THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

High-Performance Circularly Polarized Array Antenna utilizing Gap Waveguide Technology for Satcom Application

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Gothenburg, Sweden, 2025

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Technical Report No. 1111-111X
ISSN 3.1415-9265
This thesis has been prepared using LaTeX.

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Printed by Chalmers Reproservice
Gothenburg, Sweden, Feb2025

Abstract

Circularly polarized antennas operating in the Ka-band show potential for future generation of satellite communication systems due to their ability to support high-speed data transmission and reliable connectivity. In this frequency range, high-gain antenna arrays are crucial to overcome the high free-space path loss and ensure stable and efficient communication. Current solutions often feature compact designs but face challenges such as limited radiation efficiency and high manufacturing complexity. To address these issues, cavity-backed slot antennas utilizing ridge gap waveguide (RGW) technology have emerged as a promising alternative.

This thesis presents a novel circularly polarized Ka-band antenna design for satellite communication applications. The proposed antenna achieves high gain, wide axial ratio bandwidth, and good impedance matching, making it suitable for compact and efficient satellite terminals. Using corporate feed network techniques and a U-shaped radiation element, the design ensures low sidelobe levels and high circular polarisation purity.

The antenna prototype has been optimized for geostationary satellite applications, providing fixed beam patterns with peak efficiency exceeding 84%. Additionally, various coupling and feeding techniques are studied to analyze their impact on the antenna's performance and scalability. The proposed design serves as a foundation for future development of high-performance satellite communication systems, offering potential for further enhancements in multi-beam and steerable configurations.

Keywords: Ka-Band Antenna, High Gain, Circular polarization, Gap waveguide.

List of Publications

This thesis is based on the following publications:

[A] **Raha Roosefid**, Sadegh Mansouri Moghaddam, Lukas Nyström, Jian Yang, Ashraf Uz Zaman, “A 2 × 2 Ka-Band Wideband Circularly Polarized Sub-Array Antenna Based on U-shaped Slots and Gap Waveguide Technology”. Published in 2023 IEEE International Symposium on Antennas and Propagation (ISAP).

[B] **Raha Roosefid**, Jian Yang, Ashraf Uz Zaman, “Compact Circularly Polarized Antenna based on Gapwaveguide for SATCOM Applications”. Published in 2024 18th European Conference on Antennas and Propagation (EuCAP).

[C] **Raha Roosefid**, Sadegh Mansouri Moghaddam, Lukas Nyström, Jian Yang, Ashraf Uz Zaman, “Development of a High-Efficiency Circularly Polarized Ka-Band Satcom Antenna Utilizing Ridge-loaded U-shaped Radiator”. Published in IEEE Antennas and Wireless Propagation Letters, Early Access.

[D] **Raha Roosefid**, Esperanza Alfonso Alós, Thomas Schäfer, Jian Yang, Ashraf Uz Zaman, “Compact Microstrip Line to Gap Waveguide Transition suitable for Beam Steering Antenna Applications at K-band”. Accepted in Eucap 2025, Dec. 2024.

Acknowledgments

I want to express my heartfelt thanks to my supervisor, Assoc. Prof. Ashraf Uz Zaman, for his constant support and helpful guidance throughout my research. His advice and feedback have been invaluable in overcoming challenges and making progress.

I would like to express my heartfelt gratitude to my examiner, Prof. Jian Yang, along with Lukas Nyström, Sadegh Mansouri Moghaddam, and Thomas Schäfer for their wonderful support, collaboration, and insightful suggestions that have truly enhanced my work. I am also deeply appreciative of Prof. Marianna Ivashina for her kind guidance and encouraging support throughout this journey.

Special thanks to Oleg Iupikov for his assistance with testing, measurements, and 3D printing, which were essential to this project. I also want to thank Qiannan Ren, Esperanza Alfonso Alos, and all my friends for their support and kindness, which made this experience more enjoyable. Additional thanks to the Antenna Systems Group for their stimulating discussions and collaboration, which have been a significant source of motivation.

Finally, I deeply appreciate everyone who created a supportive and friendly environment that made this journey so memorable.

Acronyms

RGW:	Ridge Gap Waveguide
AiP:	Antenna in package
mmWave:	millimeter-wave
GWG:	Gap waveguide
PEC:	Perfect electric conductor
PMC:	Perfect magnetic conductor
AMC:	Artificial magnetic conductor
ARC:	Active reflection coefficient
CP:	Circular polarization

Contents

Part I

Overview

CHAPTER 1

Introduction

1.1. Advancements in Circularly Polarized Antenna Arrays for Satcom applications

The Ka-band (26.5–40 GHz) has emerged as a crucial frequency range for modern satellite communication systems. Its ability to support high-speed data transfer and deliver robust broadband services makes it highly attractive for a range of applications, including global connectivity solutions, earth observation missions, advanced remote sensing operations, 5G and etc. The unique advantages of the Ka-band lie in its broad bandwidth availability, which enables the transmission of large amounts of data with reduced latency, essential for the ever-growing demands of modern telecommunication and sensing infrastructures. Moreover, the high directivity achievable at Ka-band frequencies enhances signal accuracy, a critical factor for satellite links operating under varying atmospheric conditions [1]–[3].

In the context of fifth-generation (5G) networks, satellite communication plays a crucial role in extending coverage to remote and underserved areas, ensuring smooth connectivity and supporting the diverse requirements of 5G services. The integration of satellite links within 5G infrastructures facilitates common access, enhances network resilience, and enables efficient content delivery, thereby contributing significantly to the global deployment of 5G technologies[4], [5].

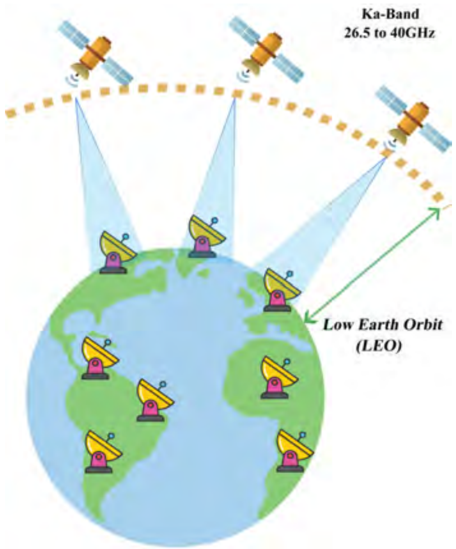


Figure 1.1: Antenna in satcom application

Recent advancements in antenna design have further augmented the efficiency of Ka-band satellite communications. Innovations such as Antenna-in-Package (AiP) configurations have been developed to meet the strict performance and integration demands of 5G applications. These designs provide practical solutions for implementing phased-array modules that work at frequencies above 20 GHz, thus improving the reliability and cost-effectiveness of next-generation communication systems.

Additionally, the development of flat panel active phased array antennas utilizing silicon radio frequency integrated circuits (RFICs) at Ka-band frequencies has shown significant potential. These advancements help create compact, high-performance antenna systems that can meet the high data rates and low latency needs of future satellite communication networks. These developments highlight the essential role of the Ka band in enhancing satellite communication technologies, especially in the era of 5G and 5G, where the demand for high-speed, reliable, and widespread connectivity is rapidly increasing[6]–[9].

1.2. Challenges in Ka-Band Satellite Communication

Despite its promising potential, the Ka-band introduces unique challenges that demand innovative design solutions to ensure reliable and efficient performance. One significant challenge is the pronounced free-space path loss, which is inherently higher at these frequencies compared to lower bands. This limitation arises due to the smaller wavelengths associated with Ka-band signals, resulting in greater energy dissipation as the signals propagate through space. Consequently, antennas with high gain and efficiency are essential to maintain adequate SNR over long distances and ensure effective communication links [4], [9].

Additionally, atmospheric attenuation is a consistent challenge in the Ka-band, significantly affecting signal quality. Rain, humidity, and other atmospheric factors create significant losses that complicate the link budget and present serious difficulties in the development of reliable communication systems. Rain fade, specifically, is an important concern, as water droplets in the atmosphere absorb and scatter the signal, causing substantial loss. These environmental effects not only limit the performance of satellite communication systems but also threaten their reliability, particularly in areas that frequently experience poor weather conditions.

Another technical obstacle is maintaining polarization purity across a wide bandwidth. Circular polarization is a crucial requirement in satellite communication to reduce the effects of signal fading and polarization mismatch. However, achieving this across the operational frequency range is complex, often requiring innovative structural designs and detailed fabrication techniques to ensure performance consistency [4], [9], [10].

Finally, the need for compact antenna systems introduces an additional level of complexity. Satellite platforms, especially small satellites and systems with several antenna arrays, have strict limitations on the size and weight of antenna designs. Finding a balance between these requirements while ensuring high performance requires innovative engineering solutions, highlighting the significance of compact, effective, and adaptable antenna structures.

Addressing these challenges motivates this research, which explores advanced antenna technologies utilising innovative structural elements and gap waveguide methodologies. By dealing with polarisation purity and design compactness, this work aims to contribute to the development of compact, high-efficiency antennas for next-generation Ka-band satellite communication [9]–[12].

1.3. Technological Solutions

Circularly polarised antennas play an essential role in reducing signal degradation caused by polarisation mismatch in satellite communication systems. Their ability to maintain polarization purity ensures reliable performance, particularly in scenarios where multipath effects and polarization shifts are common. However, designing antennas that effectively achieve circular polarization while meeting other performance requirements introduces significant challenges[9]–[12].

Microstrip-based antenna designs are often favored for their compactness and lightweight properties, making them suitable for modern satellite systems. Yet, they are affected by dielectric losses and limited efficiency, particularly at high frequencies such as those in the Ka-band. Conversely, waveguide-based antennas offer superior efficiency and greater control over polarization, but their complexity in manufacturing can be a limiting factor. Reflectarrays and lens antennas provide high gain and are capable of supporting advanced applications, but their bulkiness makes integration into compact systems difficult. These trade-offs underline the importance of exploring innovative antenna solutions to overcome the limitations inherent in these conventional designs [10], [12], [13].

Material and manufacturing challenges further compound these difficulties. At Ka-band frequencies, traditional manufacturing techniques often lack the precision required to ensure optimal performance. Material losses in substrates and issues related to thermal management in integrated designs also hinder efficiency and reliability. These obstacles necessitate the exploration of alternative approaches to antenna design and fabrication.

One promising solution lies in gap waveguide technology, which eliminates the need for electrical contacts, thereby reducing losses and simplifying manufacturing. Within this framework, ridge gap waveguides (RGWs) emerge as a powerful tool, enabling highly efficient feeding networks and compact cavity-backed slot designs. RGW technology supports high gain and maintains circular polarization across wide bandwidths, making it particularly suited for Ka-band satellite communication [10], [12], [14], [15].

This work addresses these challenges by focusing on innovative solutions that utilize the strengths of RGW (Ridge Gap Waveguide) technology. The design maintains polarization purity and high gain over a wide bandwidth while employing advanced feeding and coupling techniques to reduce sidelobes and mutual coupling. Ridge gap waveguide structures further improve compactness, efficiency, and scalability, allowing for practical implementation in various satellite systems. By comparing this approach with existing methods, such as microstrip and traditional waveguide-based designs, this work shows measurable improvements in efficiency, gain, and manufacturability, highlighting its potential to advance the field of satellite communication.

1.4. Outline of this thesis

This thesis is organized into five main chapters, each building upon the previous to present a comprehensive exploration of Ridge Gap Waveguide (RGW)-based circularly polarized (CP) antennas for Ka-band and millimeter-wave (mmWave) applications. Below is a summary of the structure and content of the thesis:

- **Chapter 1: Introduction**
  This chapter introduces the research context and motivation, highlighting the critical advancements in circularly polarized antenna arrays for satellite communication (Satcom) applications. It outlines the challenges associated with Ka-band satellite communication, such as high path loss and atmospheric attenuation, and presents RGW technology as a promising solution. The chapter concludes with the objectives of the research and the outline of the thesis.

