2025 Asia-Pacific Microwave Conference (APMC) | 979-8-3315-3455-4/25/$31.00 ©2025 IEEE | DOI: 10.1109/APMC65046.2025.11378003

Design Guidelines Using Groove Gap-Waveguide Technology for Realizing a Millimeter-Wave 4×4 Butler Beamforming Matrix for Space Multiplexing

Mohammad Alibakhshikenari[1,2]*, Bal Virdee[3], Hassan Zakeri[4], Ernesto Limiti[5], and Takfarinas Saber[1]

[1]LERO, the Research Ireland Centre for Software, College of Science and Engineering, School of Computer Science, University of Galway, H91 TK33 Galway, Ireland
[2]Department of Electrical and Electronics Engineering, Dogus University, 34775 Umraniye, Istanbul, Türkiye
[3]Center for Communications Technology, London Metropolitan University, London N7 8DB, United Kingdom
[4]Department of Electrical Engineering, Amirkabir University of Technology, 15875-4413 Tehran, Iran
[5]Electronics Engineering Department, University of Rome "Tor Vergata", 00133 Rome, Italy
*Corresponding Author: mohammad.alibakhshikenari@universityofgalway.ie

***Abstract*: This paper presents a practical design guideline for implementing a 4×4 Butler Beamforming Matrix (BBM) using Groove Gap-Waveguide (GGW) technology to enable multi-beam functionality. The proposed BBM consists of 3-dB hybrid directional couplers, crossovers, phase shifters, and phase compensators. A GGW-inspired unit-cell is optimized to provide a wide stopband spanning 22–40GHz. This unit-cell is employed to realize the BBM's structural components, ensuring broadband operation across 30–40GHz and achieving the required phase shifts for multi-beam capability. By integrating these components according to the proposed architecture, a compact and efficient 4×4 BBM suitable for antenna arrays in space multiplexing systems is realized. This design approach can be extended to other beamforming networks such as Nolen and larger-scale Butler matrices. Key advantages include a straightforward design process, wideband operation, low-loss, low-profile, ease of fabrication, and cost-effectiveness, making it well-suited for applications in satellite communications, space multiplexing, and radar tracking systems at millimeter-wave frequencies.**

***Keywords*: 4×4 Butler Beamforming Matrix (BBM), space multiplexing, groove gap-waveguide (GGW) technology, millimeter-wave (mm-wave), Ka-band.**

I. INTRODUCTION

Emerging applications in communications and radar systems at millimetre-wave (mm-wave) frequencies are driving demand for innovative beamforming solutions that combine low loss, reduced cost, ease of assembly, and lightweight design [1,2]. Conventional technologies such as microstrip [3] and substrate integrated waveguide (SIW) [4] offer simplicity and low cost but suffer from high dielectric losses, which severely impact overall antenna efficiency. Microstrip lines, while easy to fabricate, exhibit significant signal degradation due to the lossy nature of dielectric substrates. SIW technology mitigates some issues by using metallic vias as sidewalls to form waveguides in planar substrates. However, these implementations are often long, multilayered, and exhibit increased dielectric losses, further compromising performance.

Traditional all-metal waveguide structures can provide very low losses and high efficiency, but they are challenging and costly to manufacture, especially at higher frequencies due to tight fabrication tolerances and the need for perfect electrical contact between components.

To address these limitations, Gap-Waveguide (GW) technology has emerged as a viable alternative [5], offering a contactless, low-loss waveguiding mechanism. GW structures use periodic metallic pins to generate a high-impedance surface. When a metallic plate is positioned above the pins at a gap of less than a quarter wavelength, a stopband is formed that confines the electromagnetic field within a designated waveguide path, without requiring electrical contact between components [6].

There are three main variants of GW structures reported in the literature: Ridge Gap Waveguide (RGW), Groove Gap Waveguide (GGW), and Microstrip Ridge Gap Waveguide (MRGW) [5]. Among these, the GGW configuration has been shown to offer the lowest loss [6]. Structurally, GGW resembles a conventional rectangular waveguide but with metal pins in place of solid sidewalls. It supports a quasi-TE_{10} mode and is particularly suitable for high-frequency applications.

