THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Wide Scanning Gap Waveguide Slot Array Antenna for 100 GHz Applications

Mu Fang

Department of Electrical Engineering
Chalmers University of Technology
Gothenburg, Sweden, 2024

Wide Scanning Gap Waveguide Slot Array Antenna for 100 GHz Applications

Mu Fang

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

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

Printed by Chalmers Reproservice
Gothenburg, Sweden, May2024

Abstract

Frequencies at 100 GHz hold promise for the next generation of wireless communication systems due to the vast unexplored spectrum resource. In these high frequencies, high-gain phased arrays are strongly needed to overcome the high free-space path loss and achieve flexible beamforming capabilities. Current phased array solutions commonly have high integration, but also suffer from low radiation efficiency due to high dielectric loss. To achieve high radiation efficiency, all-metal phased array antennas emerge as a viable alternative solution. Furthermore, with the assistance of gap waveguide (GWG) technology, difficulty in fabricating all-metal antenna structures at high frequencies can be significantly reduced.

This thesis presents our first beam scanning array design at 100GHz, a high-efficiency one-dimensional wide-scanning solution based on GWG slot array antenna. Utilizing a novel decoupling technique, for the first time, the all-metal slot array achieves $\pm 60°$ wide-angle scanning at E-plane, with 3-dB scan loss and $>91\%$ total efficiency. Subsequently, various slot array decoupling techniques are also compared and studied to analyze their unique properties and suitable application scenarios.

The proposed slot antenna will be used to manufacture a 100 GHz phased array demonstrator, and it will also serve as the basis for future two-dimensional scanning antenna designs.

Keywords: Slot antenna, wide scanning, decoupling, phased array, 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". Accepted by EUCAP2024, Apr. 2024.

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
PEC:	Perfect electric conductor
PMC:	Perfect magnetic conductor
AMC:	Artificial magnetic conductor
ARC:	Active reflection coefficient

Contents

Abstract i

List of Papers iii

Acknowledgements v

Acronyms vi

I Overview 1

1 Introduction 3

1.1 The State-of-the-art Phased Arrays at 100 GHz 3
1.2 Gap Waveguide Technology 7
1.3 Outline of this thesis 10

2 1-Dimensional Wide-scanning Linear Polarized Phased Array 11

2.1 Challenges to Achieve Wide Scanning for Slot Array 11
2.2 Existing Decoupling Techniques for Slot Array 12
2.3 Wide Scanning Slot Array Solution Using Novel Decoupling Technique 16

2.4 Comparative Study of Three All-metal Slot Array Decoupling Techniques . . . 17

3 Summary of included papers **21**
3.1 Paper A . . . 21
3.2 Paper B . . . 22

4 Concluding Remarks and Future Work **23**

References **25**

II Papers 31

A **A1**
1 Introduction . . . A3
2 Basic Antenna Element . . . A5
2.1 Element Spacing . . . A5
2.2 Leakage and Mutual Coupling Analysis . . . A7
2.3 Active Reflection Coefficient . . . A8
3 Decoupling Technique . . . A12
3.1 Complete Wall . . . A12
3.2 Half Wall . . . A14
3.3 Versatility and General Applicability of Half Wall . . . A18
4 Embedded Pattern Discussion . . . A20
5 8×8 Slot Planar Array Prototype . . . A25
5.1 Simulation Result of the 8-Element Array with Independent Feeding Ports . . . A27
5.2 Feeding Networks for Broadside and 60° Scanning . . . A27
5.3 Simulation and Measured Results of the Prototype . . . A30
6 Conclusion . . . A32
References . . . A35

B **B1**
1 Introduction . . . B3
2 Three Decoupling Techniques . . . B4
3 Comparison of Simulation Results . . . B5
3.1 Element Spacing = $0.5\lambda_0$ . . . B5

