THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Novel Designs of Slot Array Antenna for 100 GHz Applications

Using Gap Waveguide Technology

Mu Fang

Department of Electrical Engineering
Chalmers University of Technology
Gothenburg, Sweden, 2025

Novel Designs of Slot Array Antenna for 100 GHz Applications
Using Gap Waveguide Technology

MU FANG
ISBN 978-91-8103-178-2

Selected material from the author's licentiate thesis: Wide Scanning Gap Waveguide Slot Array Antenna for 100 GHz Applications, Gothenburg, Sweden, May. 2024, is republished in this Ph.D. thesis.

Doktorsavhandlingar vid Chalmers tekniska högskola
Ny serie nr 5636
ISSN 0346-718X

Department of Electrical Engineering
Chalmers University of Technology
SE-412 96 Gothenburg, Sweden
Phone: +46 (0)31 772 1000

Printed by Chalmers Digital Printing
Gothenburg, Sweden, Feb 2025

Novel Designs of Slot Array Antenna for 100 GHz Applications
Using Gap Waveguide Technology
MU FANG
Department of Electrical Engineering
Chalmers University of Technology

Abstract

Frequencies around 100 GHz offer considerable potential for the next generation of wireless communication systems due to the abundant, yet underutilized spectral resources available. At such high frequencies, high-gain array antennas with low-loss capability are essential to compensate for the substantial free-space path loss.

Waveguide slot array antennas, owing to their low loss, high mechanical strength, and robust power-handling capabilities, present a promising solution at 100 GHz. In addition, recent advancements in gap waveguide (GWG) technology have made it easier to fabricate slot arrays at high frequencies. Building upon the traditional slot array designs and incorporating GWG, this thesis proposes two novel slot array configurations to improve antenna performance in multiple aspects.

First, a wide-scanning slot array at 100 GHz based on GWG is introduced. By leveraging a novel decoupling technique, the proposed design enables an all-metal longitudinal slot array to achieve ±60° wide-angle scanning in the E-plane for the first time, with a 3-dB scan loss and a total efficiency exceeding 91%. Second, a dual-band filtering slot array based on GWG is presented, operating at 74–78 GHz and 102–106 GHz. The main novelty of this design lies in its common waveguide channels for dual-band slot excitation and a truly shared planar aperture, enabling both broadside radiation and independent multi-channel operation.

These proposed designs provide new insights into slot array antenna design and show promising potential for future applications in 100 GHz communication systems.

Keywords: Slot array, wide scanning, decoupling, phased array, dual-band, filter, gap waveguide.

List of Publications

This thesis is based on the following publications:

[A] **Mu Fang**, Jian Yang, Thomas Emanuelsson, Ingmar Andersson, Ashraf Uz Zaman, "1-Dimensional Wide Scanning Gap Waveguide Based Slot Array Antenna using Decoupling Technique for 100 GHz Applications". Published in IEEE Transactions on Antennas and Propagation, Apr. 2024.

[B] **Mu Fang**, Jian Yang, Ashraf Uz Zaman, "A Comparative Study of Decoupling Techniques for Waveguide Slot Array Antennas". Published in EUCAP 2024, Apr. 2024.

[C] **Mu Fang**, Jian Yang, Thomas Emanuelsson, Ingmar Andersson, Ashraf Uz Zaman, "Dual-Band Filtering Slot Array Antenna for W-Band Application ". Submitted to IEEE Transactions on Antennas and Propagation (Major Revision).

Other publication by the author, not included in this thesis, is:

[D] D. Santiago, **M. Fang**, A. U. Zaman, M. A. G. Laso, T. Lopetegi and I. Arregui, "W-Band Filtering Antenna Based on a Slot Array and Stacked Coupled Resonators Using Gap Waveguide Technology". *IEEE Antennas and Wireless Propagation Letters*, Aug. 2024.

Contents

Acknowledgments

First and foremost, I extend my deepest gratitude to my supervisor, Assoc. Prof. Ashraf Uz Zaman, whose consistent support and insightful supervision have greatly enriched my research journey over the years. His creative ideas and constructive feedback were crucial in navigating the complexities and challenges of my research.

I am also thankful to my examiner, Prof. Jian Yang, for his encouragement and thoughtful care throughout the duration of this project. My gratitude extends to my manager, Prof. Marianna Ivashina, for her considerate guidance and support during my Ph.D. endeavors. I would like to express my appreciation to Prof. Rob Maaskant, who has generously shared his understanding in this area. Special thanks to Prof. Kishk for his patience and the enlightening discussions we've had, which have contributed significantly to my research development.

Sincere thanks to Dr. Pavlo Krasov, Dr. Artem Vilenskiy, and Dr. Oleg Iupikov for their generous support and valuable advice throughout my doctoral studies.

Furthermore, I would like to thank all the members of the Antenna Systems Group for their companionship and engaging discussions throughout this unique journey. I will always value the time we spent together.

Acronyms

AoC:	Antenna on chip
AiP:	Antenna in package
mmWave:	millimeter-wave
GWG:	Gap waveguide
RWG:	Ridge gap waveguide
GGW:	Groove gap waveguide
PEC:	Perfect electric conductor
PMC:	Perfect magnetic conductor
AMC:	Artificial magnetic conductor
MIMO:	Multiple-input multiple-output
ARC:	Active reflection coefficient
BPF:	Band pass filter

Part I

Overview

CHAPTER 1

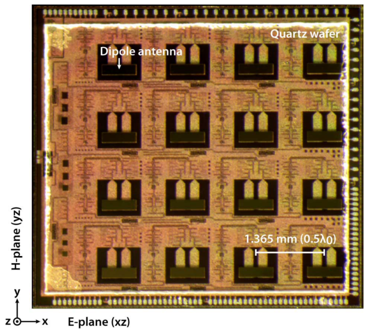
Introduction

1.1 Challenges of Wireless Communication at 100 GHz

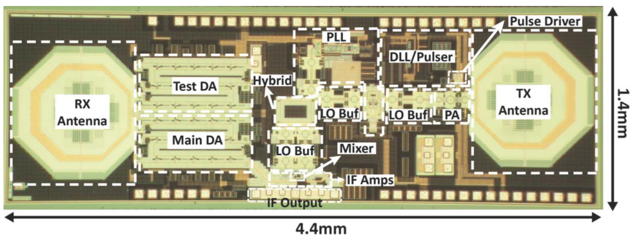
The spectrum near and above 100 GHz holds immense promise for the next generation of wireless communication systems [1]. With vast unexplored frequencies, it has the potential to achieve very high data rates and support numerous unprecedented features and functionalities, which can be suitable for various applications such as ultra-high data-rate multi-user broadband communication, ultra-low latency machine communications, wireless backhaul, virtual/augmented reality, internet of things, security & sensing, imaging, etc [1], [2].

Although the spectrum is less crowded in such high frequency ranges, new challenges arise, notably the much higher free-space path loss combined with weaker electromagnetic diffraction capability (relying more on line-of-sight transmission) [1]. Therefore, antennas with high radiation efficiency and significantly higher gain are required to overcome the path loss, implemented in various configurations such as fixed beam antennas, multiple-input multiple-output (MIMO) arrays, and phased arrays to address diverse application demands [3], [4]. In recent years, a wide range of antenna solutions at high frequency bands have been researched and developed, each with its own advantages and challenges.

For instance, for phased arrays, the predominant solutions at the W-band (75-110 GHz) currently include antenna-on-chip(AoC) [5], [6], antenna-in-package (AiP) [7], [8], and traditional PCB antennas [9], as illustrated in Fig. 1.1, 1.2 and 1.3. Among these technologies, both AoC and AiP enable miniaturization and higher integration of antennas. By embedding the antenna directly onto the chip or within the package, the overall system size is minimized, alongside a reduction in the number of connections and components on the PCB. This integration fosters a more cohesive interaction between the antenna and RF circuitry, thereby elevating integration levels.



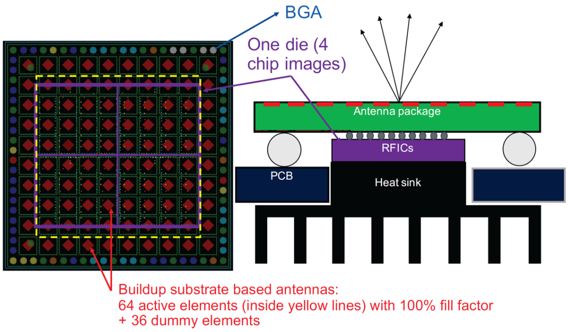
(a)



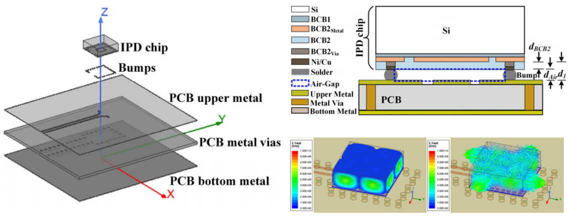
(b)

Figure 1.1: Examples of AoC phased arrays at W-band: (a) in [5], (b) in [6].

However, these methods are not without their challenges. Primarily, the



(a)



(b)

Figure 1.2: Examples of AiP phased arrays at W-band: (a) in [7], (b) in [8].

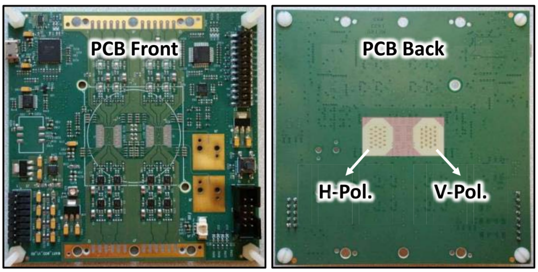


Figure 1.3: Example of a PCB phased array at W-band in [9].

materials utilized for antenna integration onto the chip or within the package can introduce significant additional losses. Such losses may lead to signal attenuation and distortion, impacting the system's performance. In [5] and [6], two AoC-based phased array designs are presented which exhibit 45% and and above 30% antenna efficiency at 110 GHz and 94 GHz, respectively. AiP solution in [8] shows 41% efficiency at 94 GHz. Similarly, phased arrays based on PCB antennas are also challenged by low efficiency issues. In [9], the efficiency of a single antenna element is round 62.5% at around 90 GHz. Moreover, for large-scale analog phased arrays with numerous antenna elements, the expanded power division network can significantly introduce greater losses, further diminishing the overall radiation efficiency [10] (examples of analog phased array architecture using division network are depicted in Fig. 1.4).

