Thesis for the Degree of Licentiate of Engineering

Towards Gap Waveguide Array Antenna for Millimeter Wave Applications

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Front Cover: The figure on the front cover is a 16 × 16 corporate-fed slot array antenna, consists of three unconnected metal layers for the 60 GHz band.

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To my family

Abstract

The millimeter wave frequency range has got a lot of attention over the past few years because it contains unused frequency spectrum resources that are suitable for delivering $Gbit/s$ end-user access in areas with high user density. Due to the limited output power that current RF active components can deliver in millimeter waves, antennas with the merits of low profile, high gain, high efficiency and low cost are needed to compensate free space path loss and increase the communication distance for the emerging high data rate wireless systems.

In order to move towards the millimeter wave frequencies we need to face significant hardware challenges, such as active and passive components integration, packaging problems and cost-effective manufacturing techniques. The gap waveguide technology shows interesting characteristics as a new waveguide structure. It may be suitable to fill the existing gap between the planar transmission lines, such as microstrip, coplanar waveguide and substrate integrated waveguide and the non-planar hollow waveguides in terms of performance, such as loss and fabrication flexibility at high frequencies. Gap waveguide has a planar profile, and it can be used as low loss distribution network for an antenna array.

This thesis mainly focuses on passive components design, in particular array antennas and bandpass filters based on gap waveguide technology. We present several low-profile multilayer corporate-fed slot array antennas with high gain, high efficiency and wide impedance bandwidth for the 60-GHz band. The aim of this thesis is to demonstrate the advantages of gap waveguide technology as an alternative to the traditional guiding structures to overcome the problem of good electrical contact due to mechanical assembly with low loss. The main challenge of gap waveguide components is the realization of the textured structure (pin surface) with a cost-effective manufacturing method. Due to the relatively complex pattern and physical dimensions of the textured structure, the fabrication of the gap prototypes introduces a challenging task, especially at millimeter wave frequencies. Therefore, we are continuously searching for effective alternative methods. A fast modern planar 3-D manufacturing method called die-sink Electric Discharge Machining (EDM) is applied for the first time to manufacture a large planar high gain antenna at the 60-GHz band. Measurement results and experimental validation are provided for the presented designs.

Keywords: aperture efficiency, Artificial Magnetic Conductor (AMC), Bandpass filter (BPF), Electric Discharge Machining (EDM), low sidelobe, gap waveguide, grating

lobe, high efficiency, millimeter wave, slot array antenna.

Preface

This thesis is in partial fulfillment for the degree of Licentiate of Engineering at Chalmers University of Technology.

The work resulting in this thesis was carried out between July 2014 and July 2016 at the Antenna Systems Division, Department of Signals and Systems, Chalmers. Professor Per-Simon Kildal is the main supervisor and Associate Professor Jian Yang is the examiner. In addition, Assistant Professor Ashraf Uz Zaman and Associate Professor Vessen Vassilev are the co-supervisors.

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Acknowledgment

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I have had great time, being surrounded by so many great friends in the large Iranian community in, and around Chalmers. Pegah, Samar, Maryam, Ramin, Kamran, Alireza, and Fatemeh, thank you all for reminding me of home, when I'm so far from it.

Last but not least, I would like to express my deepest gratitude to my parents for always being there for me, supporting and encouraging me at every step I take.

Abbas
Göteborg, August 2016

The figure is prepared using *http://www.tagxedo.com* .

List of Publications

This thesis is based on the work contained in the following appended papers:

Paper A
A. Vosoogh and P.-S. Kildal, "Simple Formula for Aperture Efficiency Reduction Due to Grating Lobes in Planar Phased Arrays," *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 4, pp. 2263–2269, 2016.

Paper B
A. Vosoogh, A. A. Brazález, and P.-S. Kildal, "A V-band Inverted Microstrip Gap Waveguide End-coupled Bandpass Filter," *IEEE Microwave and Wireless Components Letters*, vol. 26, no. 4, pp. 261-263, 2016.

Paper C
A. Vosoogh and P.-S. Kildal, "Corporate-Fed Planar 60 GHz Slot Array Made of Three Unconnected Metal Layers Using AMC pin surface for the Gap Waveguide," accepted for publication in *IEEE Antenna and Wireless Propagation Letters*, 2015.

Paper D
A. Vosoogh and P.-S. Kildal, "V-band High Efficiency Corporate-Fed 8×8 Slot Array Antenna with ETSI Class II Radiation Pattern Based on Gap Technology," in *Proceedings of the joint 2016 IEEE International Symposium on Antennas and Propagation/USNC-URSI National Radio Science meeting*, Fajardo, Puerto Rico, June 26- July 1, 2016.

Paper E
A. Vosoogh, P.-S. Kildal, and V. Vassilev, "Wideband and High-Gain Corporate-Fed Gap Waveguide Slot Array Antenna with ETSI Class II Radiation Pattern in V-band," submitted to *IEEE Transaction on Antennas and Propagation*, April 2016.

Other related publications of the Author not included in this thesis:

- P.-S. Kildal, A. Vosoogh, and S. Maci, “Fundamental Directivity Limitations of Dense Array Antennas: A Numerical Study Using Hannan’s Embedded Element Efficiency,” *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 766–769, 2016.
- A. Vosoogh, P.-S. Kildal, and V. Vassilev, “A multi-layer gap waveguide array antenna suitable for manufactured by die-sink EDM,” in *Proceedings of the 10th European Conference on Antennas and Propagation, EuCAP 2016* , Davos, Switzerland, April 2016.
- A. A. Brazález, E. Rajo-Iglesias, J. L. Vázquez-Roy, A. Vosoogh, and P.-S. Kildal, “Design and validation of microstrip gap waveguides and their transitions to rectangular waveguide, for millimeter-wave applications,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 63, no. 12, pp. 4035–4050, 2015.
- A. Vosoogh and P.-S. Kildal, “High efficiency 2×2 cavity-backed slot sub-array for 60 GHz planar array antenna based on gap technology,” in *Proceedings of the International Symposium on Antennas and Propagation, ISAP 2015*, Tasmania, Australia, November 2015.
- J. Liu, A. Vosoogh, A. Uz Zaman, and P.-S. Kildal, “Design of a cavity-backed slot array unit cell on inverted microstrip gap waveguide,” in *Proceedings of the International Symposium on Antennas and Propagation, ISAP 2015*, Tasmania, Australia, November 2015.
- A. Vosoogh, P.-S. Kildal, “Study of grating efficiency of planar arrays,” in *Proceedings of the 9th European Conference on Antennas and Propagation, EuCAP 2015* , Lisbon, Portugal, April 2015.

Acronyms

5G	Fifth Generation
AMC	Artificial Magnetic Conductor
BPF	Bandpass Filter
CNC	Computer Numerical Control
CPW	Coplanar Waveguide
EBG	Electromagnetic Bandgap
EDM	Electric Discharge Machining
ITU	International Telecommunication Union
MMIC	Monolithic Microwave Integrated Circuit
PEC	Perfect Electric Conductor
PMC	Perfect Magnetic Conductor
Q-TEM	Quasi Transverse Electromagnetic
RF	Radio Frequency
SAR	Synthetic Aperture Radar
SIW	Substrate Integrated Waveguide
SNR	Signal to Noise Ratio
TE	Transverse Electric
TEM	Transverse Electromagnetic
TM	Transverse Magnetic

Contents

II Included Papers

Part I

Introductory Chapters

Chapter 1

Introduction

The continuously growing demand for higher data rate communication leads to use higher frequency bands. There are requirements that will be challenging to address within the frequency spectrum resources. One of these challenges is how to deliver $Gbit/s$ end-user access in areas with high user densities. It is expected that there will be a need for extremely high peak data rates, in the order of 10 to 50 $Gbit/s$ in the near future [1]. To achieve these data rates, it would be beneficial to use wider frequency bands in the order of several GHz. Finding these continuous frequency bandwidths below 20 GHz is unlikely. Instead, the research effort for these ultra-high speed radio access interfaces has been targeting millimeter wave frequency range (30-300 GHz) where it could be easier to get access to wider bandwidths [1].

The use of millimeter wave frequencies is growing in many applications such as automotive anti-collision radar at 77 GHz [2] , vehicle-to-vehicle communication [3], high resolution millimeter wave imaging [4], satellites cross-link communication in space [5], indoor wireless data transmission at 60 GHz [6], and outdoor millimeter point-to-point backhaul terminals [7]. Communication at millimeter waves is advantageous because of the high attenuation in the atmosphere, and large absorption in urban scattering obstacles. This enables frequency reuse over small distances and higher security. Furthermore, there are several license free bands in millimeter wave frequency band. For example 7 GHz from 57 to 64 GHz are allocated in United States and Europe for unlicensed use.