3.2 Element Spacing = $1\lambda_0$ B7
4 Summary of the Differences B10
5 Conclusion B10
References B10

Part I

Overview

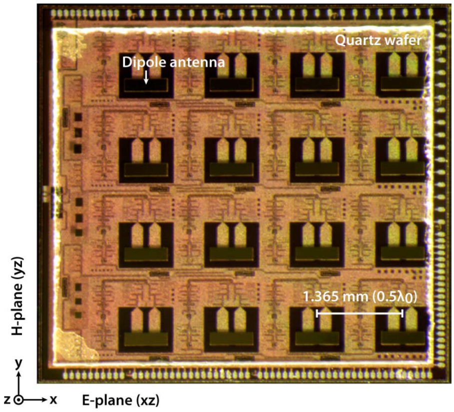
CHAPTER 1

Introduction

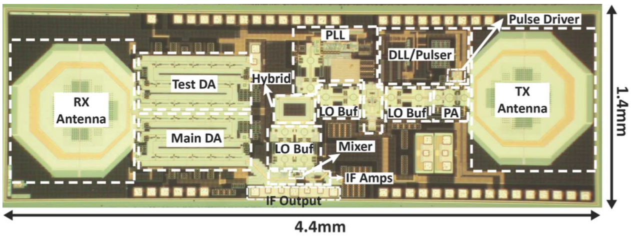
1.1 The State-of-the-art Phased Arrays at 100 GHz

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, it also presents new challenges distinct from those at lower frequencies. The foremost challenge is the much higher free-space path loss, coupled with weaker electromagnetic diffraction capability (relying more on line-of-sight transmission) [1]. To overcome the high free-space path loss and achieve flexible beamforming capabilities, utilizing high-gain phased arrays becomes a preferred choice [5] [6].



(a)

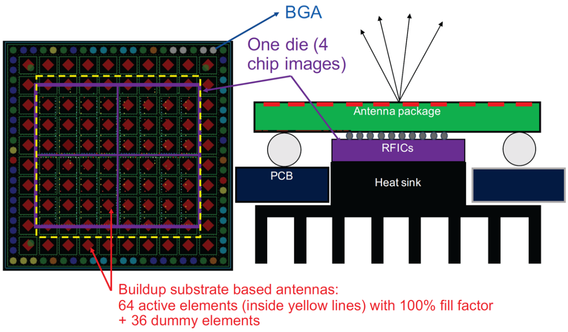


(b)

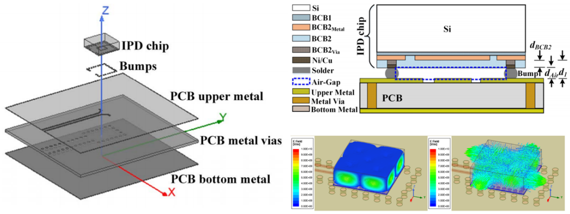
Figure 1.1: Examples of AoC phased arrays at W-band: (a) in [3], (b) in [4].

Designing high-performance phased arrays in such high-frequency bands still presents technical obstacles. Currently, the predominant solutions for phased arrays at W-band (75-110 GHz) include antenna-on-chip (AoC) [3] [4], 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.

However, these methods are not without their challenges. Primarily, the materials utilized for antenna integration onto the chip or within the package



(a)



(b)

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

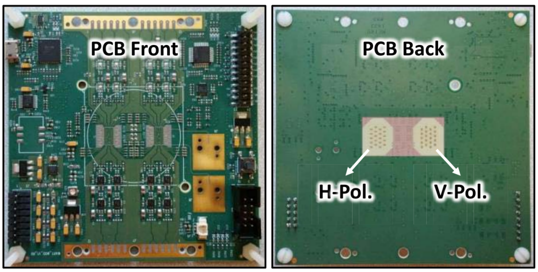


Figure 1.3: Example of a PCB phased array at W-band in [9].

can introduce additional losses. Such losses may lead to signal attenuation and distortion, impacting the system's performance. In [3] and [4], 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 94GHz. 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).