- **Chapter 2: Gap Waveguide Technology**
  This chapter provides a detailed overview of RGW technology and its theoretical underpinnings. It explains the key principles of operation, including the use of artificial magnetic conductors (AMCs) and non-touching plates to suppress surface waves and substrate losses. The chapter also discusses the different types of gap waveguides—Ridge Gap Waveguide (RGW), Groove Gap Waveguide (GGW), and Microstrip Gap Waveguide (MGW)—along with their advantages, such as high ef-

ficiency, simplified manufacturing, and scalability. Applications of RGW technology in antenna design are explored to establish its relevance to mmWave systems.

- **Chapter 3: A new solution to a Circularly Polarized Array Antenna Using RGW Technology**
  This chapter delves into the design and analysis of the proposed circularly polarized array antenna as an innovative solution. It begins with a review of the state-of-the-art in antenna design, comparing different technologies such as microstrip, spiral, reflect arrays, and conventional waveguides. Advantages in RGW-based antennas are discussed, followed by an identification of challenges in current designs. The chapter justifies the need for this research and details the proposed work, including the optimization of coupling slot geometries, compact RGW-based designs, and performance metrics. The chapter concludes with a summary of the findings and their implications for Satcom applications.

- **Chapter 4: Summary of Included Papers**
  This chapter summarizes the included papers, which form the foundation of the research. Each paper is briefly described, highlighting its contributions to the overall objectives of the thesis. The methodologies, results, and key conclusions of the papers are synthesized to showcase the progression of the research.

- **Chapter 5: Concluding Remarks and Future Work**
  The final chapter summarizes the main contributions and findings of the thesis. It reflects on the impact of the research on advancing RGW-based antenna technologies and outlines potential directions for future work. Areas such as wide-angle scanning, further optimization of RGW designs, and the integration of RGW-based antennas with adaptive systems are identified as opportunities for continued exploration.

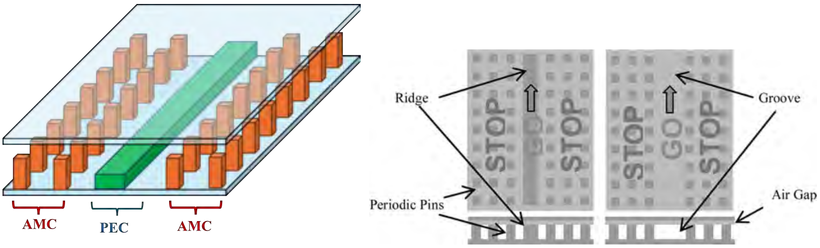
CHAPTER 2

Gap Waveguide Technology

2.1. Introduction to Gap Waveguide Technology

Gap waveguide technology was introduced as a solution to critical challenges in traditional waveguide designs, particularly at millimeter-wave frequencies. Conventional waveguides rely on precise electrical contacts to maintain performance, a requirement that becomes increasingly difficult to meet at higher frequencies due to manufacturing complexities and increased cost. Gap waveguide technology eliminates this dependency by utilizing artificial magnetic conductors (AMCs) to establish a stopband, effectively suppressing unwanted field leakage and unwanted modes over the stopband frequency band.

The AMC structure creates a high-impedance boundary, ensuring that electromagnetic waves are confined to the designated guiding path without the need for direct electrical contact among the metal blocks of the waveguide modules.. This principle not only simplifies the design and fabrication process but also improves reliability and reduces ohmic losses, which are significant in conventional designs. Using this mechanism, gap waveguides can accommodate complex guiding elements, such as ridges and grooves, to support various



(a)

(b)

Figure 2.1: Gap Waveguide structure: (a) Schematic view of the principle of a ridge gap waveguide (b) Top (upper) and front (lower) view of basic structures of ridge gap waveguide (left) and groove gap waveguide (right)

configurations without compromising efficiency.

This approach is particularly advantageous for millimeter-wave systems, where precision and performance are critical. Gap waveguide technology thus provides a robust framework for designing efficient wave propagation systems, overcoming long-term limitations in traditional waveguide architectures while enabling advanced applications in communication and sensing systems[12], [15]–[19].

2.1.1. Key Principles of Operation

The operation of gap waveguide technology is underpinned by three key principles, which collectively enable efficient and reliable signal propagation at high frequencies:

- **Artificial Magnetic Conductor (AMC)**
  The foundation of gap waveguide technology lies in the use of artificial magnetic conductors. AMCs create a high-impedance surface that behaves like a perfect magnetic conductor over a specific frequency range. This property supports only desired guided modes while effectively suppressing unwanted modes, ensuring controlled and efficient wave propagation. The AMC surface is typically realized through periodic structures, such as metal pins or textured patterns, which achieve the required

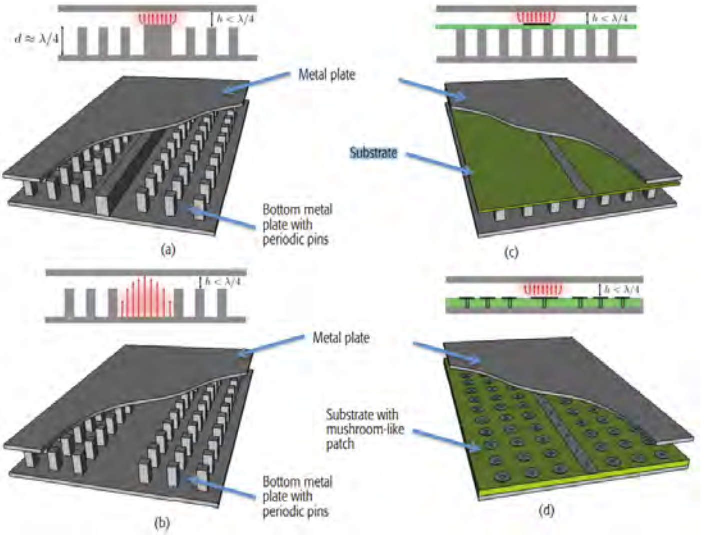


Figure 2.2: Description of the main realizations of gap waveguide technology. On top of each realization there is a figure with a cross-sectional view that shows the localization of the propagating field (red arrows): a) ridge b) groove c) inverted microstrip d) microstrip ridge [16].

high-impedance characteristics[15], [16], [20].

- **Stopband Effect**
  The introduction of a carefully designed gap between the AMC surface and a metal plate establishes a stopband effect. This gap prevents the propagation of parallel plate modes, which are a common source of interference and energy leakage in traditional waveguides. By confining electromagnetic waves to the intended guiding paths, the stopband effect ensures high signal integrity and minimizes unwanted coupling or radiation [12], [16]–[18].

- **No Electrical Contacts**
  A defining feature of gap waveguide technology is the absence of direct electrical contacts between waveguide components. Traditional waveguides often suffer from performance degradation due to imperfect metal-to-metal connections, especially at millimeter-wave frequencies where

even minor surface imperfections can lead to significant losses. Gap waveguides eliminate this issue by leveraging the AMC-based stopband, allowing the components to function without physical contact, thereby reducing losses and improving overall reliability [12], [15]–[17], [19].

2.2. Theory Behind Gap Waveguides

Gap waveguides operate based on carefully engineered electromagnetic boundaries and structural configurations that effectively guide electromagnetic waves while suppressing unwanted modes. The physical principles can be broken down into the following elements:

2.2.1. Electromagnetic Boundaries

The core concept of gap waveguides relies on a combination of **Perfect Electric Conductor (PEC)** and **Artificial Magnetic Conductor (AMC)** surfaces. These surfaces form an electromagnetic boundary condition that confines fields to specific regions.

- The **PEC boundary condition** ensures that the tangential electric field ($\mathbf{E}_t$) is zero at the conductor's surface:

  $$\mathbf{E}_t = 0 \quad \text{at PEC surface.} \tag{2.1}$$

- The **AMC boundary condition**, achieved using periodic structures like metal pins or textured surfaces, mimics a high-impedance magnetic conductor over a specific frequency range. This is characterized by the tangential magnetic field ($\mathbf{H}_t$) being zero:

  $$\mathbf{H}_t = 0 \quad \text{at AMC surface.} \tag{2.2}$$

  The stopband effect is achieved by the combination of Perfect Electric Conductor (PEC) and Perfect Magnetic Conductor (PMC) parallel plates. When the separation between the plates is less than a quarter wavelength, the stopband prevents the propagation of parallel-plate modes, allowing only the desired guided modes to propagate [15], [16], [18].

2.2.2 Guided Waves

The geometry of the gap waveguide includes **ridges**, **grooves**, or similar guiding elements placed between the PEC and AMC surfaces. The guided waves are confined to these ridges or grooves, with the surrounding AMC acting as virtual walls that prevent lateral field leakage. The wave propagation can be described using the wave equation:

$$\nabla^2 \mathbf{E} + k^2 \mathbf{E} = 0, \tag{2.3}$$

where k is the wave number. For a ridge gap waveguide, the effective wave impedance (Z) and propagation constant (β) are determined by the ridge height and the gap distance.

The electromagnetic fields in the ridge region primarily propagate in the Transverse Electromagnetic (TEM) mode. The virtual walls created by the Artificial Magnetic Conductor (AMC), along with the Perfect Electric Conductor (PEC) and Perfect Magnetic Conductor (PMC) boundaries, ensure that the energy remains confined without any physical interaction.

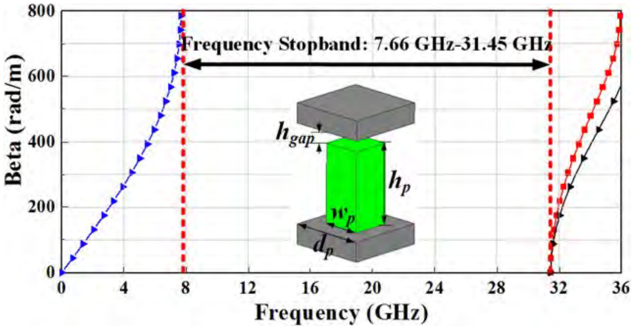


Figure 2.3: Geometries and dispersion diagrams of gap waveguide (GW)[21].

Figure 2.3 illustrates how a pin is used to create a stop band, effectively suppressing unwanted modes [12], [15]–[18], [22].

2.2.3. Non-Touching Plates

Unlike conventional waveguides that rely on precise metal-to-metal contact, gap waveguides use a **contactless configuration**. The gap between the PEC and AMC is carefully designed to suppress unwanted modes. The suppression is achieved by ensuring that the gap height (h) satisfies the quarter-wavelength condition for the stopband:

$$h < \frac{\lambda}{4}, \tag{2.4}$$

where λ is the wavelength in the medium. This condition prevents parallel-plate modes, as the AMC behaves like a high-impedance surface, reflecting nearly all incident waves [12], [16], [17], [23].

2.3. Types of Gap Waveguides

Gap waveguides include several various types, each designed for specific applications. These include Ridge Gap Waveguide (RGW), Groove Gap Waveguide (GGW), and Microstrip Gap Waveguide (MGW). Each type employs the basic principles of gap waveguide technology, while presenting distinct advantages.

2.3.1. Ridge Gap Waveguide (RGW)

The Ridge Gap Waveguide employs a raised ridge structure to guide electromagnetic waves. This ridge serves as the main guiding component, with the surrounding AMC surface creating virtual boundaries that contain the waves. RGW is especially appropriate for compact feeding networks because it can attain high efficiency in limited areas. Figure 2.6 shows a geometry of a ridge gap waveguide.

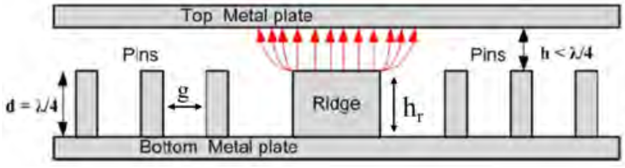


Figure 2.4: ridge gap waveguide geometry[24].