The communication distance is limited at millimeter waves, due to the high attenuation that propagating signals experience. This loss is higher at certain frequencies due to the oxygen molecule resonance frequency and water vapor [8]. Fig.1.1 shows average atmospheric absorption at millimeter wave frequencies in dB/km at sea level. The attenuation level mainly depends on temperature, pressure, and humidity. At 60 GHz, due to high atmospheric absorption, relatively secure communications can be implemented. On the other hand, the negligible atmospheric absorption at 28 and 38 GHz make these frequencies good candidates for long-range radio links and emerging

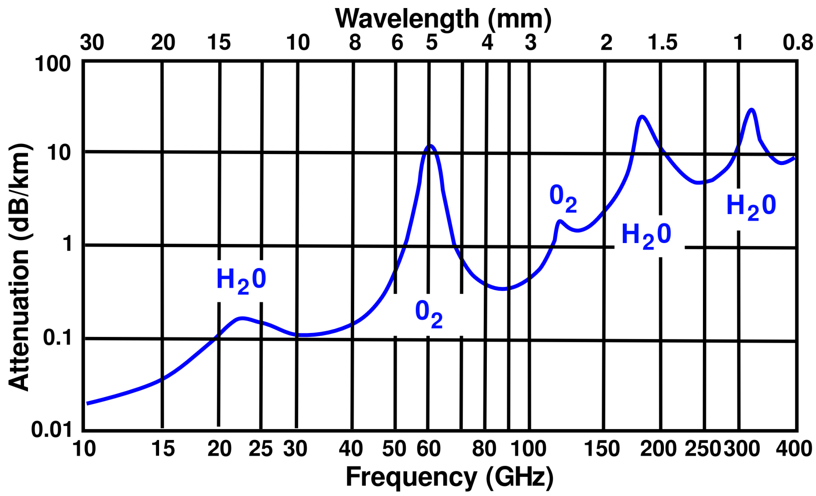


Figure 1.1: Average sea level atmospheric absorption at millimeter wave frequencies [10].

5G cellular systems.

The 60 GHz band or V-band is suitable for short-range high data rate communication systems with a low probability of intercept. The frequency band 59 to 64 GHz is attractive in particular due to a high atmospheric absorption (i.e. over 10 dB/km) which provides an opportunity for small cell backhauling. Moreover, atmospheric absorption drops down significantly in the frequency range 64-66 GHz, which is attractive for similar applications where longer communication distance are needed. For these purposes, highly-directive antennas with high aperture efficiency are needed. Directive antennas for radio links are generally realized by using reflector antennas [9]. However, planar array antennas are more attractive for these new applications, due to lower volume and weight. Furthermore, array antennas can provide rapid electronic beam steering.

In the 71-76/81-86 GHz band longer communication distance can be obtained due to relatively small gas absorption compared with the 60 GHz band. Therefore, this band is suitable for long range high-capacity communication with negligible atmospheric attenuation. Most applications are foreseen for fixed and mobile infrastructure in this band [1].

The official license and spectrum allocation are other restricting challenges that the development of the millimeter wave application is facing. Since the frequency spectrum in millimeter wave has not yet been unified in different countries, the potential frequency interference could cause legal disputes [1]. Fig.2 illustrates the potential conflict between frequency bands used for wireless backhaul in different European member countries. The green areas indicate the frequency regions that already have a primary allocation in ITU Region 1, while the yellow areas indicate harmonized frequency bands used for fixed links in Europe [1].

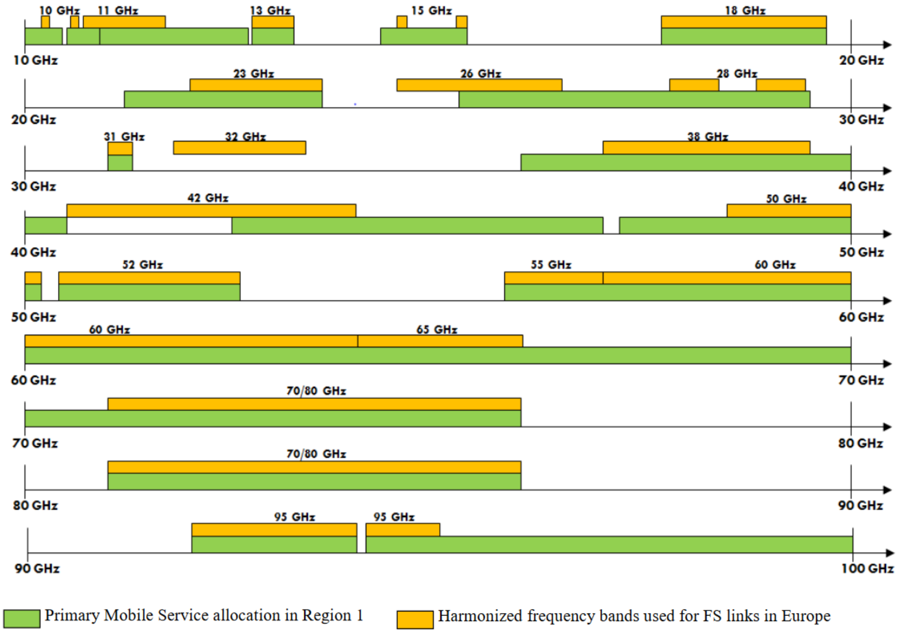


Figure 1.2: Primary allocations and harmonized frequency bands used for links [1].

At microwave frequencies, passive components such as high-Q bandpass filters and slot array antennas are commonly realized in hollow waveguide structures, due to low insertion loss and high power handling capability. However, the manufacturing cost of the hollow waveguide structures becomes too high at millimeter wave frequencies due to the strict tolerance requirements in the split-block technique. Planar technologies such as microstrip, coplanar waveguide (CPW) and substrate integrated waveguide (SIW), are more suitable for integration with active and passive components and easier to fabricate than standard hollow waveguide structures. However, these transmission lines suffer from high dielectric and ohmic losses and radiation leakage, especially when increasing the operating frequency.

To move towards millimeter wave frequencies we need to face significant hardware challenges such as active and passive components integration, packaging problem and cost-effective manufacturing techniques. The previously mentioned traditional technologies do not fulfill the strict requirements of the emerging millimeter wave applications.

1.1 Aim of the Thesis

The aim of this thesis is to demonstrate the advantages of gap waveguide technology as an alternative to the traditional guiding structures to overcome the problem of good electrical contact due to mechanical assembly with low losses, especially in millimeter wave frequencies. Moreover, the gap waveguide technology is expected to be suitable for millimeter and sub-millimeter wave frequencies, since high integration capability of active and passive components are required for these new emerging systems, although a lot of challenges are still need to be solved. Some of the major issues found at these frequencies are the strict manufacturing and assembly tolerances.

High gain antennas are essential components to compensate for the losses in point-to-point wireless links, due to the high path loss at millimeter wave. The gap waveguide technology presents some benefits for high frequency antenna applications. It has a planar profile, and it can be used as low loss distribution network for an antenna array. This thesis is mainly focused on the design of passive components, particularly array antennas and bandpass filters based on gap waveguide technology for millimeter wave applications. Several low profile multilayer corporate-fed slot array antennas with high gain, high efficiency and wide impedance bandwidth for the 60 GHz band have been designed and are thoroughly explained in this thesis.

In gap waveguide, periodic textured structures, in the form of pins or mushrooms, are used to realize an Artificial Magnetic Conductor (AMC). The fabrication of the textured structure presents a challenging task, especially at millimeter wave frequencies, due to the relatively complex pattern and physical dimensions. The conventional Computer Numerical Control (CNC) machining technique is very time-consuming and not effective to manufacture gap waveguide structures. Therefore, a fast modern planar 3-D manufacturing method called die-sink Electric Discharge Machining (EDM) is used for the first time to manufacture a large planar high gain antenna at millimeter wave. The integration of active and passive component such as bandpass filters (BPFs), diplexers, amplifiers and monolithic microwave integrated circuits (MMICs) with the feed-network of an array antenna to constitute a complete RF front-end based on gap waveguide technology is our long term goal. Therefore, we have designed a fourth order Chebyshev-type end-coupled bandpass filter based on inverted microstrip gap waveguide to provide a 2 GHz bandwidth at 60 GHz center frequency. Which later it will be integrated with an array antenna feed-network. Measurement results and experimental validation are provided for the presented designs.

1.2 Thesis Outline

The thesis is divided in two main parts. The purpose of the first part, organized in 4 chapters, is to introduce the subject and the background needed in order to better understanding of the appended papers, presented in the second part.

The first part of the thesis is organized as follows: in Chapter 2 some of traditional transmission line issues and challenges at high frequencies are indicated. This clarifies the context and motivation of the present research and how the new metamaterial-based gap waveguide technology can help to overcome the noted problems and challenges. Chapter 3 presents an overview of the gap waveguide technology and its principle. In this chapter preliminary studies of the gap waveguide are presented. Finally, Chapter 4 concludes the first part of the thesis with a brief summary of the listed contributions and the future work.

In the second part of the thesis, the most relevant contributions of the author are included in the form of five appended papers. Additionally, other related publication of the author can be found as references in the section List of Publications.