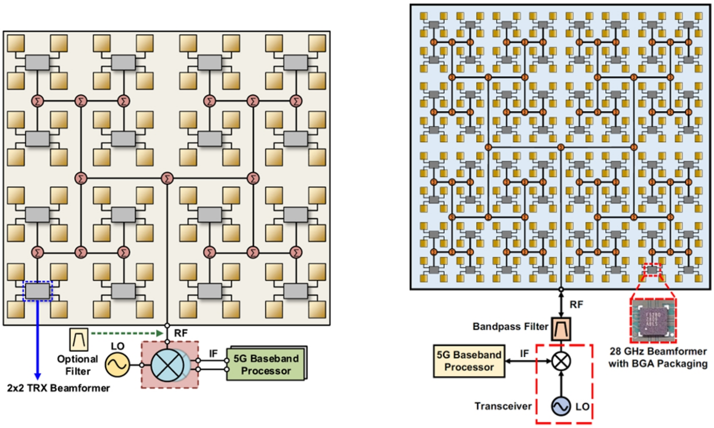


Figure 1.4: Examples of full-analog phased-array architecture using division networks: 1 to 16 in [11] (left), 1 to 64 in [12] (right).

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 the inherent low-loss characteristics, emerge as a promising alternative solution. The incorporation of metal structures can also facilitate better heat dissipation, aiding in better thermal management.

1.2 Gap Waveguide Technology

The progress of all-metal phased arrays in the high-frequency band has been traditionally limited by manufacturing complexities. In recent years, the development of gap waveguide (GWG) technology, characterized by being free of electrical contacts, has significantly reduced the manufacturing challenges and expenses of all-metal antenna arrays at mmWave frequency bands [14].

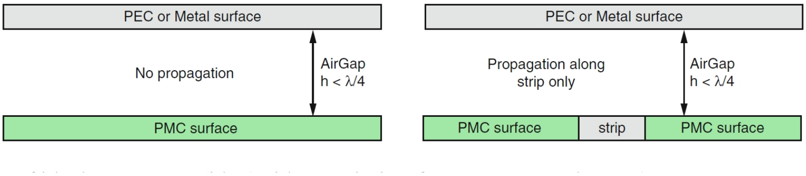


Figure 1.5: Cross section of ideal GWG [15].

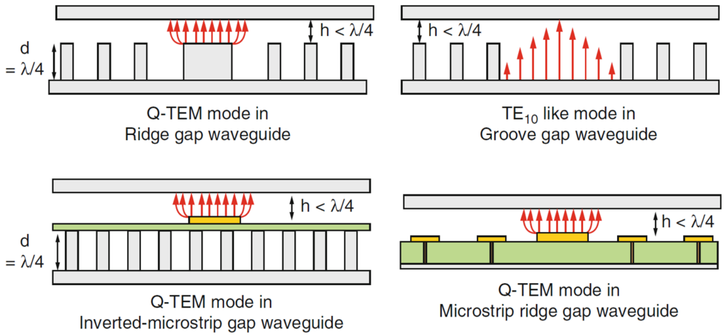


Figure 1.6: Different GWG geometries and their desired propagation modes [15].

