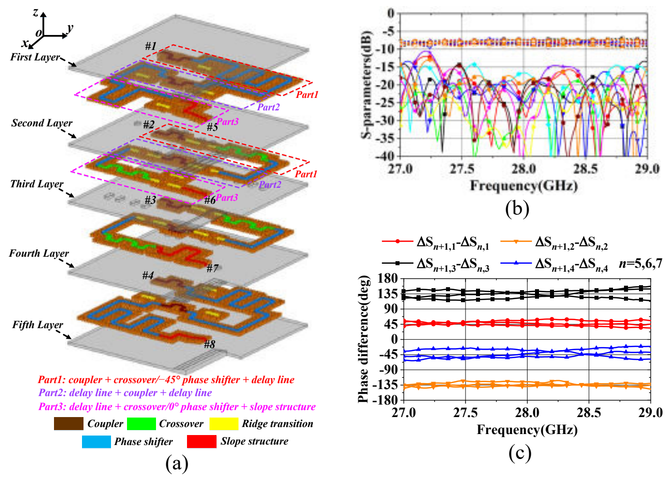

Fig. 4. (a) Structure of the triple-folded E-plane RGW 4 × 4 BM. (b) Simulated reflection, isolation, transmission coefficients and (c) simulated phase differences of the folded E-plane BM.

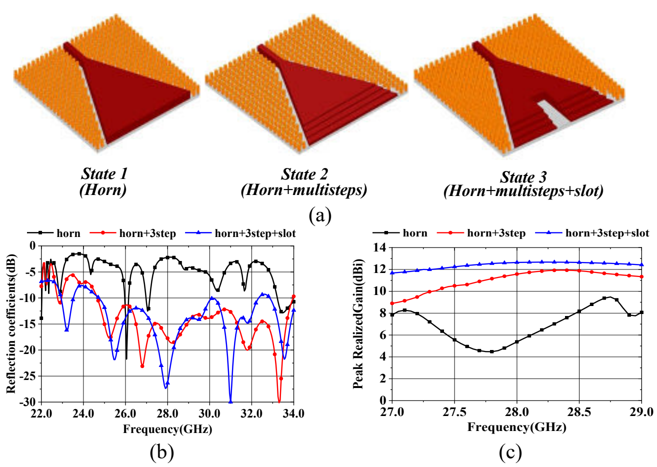

Fig. 5. (a) Structure development, (b) simulated S_{11} and (c) gain of the proposed end-fire antenna from stage 1 to stage 3.

2, multistep structure is added to improve the impedance matching with the air. Finally, an etched slot, which can adjust the wavefront and thereby enhancing the radiation gain, is further added. Comparisons among various stages are presented in Figs. 5(b) and (c). By vertically stacking the designed antenna elements, a 1×4 antenna array can be constructed. The rectangular slot structure is further optimized into a tapered slot structure to improve the impedance matching.

IV. RGW Wide-Angle Multibeam Antenna

By integrating the E-plane BFN and the antenna array, a multibeam antenna can be realized. The whole configuration of the RGW end-fire multibeam antenna is exhibited in Fig. 6(a). the simulated and measured reflection and isolation coefficients are less than −10 dB from 27 GHz to 29 GHz. Simulated and measured radiation patterns at 28 GHz are plotted in Fig. 6(b). A wide HPBW of ± 86° and peak pointing angle of ± 60° is achieved. Fig.6 (c) plots the simulated and measured radiation gains for comparison. The radiation efficiencies of the proposed multibeam antenna vary from 60.3% to 84.1% for port #1−#4. Fig 15(a) displays the perspective view, top view and side view of the assembled prototype. Each plate is separately fabricated by CNC technology.

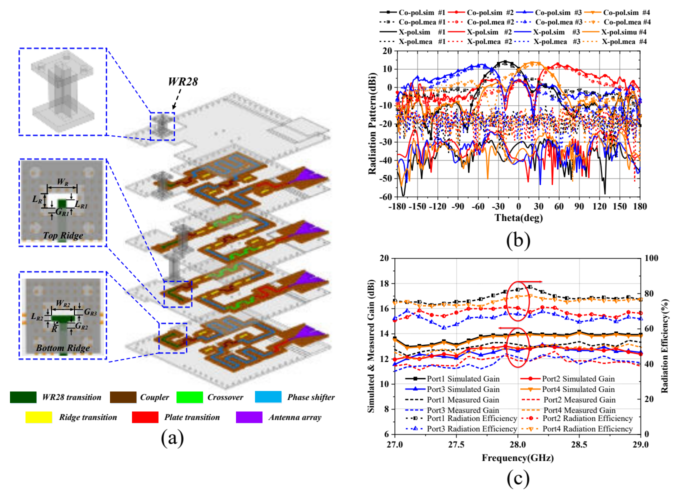

Fig. 6. (a) Perspective view, (b) measured and simulated radiation patterns at 28GHz, (c) radiation efficiency, simulated and measured gain of the designed multibeam antenna.

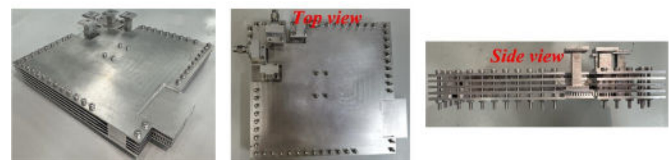

Fig. 7. Perspective view, top view, side view of assembled prototype.

V. Conclusion

An E-plane RGW 4 × 4 BM is firstly proposed and analyzed in details in this report. To construct such an E-plane BFN, an E-plane coupler, an E-plane crossover and two types of E-plane transitions employing RGW technology are designed. A triple-folded topology is adopted to further improve the compactness. A new gain-enhanced end-fire horn antenna is proposed to meet the wide-angle coverage requirement. Finally, a wide-angle highly-efficient end-fire multibeam antenna is realized. The experimental results agree well with the simulated counterparts.

VI. Future Plan and Impact Statement

I am now pursuing the M.S degree at Nanjing University of Science and Technology, majoring in Electromagnetic Field and Microwave Technology. The recognition from MTT-S Scholarship has inspired me to conduct further studies in the field of multibeam antenna under the guidance of Prof. Ji-Wei Lian. In the future, I plan to pursue a doctoral degree and delve deeper into this field that interests me.

References

[1] Y. J. Guo, M. Ansari and N. J. G. Fonseca, "Circuit type multiple beamforming networks for antenna arrays in 5G and 6G terrestrial and non-terrestrial networks," *IEEE J. Microw.*, vol. 1, no. 3, pp. 704-722, July 2021.

[2] C. Geng, J.-W. Lian and D. Ding, "Millimeter-wave highly efficient E-plane ridge gap waveguide Butler matrix for wide-angle endfire multibeam antenna applications," *IEEE Trans. Microw. Theory Techn.*, 2025, early access.

[3] K. Ding and A. A. Kishk, "2-D Butler matrix and phase-shifter group," *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 12, pp. 5554-5562, Dec. 2018.

[4] Y. Li and K.-M. Luk, "A multibeam end-fire magnetoelectric dipole antenna array for millimeter-wave applications," *IEEE Trans. Antennas Propag.*, vol. 64, no. 7, pp. 2894-2904, July 2016.