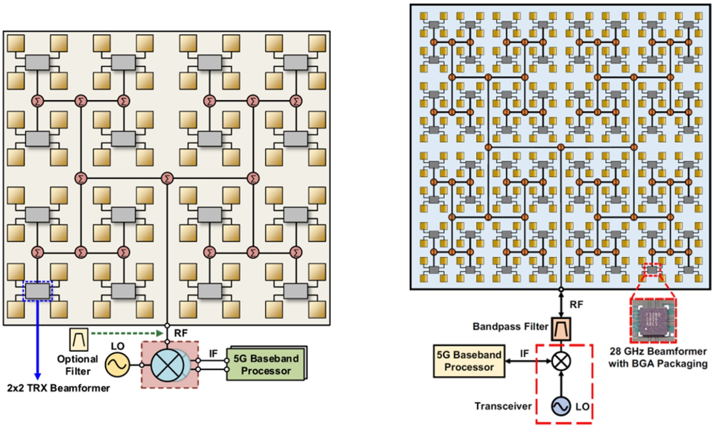


Figure 1.4: Examples of full-analog phased-array architecture using division networks: 1 to 16 in [11] (left), 1 to 64 in [12] (right).

On the other hand, the direct integration of the antenna onto the chip or within the package can compromise heat dissipation. Insufficient heat management could elevate the temperature of the chip or package, thereby affecting the system's reliability and stability [13].

In this regard, to achieve higher efficiency, all-metal phased array antennas, benefiting from their inherent low-loss characteristics, emerge as a promising alternative solution. The incorporation of metal structures also enhances heat dissipation, contributing to improved thermal management.

The advantages of all-metal antennas at high frequencies not only benefit phased array performance but are also well-suited for high-gain fixed-beam antennas and multi-channel MIMO antennas. Moreover, thanks to the shorter wavelengths at high-frequency bands, which reduce antenna size, all-metal antennas no longer face the bulky issues encountered at lower frequencies.

1.2 Gap Waveguide Technology

Despite the many advantages of all-metal antennas, their large-scale commercial applications in high-frequency bands have previously been limited, primarily due to manufacturing complexities and cost. In recent years, the development of gap waveguide (GWG) technology, characterized by being free of electrical contacts, has offered the potential to reduce the manufacturing challenges and expenses at high mmWave bands [14].

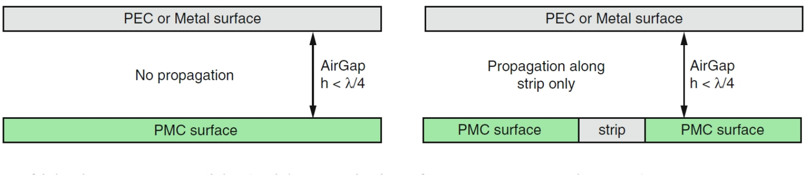


Figure 1.5: Cross section of ideal GWG [15].

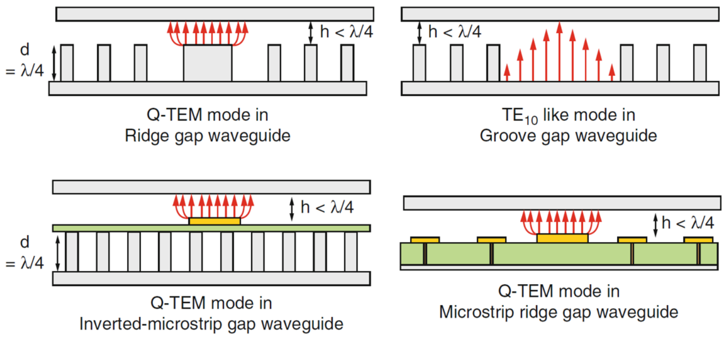


Figure 1.6: Different GWG geometries and their desired propagation modes [15].

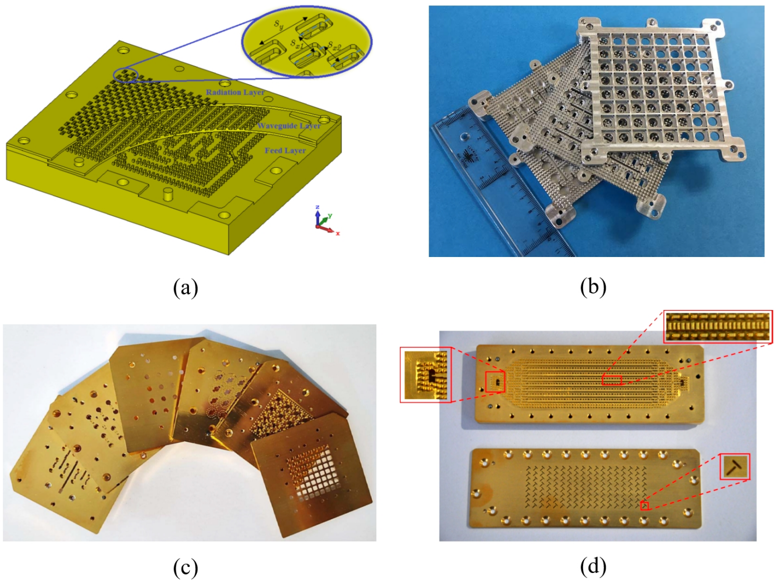


Figure 1.7: Examples of GWG-based antenna arrays: (a) in [16], (b) in [17], (c) in [18],(d) in [19].

GWG technoloy was firstly proposed in 2009 [15]. The concept derives from the cutoff characteristic of a parallel-plate waveguide setup with perfect electric conductor (PEC) and perfect magnetic conductor (PMC) plates. Specifically, when the air gap between the PEC and PMC is less than a quarter wavelength, no wave can propagate between the plates, as is illustrated in Fig. 1.5. While PMCs don't exist in nature, the PMC condition can be emulated using an artificial magnetic conductor (AMC), manifested in periodic textured structures such as metal pins or mushroom configurations. The AMC possesses a sufficiently high surface impedance to generate a stopband, inhibiting the propagation of parallel-plate modes.

In an actual GWG structure, this textured AMC surface is combined with guiding elements like ridges, grooves, or strips, completing the waveguide design, as is shown in Fig. 1.6. Electromagnetic waves can propagate along these guides, while the AMC surface effectively forms virtual lateral walls on both sides of the guiding area, thereby preventing lateral field leakage. Notably, the most common forms of GWG are ridge gap waveguide (RGW) and groove gap waveguide (GGW), owing to their fully metallic structure (Fig. 1.6).

The primary benefit of GWG technology lies in its ability to be implemented without requiring metal-to-metal contact between the smooth metal surface and the textured AMC surface. This feature enables waveguide components with complex structures to be flexibly realized in multi-layer stacked fabrication without concerns about energy leakage while also reducing costs, making it suitable for millimeter-wave (mmWave) frequency bands and potentially beyond.

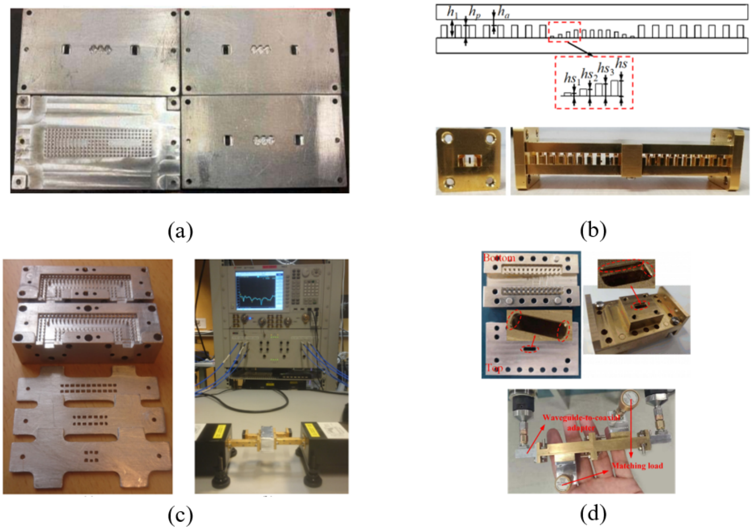


Figure 1.8: Examples of GWG-based components: (a) filter in [20], (b) filter in [21], (c) directional coupler [22],(d) orthomode transducer in [23].

In recent years, utilizing GWG technology, a great variety of waveguide-based antennas [16]–[19], [26]–[34] and components [20]–[23] have been implemented in the high mmWave bands. GWG also aligns well with low-cost manufacturing methods such as electrical discharge machining, plastic injection molding, 3D printing, and polymer micromachining technologies[35]–[39]. Some representative designs of GWG-based antennas and components are shown in Fig. 1.7 and Fig. 1.8.

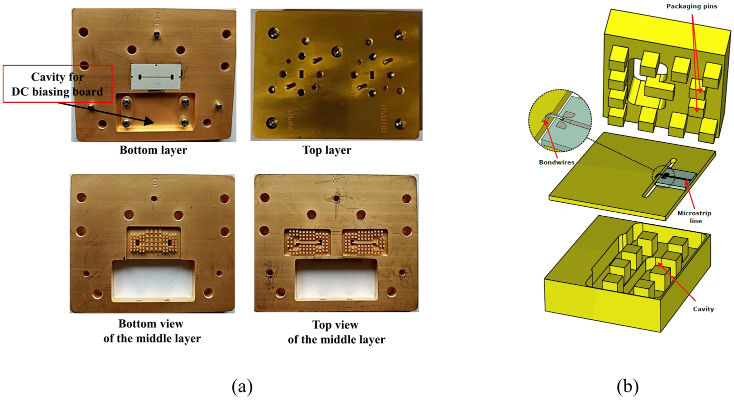


Figure 1.9: Examples of GWG-PCB transitions:(a) in [24], (b) in [25].

