Matrix-Based Millimeter-Wave Beamforming Networks Using Groove Gap-Waveguide Technology for Satellite Space Multiplexing

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***Abstract*— This paper presents an innovative design of matrix-based beamforming networks (MB BFNs) for millimeter wave (mmWave) satellite communications by integrating groove gap waveguide (GGW) technology, a low loss and wideband solution, into Butler and Nolen matrix structures. Traditional microstrip and waveguide implementations suffer from significant dielectric and radiation losses at high frequencies. The proposed GGW based approach minimizes insertion loss while enhancing bandwidth and compactness. For the first time, all key BFN components, including 90-degree hybrid couplers, phase shifters, crossovers, and phase compensating elements, are realized using a custom GGW unit cell with a broad stopband. These components enable flexible and scalable MB BFN configurations tailored for satellite space multiplexing applications.**

***Keywords*—Beamforming Networks (BFNs), groove gap-waveguide (GGW), millimeter-waves, satellite communications, Nolen and Butler Matrices, space multiplexing.**

I. INTRODUCTION

With rapid advancements in satellite communications, the millimeter wave (mmWave) band has become vital due to its large bandwidth and potential for system miniaturization [1]. Space multiplexing is a key method to enhance spectral efficiency in this domain [2], with antenna arrays employing beamforming techniques to achieve high data rates and flexible beam control [3–5].

Common beamforming networks (BFNs) include matrix-based architectures such as the Blass, Butler, and Nolen matrices [6], as well as lens-based systems like the Luneburg, Ruze, and Rotman lenses [7]. While lens-based approaches suffer from phase errors, large size, and high losses, matrix-based BFNs, particularly the Butler and Nolen matrices, offer compactness, lower loss, and more consistent performance. They eliminate dummy loads and line crossings while enabling wide bandwidth and flexible phase progression.

However, traditional implementations using printed circuit boards, microstrip lines, substrate integrated waveguides (SIWs), or standard waveguides experience high dielectric and radiation losses at mmWave frequencies. To overcome these limitations, recent research has focused on more efficient transmission technologies.

Gap waveguide transmission line (GW TL) technology has emerged as a promising solution due to its low loss, wide bandwidth, and efficient propagation characteristics [8]. This paper proposes the integration of groove gap waveguide (GGW) technology into matrix-based BFNs to mitigate structural losses, simplify integration, and extend bandwidth. The approach supports the development of low-cost multibeam systems with wide angular coverage, compatible with 5G and future mmWave satellite platforms.

II. MATRIX-BASED BEAMFORMING NETWORKS DESIGN

This work integrates groove gap waveguide (GGW) technology into matrix-based beamforming networks (MB BFNs) to address key limitations of existing designs for space multiplexing at millimeter wave (mmWave) frequencies. Advanced optimization techniques are applied to enhance the performance and scalability of the proposed architectures.

The key components including hybrid couplers, phase shifters, crossovers, and coupler insertion phase compensators are designed, optimized, and implemented based on Butler and Nolen matrix configurations. A custom GGW unit cell with a wide stopband enables scalable and flexible BFN topologies tailored to specific beam angles.

The resulting MB BFNs provide (i) compact size, (ii) wide bandwidth, (iii) multi beam operation, (iv) improved beam scanning, (v) higher efficiency, (vi) beam switching flexibility, (vii) cost effectiveness, and (viii) compatibility with next generation mmWave systems.

A) GGW-based Unit-Cell

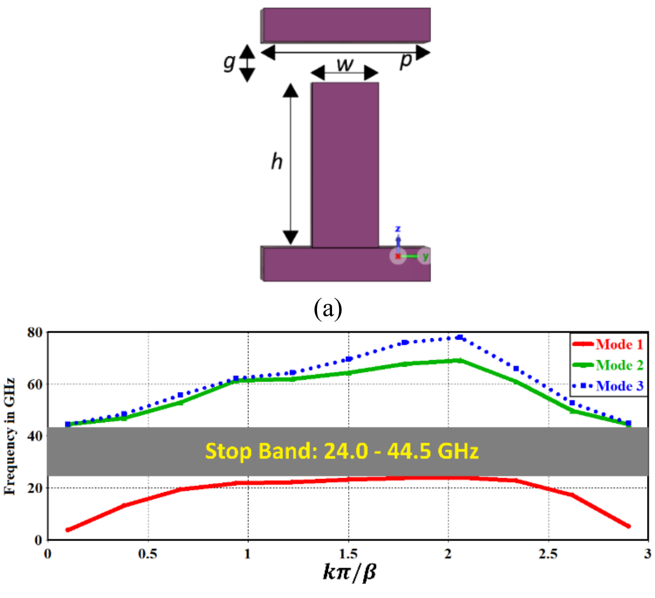
Fig. 1(a) shows the configuration of the proposed unit cell based on groove gap waveguide (GGW) technology. The main structural parameters are the gap between the pin and the top layer (g), the period (p), the height (h), and the width (w) of the pin. These parameters are optimized to provide a broad stopband covering the 5G high band, also known as the millimeter wave (mmWave) range, from 24 to 40 GHz. The optimized geometrical parameters are listed in Table I.

