

Groove Gap Waveguide Crossover for Butler Matrices and Beamforming in Millimeter-Wave Satellite Antenna Systems

Mohammad Alibakhshikenari ^{*⁽¹⁾}, Peiman Parand ⁽¹⁾, Ali Zidour ⁽²⁾, Bal S. Virdee ⁽³⁾, Patrick Longhi ⁽¹⁾, Patrizia Livreri ⁽⁴⁾, Takfarinas Saber ⁽⁵⁾, and Ernesto Limiti ⁽¹⁾

⁽¹⁾ Electronics Engineering Department, University of Rome “Tor Vergata”, 00133 Rome, Italy; (alibakhshikenari@ing.uniroma2.it, peiman.parand@students.uniroma2.eu, longhi@ing.uniroma2.it, limiti@ing.uniroma2.it)

⁽²⁾ Departemnt of Electrical Systems Engineering, Faculty of Technology, University of M'hamed Bougara, Boumerdes, Algeria; (a.zidour@univ-boumerdes.dz)

⁽³⁾ Center for Communications Technology, London Metropolitan University, London N7 8DB, UK; (b.virdee@londonmet.ac.uk)

⁽⁴⁾ Department of Engineering, University of Palermo, 90128 Palermo, Sicily, Italy; (patrizia.livreri@unipa.it)

⁽⁵⁾ Lero, Science Foundation Ireland Centre for Software, School of Computer Science, University of Galway, H91 TK33 Galway, Ireland; (takfarinas.saber@universityofgalway.ie)

Abstract

This paper presents an innovative H-plane crossover based on groove gap-waveguide (GGW) technology for high-performance millimeter-wave (mm-wave) circuits. The design facilitates the development of key transmission components, such as Butler matrices (BMs) and beamforming feeding networks (BFNs), for multi-beam antenna systems operating in the V-band spectrum (40–50 GHz). The proposed crossover is built by cascading two identical 3-dB/90° hybrid couplers. Each coupler is designed with GGW unit-cells constructed from metallic pins spaced less than a quarter-wavelength apart. This configuration creates a wide stopband of 20–57 GHz, ensuring minimal signal interference and strong impedance matching. The coupler achieves 90° phase shift, 50 dB isolation, and low insertion loss of 0.02 dB at 45 GHz, with a fractional bandwidth of 22.22%. The crossover demonstrates excellent performance over the entire V-band, making it suitable for advanced antenna systems in satellite communications and space applications. The design reduces complexity, cost, and losses typically associated with 3D and multilayer crossover technologies, providing a compact and efficient solution for mm-wave networks.

1. Introduction

A crossover is a crucial four-port microwave component that enables two distinct signals to cross without interference, while isolating the other ports. It plays an essential role in designing orthogonal transmission networks such as Butler matrices (BMs) and beamforming feeding networks (BFNs) for multi-beam antenna systems [1]. Given that multiple crossovers are often integrated within these networks, achieving low-loss and compact designs is critical [2].

Traditionally, crossovers were implemented using three-dimensional (3D) technologies and multi-layer structures, incorporating bond wires, underpasses, via-holes, and air bridges. However, these approaches increased fabrication complexity, overall cost, and often resulted in non-negligible return losses in the passband [3]. To address these issues, planar crossovers were developed, primarily utilizing

microstrip technology. Although planar designs simplified fabrication, they suffered from high signal loss, particularly in the mm-wave frequency range [4].

Recently, substrate integrated waveguides (SIWs) have emerged as a promising solution due to their low cost, high-quality factor, and superior power handling capability [5][6]. Despite these advantages, SIWs introduce design challenges and performance limitations above 30 GHz due to increased losses and design complexity [7][8].

To overcome these challenges, this paper adopts groove gap waveguide (GGW) technology [9][10], a low-loss, cost-effective approach ideal for frequencies above 30 GHz. We propose a high-performance H-plane crossover using GGW, which operates in the V-band (40–50 GHz). This design can be applied to develop BFNs and BMs with multiple beam functionalities for satellite communications and space applications.