Additionally, the integration technology associate with GWG has significantly progressed. Various designs of GWG to PCB transmission line transition have been developed [24] [25], as illustrated in Fig. 1.9. These technological developments have been crucial for the integration of GWG-based antennas and passive components with active RF electronics. Furthermore, the usage of AMC and periodic structure allows to suppress unwanted cavity modes in the active RF front-end modules [40]–[42] and enables easy integration with good thermal properties. As a result, the multi-layer assembly of the gap waveguide components are naturally advantageous in building RF wireless modules for different applications at millimeter-wave frequencies as highlighted in recent publications [43]–[45].

1.3 Waveguide Slot Array Antenna

Among the various forms of all-metal antennas, waveguide slot array antennas are widely used in wireless communication and radar systems due to their low loss, high mechanical strength, and substantial power-handling capabilities [46] [47].33

Its most commonly used form is the series-fed slot array, featuring a simple feeding mechanism, compact low-profile planar structure, and flexible array

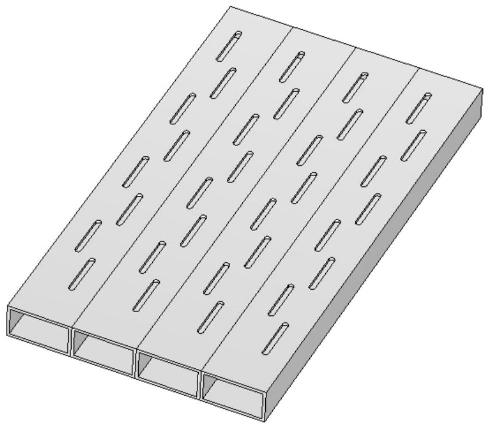


Figure 1.10: Series-fed waveguide slot array (with broad-wall longitudinal slots)

configuration, with numerous variations to offer diverse radiation performance (an example of slot array with broad-wall longitudinal slots is shown in Fig. 1.7). Beyond single-channel operation, its applications include generating high-gain fixed beams [48], enabling MIMO capabilities [49], and performing beam scanning [50]. Moreover, with the support of GWG technology, it can be easily fabricated using multilayer structures, offering significant potential for applications at 100 GHz.

Although slot arrays have been a popular and extensively studied topic for over half a century, there is still potential for innovation and customization to achieve optimized performance for specific scenarios. In this thesis, novel designs of highly efficient GWG-based slot array antennas for 100 GHz applications are proposed, aiming to enhance the performance of traditional slot arrays from different perspectives, which include realizing 1-dimensional wide scanning capabilities (up to ±60°) and achieving dual-band radiation (for both MIMO and fixed beam applications).

1.4 Outline of this thesis

Chapter 1 introduces the research background of the thesis. **Chapter** 2 presents a 1-dimensional wide-scanning slot array solution operating at 100

GHz, based on a novel decoupling technique called the "half wall." Additionally, a comparison between the proposed decoupling technique and existing methods is provided. **Chapter** 3 presents a co-aperture dual-band linearly-polarized filtering slot array operating in the 74–78 GHz and 102–106 GHz bands, featuring shared waveguide channel for dual-band slots. **Chapter 4** summarizes the included papers. Conclusions and future work plans are discussed in **Chapter** 5.

CHAPTER 2

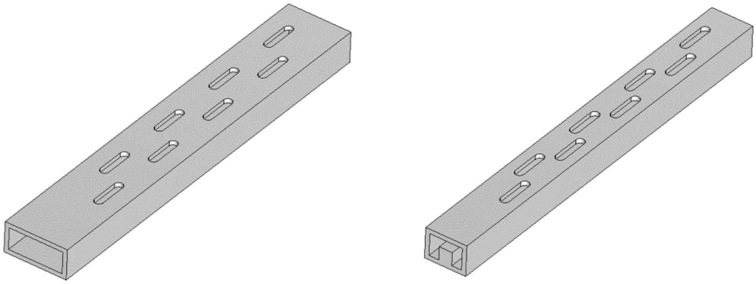
1-Dimensional Wide-scanning Linear Polarized Phased Array

This chapter introduces a GWG-based linearly-polarized 1-dimensional scanning phased array. Waveguide slot array antenna with broad wall longitudinal slots is chosen as the array element for its numerous benefits, including simple and low-profile structure, high-efficiency and high-gain capabilities, and good polarization purity.

However, conventional slot array antennas typically offer a limited scanning range due to their inherent characteristics. Our work analyzes these limitations and subsequently provides a wide-scanning all-metal slot array solution using decoupling technique.

2.1 Challenges to Achieve Wide Scanning for Slot Array

To achieve wide scanning, the spacing between elements in phased arrays typically should be around $0.5\lambda_0$ to avoid grating lobes, where λ_0 is the free-space wavelength. For traditional slot array fed by rectangular waveguide,



(a) (b)

Figure 2.1: Geometries of slot arrays based on (a) rectangular waveguide and (b) ridge waveguide .

the width of each element is usually about $0.7\lambda_0$, including the width of the waveguide broad wall and the thickness of the side wall. This dimension restricts the scanning range to approximately ±25°. To overcome this, ridge-loaded waveguide is often employed which can decrease the size of the antenna element to $0.5\lambda_0$. However, limitation still exists due to the inherent strong E-plane mutual coupling between adjacent slot array channels [51], which can cause the degradation of active reflection coefficient (ARC) at large scanning angles and lead to mismatch between antenna and power amplifier, affecting the overall system performance [52]. As a result, the available scanning range of ridge waveguide slot array is typically only ±45° [53].

Hence, an effective decoupling technique is needed to realize wide scanning capability (±60°) for slot array antennas.

2.2 Existing Decoupling Techniques for Slot Array

Over the past few decades, various methods have been explored to reduce the mutual coupling of waveguide slot array antenna, such as baffles [54], cavities [55], grooves (corrugation) [56], fences [57] [62], quasi-gap waveguide [58], electromagnetic band-gap [59], metasurface [60] and decoupling network [61]. However, these existing decoupling structures are not applicable for wide scanning need of all-metal slot arrays.

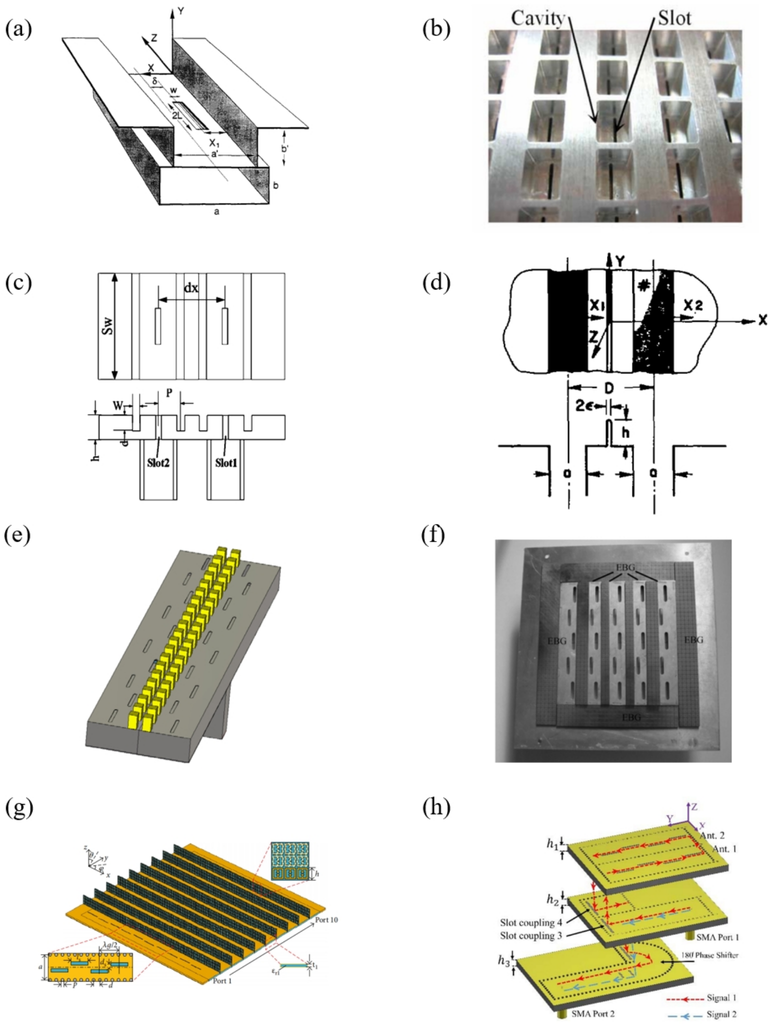


Figure 2.2: Existing decoupling techniques for slot Array: (a) baffles [54], (b) cavities [55], (c) grooves [56], (d) fences [57], (e) quasi-gap waveguide [58], (f) electromagnetic band-gap [59], (g) metasurface [60] and (h) decoupling network [61].

First of all, most of those reported techniques (except the metasurface proposed in [60]) are initially designed for slot arrays with larger than $0.5\lambda_0$, or in other words, not for wide scanning. Metal structures like baffles [54], cavities [55], quasi-gap waveguide [58] are too bulky to implement in the limited space between slot arrays with $0.5\lambda_0$ spacing. Two widely used decoupling technologies, grooves [56] and fences [57] [62], show promise to accommodate this narrow spacing due to their relatively compact structures. However, based on our investigation, both of them can only function well when they are slightly away from the radiation slots and start to lose their efficacy under $0.5\lambda_0$ element spacing (analysis of grooves and fences is given in 2.4). Electromagnetic band-gap in [59] also has the oversize problem for implementation, and its PCB structure is not suitable for the incorporation with all-metal antenna structure in the first place.