The guiding condition in RGW can be described by the effective wave impedance (Z) and propagation constant (β), determined by the ridge height (h_r) and gap distance (g):

$$Z = \sqrt{\frac{\mu}{\epsilon}}, \quad \beta = \frac{2\pi}{\lambda}, \tag{2.5}$$

where λ is the guided wavelength, μ is the permeability, and ϵ is the permittivity of the medium. The ridge's geometry ensures efficient transmission while maintaining compactness [15], [18], [19].

2.3.2 Groove Gap Waveguide (GGW)

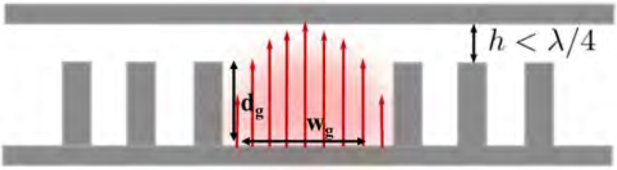


Figure 2.5: Groove gap waveguide geometry[24].

The Groove Gap Waveguide uses grooves instead of ridges to guide waves. These grooves are carved into the PEC surface, with the AMC structure forming virtual boundaries. GGW is known for its low-loss characteristics and efficient power transfer, making it ideal for high-frequency applications that require minimal energy dissipation.

In GGW, the groove depth (d_g) and width (w_g) play critical roles in determining the guided wave properties. The cutoff frequency (f_c) is given by:

$$f_c = \frac{c}{2w_g}, \tag{2.6}$$

where c is the speed of light in the medium. By carefully designing the groove dimensions, GGW achieves excellent power-handling capabilities. In Figure 2.2 (b), a structure of a groove gap waveguide has been shown [15], [16], [18], [19].

2.3.3 Microstrip Gap Waveguide (MGW)

The Microstrip Gap Waveguide combines the principles of microstrip lines with the benefits of gap waveguide technology. The Microstrip Gap Waveguide merges the concepts of microstrip lines with the advantages of gap waveguide technology.

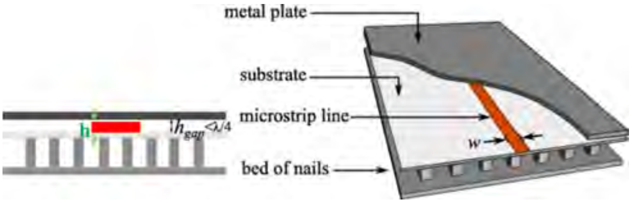


Figure 2.6: Microstrip gap waveguide geometry[25].

The characteristic impedance (Z_0) of microstrip guided waves (MGW) shares similarities with that of traditional microstrip lines; however, it experiences lower losses due to the artificial magnetic conductor (AMC) structure. This impedance can be expressed as:

$$Z_0 = \frac{1}{2\pi}\sqrt{\frac{\mu}{\epsilon}}\ln\left(1+\frac{4h}{w}\right), \tag{2.7}$$

where h represents the height of the microstrip above the AMC surface, and w denotes the width of the microstrip.

MGW is particularly advantageous for planar structures, offering compatibility with integrated circuit designs while maintaining low-loss performance [15], [18], [23], [26]–[28].

2.4. Other advantages of gap waveguide

Gap waveguides offer several other advantages over traditional waveguide technologies, making them highly desirable for modern high-frequency systems:

2.4.1. High Efficiency

Gap waveguides address issues associated with imperfect electrical contacts, which in conventional waveguides often lead to unwanted leakage. While ohmic losses may be similar in both gap waveguides and conventional waveguides, the design of gap waveguides helps minimize the leakage issues typically caused by these imperfections in electrical contacts. By minimizing surface currents and reducing resistive losses, they achieve superior efficiency, particularly at millimeter-wave frequencies. The elimination of electrical contact ensures that conduction losses, proportional to the square of the surface current density J_s, are significantly reduced:

$$P = \frac{1}{2} R_s \int |J_s|^2 \mathrm{d}A, \tag{2.8}$$

where P is the power loss, R_s is the surface resistance, and $\mathrm{d}A$ represents the surface area [15]–[18], [29].

2.4.2. Simplified Manufacturing

The design of gap waveguides is inherently tolerant to machining inaccuracies, which makes them highly suitable for scalable and cost-effective mass production. This tolerance enables the fabrication of gap waveguide components without compromising performance, even under relaxed manufacturing constraints. The elimination of electrical contacts further simplifies the manufacturing process, as precise alignment between layers is less critical. Even with machining tolerances, the gap height (h) between the artificial magnetic conductor (AMC) and perfect electric conductor (PEC) surfaces remains effective as long as it satisfies the condition:

$$h < \frac{\lambda}{4}. \tag{2.9}$$

This inherent flexibility allows gap waveguides to be made using different low-cost manufacturing methods, such as CNC milling, 3D printing, electric discharge machining (EDM), and plastic injection molding. For example, Palomares-Caballero et al. showed that 3D printing can successfully create millimeter-wave gap waveguide antennas, achieving great performance and emphasizing its potential for quick prototyping and affordable production [30]. Likewise, Yang et al. employed 3D printing to design dual-band filtering antennas, demonstrating its efficiency in producing compact and high-performance gap waveguide components for complex applications [31].

For high-precision applications, EDM processes have been successfully employed to produce multi-layer gap waveguide antennas, as demonstrated by Vosoogh et al., who highlighted the method's capability to achieve precise tolerances critical for high-frequency operations [27]. Additionally, plastic injection molding has proven effective for high-volume production of gap waveguide components. Bencivenni et al. showcased this method by manufacturing metallized plastic antennas, emphasizing its scalability and cost-efficiency for millimeter-wave systems [32]. Farjana et al. expanded on this work by combining injection molding with micromachining to realize a 140 GHz gap waveguide antenna, further demonstrating the versatility of low-cost manufacturing techniques [33].

The combination of these methods provides a comprehensive toolkit for manufacturing gap waveguides at varying scales and costs. This flexibility, coupled with the technology's inherent tolerance to machining imperfections, makes gap waveguides ideal for modern high-frequency applications where performance, scalability, and cost-effectiveness are critical.

2.4.3. Compact and Scalable

Gap waveguides support, multi-layer designs, making them ideal for complex antenna arrays and integrated systems. Their modular nature allows for scalability, enabling the design of compact systems that maintain high performance even in constrained spaces. By stacking multiple layers, gap waveguides achieve high levels of integration without compromising electromagnetic isolation between layers.

These advantages position gap waveguides as a transformative solution for next-generation communication and sensing applications, where efficiency, reliability, and scalability are paramount[17], [24], [26], [28], [34]–[36].

2.5. Applications in Antenna Design

Gap waveguides have transformed antenna design, especially in millimeter-wave and high-frequency systems, where traditional technologies encounter considerable difficulties. Their versatility is evident in three key applications:

2.5.1. Millimeter-Wave Antennas

Gap waveguides are ideally suited for frequencies above 20 GHz, where traditional waveguides struggle due to increased ohmic losses and manufacturing complexities. At millimeter-wave frequencies, the reduction of electrical contact losses in gap waveguides becomes critical, enabling efficient transmission and high-power handling. The accurate control of electromagnetic fields in the guiding structures ensures that signal degradation is kept to a minimum, even at high frequencies. This quality makes gap waveguides crucial for radar systems, satellite communication, and the new 5G networks that operate in the millimeter-wave spectrum[12], [15], [16], [19].

2.5.2. High-Gain Arrays

Gap waveguides enable the design of high-gain phased arrays by offering compact and efficient feeding networks. These feeding networks are characterized by low mutual coupling among antenna elements, which is crucial for preserving beam integrity and reducing sidelobe levels. The implementation of ridge gap waveguides (RGWs) in phased arrays facilitates highly compact configurations while maintaining reliable performance across a broad bandwidth. The mutual coupling (S_{12}) between elements is minimized due to the electromagnetic isolation provided by the AMC structures, enhancing the efficiency and gain of the array [12], [16]–[19].

2.5.3. Dual-Band Antennas and beam scanning antennas

The integration of filtering and dual-band functionalities in a single structure is simplified with gap waveguides. The inherent versatility of groove and microstrip gap waveguides allows the incorporation of frequency-selective surfaces (FSS) and bandpass filters directly within the antenna design. This reduces the overall size and complexity of the system while maintaining high performance. Dual-band capability is achieved by designing the dimensions of the gap waveguide to support two distinct frequency bands, effectively creating a multifunctional antenna system[15]–[17], [20], [37], [38].

In summary Gap waveguides have become a promising technology in advancing modern antenna designs, offering solutions to key challenges in high-frequency and millimeter-wave systems. Their versatility and robust performance make them essential for a range of applications. One critical area where gap waveguides excel is in the development of planar high-efficiency millimeter-wave antennas. These antennas operate at frequencies above 20 GHz, where traditional waveguides often struggle with increased leakage losses and manufacturing complexities. Gap waveguides address these issues by eliminating electrical contacts and minimizing resistive losses, enabling efficient energy transmission. This capability is vital for radar systems, satellite communication, and next-generation 5G networks, which demand high efficiency and reliability in the millimeter-wave spectrum.

In the context of high-gain phased arrays, gap waveguides facilitate the design of compact and efficient feeding networks that minimize mutual coupling between array elements. This is crucial for maintaining beam integrity, reducing sidelobe levels, and achieving high array efficiency. The electromagnetic isolation provided by the artificial magnetic conductor (AMC) structures ensures consistent performance across a wide bandwidth, making ridge gap waveguides (RGWs) particularly suited for phased-array configurations. The ability to manage mutual coupling, quantified by reduced S_{12} coupling coefficients, directly translates into improved gain and overall radiation performance.

Gap waveguides also simplify the integration of dual-band functionalities in antenna systems. By utilizing the flexibility of groove and microstrip gap waveguides, designers can incorporate frequency-selective surfaces (FSS) and bandpass filters directly within the antenna structure [39]. This approach minimizes the overall size and complexity of the system while maintaining high performance. Dual-band operation is particularly advantageous for combined RX-TX systems, where gap waveguides enable efficient frequency separation and minimize crosstalk. This results in robust and reliable operation across multiple frequency bands.

Moreover, gap waveguides play an important role in advanced beam-steering designs, supporting innovative feeding techniques for precise control in both one-dimensional (1D) [40], [41] and two-dimensional (2D) beam-steering applications. The precision achieved in beamforming is further enhanced by the low mutual coupling and high isolation provided by the AMC structures. This is critical for applications such as satellite tracking, automotive radar, and adaptive communication systems that rely on dynamic and accurate beam direction.

In addition to enabling precise beam steering, gap waveguides contribute to low sidelobe levels, a critical factor in improving overall radiation performance. Advanced decoupling methods inherent in gap waveguide designs suppress unwanted radiation and reduce interference, ensuring clean and efficient signal propagation [30], [42], [43]. This feature is particularly important in scenarios where interference mitigation and radiation purity are paramount, such as in high-density communication networks and sensitive sensing applications.

Together, these abilities show the significant effect of gap waveguides in antenna design. By tackling the issues of efficiency, size, scalability, and accuracy, gap waveguides not only improve current designs but also open up new possibilities for advanced solutions in high-frequency communication and sensing systems.

2.5.4. Packaging and Integration of RF Electronics

Gap waveguide technology provides a notable benefit in the packaging and integration of RF electronics. The contactless and adaptable mechanical design facilitates the effortless combination of active RF components, such as amplifiers, oscillators, and mixers, with passive waveguide elements like filters, couplers, and antennas. This capability is especially advantageous in millimeter-wave systems, where merging active and passive components frequently encounters difficulties due to cavity resonances and unwanted coupling.

The use of artificial magnetic conductors (AMCs) and periodic structures in gap waveguides suppresses unwanted cavity modes in active RF front-end modules, enhancing the electromagnetic isolation between components [44]–[46]. This capability simplifies the design of compact, interference-free modules, making gap waveguides ideal for high-frequency systems requiring precise control of electromagnetic waves.

