Thesis for the degree of Doctor of Philosophy

Gap Waveguide Technology for Millimeter Wave Applications and Integration with Antennas

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Front cover: Gap waveguide prototypes and 2-D color plots of the E-field shown in Fig. 5, pag. 78.

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To Francesco

Abstract

The increasing advance of short range wireless communications requiring high data rates and the lack of available spectrum have driven researchers and industry to move towards higher frequencies, in particular to the millimeter wave range. The opening of this wide portion of free spectrum has risen a large interest in developing mm-wave communication systems for commercial applications. Higher frequencies lead to smaller sizes of RF components including antennas, thus introducing a new trend of realizing single compact modules, where active, passive components and antennas are integrated in the same package/chip. However, the implementation of passive components and interconnected transmission lines on these modules is difficult at millimeter waves with classical technologies, such as microstrip transmission lines and waveguides. Microstrip transmission lines suffer from high dielectric and conductive losses and waveguides are difficult to combine with integrated circuits and need accurate assembly process to assure good electrical contacts when made in different blocks. Therefore, new technologies are needed in order to face the challenges of the next generation systems.
The new gap waveguide technology has been recently introduced as a promising candidate to address some of the problems faced at millimeter waves with conventional technologies. The key idea behind this circuit is based on the possibility to guide the electromagnetic field along desired directions in the gap between metal plates and to avoid any propagation along undesired directions. In this way, any leakage occurring in between the split blocks of a circuit with poor quality metal contacts as well as unwanted radiations are avoided. This condition is achieved by surrounding a metal ridge/strip, or groove, with a so-called Artificial Magnetic Conductor (AMC). When this textured layer is placed below an upper metal lid, all parallel-plate modes will be in cut-off, thus letting the propagation only in the air gap between the ridge/strip and the upper plate.
This thesis presents the development of the gap waveguide in terms of packaging capability, losses, and integration with antennas. The losses study is performed by calculating the unloaded Q-factors of resonators made in ridge and groove gap waveguides. Experimental validations show that the gap waveguide has very low losses, and in particular the groove gap waveguide has similar measured unloaded Q-factors as rectangular waveguides when they are made in different blocks. The advantage is that the AMC surface in the gap waveguide can remove any leakage from the tiny gaps between two metal plates, which is a benefit at high frequency.

The losses study is also provided for micromachined gap waveguides above 200 GHz. In addition, the idea of a contactless waveguide flange made by bed of nails is presented for high frequency measurements. This new design can avoid typical mismatch and unwanted radiations which can occur in standard waveguide flanges when they are not well tightened to the circuit under test. We also present the packaging capabilities of the gap waveguide for low frequency applications, since the metal pins become too thick, by introducing a compact periodic surface made of printed zigzag wires.
In particular, this thesis analyzes the microstrip gap waveguide, which becomes attractive for both low and high frequency applications because made in printed technology, but still allowing propagation in the air, thus being low loss. We also propose a new geometry made in microstrip gap waveguide, using a textured surface with mushroom-type electromagnetic bandgap (EBG) structure, to create the parallel-plate cut-off. This circuit represents a compact, low loss and already packaged solution, that can suppress cavity modes and radiations generated when packaging standard microstrip lines. Finally, the microstrip gap waveguide is applied as low loss feed network for horn antenna array. This thesis shows the design and experimental validation of a sixteen-element planar dual-mode horn array excited by a microstrip gap waveguide corporate feed network, which can be an advantageous solution for 60 GHz antenna applications.

Keywords: Gap Waveguides, Artificial Magnetic Conductors, Millimeter Waves, Micromachining, Losses, Waveguide Resonators, Packaging of Microwave Components, Microstrip Lines, Array Antennas.