It should be noted that, all these techniques discussed above (i.e., baffles [54], cavities [55], quasi-gap waveguide [58], grooves [56], fences [57] [62], electromagnetic band-gap [59]) result in antenna element with narrower E-plane beamwidth and higher gain, which contradicts the need for wide scanning with minimum scan loss. In the other words, their decoupling effect should actually be realized by preventing the lateral radiation in E-plane (along the metal ground).

Among the decoupling technologies mentioned above, only metasurface in [60] is proposed for wide scanning. In this design, PCB-based metasurface is placed vertically between the slot array elements to decrease the E-plane mutual coupling, and 3-dB scanning loss within ±60° scanning range is achieved. Although this technique provides a possible solution, the design shows a relatively high structural complexity. Moreover, as stated in the paper, it has only been simulated and has not been fabricated for measurement and verification. As mentioned earlier, any structures involving PCB are not suitable for all-metal slot arrays at high frequencies (including the PCB-based decoupling network in [61]), as they contradict the goal of minimizing loss. A comparison table of these decoupling techniques is summarized in Table 2.1.

Hence, to the best of the author's knowledge, no well-established decoupling methods were available that effectively address the wide scanning requirement of full-metal waveguide slot arrays, even at low frequency band. In this context, designing feasible decoupling technique will therefore be the key for achieving good scanning performance.

Table 2.1: Known Limitations of Existing Decoupling Techniques for Wide-Scanning All-Metal Slot Arrays

	Bulky Structure	Based on PCB structure	Leading to narrow beamwidth	Ineffective under small element spacing
Baffles	✓		✓	
Cavities	✓		✓	
Grooves			✓	✓
Fences			✓	✓
Quasi-gap waveguide	✓		✓	
Electromagnetic band-gap	✓	✓	✓	
Metasurface		✓		
Decoupling network		✓		

2.3 Design of Wide Scanning Slot Array Solution Using Novel Decoupling Technique

A feasible decoupling technique for wide scanning all-metal phased arrays should meet several requirements, i.e., it should be as simple as possible for easy fabrication at high frequencies, compact enough to be accommodated within the $0.5\lambda_0$ element spacing, provide a good decoupling effect, and not deteriorate the original embedded pattern (without reducing the beamwidth at the scanning plane).

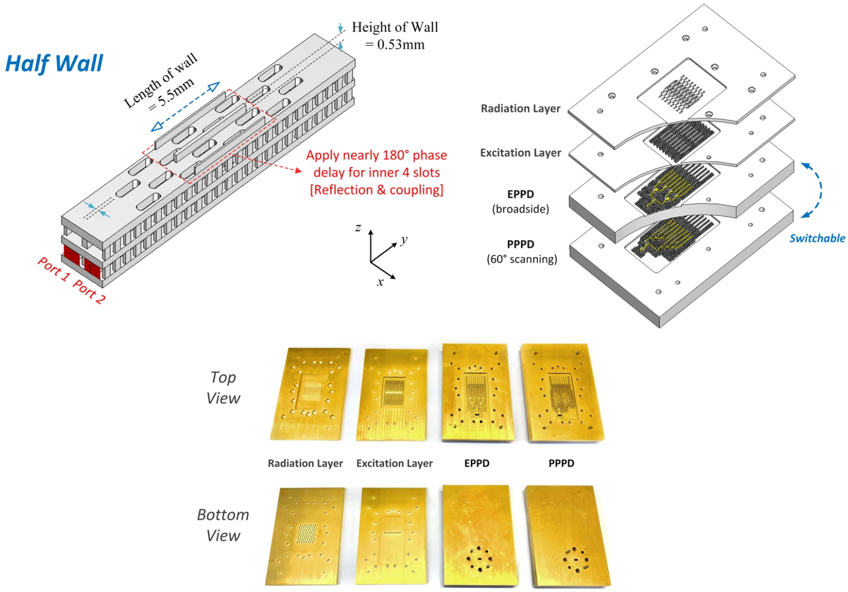
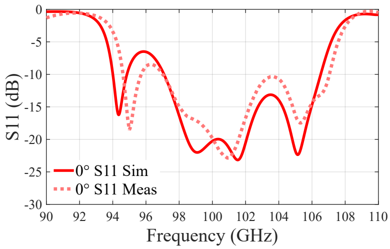


Figure 2.3: GWG Slot Array incorporated with half wall decoupling structure.

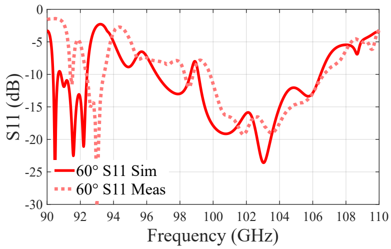
To fulfill these requirements, a novel decoupling structure named "half wall" is proposed (as depicted in Fig. 2.3) which can also improve the reflection coefficient of the slot array element at the same time. With the help of this decoupling method, the proposed GWG-based slot array achieves a more stable ARC, >91% total efficiency, and 3-dB scanning loss within the ±60° scanning range at 100 GHz band (Fig. 2.4 2.5).

It should be noted that the scanning performance is verified using two power dividers: one with a uniform phase (for broadside) and the other with a progressive phase (for 60° scanning). This approach is adopted because independent port measurement at 100 GHz is challenging due to the large size of each waveguide flange. Furthermore, the total efficiency is estimated by comparing the measured realized gain with the simulated directivity. This calculation accounts for the losses in the feeding network as well as the transition from the WR-10 feeding waveguide to RGW, meaning that the efficiency of the standalone antenna (excluding the feeding network) is expected to be higher than the measured efficiency of the prototype (91%). To obtain more accurate data on the losses from the antenna itself, further methods such as TRL calibration and back-to-back feeding network measurements can be used to de-embed the feeding network losses [63].

Relevant details of half wall technique are given in **Paper A**.



(a)

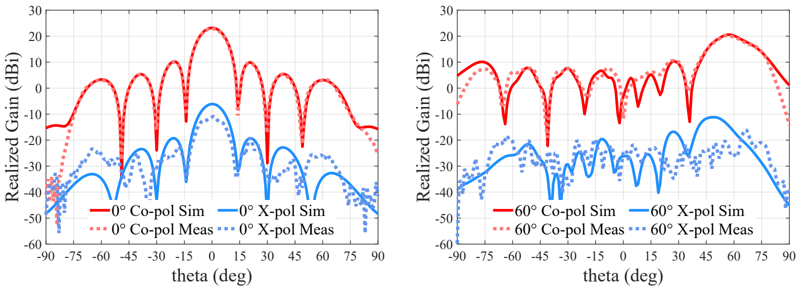


(b)

Figure 2.4: Simulated and measured S11 of the prototype for (a) broadside (0°) and (b) 60° scanning.

2.4 Comparative Study of Three All-metal Slot Array Decoupling Techniques

To develop a comprehensive understanding of different decoupling techniques for slot array, we undertook a comparative analysis of the the proposed half wall, and two prevalent decoupling structures, i.e., grooves [56] and fences [57] [62], which are also full-metal (as shown in Fig. 2.6). Their decoupling efficacy and



(a) (b)

Figure 2.5: Simulated and measured E-plane realized gain pattern (102 GHz) of the prototype.(a) broadside (0°), (b) 60° scanning.

impact on element patterns are investigated under two typical element spacings: $0.5\lambda_0$ and $1\lambda_0$.

For small element spacing ($0.5\lambda_0$), only the half wall technique provides effective decoupling (2.7), while the other two techniques become invalid. For larger element spacing ($1\lambda_0$), all three techniques are effective for decoupling (2.8). However, while the half wall can still provide a wide element pattern, corrugation and fence result in much narrower beamwidth and higher directivity and these variations in beamwidth are suitable for different application scenarios.

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

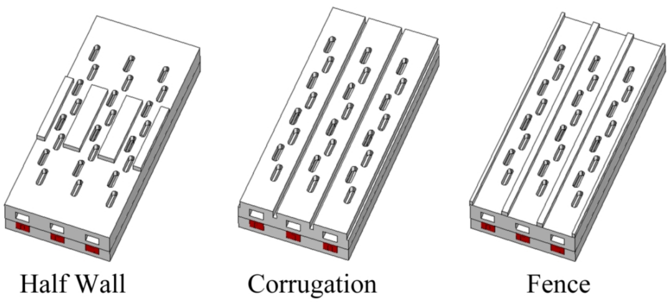
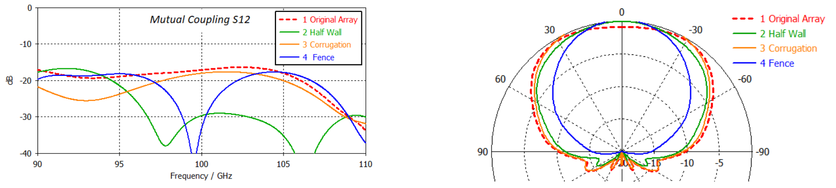
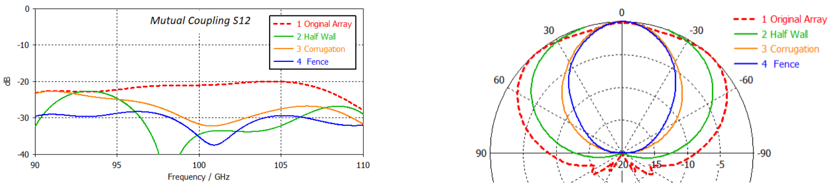


Figure 2.6: Slot array decoupling techniques: half wall, corrugation and fence.



(a) (b)

Figure 2.7: Comparison of simulated (a) mutual coupling S12 and (b) normalized E-plane embedded pattern (dB) of the central element at center frequency (100GHz), under $0.5\lambda_0$ element Spacing.



(a) (b)

Figure 2.8: Comparison of simulated (a) mutual coupling S12 and (b) normalized E-plane embedded pattern (dB) of the central element at center frequency (100GHz), under $1\lambda_0$ element Spacing.