The rest of the paper is organized as follows: Section 2 presents the GGW-based unit-cell design. Section 3 details the implementation of a 3-dB/90° hybrid coupler. Section 4 focuses on the crossover design by stacking two couplers. A performance comparison with state-of-the-art designs is provided in Section 5, and the paper concludes with a summary in Section 6. All design processes were conducted using full-wave 3D electromagnetic simulations in CST Microwave Studio.

2. GGW-Based Unit-Cell Design

To realize a wide stopband across the millimeter-wave frequency range, this research adopts the groove gap waveguide (GGW) technology for the unit-cell design. The GGW concept leverages periodic metallic pins to form waveguides without the need for electrical contact between layers, which minimizes losses and enhances performance. Each unit-cell is structured with a metallic pin connected to a bottom layer and separated from a top layer by a small gap of less than one-quarter wavelength ($\lambda/4$). The key geometric parameters influencing the unit-cell's performance include the pin height (h), pin width (W), pin period (p), and the gap distance (g) between the pin and the top layer.

The configuration of the proposed unit-cell is shown in Fig. 1(a). The dispersion diagram in Fig. 1(b) reveals that this design provides a wide stopband ranging from 20 GHz to 57 GHz, covering multiple frequency bands, including the K-band (18–27 GHz), Ka-band (27–40 GHz), and V-band (40–75 GHz). This broad stopband makes the unit-cell highly suitable for mm-wave communication applications, particularly for operating in the 40–50 GHz V-band range.

The primary goal of this research is to develop a high-performance 3-dB/90° hybrid coupler and a crossover focused at 45 GHz. These components are intended for use in advanced antenna systems, including beamforming feeding networks and Butler matrices, within satellite communications and space applications. The proposed GGW-based unit-cell is an ideal candidate due to its wide stopband and ability to support low-loss, high-performance transmission.

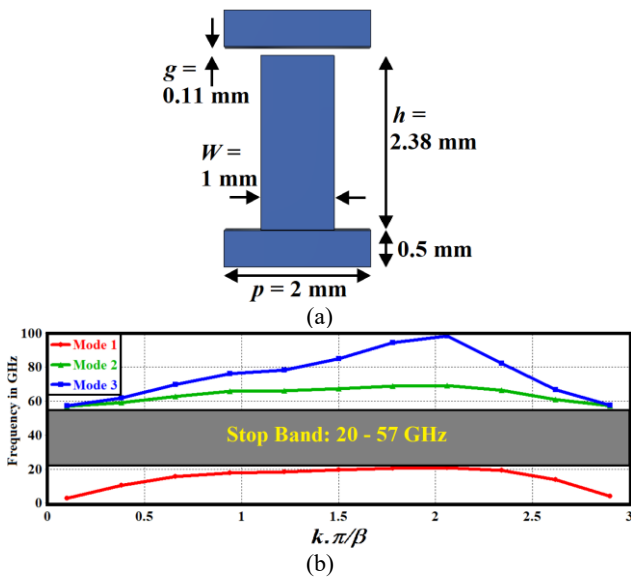


Figure 1. (a) Proposed unit-cell based on the GGW technology; and (b) its dispersion diagram.

3. 3-dB/90° Hybrid Coupler Assisted by GGW

This section applies the GGW-based unit-cell, designed in the previous section, to develop a 3-dB/90° hybrid coupler. This coupler is essential for creating a high-performance crossover that operates within the 40–50 GHz V-band millimeter-wave spectrum. To function effectively in this frequency range, the coupler's waveguide dimensions must match those of a standard WR-19 waveguide, specified as " $A \times B = 4.77 \times 2.38$ mm²" [12]. Therefore, during the unit-cell design, the height of the pin (h) and the gap (g) between the pin and the top layer should satisfy the condition $B \approx h + g = 2.38$ mm. Similarly, the waveguide width must align with $A = 4.77$ mm.