Chapter 2

Challenges at Millimeter Waves

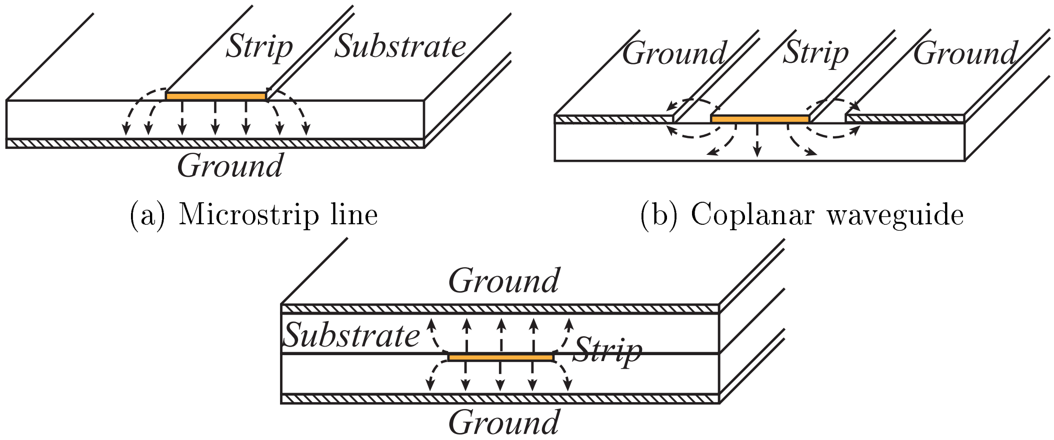
Millimeter waves spectrum was remained unused until recent years, because there were no RF electronic components able to generate or receive signal efficiently at those frequencies. Generating and receiving power in millimeter wave frequencies is a challenge, due to low output power amplifier, atmospheric and free-space path losses. The transmission range is limited and restricted mainly by the atmosphere absorption. Rain, fog, and water vapor in the air make the signal attenuation even higher. The wavelength becomes very small and raindrop size is comparable with the wavelength and therefore causes scattering. At 60 GHz, due to the oxygen molecule absorption, the situation is way worse.

According to the Friis transmission equation, the power transmitted from one antenna is received by another antenna under idealized conditions in a certain distance is given by:

$$P_{\mathrm{r}} = P_{\mathrm{t}} + G_{\mathrm{t}} + G_{\mathrm{r}} + 20\log_{10}\left(\frac{\lambda}{4\pi R}\right) \tag{2.1}$$

where P_r is the receiving signal output power, P_t is the transmitting signal output power, G_r and G_t are the receiving and transmitting antenna gains, λ is the wavelength, and R is the distance between the antennas. Free-space path loss is more critical in millimeter wave spectrum than lower frequencies due to a limitation related to their wavelength.

For a given power, the shorter the wavelength, the shorter the transmission range. In order to improve signal to noise ratio (SNR) at the receiver and thereby increase the transmission range we need to increase the power of the transmitting signal, or use more directive antennas. Due to the limited output power that the current active components can deliver in millimeter waves, we can only increase the antennas gains in order to increase the communication distance and compensate free-space path loss. Therefore, high gain and low loss antenna is one of the most necessary component of millimeter wave short- and long-range wireless communication systems. Moreover, millimeter wave hardware modules need to be compact size, highly-integrated, at the



(a) Microstrip line (b) Coplanar waveguide (c) Stripline

Figure 2.1: Planar transmission lines and fundamental E-filed mode distribution. (a) Microstrip line. (b) Coplanar waveguide. (c) Stripline.

lowest possible cost.

2.1 Traditional Transmission Line Issues at High Frequencies

Planar transmission line structures such as microstrip, CPW and stripline, are printed circuit technologies that present a compact and low cost solution. They are more suitable for integration with active and passive components and easier to fabricate than standard waveguide structures. However, these transmission lines suffer from high dielectric and ohmic losses and radiation leakage, especially when increasing the operating frequency. Fig.2.1 shows the planar transmission lines configuration and their fundamental modes distribution.

Thin film substrate layers can be used to decrease the dielectric loss [11–13]. However, in order to have a 50 Ω line impedance, a narrower strip must be used for a thin substrate, which increases the conductive losses. Due to higher resistance, narrower strip lines have higher conductive losses. Surface waves and higher order modes can also be generated especially in the presence of discontinuities, bends, open-ends and steps, for example in bandpass filters and feed-network of array antennas.

Standard hollow waveguides have some benefits compared to planar technologies such as low loss and high power handling capability (Fig.2.2). The non-planar structure of hollow waveguides makes difficult to use them in integration of passive and active components in the same module. Manufacturing and assembly tolerances, especially at millimeter waves, are the other disadvantages of this technology. However, if we want to design a high-Q filter or a low loss and high-efficiency array antenna,

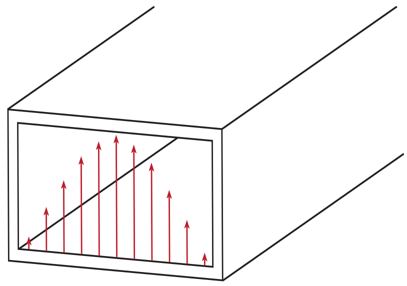


Figure 2.2: Rectangular waveguide structure and TE_{10} fundamental mode distribution.

we have to use hollow waveguide instead of dielectric based transmission lines.

The fabrication of complex waveguide structures at millimeter waves presents a challenging task. There are several ways to fabricate waveguide structures, such as CNC machining and Electronic Discharge Machining (EDM). Waveguide structures are typically manufactured in split-blocks and then can be connected by screwing, diffusion bonding or deep-brazing techniques. Accurate machining techniques are needed at millimeter wave frequencies, which is difficult, expensive, and time-consuming process.

The substrate integrated waveguide (SIW) or post-wall waveguides is introduced in [14, 15] as an attractive technology with the advantages of both planar transmission lines and hollow waveguides (Fig.2.3). The structure of SIW is similar to a rectangular dielectric-filled waveguide structure, where two rows of metalized via holes replace the narrow walls of waveguide. The upper and lower metal plates and via holes form a current loop in the cross-section, similar to metal waveguide. All these via holes should be placed closely to avoid possible leakage. Because there are vias at the sidewalls, transverse magnetic (TM) modes do not exist and therefore this transmission line only support propagation of TE_{m0} modes of the traditional rectangular waveguide.

SIW has a planar profile which makes them interesting for integration with active components. However, due to the presence of dielectric, SIW faces the same problem as microstrip transmission lines and shows higher loss than hollow waveguides. Moreover, radiation losses and leakage can occur in a bad design, because the via holes do not provide a perfect shielding [16, 17].

Although microstrip bandpass filters have simple structures, their applications are limited to microwave frequencies due to high losses. A V-band third order bandpass filter realized in SIW technology is presented in [18]. The fabricated prototype shows an insertion loss of 3 dB at the center frequency of 62 GHz, mainly due to dielectric loss. On the other hand, the fourth order Chebyshev-type end-coupled BPF, designed based on the inverted microstrip gap waveguide in [Paper B] at 60 GHz center frequency, shows around half of that insertion loss of the corresponding SIW

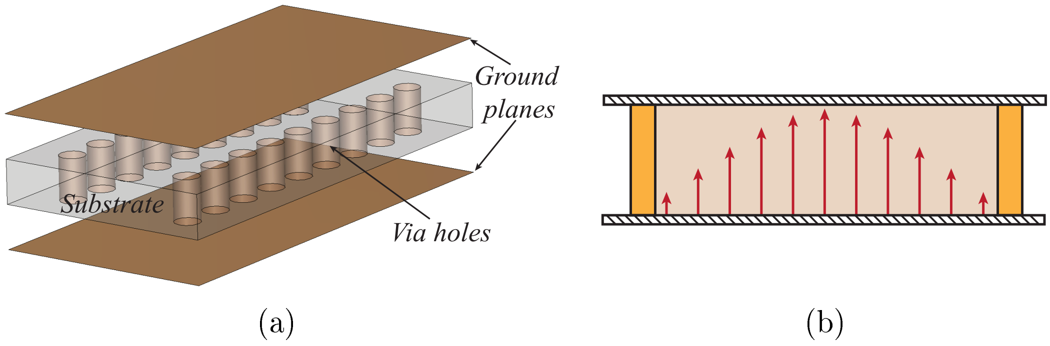


Figure 2.3: (a) Substrate Integrated Waveguide. (b) Fundamental TE_{10} mode distribution.

filter in [18].

2.2 Array Antenna Challenges

High gain, high efficiency and low profile antenna is one of the main challenges of millimeter wave wireless systems. Planar array antennas are very popular and widely used because of their advantages such as flat structure, low volume and weight. Furthermore, in array antennas the main beam direction can be rapidly changed by electronic steering. This fact makes them attractive for many applications.

In the design of a broadside-radiating antenna array, the element spacing is required to be within one wavelength to avoid high grating lobes. However, the element spacing may become larger than one wavelength in order to accommodate a fully branched also called corporate distribution network, especially at high frequencies. Therefore, it is important to know the grating lobe behavior and its effect on the aperture efficiency. [Paper A] makes such a study and validates a simple formula for the efficiency reduction due to grating lobes. Several methods have been developed to suppress grating lobes, such as aperiodic arrays configurations including rotated sub arrays [19], ring-grid array with trapezoid subarrays [20], arrays of random subarrays [21], random element and subarray positioning [22], and processing techniques in synthetic aperture radar (SAR) systems [23, 24].