CHAPTER 3

Dual-Band Co-aperture Slot Array Antenna

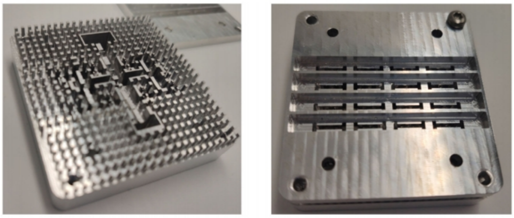
While traditional slot arrays primarily operate in a single frequency band, achieving dual-band radiation with slot arrays is appealing as it enhances system flexibility and functionality within a relatively compact size. However, exist dual-band slot array solutions face specific limitations or challenges when it comes to high-frequency applications.

This chapter introduces a simple-structured dual-band subarray operating at the W-band, featuring the implementation of dual-band longitudinal slots within a single RGW channel. The proposed subarray can operate as a single channel and can also be extended to a planar array that supports fixed-beam broadside radiation or independent operation of each channel (MIMO applications).

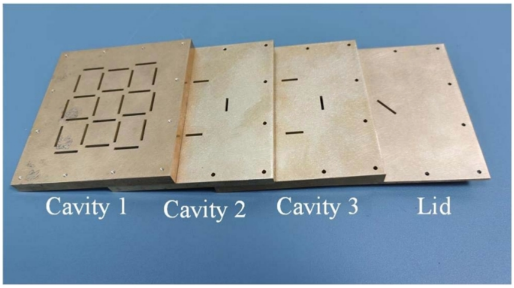
3.1 Existed Dual-band Slot Array solutions and Their Challenges at High Frequencies

In recent years, various dual-band slot array designs have been proposed, offering different performance characteristics.

In [64], a dual-band coaxial resonant cavity structure is proposed, enabling a single slot to achieve dual-band single-polarized radiation. A GWG-based corporate network feeds these cavities to realize a planar array. In [65], multiple dual-band dual-polarized slots are excited by a single high-order mode cavity resonator, eliminating the need for a power-splitting network. However, its bandwidth at both frequencies is quite narrow. It should be noted that, as both designs differ from series-fed waveguide slot arrays, they are limited to supporting broadside radiation only.



(a)



(b)

Figure 3.1: Dual-band slot arrays implemented by resonant cavities (a) in [64], (b) in [65].

A more common dual-band configuration employs multiple closely packed series-fed waveguide slot arrays [66]–[76]. This configuration enables broadside radiation while also allowing independent channel operation.

In [66]–[72], offset broad-wall longitudinal slot arrays and narrow-wall slot arrays are interlaced to realize a dual-polarized array, where the two sets of arrays can operate either at different bands or the same band benefited

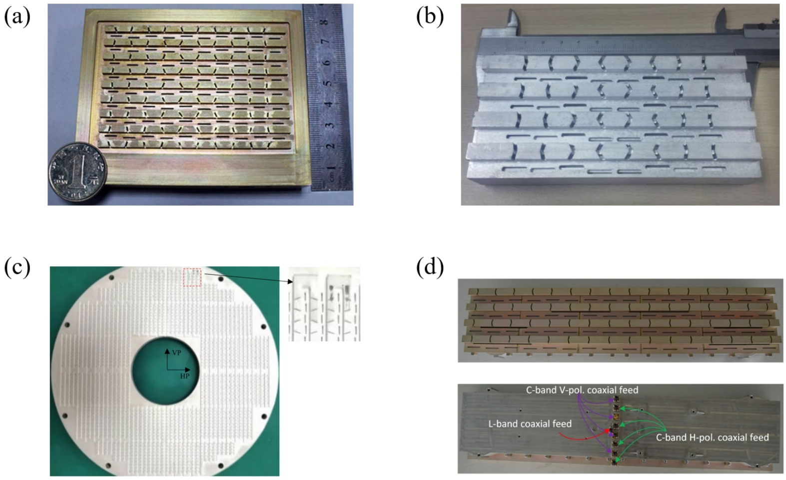
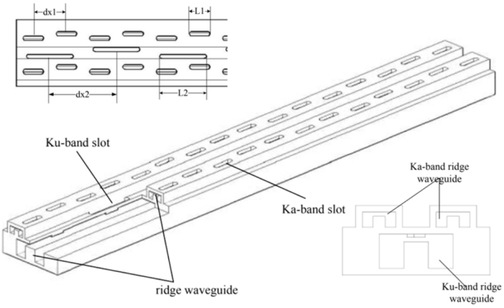


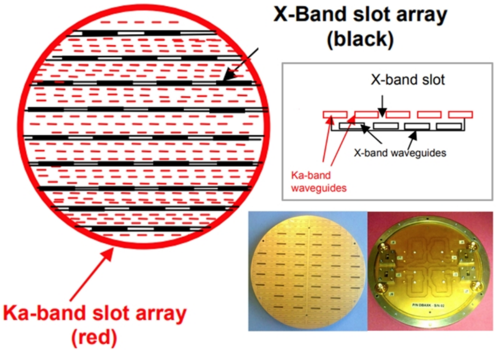
Figure 3.2: Dual-band dual-polarized slot arrays implemented by interleaved waveguide channels (a) in [67], (b) in [69], (c) in [71], (d) in [72].

from their independent channel configurations. It is worth noting that those feeding waveguides are typically loaded with a ridge to reduce the element spacing, and the side-wall slots should extend into the neighboring walls of the feeding waveguide to ensure the slot resonance, which results in a complex nonplanar structure. In [73]–[76], broad-wall longitudinal slot arrays are employed for both bands to enable dual-band single-polarized radiation. In this setup, the high-frequency (HF) slot arrays are interleaved and stacked above the low-frequency (LF) ones to minimize further the element spacing, which leads to a multi-layer structure. Although those designs featuring independent channels can achieve the desired performance, the densely arranged waveguides, non-planar apertures, and complex 3-dimensional structures can significantly increase the manufacturing complexity and cost. Particularly at high millimeter-wave frequencies, these configurations become increasingly difficult to fabricate.

In addition, several attempts have been reported to excite dual-band slots with a single waveguide channel [77]–[82], aiming to achieve dual-band radiation in a simpler structure while maintaining the flexibility of independent channel operation. In [77], [78], two sets of slots for dual bands are located



(a)



(b)

Figure 3.3: Dual-band single-polarized slot arrays implemented by interleaved and stacked waveguide channels (a) in [73], (b) in [74], (c) in [75], (d) in [76].

on opposite broad walls of the waveguide. However, this configuration only radiates in opposite directions. In [79]–[81], dual-band longitudinal slots are etched on the same broad wall of a waveguide but in different regions along the longitudinal direction, which does not create a true co-aperture. In [82], longitudinal and transverse slots are implemented on the same broad wall of a waveguide. However, this design is not a conventional series slot array, as the waveguide channel is excited by a corporate power divider at the back, resulting in a bulky structure. Moreover, most of these designs exhibit undesired impedance matching and narrow bandwidth, indicating the significant

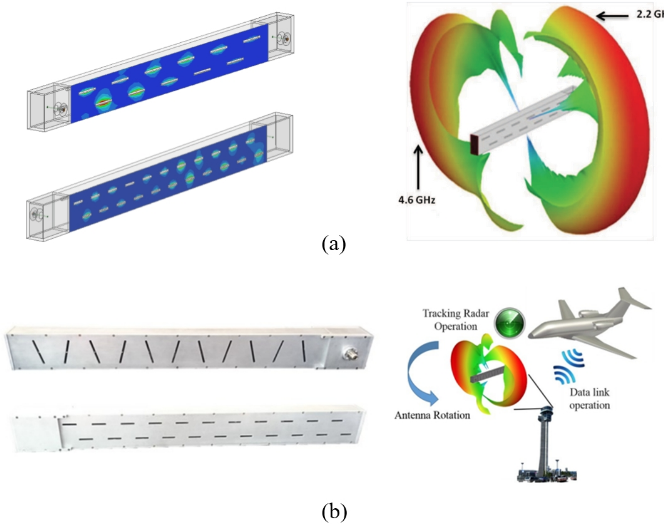


Figure 3.4: Dual-band slot arrays with bidirectional radiation (a) in [77], (b) in [78].

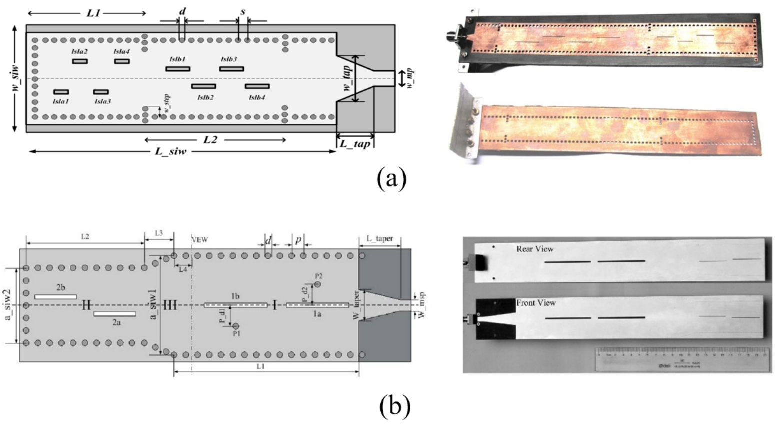


Figure 3.5: Dual-band slot arrays using single waveguide channel (distributed aperture) (a) in [79], (b) in [80].

challenge associated with this single waveguide feeding configuration.

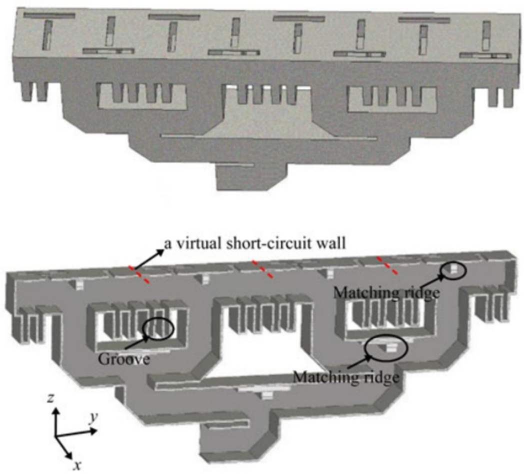


Figure 3.6: Dual-band slot array using single waveguide channel (corporate feed) in [82]

In summary, existing dual-band slot array solutions exhibit diverse characteristics and advantages but are also accompanied by certain limitations. It would be highly advantageous to propose an design that achieves true co-aperture, unidirectional dual-frequency radiation with a simple structure at high frequencies, while simultaneously supporting both broadside fixed-beam radiation and independent channel operation.