Moreover, the multi-layer assembly of gap waveguide components is inherently advantageous for developing compact RF wireless modules. By enabling vertical stacking of layers, gap waveguides facilitate the creation of dense, space-saving designs while maintaining excellent performance. This approach is highly effective for applications in point-to-point backhaul links, automotive radar, and adaptive communication systems, where miniaturization and efficiency are critical [35], [47], [48]. These multi-layer configurations also enable the integration of complex feeding networks and diplexers, further extending the utility of gap waveguide technology in advanced RF systems.

In addition to the benefits of integration, the contactless nature of gap waveguides reduces manufacturing limitations. This allows for the use of affordable fabrication methods, including CNC milling, 3D printing, and injection molding. As a result, gap waveguide technology becomes a practical option for the large-scale production of high-performance wireless modules.

2.5.5. Enhanced Role in Advanced Beam-Steering Designs

Moreover, gap waveguides play a pivotal role in advanced beam-steering designs, supporting innovative feeding techniques for precise control in both one-dimensional (1D) [40], [41] and two-dimensional (2D) beam-steering applications. The precision achieved in beamforming is further This level of control is critical (2D) beam-steering applications.

In addition to enabling precise beam steering, gap waveguides significantly contribute to achieving low sidelobe levels, an essential factor in improving overall radiation performance. Advanced decoupling methods inherent in gap waveguide designs suppress unwanted radiation and reduce interference, ensuring clean and efficient signal propagation [30], [42], [43]. This feature is particularly valuable in high-density communication networks and sensitive sensing applications, where radiation purity and interference mitigation are paramount.

Gap waveguides also help in designing antennas that can scan widely, allowing systems to cover broader angles without losing much performance. This is especially important in adaptive and multifunctional systems where the smooth combination of wide-angle scanning with beam steering improves operational flexibility.

Together, these capabilities highlight the transformative potential of gap waveguides in advanced RF systems. By tackling the challenges of integration, efficiency, compactness, scalability, and precision, gap waveguides not only improve existing designs but also create opportunities for innovative solutions in high-frequency communication and sensing systems.

CHAPTER 3

Design and Analysis of a Circularly Polarized Array Antenna Using Ridge Gap Waveguide Technology

3.1. Introduction

The field of satellite communication has experienced significant advancements, particularly with the adoption of millimeter-wave technologies at the Ka-band (26.5–40 GHz) frequency ranges. These developments address the increasing demand for rapid and dependable data transfer in diverse applications, such as global connectivity solutions and sophisticated remote sensing and Earth observation tasks. The importance of this research area is underscored by the pressing need to develop efficient, compact, and scalable antenna solutions to address challenges associated with millimeter-wave frequencies, including high path loss, narrow beamwidth, and manufacturing complexities[49].

Focusing on ridge gap waveguide (RGW) technology, this study highlights its transformative role in enabling high-performance antennas. RGW structures provide unique advantages, such as contactless layer integration and reduced ohmic losses, which make them particularly suited for millimeter-wave and Ka-band applications. These features facilitate the design of compact, high-gain antennas while maintaining low sidelobe levels and wide operational bandwidths. The ability to incorporate dual-band and beamforming functionalities further expands RGW's application scope, catering to next-generation satellite communication systems.

Motivated by the challenges and opportunities within satellite communication, this research aims to bridge the gap between current technological limitations and application demands. By utilizing RGW technology, the study addresses the pressing need for efficient high gain, compact array configurations, and robust operation at Ka-band frequencies. The findings are expected to contribute significantly to the field of satellite communications, laying a foundation for advancements in global connectivity and millimeter-wave system integration[12], [50].

3.2. State-of-the-Art in Antenna Design

3.2.1 Overview of Antenna Types

The choice of antenna types is an important step in achieving circular polarization (CP) in advanced communication systems, especially for satellite and millimeter-wave applications where performance requirements are high. Antennas must balance aspects such as efficiency, bandwidth, and polarization purity while also considering practical limitations like size, cost, and manufacturing complexity. This section offers a detailed comparison of common antenna technologies, assessing their performance, limitations, and overall suitability for CP operation in these demanding environments. By recognizing the trade-offs present in each type, this analysis emphasizes the need for customized solutions that match specific application needs.

3.2.2 Microstrip Antennas

Microstrip antennas are commonly used because they are small, lightweight, and easy to integrate with flat circuit designs. They use printed technology, which makes them affordable for mass production. However, microstrip circularly polarized (CP) antennas often experience lower radiation efficiency due to losses in the dielectric and conductor materials. Their performance at higher frequencies, such as in the Ka-band, is additionally affected by surface wave losses, which limits their use in systems that require high gain and high efficiency. Moreover, their bandwidth is usually narrow, necessitating compli-

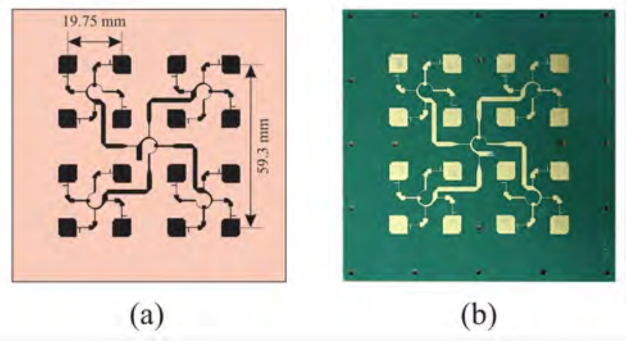


Figure 3.1: A 4 × 4 CP array antenna: (a) Optimized design. (b) Photo of prototype [51]

cated design changes to achieve wider impedance and axial ratio bandwidths, which can make production more difficult and raise costs [16], [18], [20], [52].

3.2.3 Spiral Antennas

Spiral antennas are notable for their broadband CP capabilities and ability to maintain polarization purity over wide frequency ranges, making them ideal for applications requiring dual-band or adaptive frequency performance. Their wide operational bandwidth and consistent radiation patterns provide reliable performance in dynamic environments[53], [54]. However, the inherently complex design and challenging manufacturing processes not only increase costs

Figure 3.2: A square 8 × 8 helical antenna array. [55]

but also limit their scalability, particularly in compact or densely packed arrays. Furthermore, their larger footprint compared to other CP antenna types can restrict their integration into systems with stringent space constraints[13], [56].

3.2.4 Reflect arrays

Reflect arrays are attractive because they can provide high gain and precise beam shaping, which makes them suitable for advanced communication and radar systems. By utilizing flat surfaces with individual phase control elements, they offer significant flexibility in directing and steering beams without requiring any mechanical movement. This flexibility is a major advantage for dynamic or multi-beam situations [37], [57]. However, at millimeter-wave frequencies, reflect arrays often show low radiation efficiency due to phase mismatches, which occur from sampling errors in phase control. Additionally, their performance is highly sensitive to manufacturing inaccuracies, such as surface roughness or misalignment of elements, which can diminish beam quality and reduce overall reliability. These limitations present challenges for their implementation in high-frequency, high-precision applications where efficiency and consistency are critical [58], [59].

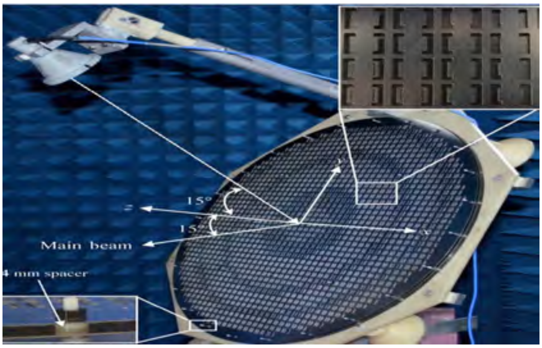


Figure 3.3: a planar reflect array. [60]

3.2.5 Conventional Waveguides

Conventional waveguide-based CP antennas are well-known for their high radiation efficiency and broad bandwidth capabilities, making them a popular choice for high-power and high-frequency applications like satellite communication and radar systems. Their capacity to manage high power levels and maintain consistent polarization purity across wide frequency ranges distinguishes them from other antenna types [12], [18]. However, these benefits are accompanied by manufacturing challenges that demand precise machining and assembly techniques. The use of high-quality materials also raises production costs. Moreover, the inherently large structure of waveguide-based designs creates significant challenges in achieving compact and lightweight configurations, which limits their integration into densely packed systems or cost-sensitive applications. These limitations require alternative solutions for modern systems that need miniaturization and affordability without sacrificing performance [16], [17], [27].

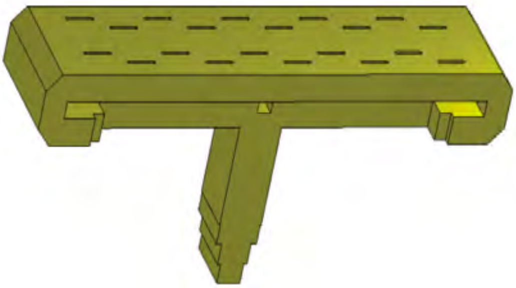


Figure 3.4: Geometry of 2 × 10 planar broadband SWA antenna with differential feeding mechanism [61].

3.3. Challenges in Current Designs

3.3.1 Surface Wave and Leakage in PCB-Based Antennas

PCB-based antennas are widely used in millimeter-wave systems due to their light weight and compact form factor. Nevertheless, at higher frequencies, these designs encounter major difficulties concerning surface waves and energy leakage [62].

Surface waves are generated due to the interaction of electromagnetic fields with the substrate. At millimeter-wave frequencies, these waves cause energy to propagate laterally within the PCB, leading to high substrate losses and degraded radiation efficiency. This issue becomes more serious with high-permittivity substrates, where the confinement of surface waves is greater, lowering the performance of the antenna even more.

Leakage currents in PCB-based antennas also present a critical issue. Imperfections in fabrication, such as uneven etching and misalignment, exacerbate unwanted electromagnetic leakage, which distorts radiation patterns and lowers overall efficiency. These challenges necessitate innovative solutions, including the use of advanced materials, precise fabrication techniques, and proper ground plane design, to mitigate these losses and enhance the performance of PCB-based antennas[63]–[65].

3.3.2 Leakage in Waveguide-Based Antennas for Non-Perfect Electric Contacts

Waveguide-based antennas are recognized for their high efficiency and low loss features, which make them suitable for applications at high frequencies. However, at millimeter-wave frequencies, the performance of these antennas can be greatly influenced by leakage due to imperfect electrical contacts.

In traditional waveguides, electrical connections between metallic surfaces are vital for ensuring proper electromagnetic confinement. Manufacturing imperfections, like uneven surfaces or misaligned joints, create gaps at the interface, which leads to energy leakage. This phenomenon not only lowers efficiency but also brings about phase errors, which degrade beam quality and raise sidelobe levels.

Ridge Gap Waveguide (RGW) technology offers an innovative solution to this problem. By eliminating the need for direct electrical contact between metal surfaces, RGW structures effectively suppress leakage currents while maintaining high efficiency. The use of artificial magnetic conductors (AMCs) and ridged structures ensures proper wave confinement, even with loose tolerances in manufacturing, making RGW-based antennas a robust alternative to traditional waveguide designs [39], [66]–[68].

3.4. Advancements in RGW-Based Antennas

Ridge Gap Waveguide (RGW) technology has transformed the design and use of antennas in millimeter-wave systems by addressing important performance issues, especially those linked to surface wave and substrate losses. Traditional antenna systems often suffer significant energy loss because of these challenges, particularly at higher frequencies like the Ka-band. RGW technology removes the requirement for continuous conductive connections between layers by utilizing artificial magnetic conductors (AMCs) and ridge structures, which effectively reduce surface waves. This results in lower substrate-related losses, improving radiation efficiency and ensuring stable performance across a wide frequency range[16], [17].