A high gain array antenna with a large number of elements requires long transmission lines in the distribution network, and these ones must have very low losses. Although microstrip and SIW arrays have low profile, they suffer from dielectric and ohmic losses, which is a disadvantage for high gain millimeter wave applications [25–27]. The losses can be partly reduced by using low loss dielectrics, but these materials are expensive, and also quite soft. Therefore, it becomes difficult to machine and make via holes through those types of planar structures. Leakage and surface waves may become a major problem in microstrip array antennas, especially

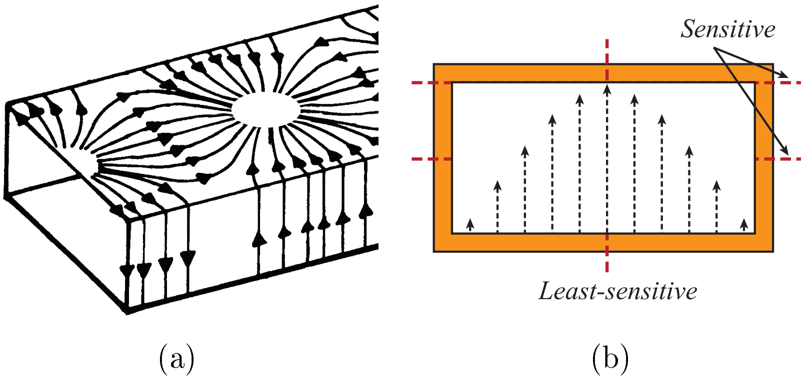
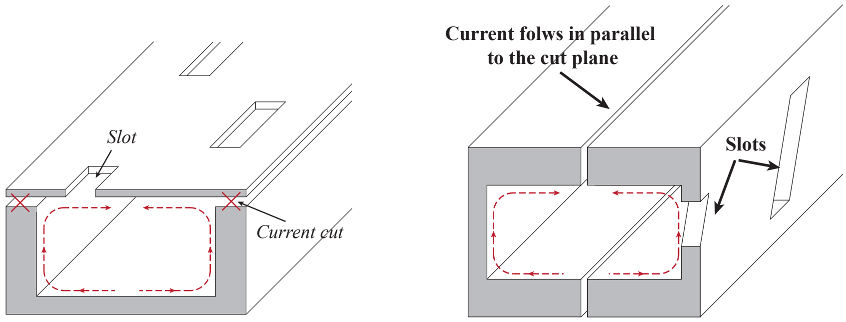


Figure 2.4: (a) Surface Currents distribution for TE_{10} mode in rectangular waveguide walls [33]. (b) Sensitive and least-sensitive places for joining walls.

in a big distribution network [28]. They can have a large effect on the radiation patterns and thus lead to reduction in antenna efficiency and thereby gain. Hybrid corporate-fed array antennas are proposed in [29] and [30] to reduce the dielectric loss of the distribution network, by using a microstrip ridge gap waveguide feed network and Substrate Integrated Cavity (SIC) radiating layer.

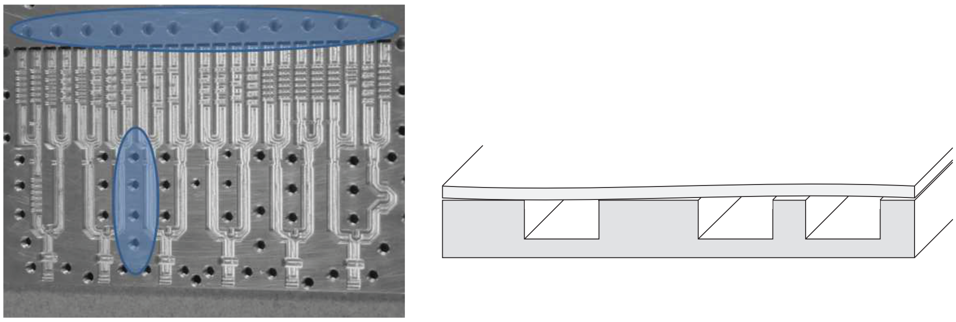
Slotted waveguide array antennas have been known for years and still are the best choice for high efficiency and high power applications. The basic principle of slot antenna is disturbing the surface current on the waveguide walls by introducing slots. Hollow waveguide distribution networks show low loss and high efficiency, which makes them suitable for such applications require high gain antennas [31, 32]. However, the tiny gaps between the antenna blocks can also cause leakage and radiation, if they disturb the surface current (Fig.2.4). Therefore, the fabrication of a complex waveguide structure is a challenging task, especially at millimeter wave frequencies. The key challenge is to achieve good electrical contact between building blocks, which increases fabrication cost and manufacturing complexity. Need for precise assembly also adds more challenges in multilayer slot array antennas. Moreover, the junctions must be protected from corrosion and oxidation.

Series-fed slotted waveguide arrays are simple but have narrow bandwidth due to the long line effect [34]. In a single layer structure, it is normally not possible to feed each radiating element in parallel (full corporate-feed) because of the space limitations associated with keeping the element spacing smaller than one wavelength (λ_0) to avoid grating lobe [35]. Multi-layer corporate distribution networks [36] show wider bandwidth than series-fed arrays [37]. In these antennas, radiating elements are fed in parallel by a corporate-feed network, formed by waveguide power dividers. However, it is very difficult to achieve good electrical contact between the vertical walls and the upper layer in a distribution network, where a narrow vertical wall is separating each closely spaced waveguide branches [37, 38].



(a) (b)

Figure 2.5: Surface current distortion in slotted waveguide antennas. (a) Current cut in broad-wall slot antenna. (b) Narrow-wall slot antenna without problem of disturbing current.



(a) (b)

Figure 2.6: (a) Array antenna feed-network with many screws. (b) Flatness problem.

To overcome the problem of leakage due to the assembly in the broad-wall slotted waveguide antenna, a narrow-wall slotted waveguide can be used (Fig.2.5). This antenna can be manufactured in E-plane spite-black without disturbing and cutting the surface current on the waveguide walls.

Flatness of the metal layers is another key to assure good electrical contact between plates. Guaranteeing good plate flatness, especially in a large surface, is not an easy task. A high-quality surface finishing over the whole metal contacts as well as good alignment of the two blocks must be achieved in order to remove the gaps between the two split-blocks and have a good electrical contact. Moreover, lots of screws are needed to assure good contact, and not always successful (Fig.2.6).

These strict mechanical requirements lead to use complex and high-precision manufacturing techniques and novel ideas. A corporate-fed multiple layers rectangular waveguide cavity-backed slot array antenna is reported in [39]. This is based on normal rectangular waveguide technology realized by diffusion bonding of many thin copper plates in order to achieve good electrical contact between all the plates. It

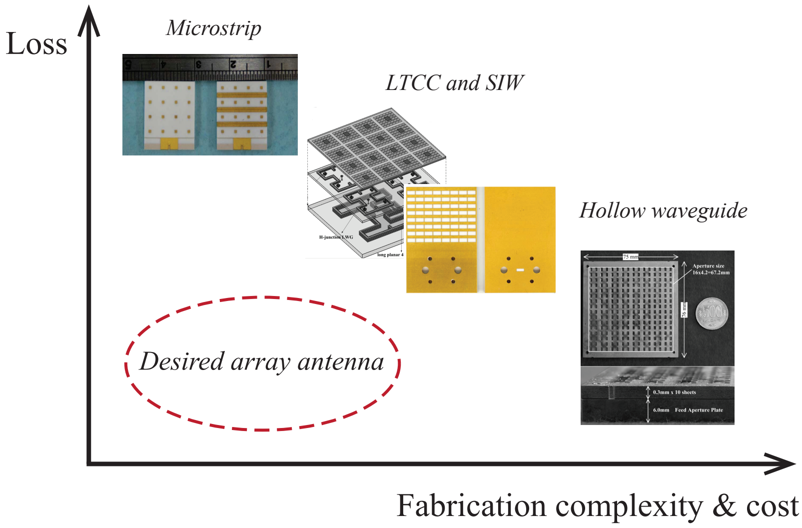


Figure 2.7: comparison of different array antennas technologies performance. (Microstrip array antennas [42], LTCC and SIW array antennas [43, 44], Hollow waveguide slot arrays [39])

shows high efficiency and wideband performance, but the diffusion bonding is expensive in mass production. Diffusion bonding is a solid-state welding technique capable of joining metals. Diffusion bonding is typically implemented by applying both high pressure and high temperature to the materials to be welded. Another attempted solution, a novel over-sized post-wall waveguide fed by a $Q-TEM$ mode array antenna in parallel-plate waveguide configuration is introduce in [40]. In this design, a compact design is achieved by using densely placed posts on the same layer as the parallel plate. This solution has a narrow bandwidth and also $Q-TEM$ mode is difficult to obtain by combining TE_{n0} modes. Several attempts have been made for solving the junction problem at the radiating layer where screws cannot be inserted, such as alternating phase-fed single-layer slotted waveguide array which removes the need of the electrical contact between plates [41].

2.3 Summary and Conclusions

In this chapter some of the issues of the traditional technologies and challenges in manufacturing of slot array antennas at high frequencies have been indicated. There exists a big gap between the planar transmission lines such as microstrip, CPW and SIW and the non-planar hollow waveguides in terms of performance such as loss and fabrication flexibility. One of the main current research challenges is to find a transmission line solution with flexible and low-cost fabrication and with low-loss at the same time. Fig.2.7 compares the performance of some reported planar high gain array antennas based on different technologies in terms of loss, fabrication complexity and cost. Microstrip and SIW array antennas have lower profile and cost than hollow waveguide arrays, but they suffer from higher loss which is a disadvantage for high gain antennas.