3.2 Design of Dual-Band Co-aperture Linearly-polarized Filtering Slot Array Antenna at W-band

A co-aperture dual-band linearly polarized slot array based on RGW, operating at the 74 - 78 GHz and 102 - 106 GHz bands, is designed. In each subarray, two groups of longitudinal slots for two frequency bands are excited by a single RGW channel to achieve dual-band unidirectional radiation, as shown in Fig. 3.7. To realize independent dual-band feeding while also pro-

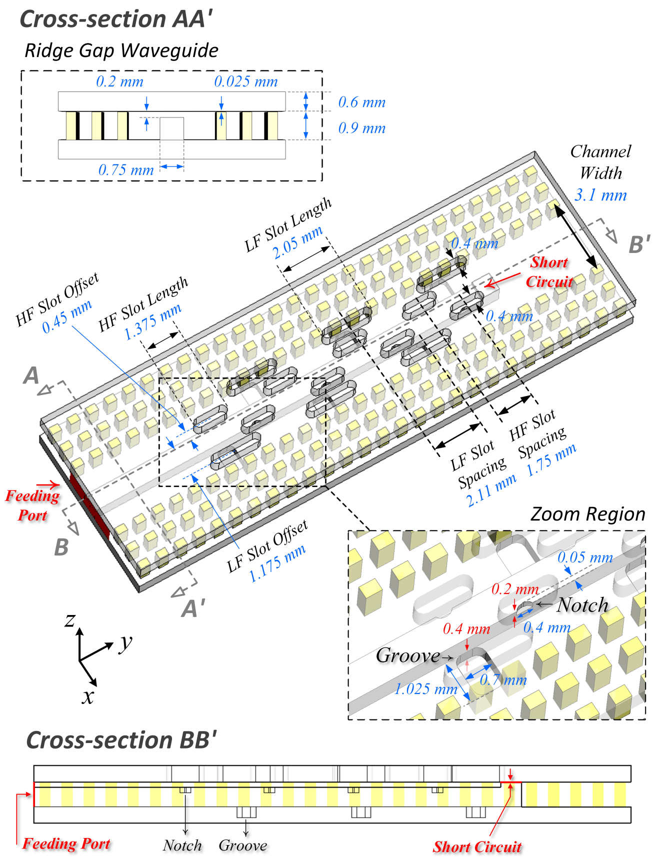


Figure 3.7: Structure of the basic dual-band subarray.

viding filtering characteristics, two bandpass filters (BPFs) are incorporated at each side of the subarray, as shown in Fig. 3.8.

The proposed subarray operates as a single channel and can be expanded into a multichannel array. It supports MIMO when each subarray is individually excited or broadside radiation when all subarrays are excited simultaneously. The MIMO capability is demonstrated through simulations and discussions using a planar array of four subarray columns. Additionally, a prototype incorporating power dividers to enable in-phase excitation at both

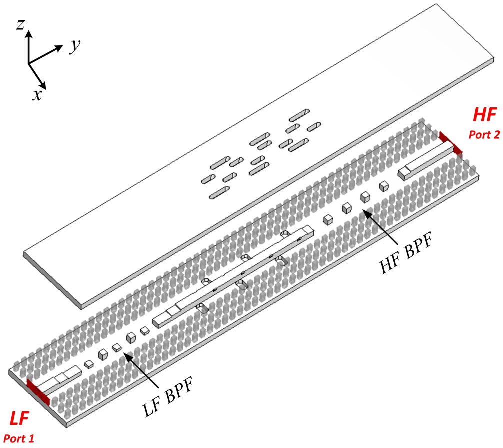


Figure 3.8: Dual-band subarray incorporated with BPFs.

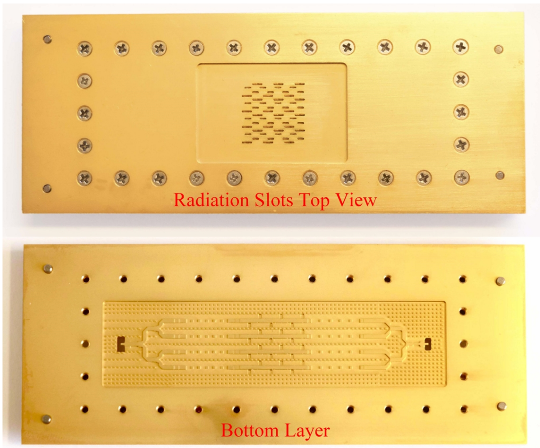


Figure 3.9: Manufactured prototype fed by power dividers.

bands was fabricated to validate the dual-band concept and its broadside radiation performance, as shown in Fig. 3.9. The simulated and measured results exhibit good agreement (Fig. 3.10 and 3.11).

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

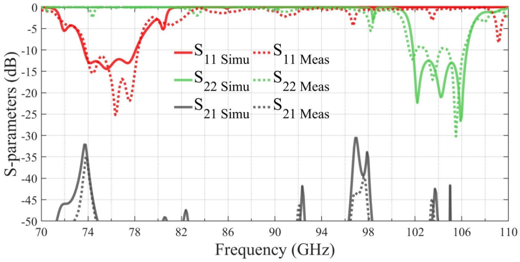


Figure 3.10: Simulated and measured S-parameters of the 4-column planar array prototype.

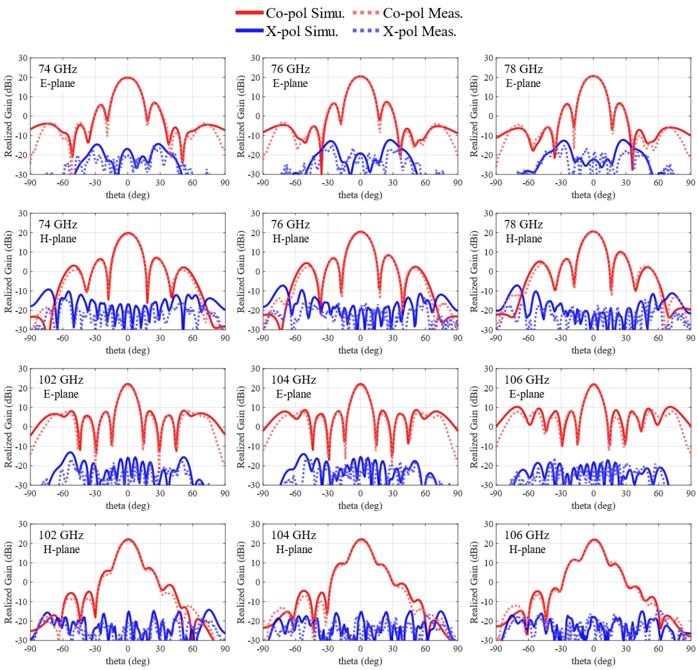


Figure 3.11: Simulated and measured radiation patterns of the 4-column planar array prototype.

CHAPTER 4

Summary of included papers

This chapter provides a summary of the included papers.

4.1 Paper A

Mu Fang, Jian Yang, Thomas Emanuelsson, Ingmar Andersson, Ashraf Uz Zaman
1-Dimensional Wide Scanning Gap Waveguide Based Slot Array Antenna using Decoupling Technique for 100 GHz Applications
Published in IEEE Transactions on Antennas and Propagation,
vol. 72, no. 4, pp. 3438–3450, Apr. 2024
©IEEE DOI: 10.1109/TAP.2024.3372147 .

This paper presents a 1-dimenional wide scanning slot array antenna based on ridge gap waveguide (RGW), operating at a 100 GHz band. A novel half wall decoupling structure is proposed to reduce the mutual coupling and the reflection coefficient simultaneously, thus achieving a more stable active reflection coefficient (ARC) within the ±60° scanning range. At the same time, special attention has been given in retaining the embedded pattern suitable for wide scanning performance.

4.2 Paper B

Mu Fang, Jian Yang, Ashraf Uz Zaman
A Comparative Study of Decoupling Techniques for Waveguide Slot Array Antennas
Published in 2024 18th European Conference on Antennas and Propagation (EuCAP),
Glasgow, United Kingdom, 2024, pp. 1-4
©IEEE DOI: 10.23919/EuCAP60739.2024.10501668 .

In this paper, we present a comparative study of three decoupling techniques for waveguide slot array antennas, including half wall, corrugation and fence. Their decoupling efficacy and impact on element patterns are investigated under two typical element spacings: $0.5\lambda_0$ and $1\lambda_0$. A summary highlighting the differences among these decoupling techniques is provided to gain insight into which specific application scenarios are best suited for each technique.

4.3 Paper C

Mu Fang, Jian Yang, Thomas Emanuelsson, Ingmar Andersson, Ashraf Uz Zaman
Dual-Band Filtering Slot Array Antenna for W-Band Application
Submitted to IEEE Transactions on Antennas and Propagation,
(Major revision)
©IEEE .

A co-aperture dual-band linearly polarized slot array based on ridge gap waveguide (RGW), operating at the 74 - 78 GHz and 102 - 106 GHz bands, is designed. In each subarray, two groups of longitudinal slots for two frequency bands are excited by a single RGW channel to achieve dual-band unidirectional radiation. Additionally, grooves and notches are implemented inside the RGW structure to improve dual-band matching, and two bandpass filters

(BPFs) are incorporated at each side of the subarray to realize independent dual-band feeding while also providing filtering characteristics. The proposed subarray not only operates as a single channel but also has the capability to expand into a multichannel array, enabling multiple-input multiple-output (MIMO) when each subarray is individually excited or broadside radiation when all subarrays are simultaneously excited. To validate the dual-band concept and its broadside radiation performance, a planar array consisting of four subarray columns was fabricated. The simulated and measured results show good agreement.