TABLE I. UNIT-CELL'S GEOMETRICAL PARAMETERS

Parameter	Value (mm)
g	0.618
p	2.500
h	2.500
w	1.000

The dispersion diagram of the proposed unit cell is plotted in Fig. 1(b), confirming a wide stopband from 24 to 44.5 GHz. Therefore, the proposed unit cell is employed to realize the structural components of the matrix-based beamforming networks, including couplers, phase shifters, crossovers, and coupler insertion phase compensators.

The following sections describe the design process for each component.



(a)

(b)

Fig.1. Unit-cell, (a) configuration based on groove gap-waveguide technology, and (b) dispersion diagram.

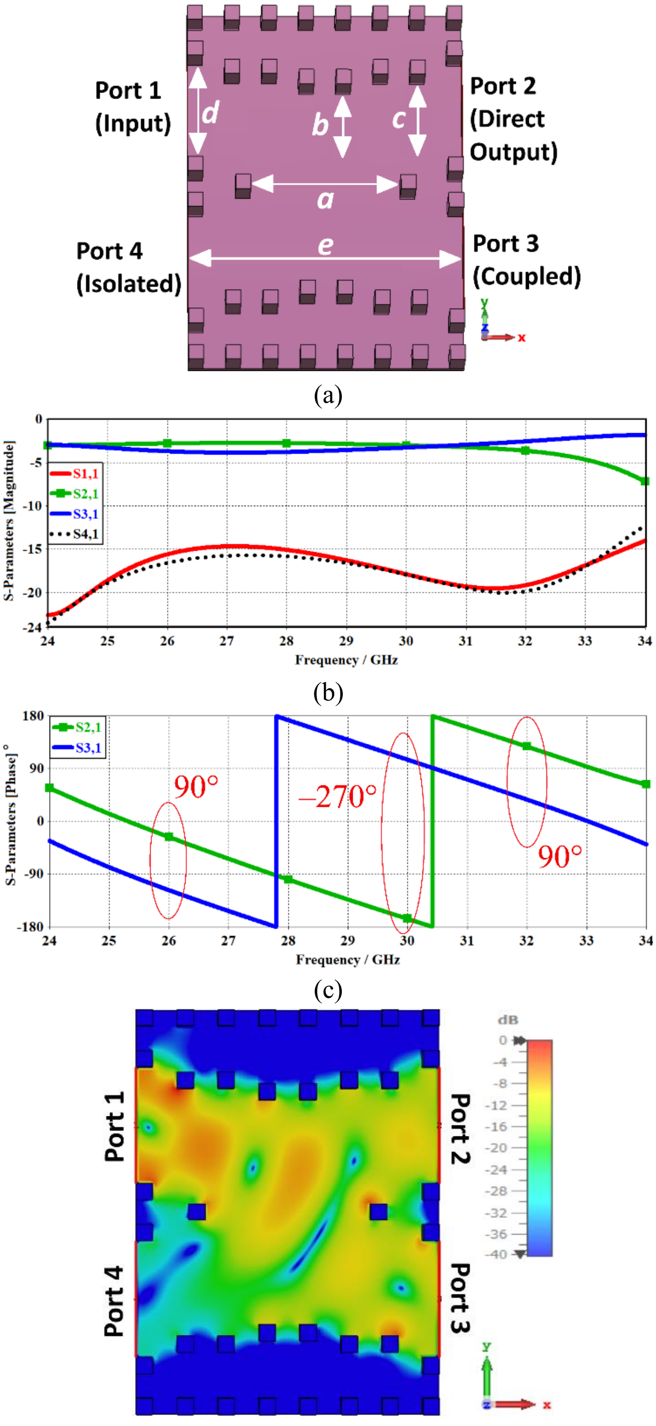
B) Hybrid Directional 90° *Coupler Design Based on GGW*

To realize matrix-based beamforming networks, directional 90° couplers with 3 dB, 4.7 dB, and 6 dB coupling levels are essential. These couplers must be modeled and integrated according to the requirements of the chosen matrix architecture, such as the Butler or Nolen matrix, and the number of input and output ports.