Therefore, we instead realize slot array antennas in separated metal layers that are assembled without requiring any metal contact between them. This is possible by using the new metamaterial-based gap waveguide technology. Our research goal is to introduce a solution to fill the mention gap between the planar transmission lines and hollow waveguides.

Chapter 3

Gap Waveguide Technology Principle and Overview

The gap waveguide technology was recently introduced in [45] as an extension of previous studies on *hard* and *soft* surfaces in [46]. In brief, gap waveguide technology can be explained as a new wave-guiding mechanism that uses a periodic electromagnetic band gap (EBG) geometry around a guiding structure, such as strip, ridge or groove to control the power flow direction. This new guiding structure is based on *soft/hard* boundary conditions and the cutoff of electromagnetic waves on a parallel *PEC/PMC* waveguide configuration. The *soft* surface has the ability to stop the propagation of any polarization wave along the surface. For example, corrugations act as a *soft* surface along its surface. On the other hand, the *hard* surface support the propagation of waves along its surface.

3.1 Gap Waveguide Concept

The basic principle operation of gap waveguide is the cut-off of a PEC/PMC parallel-plate waveguide configuration, to control the propagation of waves in desired directions between the two plates. This idea is shown in Fig.3.1. For the air gap between the two plates smaller than $\lambda/4$ no wave can propagate between the plates, due to the boundary conditions at the plates. By introducing a metal strip in the PMC surface, a *TEM* mode will be able to propagate along the strip.

In practice, the PMC condition is artificially realized by using Artificial Magnetic Conductors (AMCs) to emulate the high impedance boundary condition of a PMC surface [47]. In gap waveguides, the AMC is realized in the form of periodic textured structures (e.g. metal pins or mushroom structures) in combination with a smooth metal plate, with an air gap between them. When the air gap is smaller than quarter wavelength there is a cut-off of all mode propagation within the gap due to the high surface impedance created by periodic texture [48]. This can be used to control the

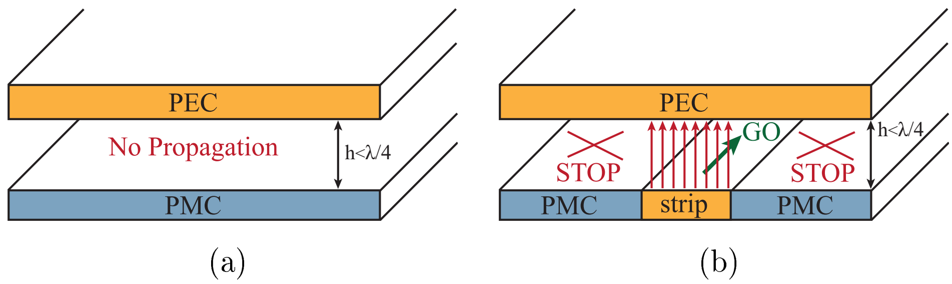


Figure 3.1: Basic principle operation of gap waveguide. (a) $PEC - PMC$ Parallel-plate electromagnetic wave Cutoff. (b) TEM local waves propagation.

propagation direction without leaking away in other directions.

Based on the guiding-line, propagation characteristics and the band gap structure, the gap waveguide can be made in different versions. Ridge gap waveguide [49], groove gap waveguide [50], microstrip gap waveguide [51], and inverted microstrip-ridge gap waveguide [52] are the four different varieties of gap waveguide technology. Fig.3.2 shows the different gap waveguide configurations and the fundamental modes.

3.2 Gap Waveguide Benefits and Early Studies

The gap waveguide has interesting characteristics such as low loss, flexible planar manufacturing, and cost-effectiveness, especially at millimeter-wave frequencies [53]. The advantage compared to microstrip transmission line, CPW and SIW is that the gap waveguide has a planar profile with low loss, since the wave propagates in the air. This new technology has almost no dielectric loss (especially in ridge and groove gap waveguide configurations), and it is mechanically more flexible to fabricate and assemble than hollow waveguide structures. Electrical contact between the building blocks is not needed in these guiding structures. This offers new opportunities for making cost-effective antennas and in particular corporate-feed networks [54–56]. Therefore, gap waveguides can be mass-produced by the usage of some low cost fabrication techniques such as injection molding, die pressing, plastic hot embossing, or die-sink EDM.

The AMC of the gap waveguide technology can be used to package active circuits [57, 58] and low-cost bandpass filters [59, 60], which thereby could be integrated with the feed network. Microstrip ans CPW transmission lines are open structures and the final product need to be protected form interference and physical damages. The traditional packaging method is based on using metal shielding boxes. One of the main drawbacks of this method is the appearance of cavity resonance modes when two of the dimensions of the box are larger than half wavelength. It is possible to suppress these resonances by adding absorber material, which introduces additional losses. The metamaterial/metasurface background of gap waveguide technology is

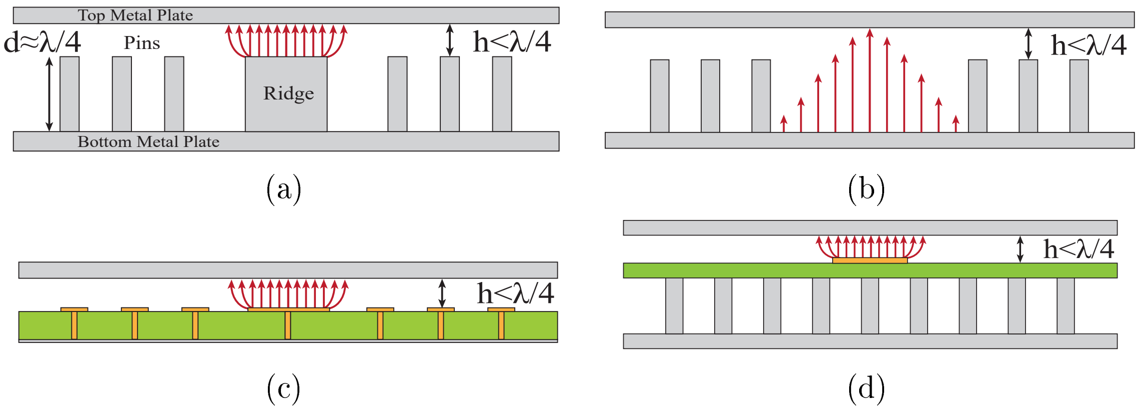


Figure 3.2: Different gap waveguide geometries and desired modes of propagation. (a) Ridge gap waveguide. (b) Groove gap waveguide. (c) Microstrip gap waveguide. (d) Inverted-microstrip gap waveguide. [61]

described in more detail in [53].

The gap waveguide technology has a stronger potential and advantages at Terahertz (THz) frequency range. The book chapter in [61] gives a handbook description of all works on gap waveguides till now with 107 references including related works.

3.3 Gap waveguide Array Antenna

As mentioned before, the periodic texture (e.g. pins or mushrooms) creates a PEC/PMC stopband for the parallel-plate modes and suppresses undesired modes and leakage. It acts as a high impedance surface when the air gap is smaller than $\lambda/4$. The dispersion diagram of the unit cell of the periodic structure is the most important parameter in designing the stopband, which is a function of the geometrical parameters of the structure [48].

The dispersion diagram of a pin unit cell used to create the stopband for the parallel plate modes is shown in Fig.3.3. The dispersion diagram is calculated using the Eigenmode solver of CST Microwave Studio for the pin unit cell with periodic boundary condition. The pin dimensions have been suitably chosen to have the V-band well inside the stopband. Fig.3.3 shows that the pin unit cell creates a parallel plate mode stopband over 40-105 GHz frequency band. There is no need for electrical contact between the textured surface and the upper metal plate, due to the electromagnetic bandgap properties of the pin surface. By introducing a ridge between the pin texture, a quasi-TEM mode propagates in the air gap between the ridge and the upper plate. Fig. 3.4 shows that there is a single propagating mode over the frequency band 40-90 GHz, which covers the whole unlicensed 60 GHz frequency band.

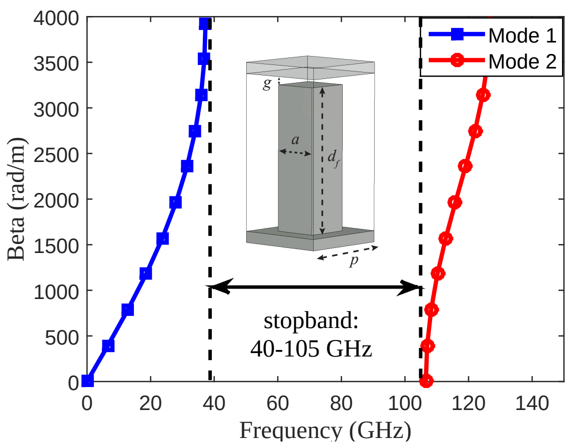


Figure 3.3: Dispersion diagram for the infinite periodic pin unit cell ($a = 0.4\ mm$, $d_f = 1.3\ mm$, $p = 0.8\ mm$, and $g = 0.05\ mm$).