CHAPTER 5

Concluding Remarks and Future Work

This thesis primarily presents two novel GWG-based slot array designs for 100 GHz applications, both of which achieve significant advancements in slot array performance. The first is a one-dimensional wide-scanning slot array antenna solution with a novel decoupling technique, enabling a fully metallic longitudinal slot array to achieve a wide-angle scan of up to $\pm 60°$ for the first time. The second design is a co-aperture dual-band filtering antenna array, which, for the first time, simultaneously achieves a shared waveguide channel for dual-band slots, unidirectional radiation, and a truly shared planar aperture. Together, these designs address the application demands for beam scanning, as well as dual-band co-aperture broadside radiation and independent channel radiation (MIMO), demonstrating strong potential for 100 GHz applications.

Future work will explore the further performance potential and applications of the proposed slot arrays, as well as investigate GWG-based 2-dimentional beam-scanning solutions and the integration of beamformer chips for a fully realized phased array.

References

[1] T. S. Rappaport *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.

[2] Federal Communications Commission, *Allocation and Service Rules for the 71–76 GHz, 81–86 GHz, and 92–95 GHz Bands*, `https://www.fcc.gov/document/allocations-and-service-rules-71-76-ghz-81-86-ghz-and-92-95-ghz-1`, FCC 03-248, 2003.

[3] S. Shahramian, M. J. Holyoak, and Y. Baeyens, "A 16-element w-band phased-array transceiver chipset with flip-chip pcb integrated antennas for multi-gigabit wireless data links," *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 7, pp. 3389–3402, 2018.

[4] A. Natarajan, A. Valdes-Garcia, B. Sadhu, S. K. Reynolds, and B. D. Parker, "*W*-band dual-polarization phased-array transceiver front-end in sige bicmos," *IEEE Transactions on Microwave Theory and Techniques*, vol. 63, no. 6, pp. 1989–2002, 2015.

[5] W. Shin, B. Ku, O. Inac, Y. Ou, and G. M. Rebeiz, "A 108–114 ghz 4×4 wafer-scale phased array transmitter with high-efficiency on-chip antennas," *IEEE Journal of Solid-State Circuits*, vol. 48, no. 9, pp. 2041–2055, Sep. 2013.

[6] A. Arbabian, S. Callender, S. Kang, M. Rangwala, and A. M. Niknejad, "A 94 ghz mm-wave-to-baseband pulsed-radar transceiver with applica-

tions in imaging and gesture recognition," *IEEE Journal of Solid-State Circuits*, vol. 48, no. 4, pp. 1055–1071, 2013.

[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 *Proc. IEEE 68th Electron. Compon. Technol. Conf.*, 2018, pp. 197–201.

[8] C.-W. Chiang, C.-T. M. Wu, N.-C. Liu, C.-J. Liang, and Y.-C. Kuan, "A cost-effective w-band antenna-in-package using ipd and pcb technologies," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 12, no. 5, pp. 822–827, 2022.

[9] S. Shahramian, M. J. Holyoak, and Y. Baeyens, "A 16-element w-band phased-array transceiver chipset with flip-chip pcb integrated antennas for multi-gigabit wireless data links," *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 7, pp. 3389–3402, Jul. 2018.

[10] M. K. Leino, R. Montoya Moreno, J. Ala-Laurinaho, R. Valkonen, and V. Viikari, "Waveguide-based phased array with integrated element-specific electronics for 28 ghz," *IEEE Access*, vol. 7, pp. 90 045–90 054, 2019.

[11] K. Kibaroglu, M. Sayginer, T. Phelps, and G. M. Rebeiz, "A 64-element 28-ghz phased-array transceiver with 52-dbm eirp and 8–12-gb/s 5g link at 300 meters without any calibration," *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 12, pp. 5796–5811, 2018.

[12] Y. Yin, Z. Zhang, T. Kanar, S. Zihir, and G. M. Rebeiz, "A 24-29.5 ghz 256-element 5g phased-array with 65.5 dbm peak eirp and 256-qam modulation," in *2020 IEEE/MTT-S International Microwave Symposium (IMS)*, 2020, pp. 687–690.

[13] C. Fulton, M. Yeary, D. Thompson, J. Lake, and A. Mitchell, "Digital phased arrays: Challenges and opportunities," *Proceedings of the IEEE*, vol. 104, no. 3, pp. 487–503, 2016.

[14] P. S. Kildal, A. U. Zaman, E. Rajo-Iglesias, E. Alfonso, and A. Valero-Nogueira, "Design and experimental verification of ridge gap waveguide in bed of nails for parallel-plate mode suppression," *IET Microwaves, Antennas & Propagation*, vol. 5, no. 3, pp. 262–270, Feb. 2011.

[15] A. U. Zaman and P.-S. Kildal, "Gap waveguides," in *Handbook of Antenna Technologies*, Springer, 2016, pp. 3273–3347.

[16] D. Zarifi, A. Farahbakhsh, and A. U. Zaman, "A gap waveguide-based d-band slot array antenna with interdigital feed network," *IEEE Transactions on Antennas and Propagation*, vol. 71, no. 9, pp. 7124–7131, 2023.

[17] M. Ferrando-Rocher, J. I. Herranz-Herruzo, A. Valero-Nogueira, B. Bernardo-Clemente, A. U. Zaman, and J. Yang, "8×8 Ka -band dual-polarized array antenna based on gap waveguide technology," *IEEE Transactions on Antennas and Propagation*, vol. 67, no. 7, pp. 4579–4588, 2019.

[18] 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.

[19] 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.

[20] M. Rezaee and A. U. Zaman, "Groove gap waveguide filter based on horizontally polarized resonators for v-band applications," *IEEE Transactions on Microwave Theory and Techniques*, vol. 68, no. 7, pp. 2601–2609, Jul. 2020.

[21] Q. Li, D. Guo, J. Mou, J. Li, and K. .-. Xu, "Groove gap waveguide bandpass filter based on spoof surface plasmon polariton for ka-band applications," *IEEE Transactions on Microwave Theory and Techniques*, vol. 72, no. 1, pp. 340–347, Jan. 2024.

[22] D. Zarifi, A. Farahbakhsh, and A. U. Zaman, "Design and fabrication of wideband millimeter-wave directional couplers with different coupling factors based on gap waveguide technology," *IEEE Access*, vol. 7, pp. 88 822–88 829, 2019.

[23] Y. Quan, J. Yang, H. Wang, and A. U. Zaman, "A simple asymmetric orthomode transducer based on groove gap waveguide," *IEEE Microwave and Wireless Components Letters*, vol. 30, no. 10, pp. 953–956, Oct. 2020.

[24] Q. Ren, A. U. Zaman, J. Yang, V. Vassilev, and C. Bencivenni, "Novel integration techniques for gap waveguides and mmics suitable for multilayer waveguide applications," *IEEE Transactions on Microwave Theory and Techniques*, vol. 70, no. 9, pp. 4120–4128, 2022.

[25] J.-L. A. Lijarcio, A. Vosoogh, V. Vassilev, *et al.*, "Substrate-less vertical chip-to-waveguide transition for w-band array antenna integration," in *2023 17th European Conference on Antennas and Propagation (EuCAP)*, 2023, pp. 1–3.

[26] D. Zarifi, A. Farahbakhsh, A. U. Zaman, and P. .-. 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, Jul. 2016.

[27] F. Fan, J. Yang, V. Vassilev, and A. U. Zaman, "Bandwidth investigation on half-height pin in ridge gap waveguide," *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 1, pp. 100–108, Jan. 2018.

[28] M. Ferrando-Rocher, A. Valero-Nogueira, J. I. Herranz-Herruzo, and J. Teniente, "60 ghz single-layer slot-array antenna fed by groove gap waveguide," *IEEE Antennas and Wireless Propagation Letters*, vol. 18, no. 5, pp. 846–850, May 2019.

[29] D. Pérez-Quintana, I. Ederra, and M. Beruete, "Bull's-eye antenna with circular polarization at millimeter waves based on ridge gap waveguide technology," *IEEE Transactions on Antennas and Propagation*, vol. 69, no. 4, pp. 2376–2379, Apr. 2021.

[30] 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, Dec. 2018.

[31] J. Yue, C. Zhou, K. Xiao, L. Ding, and S. Chai, "W-band low-sidelobe series-fed slot array antenna based on groove gap waveguide," *IEEE Antennas and Wireless Propagation Letters*, vol. 22, no. 4, pp. 908–912, Apr. 2023.

[32] A. Farahbakhsh, D. Zarifi, and A. U. Zaman, "D-band high-gain planer slot array antenna using gap waveguide technology," *IEEE Transactions on Antennas and Propagation*, vol. 73, no. 1, pp. 594–599, Jan. 2025.

[33] T. Li, A. Bhutani, and T. Zwick, "A d-band corporate-feed gap-cavity slot array antenna using virtual pec method," *IEEE Transactions on Antennas and Propagation*, vol. 70, no. 8, pp. 7258–7263, Aug. 2022.

[34] X. Ding, J. An, X. Bu, H. Han, J. Liu, and Z. S. He, "A 16 × 16-element slot array fed by double-layered gap waveguide distribution network at 160 ghz," *IEEE Access*, vol. 8, pp. 55 372–55 382, 2020.

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

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

[37] A. Tamayo-Domínguez, J. .-. Fernández-González, and M. S. Castañer, "3-d-printed modified butler matrix based on gap waveguide at w-band for monopulse radar," *IEEE Transactions on Microwave Theory and Techniques*, vol. 68, no. 3, pp. 926–938, Mar. 2020.

[38] 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, Jan. 2021.

[39] 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.

[40] A. U. Z. A. Kishk and P.-S. Kildal, "Numerical prepackaging with pmc lid - efficient and simple design procedure for microstrip circuits including the packaging," *ACES Journal*, vol. 27, no. 05, pp. 389–398, 2012.

[41] J. Y. A. U. Zaman 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*, Toronto, ON, Canada, 2010, pp. 1–4.

[42] P.-S. K. A. U. Zaman V. Vassilev 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.