The configuration of the proposed 3-dB/90° hybrid coupler is shown in Fig. 2(a). To achieve low-loss performance over the mm-wave spectrum, a periodic arrangement of metallic pins is employed. This arrangement produces a 90° phase shift between the direct output and coupled ports, which is critical for Butler matrices and beamforming feeding networks. Key design parameters for the coupler are also illustrated in Fig. 2(a).

To further optimize performance, two single pins are positioned between the waveguides at 6.8 mm from each other. These pins, spaced at twice the period of other pins, enhance impedance matching, isolation, and coupling. The overall length and width of the coupler are 15 mm and 18.5 mm, respectively.

The S-parameter results, including the reflection coefficient ($S_{11} < -10$ dB), transmission coefficients (S_{21} and S_{31}), isolation (S_{41}), and phase shift (Phase $S_{21} - \text{Phase } S_{31}$), are plotted in Figs. 2(b) and 2(c). These results indicate that the coupler operates efficiently across a wide frequency range of 40–50 GHz, with optimal performance at 45 GHz. The coupler achieves a bandwidth of 22.22% and delivers excellent values at 45 GHz: 50 dB impedance matching, 2.8 dB insertion loss, 3 dB coupling, 50 dB isolation, and a 90° phase shift.

Notably, the proposed coupler maintains consistent performance throughout the 40–50 GHz band, making it suitable for various V-band applications, including satellite and space communication systems.

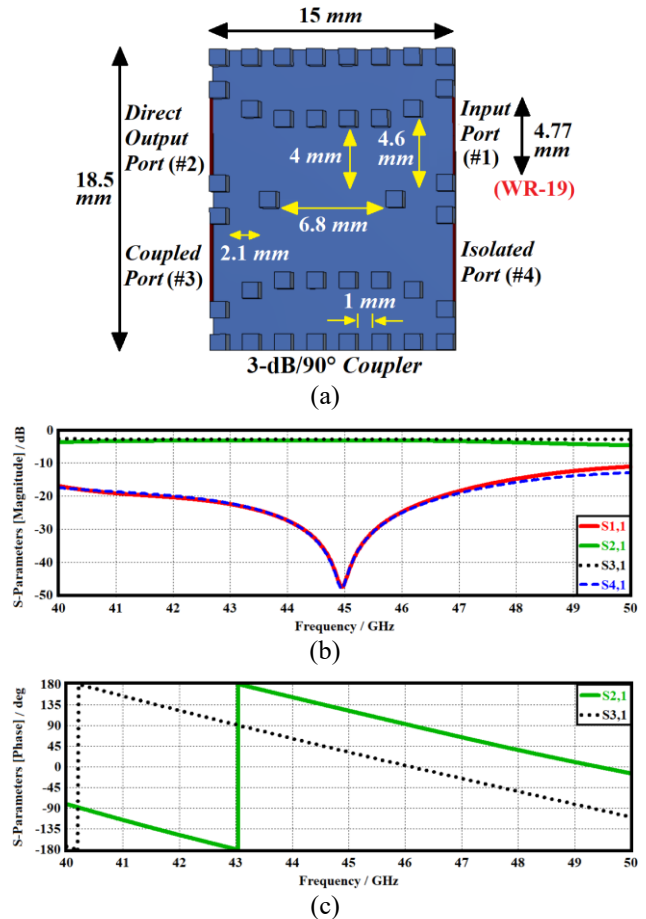


Figure 2. (a) Configuration of the proposed GGW-based 3-dB/90° coupler; (b) its S-parameter performances including reflection coefficient (S_{11}), transmission coefficients (S_{21} & S_{31}), and isolation (S_{41}); and (c) the phase-shift difference between the direct output and coupled ports (Phase $S_{21} - \text{Phase } S_{31} = 90^\circ$).