This work focuses on the design of a 4×4 Butler Beamforming Matrix (BBM) based on GGW technology for Ka-band operation, targeting satellite communication systems and space multiplexing applications. The proposed design offers multi-beam capability and is optimized for ease of fabrication, compact size, and broadband performance.

II. BUTLER BEAMFORMING MATRIX (BBM) DESIGN

The schematic diagram of the proposed 4×4 BBM is illustrated in Fig. 1. The BBM consists of 3-dB hybrid directional couplers, crossovers, phase shifters, and phase compensators. Its operation is such that, when a signal is applied to any of the input ports, it produces four output signals with equal amplitudes and specific progressive phase shifts that steer the beam in distinct directions resulting in multiple radiation beams, which makes the BBM suitable for space multiplexing and radar tracking in satellite networks.

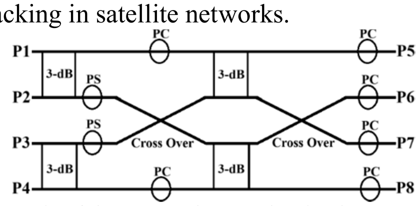


Fig.1. Schematic of the proposed BBM showing key components. PS and PC represent the phase shifter and phase compensator.

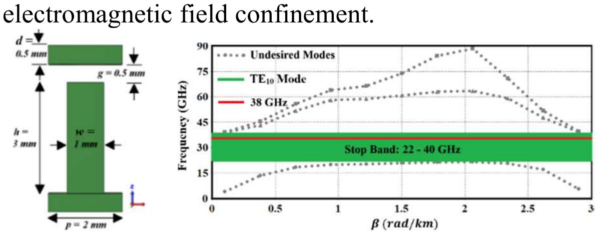
When each input port (P1–P4) is excited individually, the output ports (P5–P8) produce signals with the following relative phase distributions:

- P1 excitation → Ang. S_{61} – Ang. S_{51} = Ang. S_{71} – Ang. S_{61} = Ang. S_{81} – Ang. S_{71} = +45°
- P2 excitation → Ang. S_{61} – Ang. S_{51} = Ang. S_{71} – Ang. S_{61} = Ang. S_{81} – Ang. S_{71} = −135°
- P3 excitation → Ang. S_{61} – Ang. S_{51} = Ang. S_{71} – Ang. S_{61} = Ang. S_{81} – Ang. S_{71} = −45°
- P4 excitation → Ang. S_{61} – Ang. S_{51} = Ang. S_{71} – Ang. S_{61} = Ang. S_{81} – Ang. S_{71} = +135°

These phase distributions span the full angular space of ±360°, enabling four distinct beam directions, which are essential for space multiplexing and beam switching applications.

A) Unit-Cell Design

The foundation of the BBM lies in the GGW unit-cell, which must be carefully designed and optimized. Fig. 2(a) shows the physical layout of the unit-cell, while Fig. 2(b) presents its dispersion characteristics. To ensure operation across the 22–40 GHz band, the following parameters are set: periodicity p = 2 mm, height h = 3 mm, gap g = 0.5 mm (less than a quarter-wavelength), width w = 1 mm, and thickness d = 0.5 mm. The dispersion diagram confirms that the structure supports a single-mode propagation of the quasi-TE_{10} mode within this range, establishing a wideband stopband essential for electromagnetic field confinement.



(a) (b)

Fig.2. (a) Configuration of the GGW unit-cell, (b) dispersion diagram showing single-mode operation from 22 to 40 GHz.

B) 3-dB Hybrid Directional Coupler and Crossover Design

The 3-dB hybrid directional coupler, built from a periodic arrangement of GGW unit-cells, is depicted in Fig. 3(a). Ports P1, P2, P3, and P4 denote the input, direct output, coupled output, and isolated ports, respectively. The key geometrical parameters are: a_1 = 8.0 mm, a_2 = 4.512 mm, a_3 = 5.612 mm, a_4 = 7.112 mm, L = 15 mm, and w = 23.224 mm.