[43] A. V. 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.

[44] Q. R. et al., “An automotive polarimetric radar sensor with circular polarization based on gapwaveguide technology,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 72, no. 6, pp. 3759–3771, 2024.

[45] A. U. Z. Z. Zang Q. Ren and J. Yang, “77 ghz fully polarimetric antenna system with compact circularly polarized slots in gap waveguide for automotive radar,” *IEEE Transactions on Antennas and Propagation*, vol. 72, no. 7, pp. 5578–5588, 2024.

[46] C. A. Balanis, “Modern antenna handbook,” *Wiley*, 2011.

[47] Z. N. Chen, *Handbook of Antenna Technologies*. New York, NY, USA: Springer Publishing, 2015.

[48] C. Huang, Z. Zhao, Q. Feng, C. Wang, and X. Luo, “Grooves-assisted surface wave modulation in two-slot array for mutual coupling reduction and gain enhancement,” *IEEE Antennas Wireless Propagation Letters*, vol. 8, pp. 912–915, Jul. 2009.

[49] J. He, Y. Wu, D. Chen, M. Zhang, J. Hirokawa, and Q. Liu, “Realization of a wideband series-fed 4 × 4-element waveguide slot array in the x-band,” *IEEE Access*, vol. 9, pp. 83 666–83 675, 2021.

[50] J. .-. A. Lijarcio, A. Vosoogh, C. Bencivenni, and A. U. Zaman, “Low-cost center-fed slot array based on gap waveguide mlw coaxial line technology for e-band automotive radar,” *IEEE Trans. Antennas Propag.*, vol. 72, no. 7, pp. 5674–5681, 2024.

[51] L. Josefsson and S. R. Rengarajan, *Slotted Waveguide Array Antennas: Theory, Analysis and Design*. SciTech Publishing, an imprint of IET, 2018.

[52] C. Fager, T. Eriksson, F. Barradas, K. Hausmair, T. Cunha, and J. C. Pedro, "Linearity and efficiency in 5g transmitters: New techniques for analyzing efficiency, linearity, and linearization in a 5g active antenna transmitter context," *IEEE Microwave Magazine*, vol. 20, no. 5, pp. 35–49, May 2019.

[53] J. Zhou, H. Wang, J. Cao, G. Liang, and S. Jiang, "Ridged waveguide slot phased array for 5g millimeter-wave application," in *2019 Cross Strait Quad-Regional Radio Science and Wireless Technology Conference (CSQRWC)*, 2019, pp. 1–3.

[54] K. Forooraghi, P.-S. Kildal, and S. R. Rengarajan, "Admittance of an isolated waveguide-fed slot radiating between baffles using a spectrum of two-dimensional solutions," *IEEE Transactions on Antennas and Propagation*, vol. 41, no. 4, pp. 422–428, Apr. 1993.

[55] T. Suzuki, J. Hirokawa, and M. Ando, "Iteration-free design of waveguide slot array with cavities," *IEEE Transactions on Antennas and Propagation*, vol. 58, no. 12, pp. 3891–3897, Dec. 2010.

[56] C. Huang, Z. Zhao, Q. Feng, C. Wang, and X. Luo, "Grooves-assisted surface wave modulation in two-slot array for mutual coupling reduction and gain enhancement," *IEEE Antennas Wireless Propagation Letters*, vol. 8, pp. 912–915, Jul. 2009.

[57] R. Mailloux, "Reduction of mutual coupling using perfectly conducting fences," *IEEE Transactions on Antennas and Propagation*, vol. 19, no. 2, pp. 166–173, Mar. 1971.

[58] C. Gu, V. Fusco, M. Keaveney, M. O'Shea, and J. Breslin, "Isolation enhancement between waveguide slot arrays using quasi-gap waveguide structure," in *2020 International Conference on UK-China Emerging Technologies (UCET)*, Glasgow, UK, 2020, pp. 1–4.

[59] L. Li, X. Dang, B. Li, and C. Liang, "Analysis and design of waveguide slot antenna array integrated with electromagnetic band-gap structures," *IEEE Antennas and Wireless Propagation Letters*, vol. 5, pp. 111–115, 2006.

[60] Y. Liu, H. Yang, Z. Jin, and J. Zhu, "An improvement approach for wide-angle impedance matching using elc metasurface slabs for siw slot array antennas," *Int. J. Antennas Propag.*, vol. 2018, pp. 1–8, Apr. 2018.

[61] A. A. D. et al., “Efficient siw-feed network suppressing mutual coupling of slot antenna array,” *IEEE Transactions on Antennas and Propagation*, vol. 69, no. 9, pp. 6058–6063, 2021.

[62] T. V. Trinh, S. Trinh-Van, K.-Y. Lee, Y. Yang, and K. C. Hwang, “Design of a low-cost, low-sidelobe-level, differential-fed siw slot array antenna with zero beam squint,” *Applied Sciences*, vol. 12, no. 21, p. 10 826, Oct. 2022.

[63] M. F. A. U. Zaman P. -S. Kildal and A. Kishk, “Validation of ridge gap waveguide performance using in-house trl calibration kit,” in *Proceedings of the Fourth European Conference on Antennas and Propagation*, Barcelona, Spain, 2010, pp. 1–4.

[64] M. Ferrando-Rocher, J. I. Herranz-Herruzo, A. Valero-Nogueira, and M. Baquero-Escudero, “Dual-band single-layer slot array antenna fed by k/ka-band dual-mode resonators in gap waveguide technology,” *IEEE Antennas Wireless Propag. Lett.*, vol. 20, no. 3, pp. 416–420, Mar. 2021.

[65] J. .-. Lin, Y. Yang, S. .-. Wong, and Y. Li, “High-order modes analysis and its applications to dual-band dual-polarized filtering cavity slot arrays,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 69, no. 6, pp. 3084–3092, Jun. 2021.

[66] A. G. Derneryd and A. Lagerstedt, “Novel slotted waveguide antenna with polarimetric capabilities,” in *Proc. IGARSS*, vol. 3, Florence, Italy, 1995, pp. 2054–2056.

[67] T. Li, H. Meng, and W. Dou, “Design and implementation of dual-frequency dual-polarization slotted waveguide antenna array for ka-band application,” *IEEE Ant. Wireless Propag. Lett.*, vol. 13, pp. 1317–1320, 2014.

[68] Y.-J. Cong and W.-B. Dou, “Design of dual-polarized waveguide slotted antenna array for ka-band application,” in *Proc. ISAPE*, Guangzhou, China, 2010, pp. 97–100.

[69] H. Luo, Y. Xiao, X. Lu, and H. Sun, “Design of a dual-polarization single-ridged waveguide slot array with enhanced bandwidth,” *IEEE Antennas and Wireless Propagation Letters*, vol. 18, no. 1, pp. 138–142, Jan. 2019.

[70] W. Wang, J. Jin, J.-G. Lu, and S.-S. Zhong, "Waveguide slotted antenna array with broadband, dual-polarization and low cross-polarization for x-band sar applications," in *Proc. IEEE Int. Radar Conf.*, May 2005, pp. 653–656.

[71] Z.-X. Wang *et al.*, "Design of w-band dual polarized slotted waveguide array antenna on an annular disk," *J. Infrared Millim. Terahertz Waves*, vol. 44, no. 1-2, pp. 151–168, 2023.

[72] M. Chen, X. Fang, W. Wang, H. Zhang, and G. Huang, "Dual-band dual-polarized waveguide slot antenna for sar applications," *IEEE Ant. Wireless Propag. Lett.*, vol. 19, no. 10, pp. 1719–1723, Aug. 2020.

[73] Y. Rao, H. Zhang, and G. Sun, "Shared aperture dual-band waveguide slot antenna," in *2020 IEEE Int. Symp. Antennas Propag. and North American Radio Science Meeting*, 2020, pp. 693–694.

[74] G. Colangelo and R. Vitiello, "Shared aperture dual band printed antenna," in *Proc. Int. Conf. Electromag. Adv. Appl.*, 2011, pp. 1092–1095.

[75] Y.-Y. Liu, F.-w. Yao, and Y.-B. Shang, "Co-aperture dualband waveguide monopulse antenna," in *2013 International Symposium on Antennas and Propagation (ISAP)*, 2013, pp. 1–3.

[76] D.-J. Wei, J. Li, G. Yang, J. Liu, and J.-J. Yang, "Design of compact dual-band siw slotted array antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 6, pp. 1085–1089, Jun. 2018.

[77] I. F. da Costa, D. H. Spadoti, and S. A. Cerqueira, "Dual-band slotted waveguide antenna array for communication, maritime navigation and surveillance radar," in *2015 International Workshop on Telecommunications (IWT)*, Santa Rita do Sapucai, Brazil, 2015, pp. 1–4.

[78] C. S. Arismar *et al.*, "A novel dual-polarization and dual-band slotted waveguide antenna array for dual-use radars," in *2016 10th European Conference on Antennas and Propagation (EuCAP)*, Davos, Switzerland, 2016, pp. 1–4.

[79] S. Mukherjee, K. V. Srivastava, and A. Biswas, "Implementation of dualfrequency longitudinal slot array antenna on substrate integrated waveguide at x-band," in *Proc. Eur. Conf. Microw.*, Nuremberg, Germany, 2013, pp. 195–198.

[80] Z. Zeng, W. Hong, Z. Kuai, H. Tang, and J. Chen, “The design and experiment of a dual-band omni-directional siw slot array antenna,” in *Proc. Asia Pac. Microw. Conf.*, Bangkok, Thailand, 2007, pp. 1–4.

[81] P. Kumawat and S. Joshi, “5g dual-band slotted siw array antenna,” *Journal of Taibah Univ. for Science*, vol. 15, no. 1, pp. 321–328, 2021.

[82] J. Gao, T. Li, H. Wang, X. Lei, and K. Wang, “A compact dual-band dual-linearly polarized waveguide slot array antenna with groove at waveguide bottom,” *International Journal of Microwave and Wireless Technologies*, vol. 15, no. 7, pp. 1205–1211, 2023.