# Innovative UWB Phase Shifters Using Groove Gap-Waveguide Technology Inspired by Metasurfaces for Beamforming Networks Operating at 100 GHz

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***Abstract:*** **This paper presents the design of four phase shifters (+45°, +90°, +135°, +180°) for matrix-based beamforming networks (MB-BFN) in mm-wave antenna arrays. Utilizing groove gap-waveguide (GGW) technology with unequal-width, equal-length transmission lines, the design incorporates metasurface principles to achieve perfect magnetic conductor (PMC) boundary conditions. The metasurface features a "bed-of-nails" structure, where metal pins are connected to a bottom layer and spaced <λ/4 from a top plate. This configuration provides a UWB stop-band over the 80–110 GHz spectrum, ensuring effective phase shifting at 100 GHz within the ultra-wideband range.**

***Keywords:*** **UWB phase-shifters, GGW, metasurface, MB-BFN, antenna array systems, PMC, mm-Wave, 100 GHz, stop-band.**

## I. INTRODUCTION

To enhance data capacity and enable flexible beam switching or scanning for space multiplexing, antenna array systems frequently use beamforming techniques. These techniques allow for signal generation with specific magnitudes and phase differences. Notable methods for designing beamforming networks (BFNs) include Blass matrices, Butler matrices, Nolen matrices [1], and lens antennas like Luneburg, Ruze, and Rotman lenses [2]. However, lenses face challenges such as time delay beamforming, phase errors, limited angular range, bandwidth constraints, large size, high losses, and non-planar structures, making them less suitable for mm-wave operations.

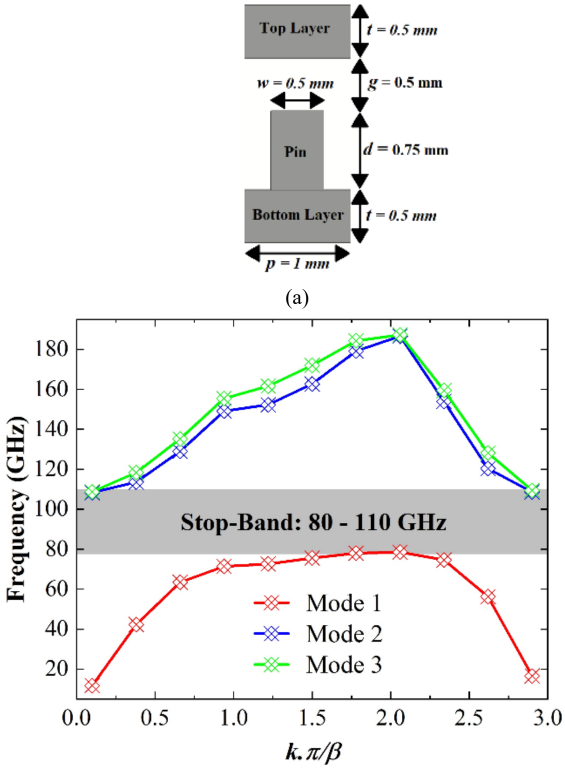
In contrast, Blass, Nolen, and Butler matrices employ matrix-based beamforming networks (MB-BFNs), which offer advantages like smaller size, lower losses, and suitability for the mm-wave band. These matrices are preferred for their organizational consistency, wide bandwidth, flexible phase progression, and low-loss characteristics [3]. They have been implemented in various technologies, including printed circuit boards (PCBs), microstrip lines, substrate integrated waveguides (SIWs), and conventional waveguides [4,5]. However, these technologies often suffer from high dielectric and radiation losses, which limit performance and bandwidth [6], making them inadequate for modern 5G bands such as Sub-6 GHz and the mm-wave spectrum.

Gap waveguide transmission line (GW-TL) technology offers a promising alternative for the mm-wave spectrum due to its low losses, wide bandwidth, and efficient propagation [7]. This technology utilizes parallel-plate waveguides and leverages boundary conditions and canonical surfaces to manipulate electromagnetic wave propagation [8].