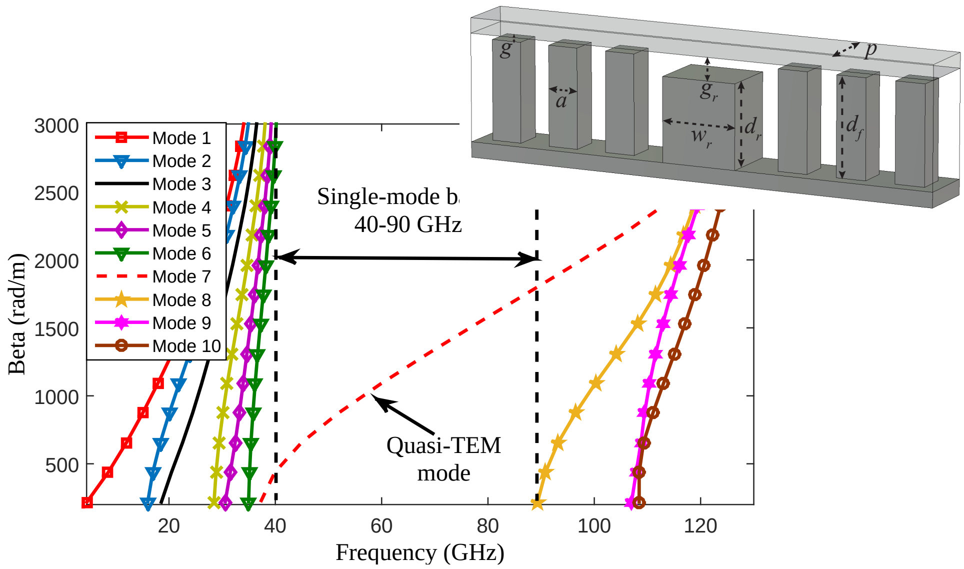


Figure 3.4: Dispersion diagram for the infinite periodic unit cell including a ridge embedded within a pin texture ($a = 0.4\ mm$, $d_f = 1.3\ mm$, $p = 0.8\ mm$, $g = 0.05\ mm$, $g_r = 0.25\ mm$, $w_r = 1\ mm$, and $d_r = 1.1\ mm$).

We have designed several low-profile array antennas with high efficiency and wide impedance bandwidth based on gap waveguide technology to demonstrate the advantages of this new guiding structure with flexible mechanical assembly and low loss. The main challenge of gap waveguide components is the realization of the textured structure (pin surface) with a cost-effective method. Due to the relatively complex pattern and physical dimensions of the textured structure, the fabrication of the product presents a challenging task, especially at millimeter wave frequencies. In our first

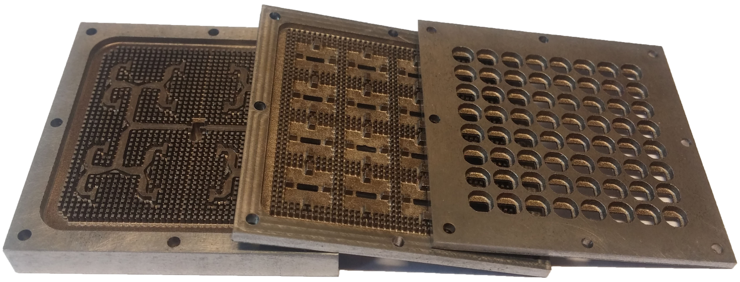
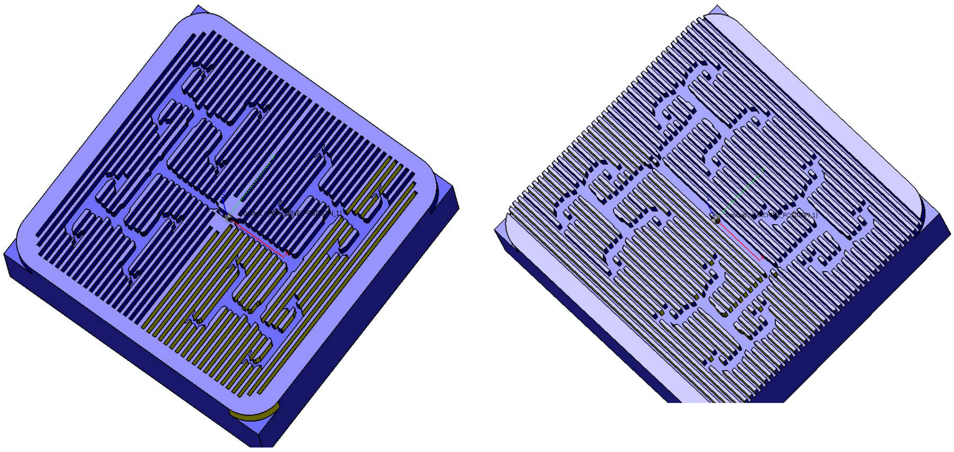


Figure 3.5: Photograph of a 8×8 gap waveguide slot array antenna fabricated by die-sink EDM.

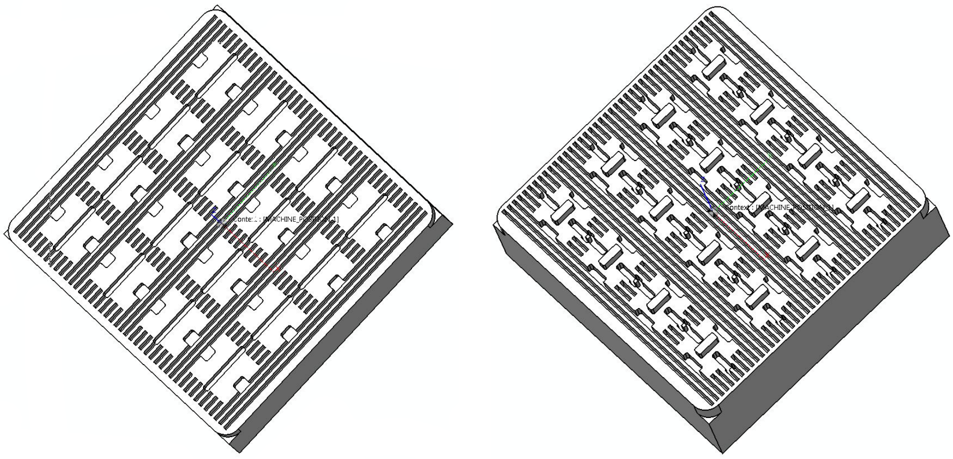


(a) (b)

Figure 3.6: Graphite electrodes used to form the distribution network. (a) Electrode with ridges in transverse direction. (b) Electrode with ridges in longitudinal direction.

attempt, [Paper C], a 8×8 slot array antenna with ridge gap waveguide corporate distribution network in the 60 GHz band is fabricated with CNC machining. CNC machining technique is very time-consuming and not effective to manufacture gap waveguide structures. Therefore, we searched for more effective alternative methods. In [Paper E] a fast modern planar 3-D method called die-sink Electric Discharge Machining (EDM) is used for the first time to manufacture a large planar high gain antenna at millimeter wave.

A photograph of a multilayer corporate-fed 8×8 cavity-backed slot array antenna for the 60-GHz band applications is shown in Fig. 3.5. The antenna's structure is similar to the presented array in [Paper E] and here we present the EDM fabrication method in more detail. The antenna is designed using the stopband property of the pin unit cell presented in Fig.3.3. The antenna consists of three unconnected metal layers, i.e. the radiating layer, the cavity layer, and the distribution layer. All three layers are separated by a small gap. A multilayer configuration is used in



(a) (b)

Figure 3.7: Graphite electrodes used to form the Cavity layer. (a) Electrode with ridges in transverse direction. (b) Electrode with ridges in longitudinal direction.

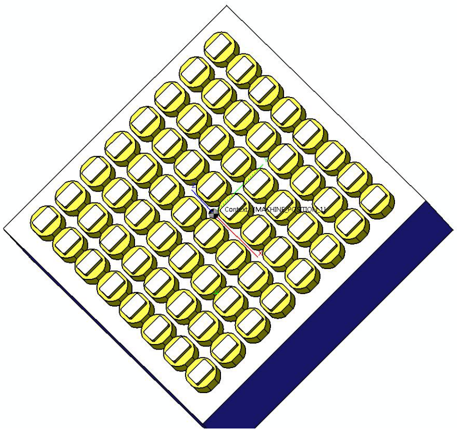


Figure 3.8: Graphite electrode used to form radiating layer.

the design procedure, due to the limited space for the corporate-fed excitation of the radiating elements. The designed antenna has a simple mechanical assembly without any requirement of electrical contact between the building blocks.

A fully corporate distribution network is designed in ridge gap waveguide in the lower layer. The antenna input is a standard WR-15 rectangular waveguide placed at its back side. A wideband and compact hybrid transition-splitter is designed to match the rectangular input waveguide to the ridge gap waveguide. The radiating parts consists of 2×2 cavity-backed slot subarrays in two separated layers, i.e. the cavity and slot layers. The cavities are formed by pins on the middle layer. The prototype is manufactured by die-sink EDM technique. In this manufacturing process, the desired pattern is formed by rapidly recurring electrical discharges between the workpiece and an electrode, separated by a dielectric liquid. The electrode contains the negative of the desired pattern and the high energy sparks makes this pattern form a footprint in the surface of the workpiece.