Preface

This thesis is in fulfillment for the degree of Doctor of Philosophy at Chalmers University of Technology.
The work has been carried out at the Antenna Group, Department of Signals and Systems, in Chalmers between January 2009 and November 2013. Professor Per-Simon Kildal is the main supervisor and examiner, Professor Eva Rajo-Iglesias is the co-supervisor.
The work has been financially supported by the Swedish Research Council (VR) and by the Strategic Research Center on Microwave Antenna Systems (CHARMANT) within the Swedish Foundation for Strategic Research (SSF). The work has also been an in kind contribution to a gap waveguide project within the Chase VINN Excellence Center at Chalmers, funded by VINNOVA.

List of Publications

This thesis is based on the work contained in the following publications

Paper A
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Paper B
E. Rajo-Iglesias, E. Pucci, A. A. Kishk, and P.-S. Kildal, "Suppression of parallel plate modes in low frequency microstrip circuit packages using lid of printed *zigzag* wires", *IEEE Microwave and Wireless Components Letters*, Vol. 23, No. 7, July 2013.

Paper C
E. Pucci, A. U. Zaman, E. Rajo-Iglesias, P.-S. Kildal, and A. A. Kishk, "Study of Q-factors of ridge and groove gap waveguide resonators", *IET Microwaves, Antennas & Propagation*, Vol. 7, No. 11, pp. 900-908, August 2013.

Paper D
E. Pucci, and P.-S. Kildal, "Contactless non-leaking waveguide flange realized by bed of nails for millimeter wave applications", in *Proceedings of the Sixth European Conference on Antennas and Propagation, EuCAP*, March 2012.

Paper E
E. Pucci, E. Rajo-Iglesias, J.-L. Vazquez-Roy, and P.-S. Kildal, "Planar dual-mode horn array with corporate-feed network in inverted microstrip gap waveguide", submitted to *IEEE Transactions on Antennas and Propagation*, August 2013.

Other related publications by the Author, not included in the thesis:

- E. Pucci, E. Rajo-Iglesias, J.-L. Vazquez-Roy, and P.-S. Kildal, "Design of a four-element horn antenna array fed by inverted microstrip gap waveguide", in *Proceedings of the IEEE Antennas and Propagation Society International Symposium, APS*, July 2013.
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Elena
Göteborg, October 2013

Contents

Abbreviations and Acronyms

AMC:	Artificial Magnetic Conductor
CPW:	Coplanar Waveguide
EBG:	Electromagnetic Bandgap
4G:	Fourth Generation
G-CPW:	Grounded Coplanar Waveguide
LTE:	Long Term Evolution
MEMS:	Micro-Electro-Mechanical System
MMIC:	Monolithic Microwave Integrated Circuit
PEC:	Perfect Electric Conductor
PMC:	Perfect Magnetic Conductor
RF:	Radio Frequency
SIW:	Substrate Integrated Waveguide
TE:	Transverse Electric
TEM:	Transverse Electromagnetic
TM:	Transverse Magnetic
VNA:	Vector Network Analyzer
VoIP:	Voice Over Internet Protocol
WiGig:	Wireless Gigabit
WLAN:	Wireless Local Area Network

WPAN: Wireless Personal Area Network

Part I
Introduction

Chapter 1

Introduction

Information and communication technology advanced so fast in the last decades having a direct impact in the society in general.
Globalization has generated more flexible and independent organizations and communication technology is seen as one tool to make them competitive. Just to think how markets became more efficient and coordinated by the introduction of internet thirty years ago, affecting levels of social interactions: having joint meeting and conferences even if geographically located in different places as well as communicating in a faster and cheaper way by electronic mails.
Nowadays coordination and knowledge among people are facilitated by the rapid advance of wireless communications compared to the past. Wi-Fi networks are now spread almost everywhere allowing users to connect anytime on their smartphones, tablets or laptops and exchanging data and VoIP traffic to a considerable rate. As a consequence, easy and fast connectivity has led to a rapid increase of the number of users per area. In 2010 the number of users was exceeding five billion and expected to rise even more in the next coming years [1].
Most wireless and mobile communications operate at frequencies between 800 MHz and 3 GHz. Such frequencies have good propagation characteristics with less attenuation and large wavelengths, providing a long distance coverage. Fewer cell sites also require lower costs, as the same network can be