The E-field distribution of the proposed coupler at 45 GHz is shown in Fig. 3. It illustrates how the coupler efficiently transfers electromagnetic signals from the input port to both the direct output and coupled ports, each with equal power

levels of 3 dB. The figure also highlights the high isolation between the input and isolated ports, confirming the excellent performance of the 3-dB coupler designed with GGW technology.

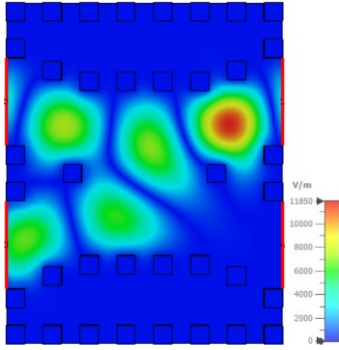


Figure 3. E-field distribution of the coupler at 45 GHz.

4. Crossover Design by Stacking Two Identical 3-dB/90° Hybrid Couplers

To achieve a wideband H-plane crossover with low insertion loss across the entire frequency band, two identical 3-dB/90° hybrid couplers, designed in the previous section, are cascaded. The configuration of the proposed crossover is shown in Fig. 4(a). Optimization involves adjusting the length of the interconnection at the center of the crossover to ensure adequate isolation and reflection while minimizing coupling between the two couplers.

The width of the crossover matches that of the coupler (18.5 mm), while its length is approximately twice that of the coupler, resulting in a total length of 29 mm. A 1 mm reduction is made by eliminating an extra pin at the junction where the two couplers are connected. Since the same pin can serve both couplers at the connection point, only one pin is necessary, which reduces the overall length by 1 mm.

As described by Eqn. (1), when an input signal is applied at Port 1, the first coupler splits it evenly, and the second coupler recombines it at output Port 3. Meanwhile, Port 4 is isolated, demonstrating effective signal routing and low insertion loss [2].

$$S = e^{j\varphi} \begin{bmatrix} 0010 \\ 0001 \\ 1000 \\ 0100 \end{bmatrix} \quad (1)$$

The S-parameter performance of the proposed crossover, shown in Fig. 4(b), indicates that, like the coupler design, it operates effectively over a wide frequency range of 40–50 GHz, with optimal performance centered at 45 GHz. The crossover achieves a fractional bandwidth of 22.22% and exhibits excellent impedance matching and isolation values of 50 dB and 30 dB, respectively, at 45 GHz.

Constructed by cascading two 3-dB/90° hybrid couplers, the crossover efficiently routes signals with minimal loss. When an input signal passes through the first coupler and then the second, it produces an extremely low insertion loss (S_{31}) of just 0.028 dB at 45 GHz. Fig. 4(b) further highlights the crossover's consistent and high performance across the entire

40–50 GHz band, making it well-suited for applications such as multi-beam array beamforming feeding networks and Butler matrices in satellite communication and space systems operating in the V-band mm-wave spectrum.

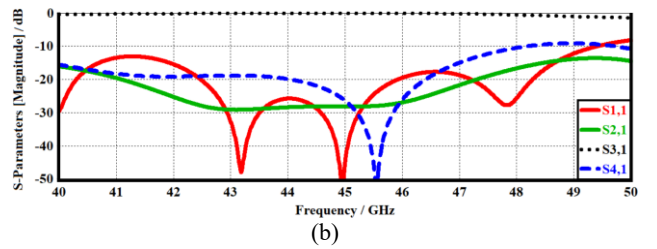
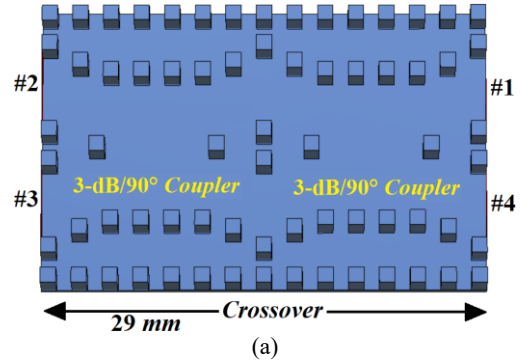


Figure 4. (a) Configuration of the proposed crossover based on GGW; and (b) its S-parameter performance.