Beyond its loss-reduction capabilities, RGW technology offers exceptional integration advantages for RF systems. The contactless nature of its design simplifies the connection between components, enabling seamless integration with other RF elements such as power dividers, filters, and diplexers. This configurable reduces system complexity and enhances overall reliability [12], [18].

Moreover, RGW technology supports cost-effective manufacturing methods, including CNC milling, injection moulding, and 3D printing, making it viable for large-scale production. Its design inherently tolerates machining imperfections, further driving down manufacturing costs without compromising performance. The multi-layer configuration capability of RGW allows for compact and efficient designs, enabling the realization of dense antenna arrays and sophisticated RF systems. This facilitates the development of high-gain, high-efficiency antennas suited for applications such as satellite communication, automotive radar, and next-generation wireless networks[15], [27], [36], [69].

3.5. Challenges in Current Designs

- **Efficiency and Scalability**
  Achieving high radiation efficiency at millimeter-wave (mmWave) frequencies presents a significant challenge due to inherent losses and limitations in traditional antenna designs. At these frequencies, surface wave losses, conductor losses, and dielectric losses substantially degrade the overall system efficiency. Furthermore, the compact nature of millimeter-

wave systems increases these issues, as the proximity of components can lead to increased mutual coupling and interference. These challenges necessitate innovative approaches to ensure that the radiation efficiency remains high without compromising other performance metrics [70], [71].

In large antenna arrays, such as those employed in Ka-band satellite communication systems, the scalability of the design is equally critical. One of the primary limitations lies in the complexity of power divider configurations. Traditional power divider networks, such as series-fed or corporate-fed structures, encounter significant challenges in maintaining uniform power distribution across large arrays. These include phase mismatches, amplitude imbalances, and increased insertion losses, which degrade the overall radiation performance of the array. Moreover, the physical size of traditional power divider networks often limits their application in densely packed arrays, making them unsuitable for compact and high-performance systems[72]–[74].

Ridge Gap Waveguide (RGW) technology addresses these challenges by providing a highly efficient and scalable solution. Its ability to suppress surface wave and substrate losses directly improves radiation efficiency, making it well-suited for mmWave applications. The unique contactless design of RGW enables compact and low-loss power divider configurations, overcoming the limitations of traditional approaches. By incorporating features like ridge-loaded cavities and optimized coupling slots, RGW-based designs ensure uniform phase and amplitude distribution across the array, minimizing sidelobe levels and enhancing gain. Additionally, the modular nature of RGW facilitates the seamless scaling of arrays to larger configurations without compromising efficiency or introducing fabrication complexities [42], [75], [76].

In our work, these principles are applied to the design of a high-efficiency Ka-band circularly polarized array, addressing the challenges of power distribution and scalability in large arrays. The use of an RGW-based power divider, combining T-junctions and H-junctions, ensures even power distribution to all elements while maintaining a compact and efficient layout. This innovative approach not only enhances the radiation performance of the array but also demonstrates the potential for scalability in future satellite communication systems.

By addressing both efficiency and scalability, our work exemplifies how advanced design methodologies can overcome the limitations of traditional systems, paving the way for next-generation mmWave antennas.

- **Design Complexity and Cost**

  Designing efficient antennas at millimeter-wave (mmWave) frequencies comes with significant challenges related to complexity and cost, particularly in traditional waveguide-based systems. Conventional waveguides, while offering excellent efficiency and bandwidth, require high precision in fabrication to maintain performance at mmWave frequencies. The need for precise dimensional tolerances to prevent performance degradation due to phase mismatches and unwanted mode generation significantly increases manufacturing complexity.

  Traditional manufacturing methods, such as CNC milling, must achieve extremely tight tolerances to maintain the integrity of the waveguide structure at high frequencies. While effective, these methods are costly, particularly for intricate designs with multi-layer configurations or complex feeding networks. Similarly, while 3D printing has emerged as a potential solution for prototyping and small-scale production, the precision required for mmWave applications often necessitates post-processing steps, such as surface metallization, further increasing costs and complexity [77]–[79].

  In contrast, Ridge Gap Waveguide (RGW) technology provides a more efficient approach by inherently simplifying the manufacturing process. The contactless nature of RGW structures reduces the need for precise alignment between layers, relaxing tolerance requirements. Furthermore, RGW's compatibility with a variety of manufacturing techniques, such as CNC milling, 3D printing, and injection moulding, offers flexibility in balancing performance and cost. This adaptability is particularly beneficial for large-scale production, where cost-effectiveness is paramount [36], [80].

  our work illustrates the practical advantages of RGW technology in addressing these challenges. By utilizing a compact RGW-based design, the need for complex mechanical connections is eliminated, simplifying the fabrication process. Additionally, the use of cost-effective manufacturing techniques, such as CNC milling with relaxed tolerances, demonstrates how high-performance mmWave antennas can be achieved without prohibitive costs. This approach highlights the potential for RGW technology to reduce design complexity and manufacturing expenses while maintaining the strict performance requirements necessary for Ka-band satellite communication systems.

By addressing design complexity and cost, our research highlights the practicality of RGW technology as a feasible alternative to traditional waveguides, creating the way for affordable and efficient solutions in modern communication systems.

3.6. Justification for the Research

The increasing need for satellite communication and millimeter-wave systems necessitates advancements in antenna design that address key challenges such as efficiency, scalability, and manufacturability. This research directly responds to these challenges by introducing innovative design features and methods, particularly emphasizing the application of Ridge Gap Waveguide (RGW) technology for high-performance Ka-band antennas.

One of the key contributions of this work is the utilization of novel radiating elements, such as U-shaped slots combined with bone-shaped coupling slots. These elements are strategically designed to optimize circular polarization (CP) performance by improving axial ratio bandwidth while maintaining compactness. The U-shaped slot, in particular, facilitates efficient radiation and wide bandwidth in a compact form factor, making it ideal for space-constrained satellite applications. The bone-shaped coupling slot further enhances this design by providing efficient energy transfer while reducing mutual coupling, ensuring consistent performance across the antenna array. This innovative combination of radiating and coupling elements advances CP antenna design for mmWave applications [17], [81], [82].

Additionally, this research proposes innovative feeding and power divider designs utilized for RGW-based antennas. The compact feeding network, integrating ridge-loaded cavities and optimized coupling mechanisms, ensures uniform power distribution and minimizes phase and amplitude variations among radiating elements. The use of T-junctions and H-junctions in the power divider design not only enhances impedance matching but also supports scalability, enabling the development of large, high-gain arrays with minimal sidelobe levels. These features directly address the limitations of traditional feeding networks, which often suffer from high insertion losses and design complexity in large arrays.

The adoption of RGW technology in this research also provides significant benefits in terms of compact, efficient, and cost-effective designs. By eliminating the need for electrical contacts and minimizing surface wave and substrate losses, RGW technology inherently improves radiation efficiency and reduces complexity. Furthermore, its compatibility with a variety of manufacturing techniques, such as CNC milling and 3D printing, enables cost-effective fabrication with relaxed tolerance requirements. These advantages make RGW-based designs not only high-performing but also practical for large-scale production, addressing the economic and performance constraints of modern satellite communication systems.

3.7. Literature Gaps

Despite significant advancements in millimeter-wave (mmWave) and Ka-band antenna technologies, several critical gaps remain in the existing literature, particularly in the context of Ridge Gap Waveguide (RGW)-based designs. Addressing these gaps is essential for advancing the state of the art and enabling high-performance systems for satellite communication and other high-frequency applications.

One major gap lies in the lack of well-documented decoupling techniques for slot arrays with tight element spacing. As antenna arrays become more compact to accommodate higher densities and miniaturization requirements, mutual coupling between elements becomes a critical issue. High levels of coupling degrade radiation performance, resulting in increased sidelobe levels and reduced efficiency. While existing studies propose methods for decoupling in conventional waveguide and microstrip arrays, there is limited research focused on techniques adapted to RGW slot arrays. This oversight restricts the development of high-gain, tightly packed arrays that are crucial for satellite communication and radar systems operating at mmWave frequencies.

By addressing these gaps, this research contributes to the advancement of RGW-based antenna systems. Novel decoupling techniques for tightly spaced arrays and scalable designs enabling wide-angle scanning represent critical areas of innovation that enhance the practical applicability and performance of RGW technology in modern communication and radar systems.

3.8. Proposed Work

This research focuses on addressing significant challenges in high-frequency antenna systems by utilizing Ridge Gap Waveguide (RGW) technology. The goal is to create compact and efficient designs suitable for Ka-band and millimeter-wave (mmWave) applications. The proposed work presents new solutions to address current limitations related to high gain, high efficiency, and scalability. In doing so, it turns recognized gaps in the literature into opportunities for progress.

3.7.1 Compact RGW-Based Designs for Ka-Band and mm-Wave Frequencies

The primary objective is to design high-efficiency, circularly polarized (CP) antennas that operate at Ka-band and mmWave frequencies. The proposed designs integrate compact RGW technology, which eliminates surface wave and substrate losses while enabling highly efficient radiation. Key innovations include the use of U-shaped slots and bone-shaped coupling slots, which enhance the bandwidth of the axial ratio and maintain excellent impedance matching.

The U-shaped design is based on its ability to provide several key advantages. Its symmetric structure supports effective circular polarization, its compact shape enhances the antenna's applicability in space-constrained applications, and its configuration allows for broader bandwidth and superior impedance matching. Additionally, the U-shaped element simplifies the antenna's feeding mechanism, which reduces manufacturing complexity and cost while improving reliability. These characteristics collectively make the U-shaped antenna highly suitable for advanced communication systems where performance and efficiency are important. The antenna design incorporates a short ridge that is excited via a bone-shaped coupling slot adjacent to it on the middle layer. This is overlaid by a U-shaped radiating slot positioned on the top plate. Strategically placed periodic pins around the U-shaped slot on the middle layer form a cavity, crucial for establishing a stop band that selectively blocks specific frequencies from passing through while allowing others to pass. The cavity at the back of the antenna plays a critical role, enabling focused radiation in the +z direction.

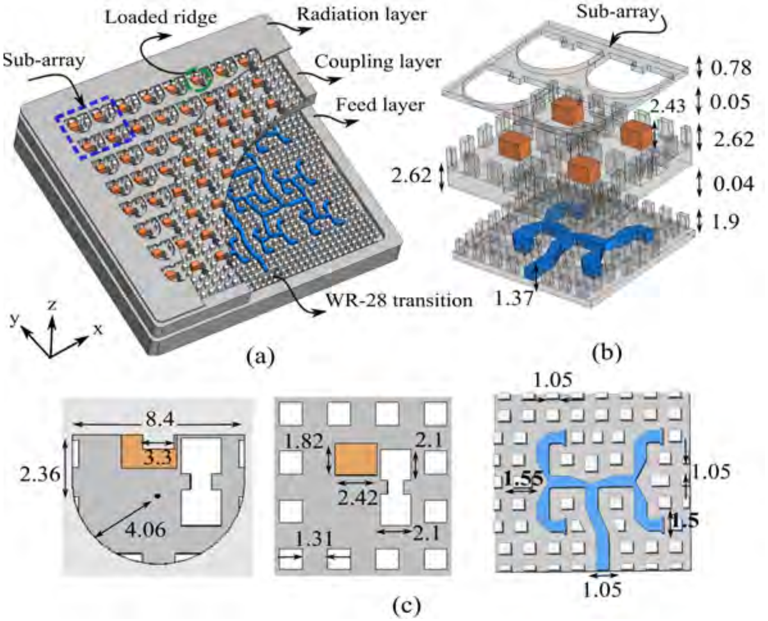


Figure 3.5: (a) Full structure. (b) 2 × 2 subarray. (c) U-shaped element and subarray.