We used several electrodes with different details of the resulting texture to manufacture each layer. Fig.3.6 shows the two graphite electrodes used to form the distribution network of the antenna. In order to form the pin texture, first an electrode containing small transversal ridges burns the metal surface and after that the procedure completes with another electrode with ridges in longitudinal direction. The other graphite electrodes used to form cavity and radiation layers are shown in Fig.3.7 and Fig.3.8, respectively.

Chapter 4

Contributions and Future Work

The gap waveguide technology shows interesting properties as a new waveguide structure, and may be suitable to fill the existing big gap between the planar printed transmission lines and the non-planar hollow waveguides in terms of loss and fabrication flexibility at high frequency bands. This thesis presents a collection of recent development of the gap waveguide passive components, such as bandpass filters and planar array antennas. In the first part of the thesis, the reader is provided with an introduction and the background needed to understand the work described in the five appended papers. This section summarizes the contributions by the author.

Paper A: Simple Formula for Aperture Efficiency Reduction Due to Grating Lobes in Planar Phased Arrays

In this paper, we make a generic study of grating lobes in a large slot array. A simple formula called "*grating efficiency*" is presented for aperture efficiency reduction due to the power lost in the grating lobes, see Chapter 10 in [62]. Array antennas with element spacing greater than one wavelength will produce grating lobes. Grating lobes are not a big problem in most new millimeter wave applications, except for the fact that they reduce the aperture efficiency, and thereby the directivity. We numerically verify this simple formula for a uniformly excited 32×32 element array of slots in an infinite ground plane.

Paper B: A V-band Inverted Microstrip Gap Waveguide End-coupled Bandpass Filter

The main goal of this paper is to show that low cost end-coupled bandpass filters are feasible at millimeter frequencies by using inverted microstrip gap waveguide technology. The inverted microstrip gap waveguide is advantageous for millimeter wave applications because of its low loss, self-packaging characteristics, and cost-effectiveness. Since the wave propagates mainly in the air and surface waves do not exist, the width of the lines in gap waveguides become wider than typical microstrip and SIW. A fourth order Chebyshev-type end-coupled BPF is designed to provide a 2 GHz bandwidth at 60 GHz center frequency. The fabricated prototype embedded within a 10 cm inverted microstrip gap waveguide, containing two back-to-back transitions to rectangular waveguide presented in [52]. Measurement results confirmed that the overall loss in inverted microstrip gap waveguide is lower than in conventional microstrip and SIW filters. Therefore, inverted microstrip gap waveguide has advantages of both easy PCB fabrication, and packaging characteristics of gap technologies. The fabricated prototype exhibits an insertion loss of 3 dB in the passband. However, the insertion loss of the filter itself is better than 1.6 dB. The measured results show that insertion loss of the inverted microstrip gap waveguide filter is around half of a corresponding SIW filter in [18]. The designed filter has a planar structure and acceptable loss, thereby becoming suitable for integration with active and passive components.

Paper C: Corporate-Fed Planar 60 GHz Slot Array Made of Three Unconnected Metal Layers Using AMC pin surface for the Gap Waveguide

In this paper, we propose a high efficiency and low profile corporate-fed 8×8-slot array antenna in the 60 GHz band. The antenna is built using three unconnected metal layers based on Artificial Magnetic Conductor (AMC) in gap waveguide technology. A 2×2 cavity-backed slot subarray is designed in a groove gap waveguide cavity. The cavity is fed through a coupling slot from a ridge gap waveguide corporate-feed network in the lower layer. The antenna shows better radiation pattern and higher aperture efficiency than the presented antenna in [56]. The fabricated antenna shows a relative bandwidth of 14% with input reflection coefficient better than -10 dB and an overall aperture efficiency larger than 65% (i.e., -2 dB) with about 25 dBi realized gain between 56.2 and 65.0 GHz. This paper presents for the first time such 8×8-slot planar array based on a fully corporate distribution network in ridge gap waveguide technology.

Paper D: V-band High Efficiency Corporate-Fed 8×8 Slot Array Antenna with ETSI Class II Radiation Pattern Based on Gap Technology

This paper is a follow-up work of the previous paper. The purpose is to improve the radiation pattern of the antenna presented in [Paper C]. The co-polar radiation pattern and sidelobe levels of the antenna are improved by using a simple slot-tilting method to fulfill the radiation pattern requirement of the ETSI 302 standard for fixed radio links. Thereby, the sidelobes in the principle planes of the array are not appearing in the E- and H-planes, assumed to correspond to horizontal and vertical planes. The fabricated prototype has a relative bandwidth of 12% with input reflection coefficient better than -10 dB. The E- and H-planes radiation patterns satisfy the ETSI class II co-polar sidelobe envelope over 57-65 GHz frequency band.

Paper E: Wideband and High-Gain Corporate-Fed Gap Waveguide Slot Array Antenna with ETSI Class II Radiation Pattern in V-band

In this paper, we present a low profile multilayer corporate-fed 16×16 slot array antenna with high gain, high efficiency and wide impedance bandwidth for the 60 GHz band. The proposed antenna consists of three unconnected metal layers similar to presented array antenna in [Paper C]. A new wide bandwidth air-filled cavity-backed 2×2 slot subarray is designed to cover the whole unlicensed 60 GHz frequency band. A prototype consisting of 16×16 slots is manufactured by a fast modern planar 3-D machining method, i.e. die-sink Electric Discharge Machining (EDM). This is used for the first time to manufacture a large planar high gain antenna at millimeter-wave, as far as we know. The fabricated prototype has a relative impedance bandwidth of 17.6% with input reflection coefficient better than -10 dB. The E- and H-planes radiation patterns satisfy the ETSI class II co-polar sidelobe envelope, and the measured cross-polar level is more than -30 dB below the copolar level over the 56-75 GHz frequency band. The measured total aperture efficiency is better than 60% over the same band.

4.1 Future Work

Our main research goal is to develop a complete RF front-end demonstrator based on gap waveguide technology and find a flexible and low-cost fabrication with low-loss solution. Therefore, our future research direction and main steps to address the remain issues are as follow:

• In gap waveguide we do not need any electrical contact between the building blocks, thanks to the stopband created by the periodic texture. However, the *"aspect ratio"* of the pins (the ratio between the width and height of pins), is very high and therefore, the final prototype is not suitable to be mass-produced by the usage of some low cost fabrication techniques such as injection molding. The current aspect ratio of the pin texture of the designed array antennas in appended papers is around 1:3, and an aspect ration smaller than 1 is demanding. Therefore, we need to find a solution to decrease the pins aspect ratio. On solution is presented in [63] by using half-height pins.

• **Gap Waveguide Array Antenna for E-band Applications**. The E-band frequency range (71-76/81-86 GHz) is one of the interesting millimeter wave band due to low atmospheric attenuation, for long-range high-capacity wireless communication systems. To cover the whole frequency range from 71-86 GHz, we need a wideband

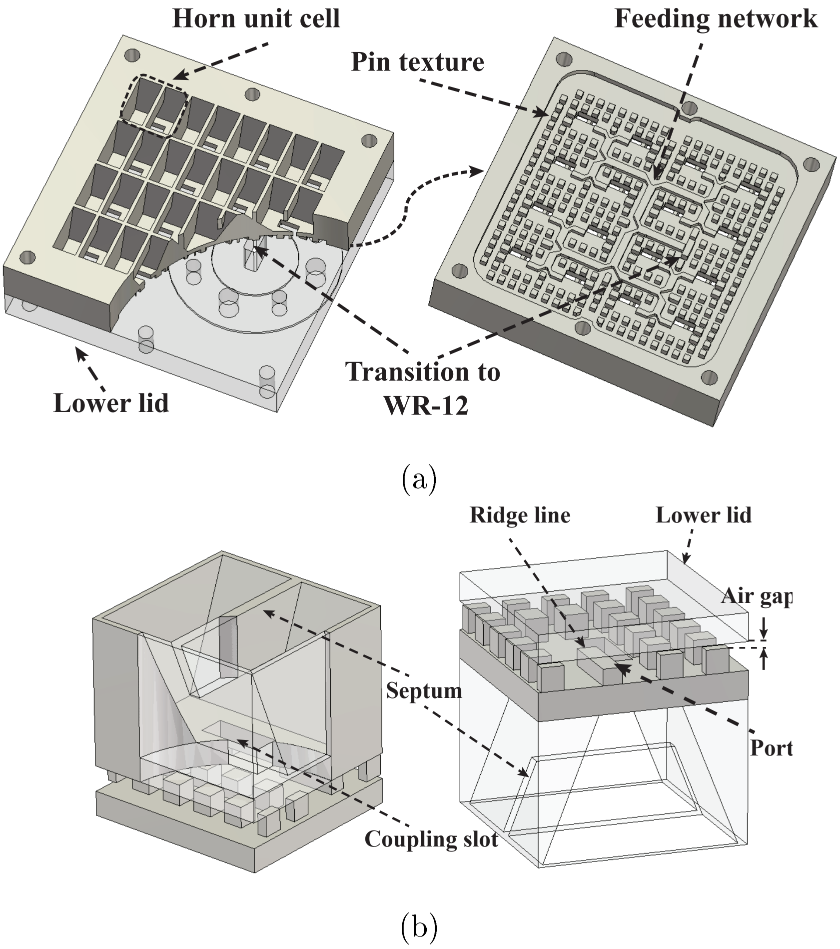


Figure 4.1: (a) Configuration of the corporate-fed horn array antenna with feed-network on the back side of the radiating layer. (b) The proposed horn unit cell.

antenna with a relative impedance bandwidth of more than 19%, which is challenging with common slot array antennas. We have improved the performance of horn unit cell presented in [55], by introducing a septum in the E-plane of the horn. The proposed antenna has a relative bandwidth of 24% with input reflection coefficient better than -10 dB and simulated total antenna efficiency better than 85% over the 69-88 GHz frequency band (Fig.4.1). We are going to manufacture and measure a prototype consisting of 4×4 element horn array antenna with different fabrication methods, such as Direct Metal Laser Sintering (DMLS) 3-D printing and die-sink EDM techniques.