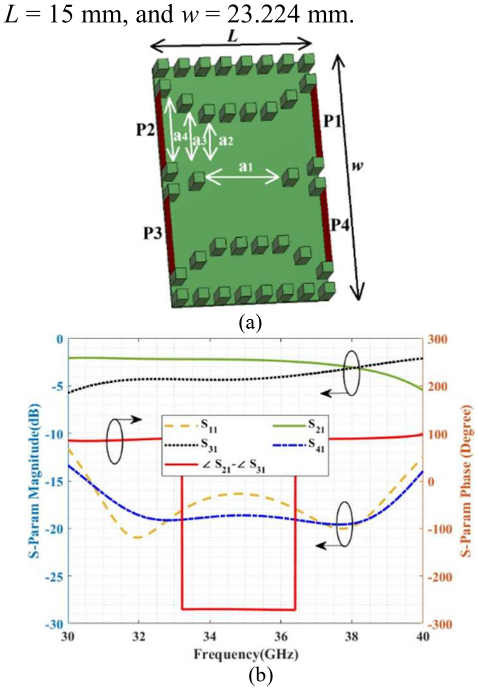


Fig.3. (a) Layout of the proposed 3-dB GGW directional coupler. (b) S-parameter results: reflection, transmission, isolation, and phase difference between direct and coupled ports.

Fig. 3(b) displays the S-parameters, demonstrating excellent reflection, transmission and isolation performance from 30–40 GHz, with optimal behaviour at 38 GHz. The required 90° phase difference between the direct and coupled outputs is confirmed as well.

Crossover structures in the BBM are realized by cascading two of these 3-dB couplers, maintaining compactness and low insertion-loss [7].

C) Phase Shifter and Phase Compensator Design

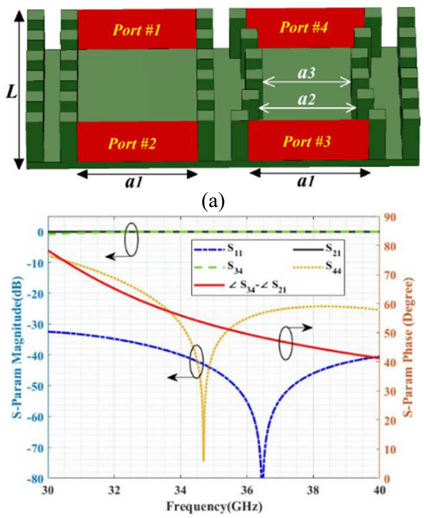
To achieve the necessary phase shifts, four implementation techniques were considered:

(i) unequal length & unequal width,
(ii) equal length & equal width,
(iii) unequal length & equal width, and
(iv) equal length & unequal width.

This work adopts the fourth approach, equal length with unequal width, for both the phase shifter and the phase compensators. Fig. 4(a) illustrates the design of the 45° phase shifter, with dimensions: a_1 = 7.122 mm, a_2 = 5.792 mm, a_3 = 5.312 mm, and L = 11 mm.

The reflection and transmission performance are shown in Fig. 4(b), indicating a return loss better than 20 dB and near-zero transmission loss at 38 GHz. This figure also confirms that the desired 90° phase shift is achieved with high precision at 38 GHz.

The same technique is applied to design the insertion phase compensators required by the couplers, as depicted in the schematic in Fig. 1.



(b)

Fig.4. (a) Configuration of the 45° phase shifter. (b) Reflection-, transmission- coefficients, and phase shift vs. frequency, centered at 38 GHz.

By integrating the optimized directional couplers, phase shifters, cross overs, and phase compensators, the proposed 4×4 BBM achieves broadband operation from 30–40 GHz along with relative phase distributions centered at 38 GHz, ideal for advanced beamforming applications in space multiplexing, satellite communication, and radar tracking systems over mm-wave spectrum as exhibited in Fig.5.

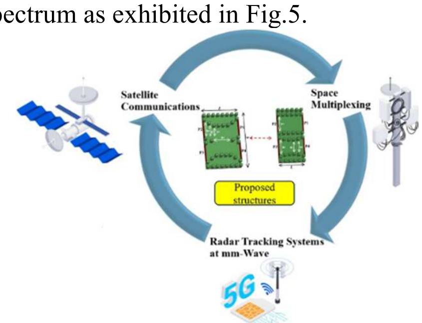


Fig.5. Advanced beamforming applications of the proposed 4×4 BBM using the realized 3-dB coupler and 45° phase shifter.