used to cover larger areas. However, the exponential increase of the number of users per covered area, moved the main focus of the operators on capacity rather than coverage. E.g., it only takes few users streaming a video simultaneously to consume a large amount of capacity. Therefore, the high capacity is today the main goal of advanced wireless technologies.
Another problem faced by the operators is the scarcity of available spectrum, and the expansion of 4G technologies, like LTE, depends on the availability of the spectrum.
For these reasons, a wide interest in using higher frequencies, in particular in exploring the millimeter wave band, has recently grown [2]. The higher the carrier frequency, the higher the data rate. The use of high frequency bands require more cell sites per covered area, with the advantage of obtaining much higher capacity.
Propagation at millimeter waves is susceptible to atmospheric absorption attenuating the propagating waves. While this attenuation is undesirable when seeking a long coverage range, it is useful when operating over short distances to contain interference between different unlicensed spectrum applications. Therefore, this motivation has driven to move towards unlicensed frequency bands, such as the 60-GHz band (57-64 GHz), the 76-81 GHz band, and above 100 GHz, with the benefits of immunity to interference, high security characteristics and frequency reuse, which can provide multi-Gbit/s wireless communications. These characteristics open up to a set of new applications, e.g., multi Gbit/s short-range wireless communications.

1.1 Millimeter Wave Applications

The millimeter wave range includes frequency from 30 to 300 GHz, with wavelengths between 10 mm and 1 mm, so called mm-waves. At these frequencies the propagating signal suffers from attenuation due to the atmospheric absorption and cannot be used for long distance communications, but it is very attractive for short distance high speed applications, because oxygen absorption and narrow antenna beam allow for short transmission distances with no wall penetration. Summarizing, the use of the millimeter wave range presents the following benefits:

- Unlicensed bands
- Secure transmission
- No interference
- Frequency re-use
- High gain antenna physically small
- Moderated multipath and fading effects by the use of high directive antennas
- Multi Gbit/s short-range wireless communications

These advantages imply the use of millimeter wave systems to satisfy several demands, e.g., from satellite communications to security systems, and more.

Typical applications include high quality video transmission with gigabit data rate. In particular, the unlicensed 57 to 64 GHz band is of big interest for high data rate Wireless Local Area Networks (WLANs), also called WiGig (Wireless Gigabit), providing data rate up to 7 Gbits/s, with steerable antennas and beamforming with a maximum range of about 10 meters [3, 4].

Millimeter wave radar for automotive applications including safety devices, cruise control, automatic braking and collision warning, is very popular nowadays [5]. The radar fine resolution permits to detect small objects in movement with high precision. These radars use the 76- to 81-GHz band.

Mm-wave systems are also becoming attractive for point-to-point wireless communication links, to be used as backhaul in base stations using LTE 4G cellular services in high-density areas [6].

1.2 Waveguides and Transmission Lines Technologies

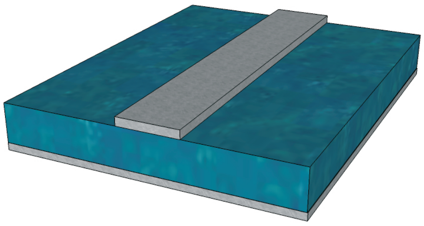
The need to shift to high frequencies has also driven research and development to make efficient integrated circuit technologies [7]. These technologies combine analog and digital radio in one small and cheaper module which also requires the integration of the antenna within the same chip. These circuits need at the same time powerful passive components, occupying low volume. However, the implementation of passive components and interconnected transmission lines on these modules is difficult at millimeter waves with classical technologies, such as microstrip lines and waveguides. Hence, there is a need to develop new technologies with high performance and multi functionality.