In this work, a 3 dB, 90° hybrid directional coupler is designed as shown in Fig. 2(a). Its main structural parameters are listed in Table II. In this table, WR 28 refers to the WR 28 waveguide adapter, which operates within the 26.5 to 40 GHz frequency range, commonly known as the Ka band. By applying the same design approach and adjusting the parameters in Table II, other coupling values can also be obtained.

TABLE II. COUPLER'S STRATURAL PARAMETERS

Parameter	Value (mm)
a	10.100
b	5.112
c	5.812
d	7.112 (WR-28)
e	18.500



(a)

(b)

(c)

(d)

Fig.2. 3dB/90° hybrid directional coupler, (a) topology, (b) S-parameters: S_{11}<-15dB; S_{21} & S_{31}; and S_{41} represent the reflection coefficient; transmission coefficients; and isolation>15dB, (c) 90° phase-shift difference between the direct output and coupled ports, i.e. Ang. S_{21} – Ang. S_{31} = 90°, and (d) surface current distribution at 30 GHz.

The S parameter results of the 3 dB, 90° directional coupler, including the reflection coefficient (S_{11} < 15 dB), transmission coefficients (S_{21} and S_{31}), and isolation (S_{41}), as well as the 90° phase shift between the direct and coupled ports (Ang. S_{21} – Ang. S_{31} = 90°), are shown in Figs. 2(b) and 2(c). The results confirm that the proposed directional coupler provides a wide operational bandwidth across the 5G high band (24 to 34 GHz), with a design focus at 30 GHz. Furthermore, a stable 90° phase difference between the output ports is maintained across the entire band. The surface current distribution at 30 GHz is illustrated in Fig. 2(d).

C) Phase Shifter Design Based on the GGW Concept

Phase shifters are typically designed using three approaches: unequal width and unequal length, unequal width and equal length, or equal width and unequal length transmission lines.

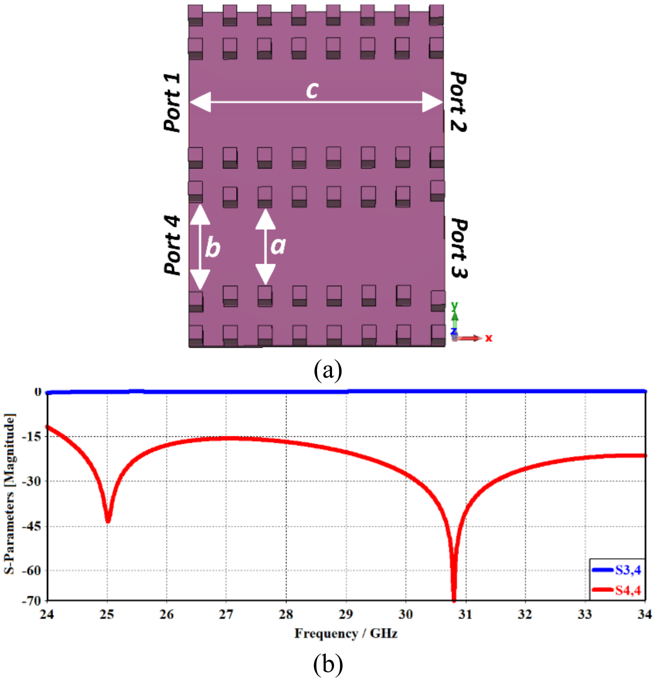
To realize any matrix-based beamforming network, it is necessary to design 45°, 90°, 135°, and 180° phase shifters and integrate them according to the topology of the matrix. In this work, a 45° phase shifter is designed and implemented, with its main geometrical parameters listed in Table III. This phase shifter is modeled using the unequal width and equal length transmission line concept, as shown in Fig. 3(a). By optimizing the structural parameters, the other required phase shifters can also be easily designed.

Fig. 3(b) presents the reflection (S_{44}) and transmission (S_{34}) coefficients, which are better than 15 dB and approximately zero across the entire frequency band from 24 to 34 GHz. In addition, Fig. 3(c) shows the phase shift response, demonstrating an accurate 45° phase shift at 30 GHz. The surface current distribution at 30 GHz is illustrated in Fig. 3(d).