The E-field distribution of the proposed GGW-based crossover at 45 GHz is shown in Fig. 5. It demonstrates high isolation between ports and minimal insertion loss, confirming the effectiveness and accuracy of the proposed design methodology.

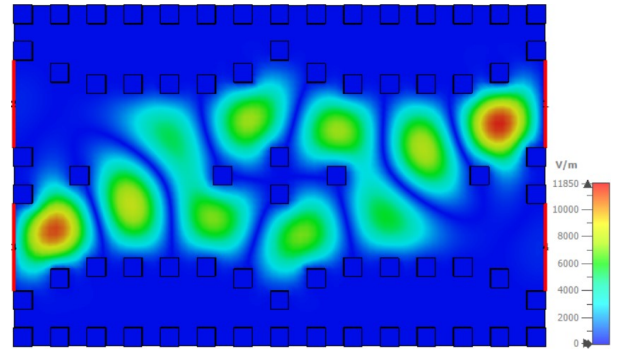


Figure 5. E-field distribution of the crossover at 45 GHz.

5. State-of-the-Art Comparison

The performance of the proposed groove gap waveguide (GGW) assisted crossover is compared with other works in the literature, as summarized in Table 1. The comparison is based on key parameters including applied methodology (AM), frequency bandwidth (FB), impedance matching (IM), isolation (IS), insertion loss (IL), and design complexity (DC).

The results show that the proposed crossover achieves a wide bandwidth (40–50 GHz), excellent impedance matching (50 dB), high isolation (30 dB), and extremely low insertion loss (0.028 dB), all while maintaining a simple design. These

performance metrics outperform many state-of-the-art crossovers, particularly in terms of bandwidth, insertion loss, and impedance matching.

Unlike other designs that require complex technologies such as substrate integrated waveguide (SIW), stripline, or branch-line couplers, the GGW-based crossover offers a compact and efficient solution due to its optimized use of metallic pins. This contributes to footprint reduction and improved design simplicity. Furthermore, the structure can be easily scaled or extended to more complex circuits, such as beamforming feeding networks and Butler matrices, for use in multiple beam antenna systems.

Table 1. State-of-the-Art Comparison.

Ref.	AM	FB (GHz)	IM (dB)	IS (dB)	IL (dB)	DC
[1]-1 st	SIW	22–30	35	15	2.4	Complex
[1]-2 nd	Stripline	22–30	25	17	1.5	Medium
[2]	SIW	9–18	20	20	1.5	Complex
[13]-1 st	Branch-line	27.5–28.5	15.6	30.8	1.1	Medium
[13]-2 nd	Branch-line	27.5–28.5	24.8	12.6	1.0	Medium
[14]	AMC and EBG	24–30	15	15	0.8	Complex
This Work	GGW	40–50	50	30	0.028	Simple

6. Conclusion

This article presents the analysis of a high-performance H-plane crossover designed using groove gap waveguide technology. The proposed crossover, constructed by stacking two symmetrical 3-dB/90° hybrid couplers, operates efficiently over a wide frequency range of 40–50 GHz, with optimal performance focused at 45 GHz. The design achieves an exceptionally low transmission loss of 0.02 dB across the entire band, along with excellent port isolation and impedance matching. These results confirm that the GGW-based crossover is well-suited for the development of Butler matrices and beamforming feeding networks with multiple beam functionalities. This makes it highly applicable for antenna array systems used in space multiplexing, particularly in millimeter-wave (mm-wave) satellite communication and space applications.

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