III. Conclusion

This paper presents a robust and practical design methodology for realizing a high-performance 4×4 Butler Beamforming Matrix (BBM) based on Groove Gap-Waveguide (GGW) technology. A detailed schematic of the BBM architecture is introduced, highlighting its key components: 3-dB hybrid couplers, phase shifters, crossovers, and phase compensators.

The design begins with the modelling and optimization of a GGW unit-cell, tuned for wideband performance across the Ka-band (30–40 GHz) by adjusting the periodicity, pin height, width, and gap spacing. This unit-cell is then used as the foundational element to construct all functional components of the BBM.

The integration of these components yields a BBM capable of producing equal-magnitude and phase-shifted output signals for multiple beams, making it suitable for space multiplexing and radar tracking systems. The approach offers notable advantages including wideband operation, low loss, low profile, ease of fabrication, and scalability to other matrix configurations beyond the 4×4 Butler structure.

Importantly, the proposed design guideline is not limited to the 4×4 BBM; it can be extended to the design of other beamforming networks such as Nolen matrices or Butler matrices of arbitrary sizes. This makes the methodology a strong candidate for next-generation mm-wave systems in satellite communications and beyond.

Acknowledgment

Co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency. Neither the European Union nor the granting authority can be held responsible for them. Besides that, this publication has emanated from research jointly funded by Taighde Éireann – Research Ireland under Grant number 13/RC/2094_2, the European Union's Marie Sklodowska-Curie Actions under grant number 101126578 and was supported in part by University of Galway.

References

[1] A. Tamayo-Domínguez et al., *"3-D-Printed Modified Butler Matrix Based on Gap Waveguide at W-Band for Monopulse Radar,"* IEEE Transactions on Microwave Theory and Techniques, vol. 68, no. 3, pp. 926–938, Mar. 2020.

[2] A. K. Vallappil et al., "Butler Matrix Based Beamforming Networks for Phased Array Antenna Systems: A Comprehensive Review and Future Directions for 5G Applications," IEEE Access, vol. 9, pp. 3970-3987, 2021.

[3] S. Tang et al.,*"Beamforming Network Design Utilizing Node Microstrip Architectures for Dual-Polarized Endfire Millimeter-Wave Antenna Arrays,"* IEEE Transactions on Antennas and Propagation, vol. 71, no. 6, pp. 4862–4873, Jun. 2023.

[4] M. M. Pezhman, A.-A. Heidari, and A. Ghafoorzadeh-Yazdi, *"A Novel Single-Layer SIW 6×6 Beamforming Network for 5G Applications,"* AEU - International Journal of Electronics and Communications, vol. 155, p. 154380, 2022.

[5] W. Y. Yong et al., *"An Overview of Recent Development of the Gap-Waveguide Technology for mmWave and Sub-THz Applications,"* IEEE Access, vol. 11, pp. 69378–69400, 2023.

[6] Y. Shi et al., *"Gap Waveguide Technology: An Overview of Millimeter-Wave Circuits Based on Gap Waveguide Technology Using Different Fabrication Technologies,"* IEEE Microwave Magazine, vol. 24, no. 1, pp. 62–73, Jan. 2023.

[7] Mohammad Alibakhshikenari et al., "Groove Gap Waveguide Crossover for Butler Matrices and Beamforming in Millimeter-Wave Satellite Antenna Systems", 35th International Conference Radioelektronika, pp. 1-4, Czech Republic, 12 - 14 May 2025.

[8] Mohammad Alibakhshikenari et al., "Innovative UWB Phase Shifters Using Groove Gap-Waveguide Technology Inspired by Metasurfaces for Beamforming Networks Operating at 100 GHz", 36th IEEE Asia-Pacific Microwave Conference (APMC), pp. 740 – 742, Bali, Indonesia, 17 – 20 November 2024.