The design procedure for the crossover and the coupler insertion phase compensator follows the same steps used for the proposed coupler and phase shifter. Specifically, by cascading two 3 dB, 90° hybrid directional couplers, the required crossover with similar performance can be realized. Furthermore, by optimizing the main structural parameter of the phase shifter, namely "*a*" as shown in Fig. 3(a), a coupler insertion phase compensator with any desired value can be designed.

TABLE III. PHASE SHIFTER'S GEOMETRICAL PARAMETERS

Parameter	Value (mm)
a	6.312
b	7.112
c	18.500



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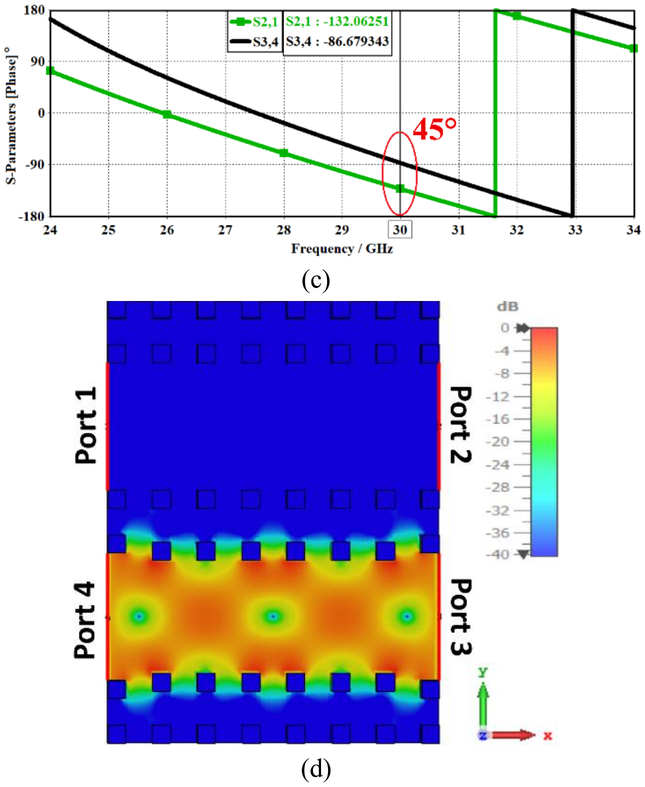

(c)

(d)

Fig.3. 45° phase shifter design, (a) layout, (b) reflection coefficient (S_{44}<-15 dB) and transmission coefficient (S_{34}≅0), (c) 45° phase shift, and (d) surface current distribution at 30 GHz.

APPLICATION

The proposed GGW based beamforming network and its key components, the hybrid directional coupler and phase shifter, are suitable for several high frequency applications, as shown in Fig. 4. In satellite communications, they enable multi beam generation and precise beam steering with low loss and wide bandwidth. In radar tracking systems at millimeter wave frequencies, the components provide accurate phase control and high efficiency, improving detection and angular resolution. In space multiplexing systems, the network supports multiple simultaneous beams, enhancing spectral efficiency and link capacity for next generation 5G and 6G platforms. The proposed GGW based structures offer compactness, low loss, and wideband performance suitable for advanced communication and sensing applications.

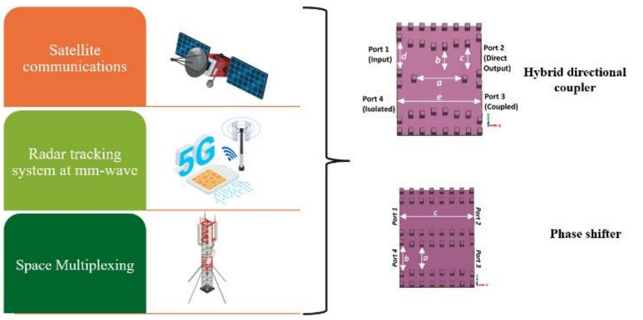

Fig.4. Application scenarios and corresponding GGW based components: satellite communications, radar tracking systems at millimeter wave frequencies, and space multiplexing, along with the designed hybrid directional coupler and phase shifter.

CONCLUSION

This This research work has demonstrated the application of groove gap waveguide (GGW) technology to implement the structural elements of Nolen and Butler beamforming matrices operating over the 5G high band from 24 to 34 GHz. The proposed components, which feature compact size, wide bandwidth, low loss, excellent phase response, and simple layout, can be employed to realize matrix-based beamforming systems for advanced space and satellite communication applications.

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