By incorporating GW-TL technology, MB-BFNs can achieve minimal transmission losses, wide operational bandwidth, and high efficiency—essential for mm-wave applications. This research focuses on developing and investigating four wideband phase shifters (+45°, +90°, +135°, and +180°), crucial components in MB-BFNs. These phase shifters, based on groove GW technology and metasurface principles, are designed to operate within the 80–110 GHz range, with a particular focus on 100 GHz.

## II. Unit-Cell Design

The proposed unit-cell consists of three structural elements: (i) a metal pin, (ii) a bottom metal plate, and (iii) a top metal plate. As illustrated in Fig. 1, the metal pin is connected to the bottom metal plate and is spaced at a distance $h < \lambda/4$, where λ is the free-space wavelength at 100 GHz. To achieve an ultra-wideband (UWB) stop-band from 80 to 110 GHz, the main structural parameters of the unit-cell are: (i) the height of the pin, $d = 0.75$ mm; (ii) the gap distance between the pin and the top metal plate, $g = 0.5$ mm; and (iii) the period of the pins, $p = 1$ mm. The geometrical parameters of the unit-cell are detailed in Fig. 1(a), and its dispersion diagram is presented in Fig. 1(b).



(a)

(b)

Fig.1. (a) The proposed unit-cell along with its structural parameters, and (b) dispersion diagram.

## III. Phase-Shifter Designs Based on GGW and Metasurafce Concepts

The unit-cell described previously is used to implement the proposed phase shifters, which are integral to groove gap-waveguide (GGW) technology. The phase shifters include +45°, +90°, +135°, and +180° shifts, which are crucial for developing matrix-based beamforming networks (MB-BFNs) in antenna array systems. These phase shifters help increase data capacity and enable flexible beam switching or scanning for space multiplexing.

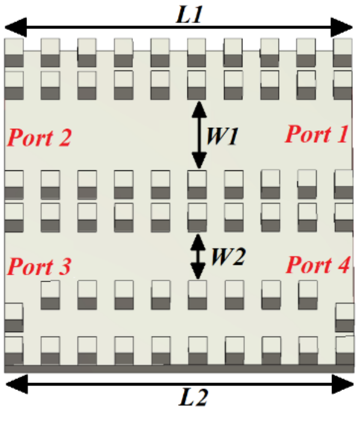
This research investigates these phase shifters using unequal-width ($W_1 \neq W_2$) and equal-length ($L_1 = L_2$) GGW transmission lines (TLs). As illustrated in Fig. 2, the design incorporates a parallel-plate waveguide, with two unconnected metal plates acting as ideal perfect electric conductors (PEC), allowing electromagnetic (EM) wave propagation. Replacing one plate with an ideal perfect magnetic conductor (PMC) theoretically prevents wave propagation if the plate separation is less than one-quarter of the wavelength (λ/4). While true PMCs do not exist, metasurfaces with periodic structures can simulate PMC conditions within a specific frequency range.

In this setup, a “bed of nails” or “metal pins” metasurface provides wideband, isotropic characteristics with minimal losses due to its metallic composition. Introducing a PEC groove in the middle of the PMC surface confines the signal to propagate along the groove, minimizing leakage and losses. The design prevents unwanted radiation from discontinuities or corners by ensuring that EM modes do not propagate outside the PEC/PEC area.