1.2.1 Microstrip, Coplanar Waveguides and Grounded Coplanar Waveguides

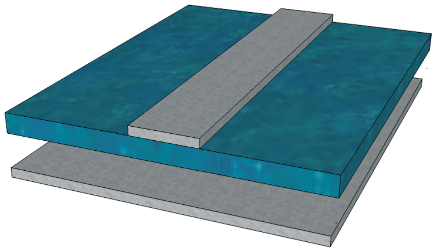
Microstrip, coplanar waveguides (CPW) and grounded coplanar waveguides (G-CPW) [8, 9], shown in Fig. 1.1, are printed circuits presenting a compact design which can be directly adapted to the conventional transistors technology. The main problem of conventional transmission lines is that they suffer from significant losses at the millimeter wave range.

Dielectric losses are an issue due to the use of substrate materials. Microstrip lines with a thin film substrate layer can be used, but lowering the thickness of the material implies as well a narrower metal strip line to meet the 50Ω line impedance, having the effect of increasing the conductive losses.

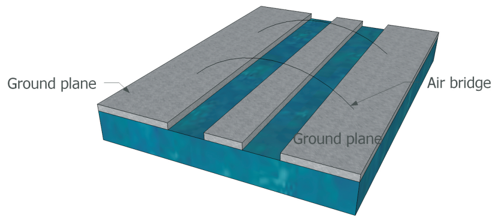
Conductive losses increase for narrower strip lines, due to their greater resistance. Surface waves can also be generated at the dielectric interface, in the presence of discontinuities, such as bends, open-ends, steps and junctions. They radiate and increase interference and coupling between multiple microstrip circuits.



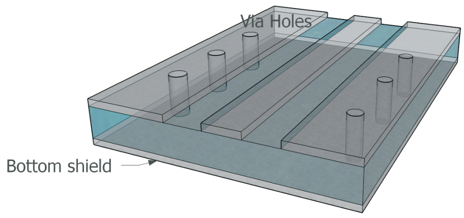
(a) Microstrip Line



(b) Suspended Microstrip Line



(c) Coplanar Waveguide



(d) Grounded Coplanar Waveguide

Figure 1.1

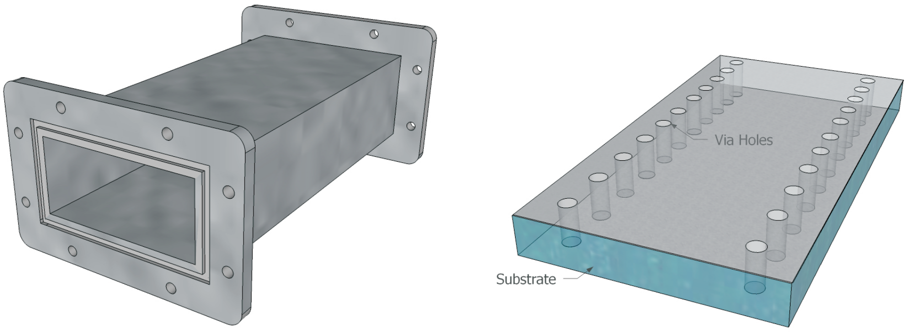
Dielectric losses can be reduced by using the so-called suspended microstrip line, which is realized by suspending the substrate over the air, as shown in Fig.1.1(b). In this way the field is mostly contained in the air between the end of the substrate and the ground plane. However, the increased distance between the strip line and the ground increases the microstrip's tendency to radiate.

Coplanar waveguides, in Fig. 1.1(c), have a central strip line separated from two ground planes by two gaps. The CPW presents more flexibility in the design by adjusting the gaps to the signal line width. Also, all conductors are located on the same layer and the ground connections through via holes are eliminated. However, this structure suffers as well from dielectric losses. Another problem faced with CPWs is the excitation of unwanted modes due to discontinuities, such as, bends or T-junctions, causing different potentials between the two ground planes. This drawback is avoided by inserting air bridges over the center conductor, to force the same potential on both ground planes. However, the inclusion of air bridges adds complexity to the production process.