• **GAP MEMS Array Antenna**. The frequency range above 100 GHz has got a lot of attention over the last few years. The 145-GHz band is another interesting frequency band for point-to-point radio link systems. The gap waveguide technology

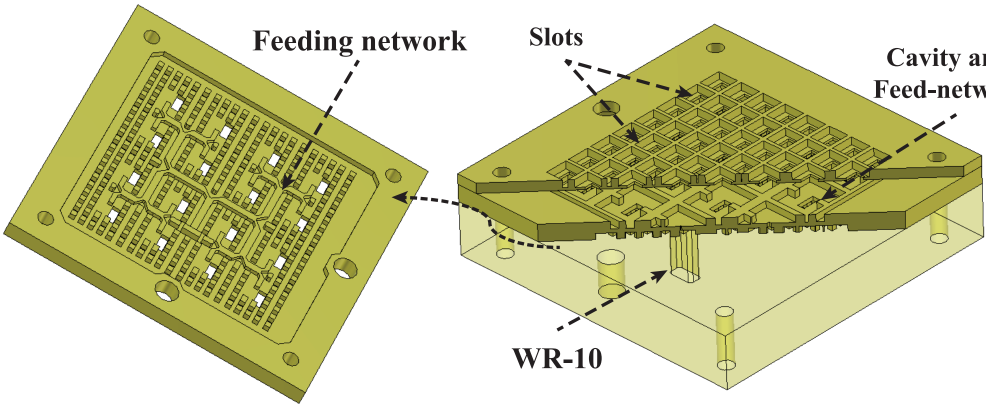


Figure 4.2: The proposed 8×8 Gap MEMS slot array antenna with ridge gap waveguide feed network.

has more potential and advantages at these frequency ranges. New fabrication techniques need to be used for effective manufacturing above 100 GHz. Micro-Electro-Mechanical-Systems (MEMS) silicon etching and micromachining could be a good solution to manufacture gap waveguide components. We have started the design of a planar array antenna to be manufactured by MEMS technology at 145 GHz. The plan is to realize GAP waveguide MEMS planar array antenna above 100 GHz. Fig.4.2 shows the proposed slot array antenna for the 145 GHz band.

• **Planar array antenna with integrated diplexer**. Diplexers are one of the important and integral part of many communication systems. Easy integration is one of the advantages of our technology, since gap waveguide has a open structure. We have done the initial design and full-wave simulations, in order to realize the integration of diplexer with feed-network of a array antenna. The proposed technique allows for the design of a high performance module that integrates the diplexer with the antenna efficiently with similar size to the antenna. The designed antenna is shown in Fig.4.3. We have selected 28 GHz frequency band to have less strict fabrication tolerances.

• **Active component integration and planar steerable beam array antenna**. The final piece of the puzzle of the complete gap waveguide RF front-end is integrating active electronic devices with the feed-network of array antenna. There is ongoing research on new contact-less transitions and MMIC integration with different gap waveguide variants. We have started the process of the integration of MMICs with a planar array antenna. The goal is to design a steerable beam array antenna with self-alignment capability. Fig.4.4 shows the sketch of this idea.

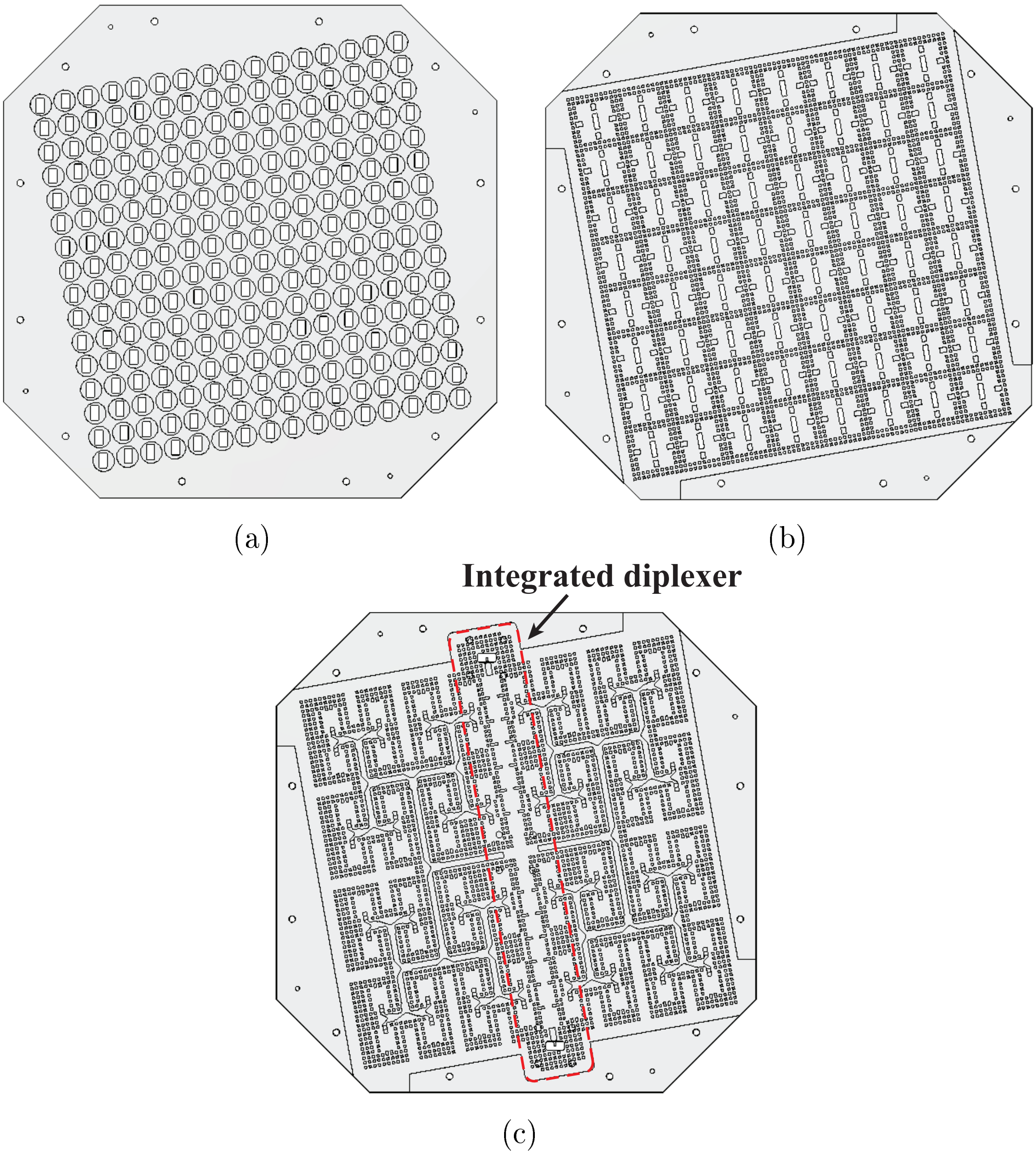


Figure 4.3: The designed 16 × 16 slot array antenna with integrated diplexer within the feed network. (a) Radiating layer. (b) Cavity layer. (c) Feed-network with integrated diplexer.

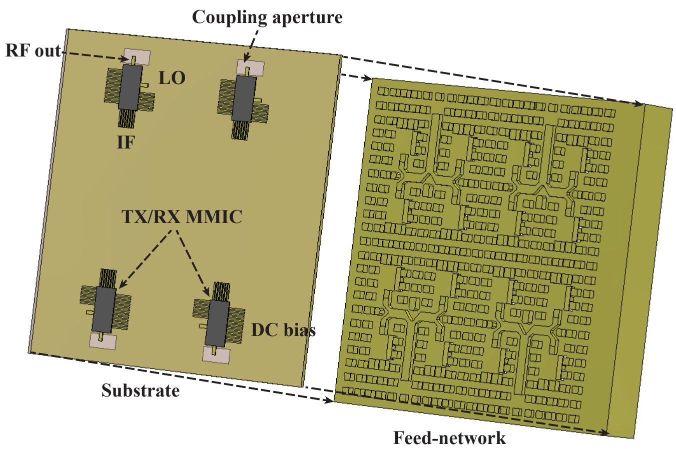


Figure 4.4: Sketch of the proposed steerable planar array antenna with integrated RF electronics under investigation.

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Part II

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