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

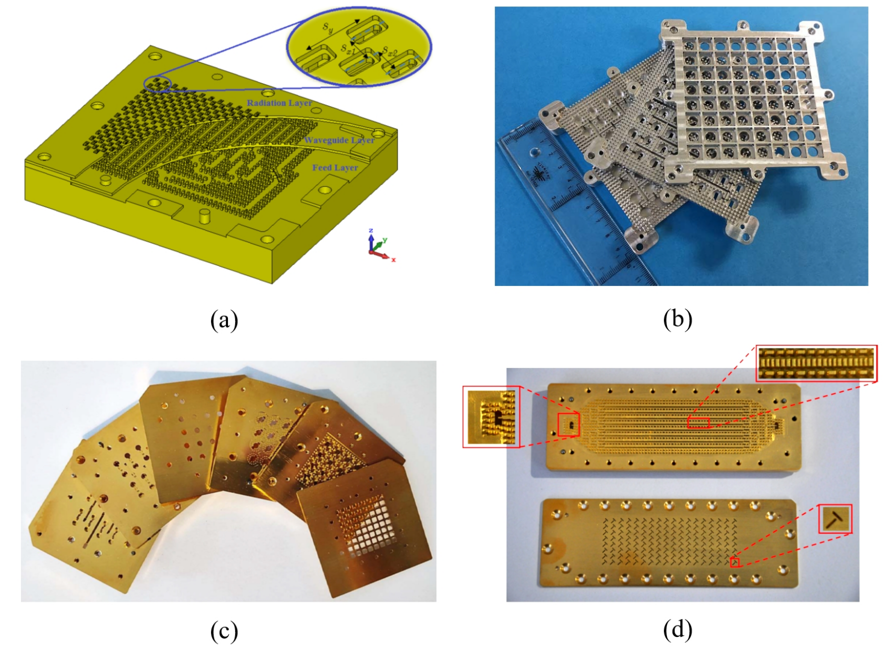


Figure 1.7: Examples of GWG-based antenna arrays: (a) in [16], (b) in [17], (c) in [18],(d) in [19].

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 gap waveguide 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.

The primary benefit of the gap waveguide design lies in its ability to be implemented without the need for metal-to-metal contact between the smooth metal surface and the textured AMC surface. This feature facilitates the low-cost production of low-loss waveguide components, suitable for millimeter-

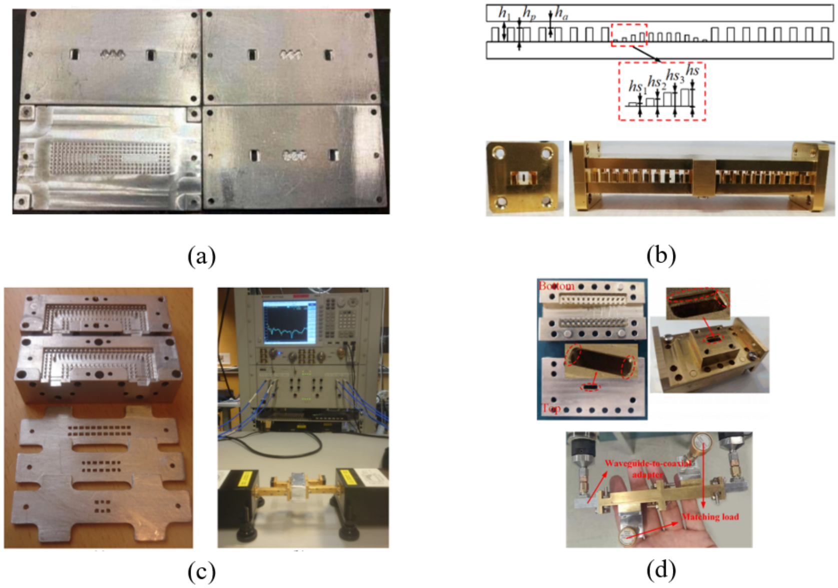
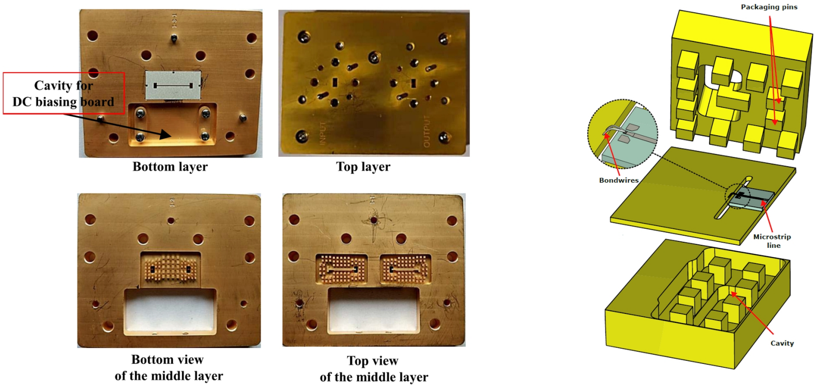


Figure 1.8: Examples of GWG-based components: (a) filter in [26], (b) filter in [27], (c) directional coupler [28],(d) orthomode transducer in [29].

wave (mmWave) frequency bands and potentially beyond.