Another key feature of this design is the introduction of asymmetry in the cavity layer by the introduction of the short ridge next to the feeding slot, which creates an electric field (E-field) distribution with nearly identical magnitudes and a 90-degree difference in phase between the two E-field components E_x and E_y in the cavity. Here, E_x and E_y refer to the components of the E-field in x and y directions, respectively. By exciting the cavity shown in Fig. 3.5, right-hand circular polarization (RHCP) is achieved. Fig. 3.6 shows the E-field distribution at different phases across the U-shaped slot when the coupling slot is excited. By examining this at varied time phases within one cycle, a noticeable E-field rotation can be seen, which indicates that the element radiates with RHCP.

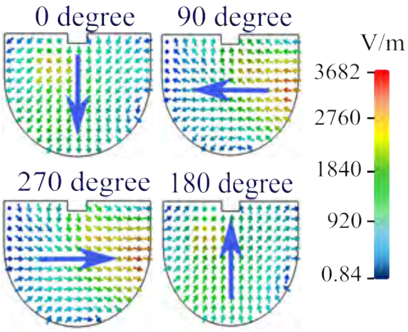
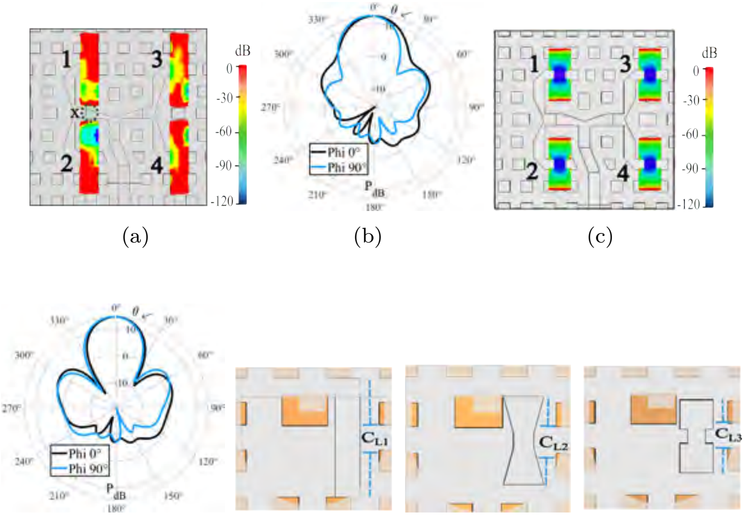


Figure 3.6: E-field distribution

As shown in Figure 3.5.(c), a U-shaped radiating element serves as the radiating component in this design. This element features a cavity-backed configuration enhanced by a ridge. The cavity is activated through a ridge that uses a bone-shaped coupling slot for feeding.

3.7.2 Optimization of Coupling Slot Geometries for Antenna Design

Different coupling slot geometries were studied to optimize design, balancing size with cut-off frequency. This analysis was crucial for understanding how a slot's dimensions affect its electromagnetic properties, particularly resonant frequency. Three geometries were evaluated: rectangular, bowtie, and bone-shaped, shown in Fig. 3.7 (e)-(g). These designs were assessed for impedance-matching, compactness, and overall antenna performance.



(a) (b) (c)

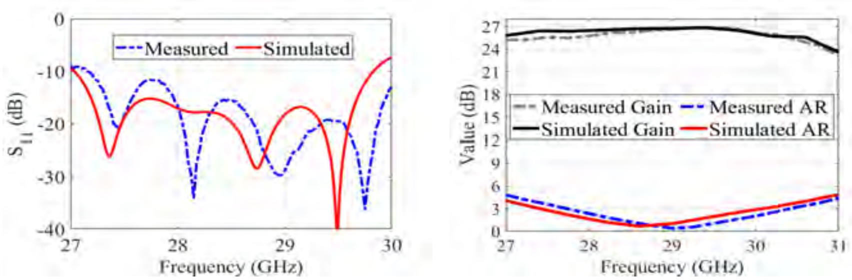
(d) (e) (f) (g)

Figure 3.7: (a) E-field distribution on rectangular coupling slot. (b) 2D radiation pattern for rectangular coupling slot. (c) E-Field distribution on bone-shaped coupling slot. (d) 2D radiation pattern for bone-shaped coupling slot. (e) Rectangular-shaped coupling slot (C_{L1}= 6.1mm). (f) Bowtie-shaped coupling slot (C_{L2}= 5.02mm). (g) Bone-shaped coupling slot (C_{L3}= 4.76mm).

3.7.3 Overall performance

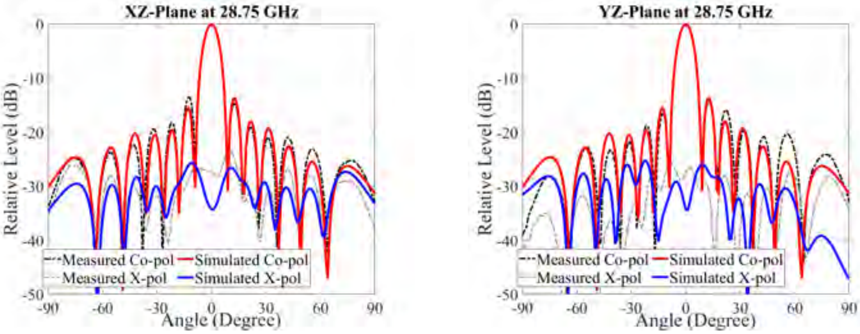
Upon completing the design and validation of the sub-array results, a 64-element array was deisgned to demonstrate scalability and practical performance. The complete structure was meticulously realized using Ridge Gap Waveguide (RGW) technology and simulated to ensure alignment with design specifications. For physical validation, the array was fabricated through conventional CNC milling, ensuring the structural and electromagnetic integrity required for high-frequency operations. Measurements were conducted in an anechoic chamber to evaluate key performance metrics under anechoic condition.

The validation process included a thorough examination of the array's operating frequency range, axial ratio, and radiation efficiency over the bandwidth. The figures 3.8 to 3.10 presented illustrate these parameters clearly, demonstrating the array's capacity to maintain circular polarization (axial ratio below 3 dB) and reach high efficiency across the bandwidth. The measured results closely match the simulated data, verifying the design's reliability and the success of the proposed methods. This successful implementation highlights the practical usefulness of the design for high-performance Ka-band satellite communication systems.



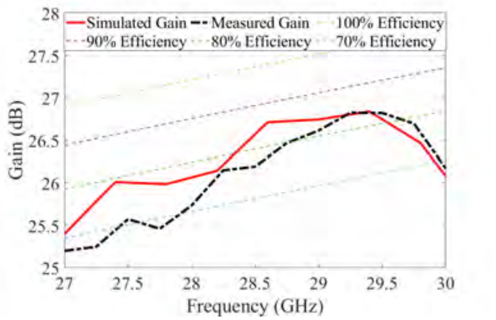
(a) (b)

Figure 3.8: (a) Comparison of measured and simulated S_{11}. (b) Simulated and measured values of realized gain and axial ratio.



(a) (b)

Figure 3.9: Comparison of far-field results in different planes at the centre frequency: (a) XZ-Plane. (b) YZ-Plane.



(a)

Figure 3.10: Radiation efficiency of the designed and manufactured array antenna.

3.9. Summary

This chapter has reviewed the current state of the art in antenna design for millimeter-wave (mmWave) and Ka-band applications, focusing on Ridge Gap Waveguide (RGW) technology and its potential to address critical challenges in high-frequency systems. The insights from the literature highlight several key advancements and limitations:

- **Advancements in Antenna Technologies**
  Various antenna designs, including microstrip, spiral, reflect arrays, and conventional waveguides, have been explored for circular polarization (CP). While each offers unique benefits, limitations such as low radiation efficiency, design complexity, and high manufacturing costs underscore the need for innovative solutions.

- **Strengths of RGW Technology**
  RGW technology emerges as a transformative solution, effectively mitigating surface wave and substrate losses, simplifying manufacturing processes, and enabling scalable, compact designs. Its versatility and efficiency make it well-suited for mmWave and Ka-band applications, particularly in satellite communication and beamforming systems.

- **Identified Literature Gaps**
  The review identified gaps in compression techniques for tightly spaced

slot arrays and the absence of practical demonstrations showcasing the efficiency of RGW-based designs for fixed-beam applications. These limitations present opportunities for further optimization and innovation.

- **Proposed Research Directions**
  Building on these insights, this research proposes compact RGW-based designs with a focus on cost-effective and scalable configurations to address the identified gaps. The emphasis is on developing high-efficiency antenna systems that meet the demanding requirements of modern communication technologies.

This chapter establishes the foundation for the subsequent research, which focuses on leveraging RGW technology to overcome existing challenges and advance antenna designs for mmWave and Ka-band systems. The following chapters will detail the methodologies, proposed designs, and experimental validations that aim to realize these objectives.

Further details of the discussion are given in **Paper C**.

CHAPTER 4

Summary of included papers

This chapter provides a summary of the included papers.

4.1. Paper A

Raha Roosefid, Sadegh Mansouri Moghaddam, Lukas Nyström, Jian Yang, Ashraf Uz Zaman
A 2×2 Ka-Band Wideband Circularly Polarized Sub-Array Antenna Based on U-shaped Slots and Gap Waveguide Technology
Published in 2023 IEEE International Symposium on Antennas and Propagation (ISAP),
Date of Conference: 30 October 2023 – 02 November 2023
©DOI: 10.1109/ISAP57493.2023.10388825
Conference Location: Kuala Lumpur, Malaysia .

This paper presents a 2×2 Ka-band wideband circularly polarized sub-array antenna leveraging U-shaped slots and gap waveguide technology. The design achieves a low axial ratio below 3 dB, a gain of 12.3 dBi at 31.5 GHz, and low sidelobe levels across a bandwidth of 28–34.6 GHz. The compact, planar structure ensures high efficiency and cost-effective fabrication. It provides a promising solution for next-generation satellite communication systems.

4.2. Paper B

Raha Roosefid, Jian Yang, Ashraf Uz Zaman
Compact Circularly Polarized Antenna based on Gapwaveguide for SATCOM Applications
Published in 2024 18th European Conference on Antennas and Propagation (EuCAP),
Date of Conference: 17–22 March 2024
©DOI: 10.23919/EuCAP60739.2024.10501326
Conference Location: Glasgow, United Kingdom .

This paper presents a novel compact U-shaped slot antenna array operating in the Ka-band for satellite communication applications. The design integrates a ridge-loaded cavity structure with a corporate feed network, achieving excellent axial ratio (AR) and impedance bandwidths. Simulated results demonstrate a peak gain of 27 dBi with sidelobe levels below -13 dB across the 27.5–30 GHz band. The proposed antenna provides a high-efficiency, cost-effective solution for next-generation satellite systems.

4.3. Paper C

Raha Roosefid, Sadegh Mansouri Moghaddam, Lukas Nyström, Jian Yang, Ashraf Uz Zaman
Development of a High-Efficiency Circularly Polarized Ka-Band Satcom Antenna Utilizing Ridge-loaded U-shaped Radiator
Published in IEEE Antennas and Wireless Propagation Letters,
vol. xx, no. xx, pp. 1–5, Nov. 2024
©IEEE DOI: 10.1109/LAWP.2024.3506452 .

The paper introduces a novel, high-efficiency circularly polarized Ka-band Satcom antenna leveraging ridge-loaded U-shaped radiators. This two-layer cavity-backed slot array utilizes Ridge Gap Waveguide (RGW) technology to minimize substrate and surface wave losses. The proposed design achieves a circular polarization bandwidth of 8.6% (27.5–30 GHz), a peak gain of 27 dBi, and a sidelobe level below -13 dB, making it suitable for geostationary satellite applications. Key innovations include a U-shaped radiator, a bone-shaped coupling slot, and a compact corporate feeding network, enabling superior impedance matching and radiation performance.

4.4. Paper D

Raha Roosefid, Esperanza Alfonso Alós, Thomas Schäfer, Jian Yang, Ashraf Uz Zaman
Compact Microstrip Line to Gap Waveguide Transition suitable for Beam Steering Antenna Applications at K-band
Accepted in Eucap 2025, Dec. 2024,
Date of Conference: 31 March 2025 – 04 April 2025
©
Conference Location: Stockholm, Sweden .