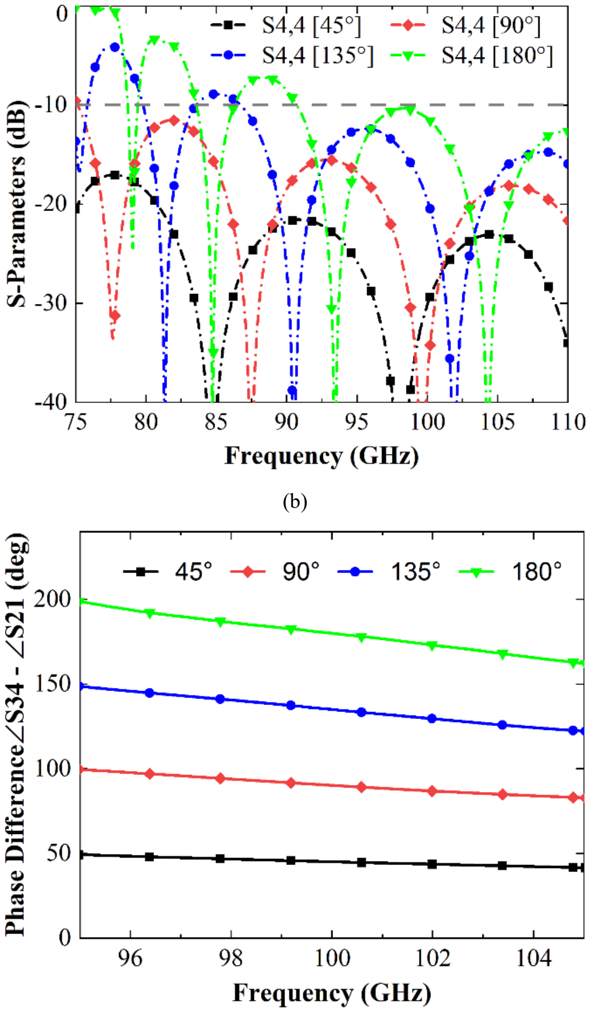
Fig. 2(a) shows that all phase shifters share the same length, with the width of the GGW-TL being the key parameter for achieving different phase shifts, as detailed in Table 1. The WR-10 waveguide flange (75–110 GHz) is used to excite the phase shifters. Performance results, shown in Figs. 2(b) and (c), indicate that all phase shifters operate over an ultra-wideband (UWB) spectrum of 80–110 GHz. At 100 GHz, the phase shifts of +45°, +90°, +135°, and +180° are achieved, demonstrating the effectiveness of these phase shifters for MB-BFNs in antenna array systems operating around 100 GHz.

TABLE.I. PHASE-SHIFTERS’ PARAMETERS.

| **Phase-shifter** | **Width (W2)** | **Length ($L_1 = L_2$)** | **Width (W1)** |
|---|---|---|---|
| +45° | 2.2830 mm | 9.5 mm | 2.54 mm |
| +90° | 2.1010 mm | 9.5 mm | 2.54 mm |
| +135° | 1.9675 mm | 9.5 mm | 2.54 mm |
| +180° | 1.8622 mm | 9.5 mm | 2.54 mm |



(a)



(b)

(c)

Fig.2. (a) Configuration of the proposed GGW-based phase-shifters, (b) reflection coefficients, and (c) phase shifts.

## IV. CONCLUSION

In this article we have investigated the feasibility and effectiveness of using fundamental phase shifters in the development of matrix-based beamforming networks (MB-BFNs) for antenna array systems, specifically targeting applications in space multiplexing. The study successfully demonstrates the implementation of phase shifters with phase shifts of +45°, +90°, +135°, and +180° using groove gap-waveguide (GGW) technology. This technology integrates cascaded metal pins within a metasurface design to achieve perfect magnetic conductor (PMC) boundary conditions, which is crucial for precise phase control and minimal signal loss.

The proposed unit-cell design effectively provides an ultra-wideband (UWB) stop-band ranging from 80 GHz to 110 GHz. This wideband characteristic ensures that the phase shifters can operate efficiently across the entire UWB spectrum, with particular emphasis on optimizing performance at 100 GHz. The use of unequal-width ($W_1 \neq W_2$) and equal-length ($L_1 = L_2$) transmission lines (TLs) within the GGW framework allows for the precise tuning of phase shifts, essential for achieving the desired beamforming capabilities.

The integration of GGW technology and metasurface principles results in phase shifters that exhibit significant advantages, including reduced signal losses and enhanced operational bandwidth. These advancements contribute to the overall performance of MB-BFNs, offering improved data capacities and enabling more flexible beam switching and scanning capabilities. This research highlights the potential of GGW-based phase shifters to advance the field of antenna array systems, providing a robust solution for complex space multiplexing applications in the millimeter-wave spectrum. Future work could explore further optimizations of the unit-cell design and its integration into larger beamforming networks to fully realize its potential in practical applications.

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