In recent years, utilizing GWG technology, a great variety of waveguide-based antennas [16]–[25] and components [26]–[29] 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[30]–[34] . Some representative designs of GWG-based antennas and components are shown in Fig. 1.7 and Fig. 1.8.

Moreover, the integration technology associate with GWG has significantly progressed. Various designs of GWG to PCB transmission line transition have been developed [35] [36], as illustrated in Fig. 1.9. These technological developments have been crucial in establishing the basis for GWG-based phased array designs.



(a) (b)

Figure 1.9: Examples of GWG-PCB transitions:(a) in [35], (b) in [36].

1.3 Outline of this thesis

The goal of this research is to explore high-efficient GWG-based phased arrays for 100 GHz applications. We have proposed a 1-dimensional wide scanning solution, which is discussed in **Chapter** 2. **Chapter 3** gives a summary of included papers. Conclusions and plans for future work are presented in **Chapter** 4.

CHAPTER 2

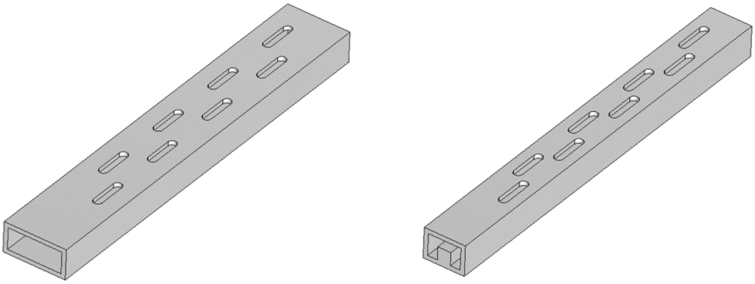
1-Dimensional Wide-scanning Linear Polarized Phased Array

Our first work focuses on GWG-based linearly polarized 1-dimensional scanning phased array. Waveguide slot array antenna (incorporated with broad wall longitudinal slots) is chosen as the array element for its numerous benefits, including simple and low-profile structure, robustness and durability, high power handling ability, 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. This chapter will analyze these limitations and subsequently provide a wide scanning all-metal slot array solution.

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-



(a) (b)

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

space wavelength. For traditional slot array fed by rectangular 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 in slot array antennas [37], which can cause the degradation of active reflection coefficient (ARC) at large scanning angles and further cause mismatch between antenna and power amplifier, affecting the overall system performance [38]. As a result, the typical scanning range of ridge waveguide slot array is only ±45° [39].

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 [40], cavities [41], grooves (corrugation) [42], fences [43] [48], quasi-gap waveguide [44], electromagnetic band-gap [45], metasurface [46] and decoupling network [47]. However, these existing decoupling structures are not applicable for wide scan-