This paper presents a novel microstrip-to-waveguide transition specifically designed for beam steering antenna applications at K-band frequencies. Utilizing gap waveguide technology, the design ensures efficient signal transmission with minimal loss and seamless integration between planar circuits and waveguide structures. A bone-shaped coupling slot and a "bed-of-nails" structure are employed to optimize energy transfer and suppress undesired radiation. Simulated results demonstrate excellent performance, achieving a bandwidth of 12.7% (17.4–19.75 GHz) with an insertion loss below 0.45 dB. The transition's compactness and high efficiency make it ideal for modern beamforming and scanning antenna systems.

CHAPTER 5

Concluding Remarks and Future Work

This thesis presents the design and development of a circularly polarized array antenna utilizing Ridge Gap Waveguide (RGW) technology for Ka-band satellite communication. The proposed design features a compact and efficient cavity-backed slot array, achieving high gain and excellent polarization purity. The work demonstrates the feasibility and advantages of RGW-based antenna solutions for satellite applications in the Ka-band.

Future work will aim to enhance the design by achieving broader bandwidths and developing a dual-band RX-TX antenna capable of supporting both transmission and reception band. Additionally, efforts will focus on creating a dual-band antenna with advanced 1-dimensional beam-steering capabilities to further improve versatility and performance.

References

[1] S. Mener, R. Gillard, and L. Roy, "A dual-band dual-circular-polarization antenna for ka-band satellite communications," *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 274–277, 2017.

[2] J. F. Zhang, T. J. Li, and Y. J. Cheng, "K-/ka-band circular-polarized shared-aperture phased array antenna for satellite communication," in *2022 IEEE Conference on Antenna Measurements and Applications (CAMA)*, 2022, pp. 1–3.

[3] H. Zhao, P. F. Gu, Z. H. Fan, *et al.*, "Ultrawideband dual circularly polarized waveguide array antenna for k- and ka-bands satellite communications," *IEEE Antennas and Wireless Propagation Letters*, vol. 22, no. 8, pp. 1808–1812, 2023.

[4] T. S. Rappaport, Y. Xing, O. Kanhere, *et al.*, "Wireless communications and applications above 100 ghz: Opportunities and challenges for 6g and beyond," *IEEE access*, vol. 7, pp. 78 729–78 757, 2019.

[5] B. Di, L. Song, Y. Li, and H. V. Poor, "Ultra-dense leo: Integration of satellite access networks into 5g and beyond," *IEEE Wireless Communications*, vol. 26, no. 2, pp. 62–69, 2019.

[6] L. Bariah, L. Mohjazi, S. Muhaidat, *et al.*, "A prospective look: Key enabling technologies, applications and open research topics in 6g networks," *IEEE access*, vol. 8, pp. 174 792–174 820, 2020.

[7] X. Gu, D. Liu, C. Baks, J.-O. Plouchart, W. Lee, and A. Valdes-Garcia, “An enhanced 64-element dual-polarization antenna array package for w-band communication and imaging applications,” in *2018 IEEE 68th Electronic Components and Technology Conference (ECTC)*, IEEE, 2018, pp. 197–201.

[8] C. Mao, M. Khalily, P. Xiao, L. Zhang, and R. Tafazolli, “High-gain phased array antenna with endfire radiation for 26 ghz wide-beam-scanning applications,” *IEEE Transactions on Antennas and Propagation*, vol. 69, no. 5, pp. 3015–3020, 2020.

[9] K. C. Dimitrov, Y. Lee, B.-W. Min, J. Park, J. Jeong, and H.-J. Kim, “Circularly polarized t-shaped slot waveguide array antenna for satellite communications,” *IEEE Antennas and Wireless Propagation Letters*, vol. 19, no. 2, pp. 317–321, 2019.

[10] Q. Ren, A. U. Zaman, and J. Yang, “Dual-circularly polarized array antenna based on gap waveguide utilizing double-grooved circular waveguide polarizer,” *IEEE Transactions on Antennas and Propagation*, vol. 70, no. 11, pp. 10 436–10 444, 2022.

[11] J. I. Herranz-Herruzo, M. Ferrando-Rocher, A. Valero-Nogueira, and B. Bernardo-Clemente, “Novel asymmetric t-shaped radiating element for circularly-polarized waveguide slot arrays,” *IEEE Transactions on Antennas and Propagation*, vol. 69, no. 11, pp. 7452–7461, 2021.

[12] M. Ferrando-Rocher, J. I. Herranz-Herruzo, A. Valero-Nogueira, and B. Bernardo-Clemente, “Dual circularly polarized aperture array antenna in gap waveguide for high-efficiency ka-band satellite communications,” *IEEE Open Journal of Antennas and Propagation*, vol. 1, pp. 283–289, 2020.

[13] D. Jia, Y. He, N. Ding, J. Zhou, B. Du, and W. Zhang, “Beam-steering flat lens antenna based on multilayer gradient index metamaterials,” *IEEE Antennas and Wireless Propagation Letters*, vol. 17, no. 8, pp. 1510–1514, 2018.

[14] J. Liu, A. Vosoogh, A. U. Zaman, and J. Yang, “A slot array antenna with single-layered corporate-feed based on ridge gap waveguide in the 60 ghz band,” *IEEE Transactions on Antennas and Propagation*, vol. 67, no. 3, pp. 1650–1658, 2019.

[15] S. Farjana, M. Ghaderi, A. U. Zaman, S. Rahiminejad, P. Lundgren, and P. Enoksson, "Low-loss gap waveguide transmission line and transitions at 220–320 ghz using dry film micromachining," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 11, no. 11, pp. 2012–2021, 2021.

[16] E. Rajo-Iglesias, M. Ferrando-Rocher, and A. U. Zaman, "Gap waveguide technology for millimeter-wave antenna systems," *IEEE Communications Magazine*, vol. 56, no. 7, pp. 14–20, 2018.

[17] Q. Ren, A. U. Zaman, and J. Yang, "Dual-circularly polarized array antenna based on gap waveguide utilizing double-grooved circular waveguide polarizer," *IEEE Transactions on Antennas and Propagation*, vol. 70, no. 11, pp. 10 436–10 444, 2022.

[18] D. Zarifi, A. Farahbakhsh, A. U. Zaman, and P.-S. Kildal, "Design and fabrication of a high-gain 60-ghz corrugated slot antenna array with ridge gap waveguide distribution layer," *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 7, pp. 2905–2913, 2016.

[19] A. Vosoogh, A. Haddadi, A. U. Zaman, J. Yang, H. Zirath, and A. A. Kishk, "W-band low-profile monopulse slot array antenna based on gap waveguide corporate-feed network," *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 12, pp. 6997–7009, 2018.

[20] M. Ferrando-Rocher, J. I. Herranz-Herruzo, A. Valero-Nogueira, and B. Bernardo-Clemente, "Switchable t-slot for dual-circularly-polarized slot-array antennas in ka-band," *IEEE Antennas and Wireless Propagation Letters*, vol. 20, no. 10, pp. 1953–1957, 2021.

[21] E. Wang and Z. Yan, "A constant phase stable over the wideband for beam steering antenna applications," *International Journal of RF and Microwave Computer-Aided Engineering*, vol. 32, no. 12, Sep. 2022, Published as part of Wiley's Forward Series. Open access journal.

[22] M. Gadelrab, S. I. Shams, M. Elsaadany, and A. Sebak, "Ridge gap waveguide low pass filters: A systematic design approach," *IEEE Access*, 2024.

[23] E. Rajo-Iglesias and P.-S. Kildal, "Cut-off bandwidth of metamaterial-based parallel plate gap waveguide with one textured metal pin surface," in *2009 3rd European Conference on Antennas and Propagation*, 2009, pp. 33–36.

[24] A. U. Zaman, A. Algaba Brazález, and P.-S. Kildal, "Design of band-pass filter using gap waveguide technology," in *Millimetre Wave Days, 23-25 May 2011, Espoo Finland (6th ESA Workshop on Millimetre-Wave Technology and Applications and 4th Global Symposium on Millimeter Waves)*, 2011.

[25] F. Pizarro, C. Sánchez-Cabello, J.-L. Vazquez-Roy, and E. Rajo-Iglesias, "Considerations of impedance sensitivity and losses in designing inverted microstrip gap waveguides," *AEU - International Journal of Electronics and Communications*, vol. 124, p. 153 353, 2020, ISSN: 1434-8411.

[26] H. Raza, J. Yang, P.-S. Kildal, and E. A. Alós, "Microstrip-ridge gap waveguide–study of losses, bends, and transition to wr-15," *IEEE transactions on microwave theory and techniques*, vol. 62, no. 9, pp. 1943–1952, 2014.

[27] A. Vosoogh, P.-S. Kildal, and V. Vassilev, "A multi-layer gap waveguide array antenna suitable for manufactured by die-sink edm," in *2016 10th European Conference on Antennas and Propagation (EuCAP)*, IEEE, 2016, pp. 1–4.

[28] A. U. Zaman, T. Vukusic, M. Alexanderson, and P.-S. Kildal, "Design of a simple transition from microstrip to ridge gap waveguide suited for mmic and antenna integration," *IEEE Antennas and wireless propagation letters*, vol. 12, pp. 1558–1561, 2013.

[29] E. Pucci, A. U. Zaman, E. Rajo-Iglesias, P.-S. Kildal, and A. Kishk, "Losses in ridge gap waveguide compared with rectangular waveguides and microstrip transmission lines," in *Proceedings of the Fourth European Conference on Antennas and Propagation*, IEEE, 2010, pp. 1–4.

[30] A. Palomares-Caballero, A. Alex-Amor, J. Valenzuela-Valdés, and P. Padilla, "Millimeter-wave 3-d-printed antenna array based on gap-waveguide technology and split e-plane waveguide," *IEEE Transactions on Antennas and Propagation*, vol. 69, no. 1, pp. 164–172, 2020.

[31] X. Yang, G. Zhang, W. Zhang, *et al.*, "Design of dual-band filtering antenna based on 3-d printed half-mode gap waveguide quadruple-mode resonator," *IEEE Antennas and Wireless Propagation Letters*, 2023.

[32] C. Bencivenni, A. Haddadi, A. Vosoogh, and S. Carlsson, “High-volume manufacturing of metallized plastic gapwaves antennas for mmwave applications,” in *2023 17th European Conference on Antennas and Propagation (EuCAP)*, IEEE, 2023, pp. 1–4.

[33] S. Farjana, M. Ghaderi, A. U. Zaman, *et al.*, “Realizing a 140 ghz gap waveguide–based array antenna by low-cost injection molding and micromachining,” *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 42, pp. 893–914, 2021.

[34] Z. Zang, A. U. Zaman, and J. Yang, “Single layer dual circularly polarized antenna array based on ridge gap waveguide for 77 ghz automotive radar,” *IEEE Transactions on Antennas and Propagation*, vol. 70, no. 7, pp. 5977–5982, 2022.

[35] Z. Zang, A. U. Zaman, and J. Yang, “Single-layer dual-circularly polarized series-fed gap waveguide-based slot array for a 77 ghz automotive radar,” *IEEE Transactions on Antennas and Propagation*, vol. 71, no. 5, pp. 3775–3784, 2023.

[36] Q. Ren, C. Bencivenni, G. Carluccio, *et al.*, “Gapwaveguide automotive imaging radar antenna with launcher in package technology,” *IEEE Access*, vol. 11, pp. 37 483–37 493, 2023.

[37] D. Martinez-de-Rioja, R. Florencio, J. A. Encinar, E. Carrasco, and R. R. Boix, “Dual-frequency reflectarray cell to provide opposite phase shift in dual circular polarization with application in multibeam satellite antennas,” *IEEE Antennas and Wireless Propagation Letters*, vol. 18, no. 8, pp. 1591–1595, 2019.