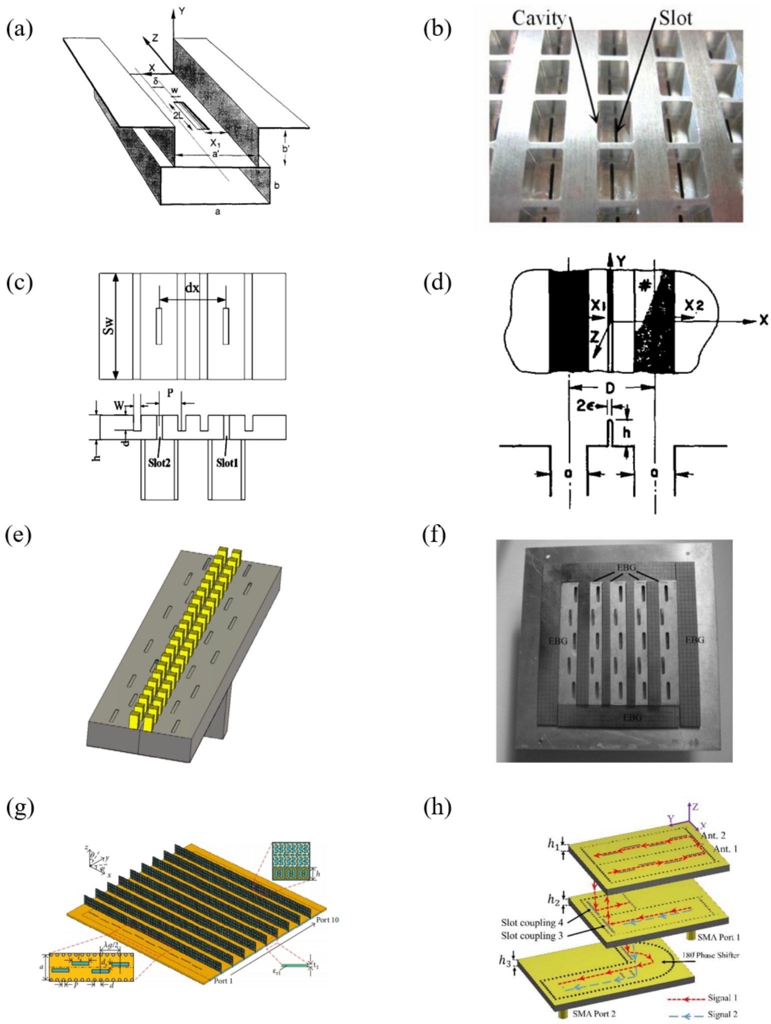


Figure 2.2: Existing decoupling techniques for slot Array: (a) baffles [40], (b) cavities [41], (c) grooves [42], (d) fences [43], (e) quasi-gap waveguide [44], (f) electromagnetic band-gap [45], (g) metasurface [46] and (h) decoupling network [47].

ning need of all-metal slot arrays.

First of all, most of those report techniques (except the metasurface proposed in [46]) are initially designed for slot arrays with larger than $0.5\lambda_0$, or in other words, they are not for wide scanning. Metal structures like baffles [40], cavities [41], quasi-gap waveguide [44] are too bulky to implement in the limited space between slot arrays with $0.5\lambda_0$ spacing. Two widely used decoupling technologies grooves [42] and fences [43] [48] show promise to accommodate this narrow spacing due to their relatively compact structures. However, base on our investigation, they can only operate well when they are slightly away from the radiation slots and start to lose their efficacy under $0.5\lambda_0$ element spacing (analyis of grooves and fences is given in 2.4). Electromagnetic band-gap in [45] 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 [40], cavities [41], quasi-gap waveguide [44], grooves [42], fences [43] [48], electromagnetic band-gap [45]) result in antenna element with narrower E-plane beamwidth and higher gain, which contradicts the need for wide scanning. 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 [46] is proposed for wide scanning. In this design, metasurface is placed vertically between the slot array elements to deal with the E-plane mutual coupling, and 3-dB scanning loss within $\pm 60°$ scanning range is achieved. Although this technique provides a possible solution, the metasurface structure will bring certain structural complexity and processing difficulty (also this design is not fabricated for measurement and verification in the paper). Again, as mentioned before, any structures involving PCB are not suitable for all-metal slot array in high-frequencies (including the PCB-based decoupling network in [47].A comparison table of these decoupling techniques is summarized in Table 2.1.

Hence, to the best of the authors' knowledge, no well-established decoupling methods are currently 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 to 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 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 alter the original embedded pattern (without reducing the beamwidth at the scanning plane).

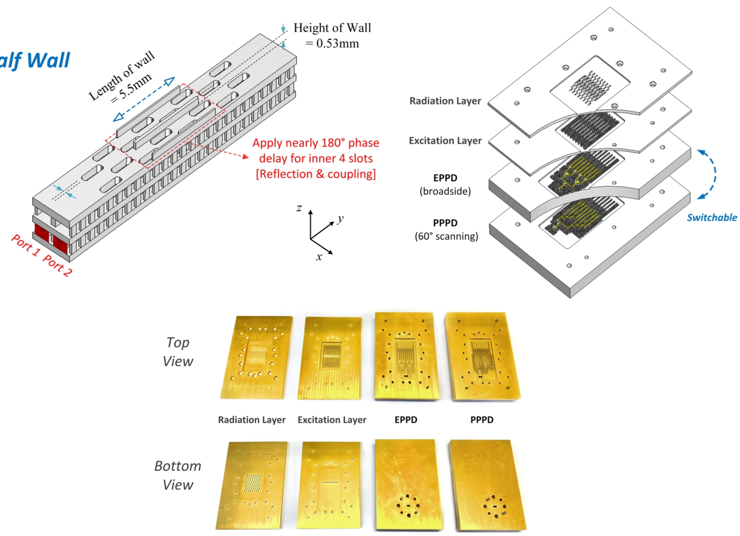
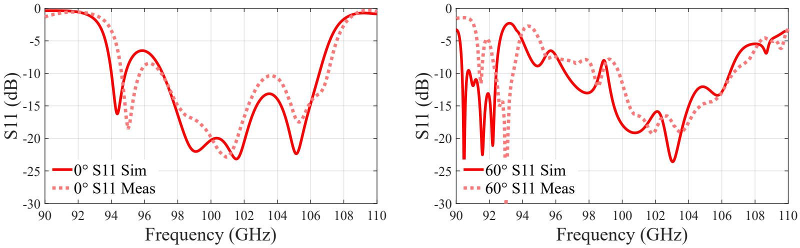


Figure 2.3: GWG Slot Array incorporated with half wall decoupling structure.

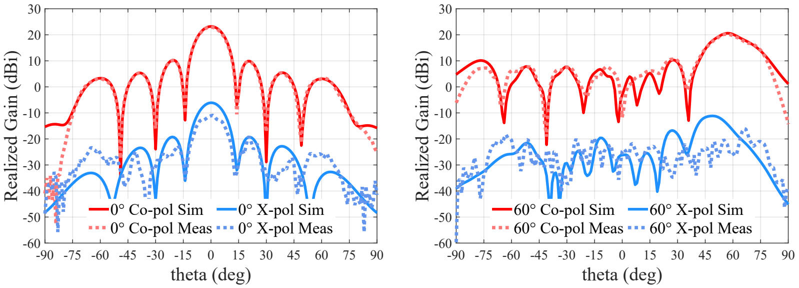
To fulfill these requirements, we propose a novel decoupling structure named "half wall" (as depicted in Fig. 2.3) which can also improve the reflection coefficient of the slot array element at the same time. With the help of this decoupling method, the proposed GWG-based slot array achieves a more stable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

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.



(a) (b)

Figure 2.5: Simulated and measured E-plane realized gain pattern (102 GHz) of the prototype.(a) broadside (0°), (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 [42] and fences [43] [48], which are also full-metal (as shown in Fig. 2.6). Their decoupling efficacy and impact on element patterns are investigated under two typical element spacings: $0.5\lambda_0$ and $1\lambda_0$.