[38] A. U. Zaman, P.-S. Kildal, and A. A. Kishk, “Narrow-band microwave filter using high-q groove gap waveguide resonators with manufacturing flexibility and no sidewalls,” *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 2, no. 11, pp. 1882–1889, 2012.

[39] W. Y. Yong, A. Hadaddi, and A. A. Glazunov, “Design and characterization of the fully metallic gap waveguide-based frequency selective radome for millimeter wave fixed beam array antenna,” *IEEE Transactions on Antennas and Propagation*, vol. 71, no. 1, pp. 531–541, 2022.

[40] M. Fang, J. Yang, T. Emanuelsson, I. Andersson, and A. U. Zaman, "1-dimensional wide scanning gap waveguide based slot array antenna using decoupling technique for 100 ghz applications," *IEEE Transactions on Antennas and Propagation*, 2024.

[41] A. Bagheri, H. Karlsson, C. Bencivenni, *et al.*, "A 16× 16 45 slant-polarized gapwaveguide phased array with 65-dbm eirp at 28 ghz," *IEEE Transactions on Antennas and Propagation*, vol. 71, no. 2, pp. 1319–1329, 2022.

[42] D. Zarifi, A. S. Saber, and A. U. Zaman, "A high-gain gap waveguide-based 16× 16 slot antenna array with low sidelobe level for mmwave applications," *Scientific Reports*, vol. 14, no. 1, p. 31 458, 2024.

[43] Z. Tao, Z. Peng, H. Yong, L. Xunxun, M. Yao, and L. Chao, "Design and fabrication of a high-gain low-sidelobe v-band wideband gap waveguide slot antenna array," in *2021 2nd China International SAR Symposium (CISS)*, IEEE, 2021, pp. 1–3.

[44] A. Kishk, A. U. Zaman, and P.-S. Kildal, "Numerical prepackaging with pmc lid-efficient and simple design procedure for microstrip circuits including the packaging," *The Applied Computational Electromagnetics Society Journal (ACES)*, pp. 389–398, 2012.

[45] A. U. Zaman, J. Yang, and P.-S. Kildal, "Using lid of pins for packaging of microstrip board for descrambling the ports of eleven antenna for radio telescope applications," in *2010 IEEE Antennas and Propagation Society International Symposium*, IEEE, 2010, pp. 1–4.

[46] A. U. Zaman, V. Vassilev, P.-S. Kildal, and H. Zirath, "Millimeter wave e-plane transition from waveguide to microstrip line with large substrate size related to mmic integration," *IEEE Microwave and Wireless Components Letters*, vol. 26, no. 7, pp. 481–483, 2016.

[47] A. Vosoogh, M. S. Sorkherizi, V. Vassilev, *et al.*, "Compact integrated full-duplex gap waveguide-based radio front end for multi-gbit/s point-to-point backhaul links at e-band," *IEEE Transactions on Microwave Theory and Techniques*, vol. 67, no. 9, pp. 3783–3797, 2019.

[48] Q. Ren, O. Eriksson, P. Thalya, *et al.*, "An automotive polarimetric radar sensor with circular polarization based on gapwaveguide technology," *IEEE Transactions on Microwave Theory and Techniques*, 2023.

[49] M. Ferrando-Rocher, B. Mayor, S. Marini, A. Valero-Nogueira, and J. I. Herranz-Herruzo, "A ka-band compact single-layer gap waveguide monopulse slot array antenna," in *2021 XXXIVth General Assembly and Scientific Symposium of the International Union of Radio Science (URSI GASS)*, 2021, pp. 01–03.

[50] Z. J. Xiao, J. H. Zhai, and Y. F. Cao, "Wideband circularly polarized millimeter-wave antenna and its array for ka-band satellite communication," in *2023 16th UK-Europe-China Workshop on Millimetre Waves and Terahertz Technologies (UCMMT)*, vol. 1, 2023, pp. 1–3.

[51] M. Elahi, S. Trinh-Van, Y. Yang, K.-Y. Lee, and K.-C. Hwang, "Compact and high gain 4 × 4 circularly polarized microstrip patch antenna array for next generation small satellite," *Applied Sciences*, vol. 11, no. 19, 2021, ISSN: 2076-3417.

[52] A. J. Lozada and D. Su, "Microstrip antenna for satellite communications," in *2008 8th International Symposium on Antennas, Propagation and EM Theory*, 2008, pp. 320–322.

[53] R. Xu, J.-Y. Li, J. Liu, S.-G. Zhou, and K. Wei, "Design of spiral slot-based dual-wideband dual-sense cp antenna," *IET Microwaves, Antennas & Propagation*, vol. 13, no. 1, pp. 76–81, 2019.

[54] W. Cao, A. Liu, B. Zhang, T. Yu, and Z. Qian, "Dual-band spiral patch-slot antenna with omnidirectional cp and unidirectional cp properties," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 4, pp. 2286–2289, 2012.

[55] Y. Andreev, V. Koshelev, and S. Smirnov, "Characteristics of an ultra-wideband 8x8 array of cylindrical helical antennas," Sep. 2018, pp. 66–69.

[56] P. Naseri, S. A. Matos, J. R. Costa, C. A. Fernandes, and N. J. Fonseca, "Dual-band dual-linear-to-circular polarization converter in transmission mode application to K/Ka-band satellite communications," *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 12, pp. 7128–7137, 2018.

[57] R. Florencio, R. R. Boix, and J. A. Encinar, "Design of a reflectarray antenna at 300 ghz based on cells with three coplanar dipoles," in *2013 IEEE Antennas and Propagation Society International Symposium (APSURSI)*, IEEE, 2013, pp. 1350–1351.

[58] J. A. Ganie and K. Saurav, "1-bit circular polarization reflectarray antenna for uplink satellite communication at ka-band," in *2022 IEEE Microwaves, Antennas, and Propagation Conference (MAPCON)*, IEEE, 2022, pp. 1604–1609.

[59] S. Montori, F. Cacciamani, R. V. Gatti, *et al.*, "A transportable reflectarray antenna for satellite ku-band emergency communications," *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 4, pp. 1393–1407, 2015.

[60] Wikipedia contributors, *Reflectarray antenna — Wikipedia, the free encyclopedia*, [Online; accessed 7-January-2025], 2025.

[61] Y. Tyagi and P. Mevada, "Broadband slotted waveguide array antenna," in InTech, 2016, Chapter available under CC BY 3.0 License. [Online; accessed 7-January-2025].

[62] D. Pozar, "Microstrip antennas," *Proceedings of the IEEE*, vol. 80, no. 1, pp. 79–91, 1992.

[63] D. Sievenpiper, L. Zhang, R. F. Broas, N. G. Alexopolous, and E. Yablonovitch, "High-impedance electromagnetic surfaces with a forbidden frequency band," *IEEE Transactions on Microwave Theory and techniques*, vol. 47, no. 11, pp. 2059–2074, 1999.

[64] M. H. Novak, F. A. Miranda, and J. L. Volakis, "Ultra-wideband phased array for millimeter-wave ism and 5g bands, realized in pcb," *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 12, pp. 6930–6938, 2018.

[65] F. Monticone and A. Alu, "Leaky-wave theory, techniques, and applications: From microwaves to visible frequencies," *Proceedings of the IEEE*, vol. 103, no. 5, pp. 793–821, 2015.

[66] A. A. Brazález, J. Flygare, J. Yang, V. Vassilev, M. Baquero-Escudero, and P.-S. Kildal, "Design of F-band transition from microstrip to ridge gap waveguide including monte carlo assembly tolerance analysis," *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 4, pp. 1245–1254, 2016.

[67] E. Alfonso, M. Baquero, P.-S. Kildal, A. Valero-Nogueira, E. Rajo-Iglesias, and J. I. Herranz, "Design of microwave circuits in ridge-gap waveguide technology," in *2010 IEEE MTT-S International Microwave Symposium*, 2010, pp. 1544–1547.

[68] A. Wilcher, H.-I. Kim, Z. Jia, *et al.*, "Surface micromachined integrable high efficiency ridge gap waveguide bandpass filter for g-band 6g applications," in *2023 IEEE 73rd Electronic Components and Technology Conference (ECTC)*, IEEE, 2023, pp. 1499–1503.

[69] J. I. Herranz-Herruzo, M. Ferrando-Rocher, A. Valero-Nogueira, and B. Bernardo-Clemente, "Wideband circularly polarized mm-wave array antenna using h-shaped low-axial-ratio apertures," *IEEE Transactions on Antennas and Propagation*, vol. 71, no. 5, pp. 4564–4569, 2023.

[70] M. M. Sani, R. Chowdhury, and R. K. Chaudhary, "An ultra-wideband rectangular dielectric resonator antenna with mimo configuration," *IEEE Access*, vol. 8, pp. 139 658–139 669, 2020.

[71] S. Ghosh and D. Sen, "An inclusive survey on array antenna design for millimeter-wave communications," *IEEE Access*, vol. 7, pp. 83 137–83 161, 2019.

[72] F. Sun, Y. Li, J. Wang, L. Ge, J. Chen, and W. Qin, "Bandwidth enhancement of millimeter-wave large-scale antenna arrays using x-type full-corporate waveguide feed networks," *IEEE Open Journal of Antennas and Propagation*, vol. 3, pp. 1044–1056, 2022.

[73] A. Castellá-Montoro, M. Ferrando-Rocher, J. I. Herranz-Herruzo, and A. Valero-Nogueira, "Low-sidelobe flat panel array fed by a 3d-printed half-mode gap waveguide amplitude-tapering network," *IEEE Access*, vol. 12, pp. 2607–2614, 2023.

[74] A. K. Khandani, A. Farahbakhsh, D. Zarifi, and A. U. Zaman, "Millimeter wave wideband and low-loss compact power divider based on gap waveguide: For use in wideband antenna array system," *IEEE Access*, 2024.

[75] M. M. M. Ali, Z. Mousavirazi, H. Naseri, and T. A. Denidni, "Design of low-loss printed ridge-gap-waveguide crossover for millimeter-wave applications," in *2022 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (AP-S/URSI)*, 2022, pp. 547–548.

[76] W. Y. Yong, A. Vosoogh, A. Bagheri, C. Van de Ven, A. Hadaddi, and A. A. Glazunov, “An overview of recent development of the gap-waveguide technology for mmwave and sub-thz applications,” *IEEE Access*, 2023.

[77] D. Santiago, M. A. Laso, T. Lopetegi, and I. Arregui, “Novel design method for millimeter-wave gap waveguide low-pass filters using advanced manufacturing techniques,” *IEEE Access*, 2023.

[78] T. Whittaker, S. Zhang, A. Powell, C. J. Stevens, J. Y. C. Vardaxoglou, and W. Whittow, “3d printing materials and techniques for antennas and metamaterials: A survey of the latest advances,” *IEEE Antennas and Propagation Magazine*, vol. 65, no. 3, pp. 10–20, 2022.

[79] O. S. Hassan, K. H. Ali, and M. A. Abou-Khousa, “3d-printed mm-wave reflectarray with coaxial unit cell,” *IEEE Transactions on Antennas and Propagation*, 2024.

[80] D. Helena, A. Ramos, T. Varum, and J. N. Matos, “Antenna design using modern additive manufacturing technology: A review,” *IEEE Access*, vol. 8, pp. 177 064–177 083, 2020.

[81] R. Bahr, B. Tehrani, and M. M. Tentzeris, “Exploring 3-d printing for new applications: Novel inkjet-and 3-d-printed millimeter-wave components, interconnects, and systems,” *IEEE Microwave magazine*, vol. 19, no. 1, pp. 57–66, 2017.

[82] C. Tomassoni, O. A. Peverini, G. Venanzoni, G. Addamo, F. Paonessa, and G. Virone, “3d printing of microwave and millimeter-wave filters: Additive manufacturing technologies applied in the development of high-performance filters with novel topologies,” *IEEE Microwave Magazine*, vol. 21, no. 6, pp. 24–45, 2020.