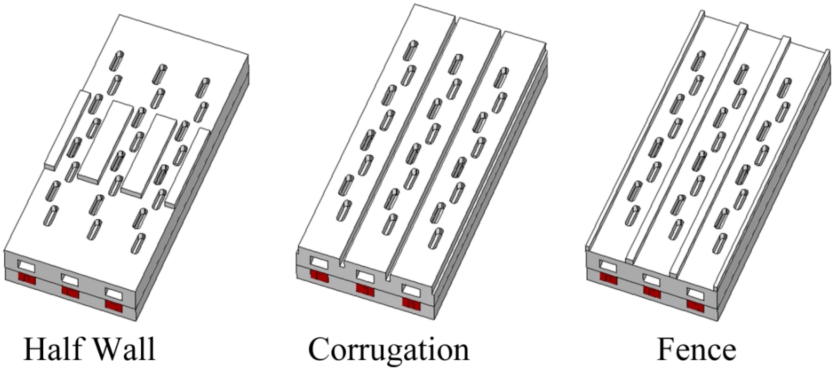
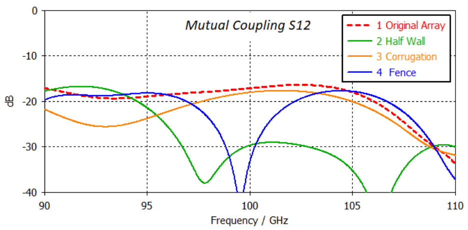
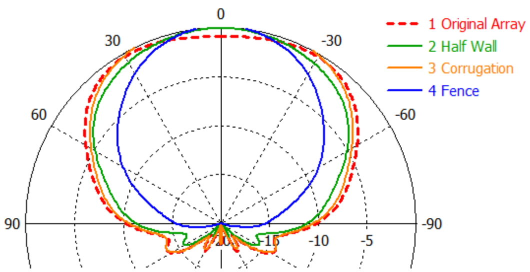


Figure 2.6: Slot array decoupling techniques: half wall, corrugation and fence.

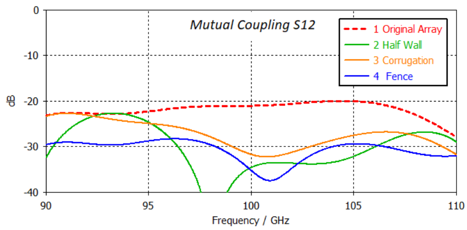


(a)

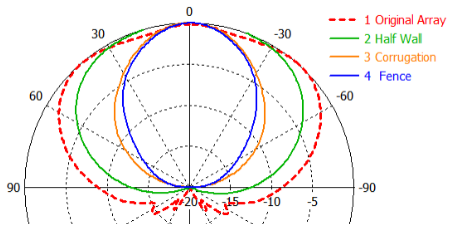


(b)

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.

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**.

CHAPTER 3

Summary of included papers

This chapter provides a summary of the included papers.

3.1 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.

3.2 Paper B

Mu Fang, Jian Yang, Ashraf Uz Zaman
A Comparative Study of Decoupling Techniques for Waveguide Slot Array Antennas
Accepted by EUCAP2024,
Apr. 2024

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.

CHAPTER 4

Concluding Remarks and Future Work

This thesis presents our first work of GWG phased array design, a 1-dimensional wide scanning solution based on RGW slot array antenna with novel decoupling technique. The proposed design exhibits good scanning performance and high efficiency, demonstrating the feasibility and advantages of GWG phased array solutions at 100 GHz. Our future work will focus on exploring 1-dimensional scanning solution with wider bandwidth, as well as 2-dimensional scanning solution. Additionnally, we will also investigate GWG-based co-aperture dual-band filtering antenna array for 100 GHz application.

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] 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.

[4] A. Arbabian, S. Callender, S. Kang, M. Rangwala, and A. M. Niknejad, "A 94 ghz mm-wave-to-baseband pulsed-radar transceiver with applications in imaging and gesture recognition," *IEEE Journal of Solid-State Circuits*, vol. 48, no. 4, pp. 1055–1071, 2013.

[5] 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.

[6] 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.

[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] 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.

[21] 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.

[22] 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.

[23] 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.

[24] 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.

[25] 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.

[26] 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.

[27] 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.

[28] 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.

[29] 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.

[30] 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.

[31] 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.

[32] 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.

[33] 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.

[34] 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.

[35] 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.

[36] 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.

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

[38] 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.

[39] 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.

[40] 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.

[41] 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.

[42] 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.

[43] 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.

[44] 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.

[45] 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.

[46] 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.

[47] 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.

[48] 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.