The grounded coplanar waveguide, in Fig. 1.1(d), has less losses than the CPW, as a metal shield is used on the bottom to provide isolation from other circuits in lower layers. Proper grounding is provided by using via holes between the ground planes and the bottom shield. However, also this version presents the problem of losses at high frequency.
In addition, these circuits are typically packaged within an enclosure, when integrated in a complete circuit, and cavity modes may appear affecting their performance.

1.2.2 Hollow Waveguides and Substrate Integrated Waveguides

Standard hollow waveguides are guiding metallic structures that compared to microstrip transmission lines are shielded, have high power handling capability and low losses because made of only metal [10]. A sketch of the hollow rectangular waveguide is shown in Fig. 1.2(a). The disadvantage of waveguides is their non-planar design which makes difficult to adapt these structures to the current trend of all-in-one chip integrated circuits with passive and active components in the same module. Also, they need to be enclosed by vertical metal walls, which cannot be manufactured with the same techniques used for printed circuit boards. Waveguides are typically fabricated with conventional machining. However, at millimeter waves the wavelength becomes very small and the realization with current machining techniques is complex and time consuming. Very accurate machining techniques are needed in order to assure good electrical contacts between the waveguides split blocks. These processes are difficult and expensive to achieve for mass production. Hence, manufacturing tolerances are a critical problem at high frequency affecting the waveguide performance. Moreover, the transitions needed in order to adapt the waveguide components to the planar integrated circuits are difficult and bulky to realize.
The substrate integrated waveguide (SIW), illustrated in Fig. 1.2(b), has been lately introduced [11, 12]. It is a planar waveguide, realized in printed technology. The field is traveling in the substrate, between two rows of via



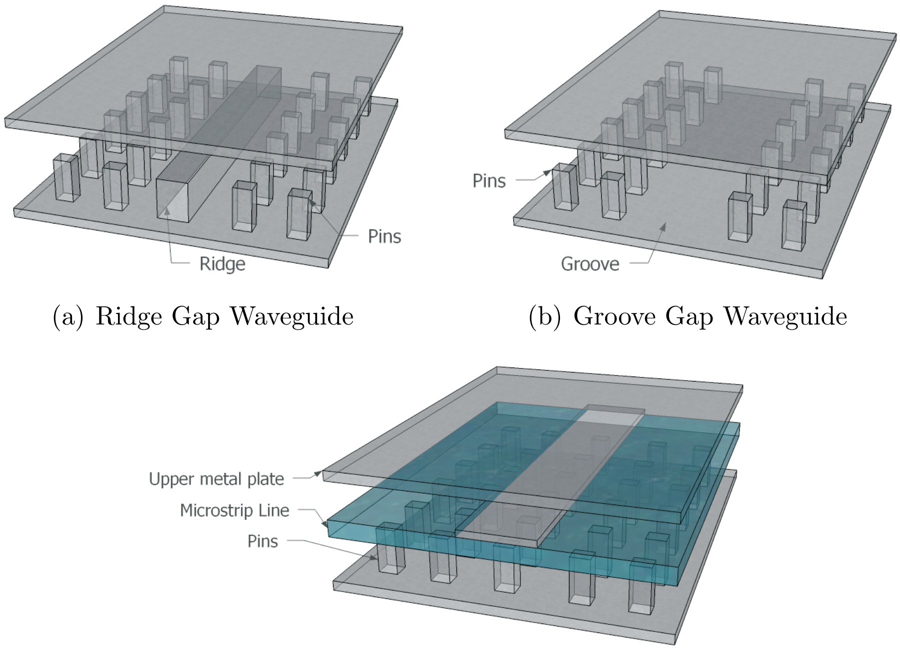
(a) Hollow Rectangular Waveguide (b) Substrate Integrated Waveguide

Figure 1.2

holes replacing the vertical metal walls of hollow waveguides. Therefore, the SIW presents similar dispersion characteristics as standard waveguides, but it can be adapted to printed circuit boards. However, the SIW faces the same problem as microstrip transmission lines at the millimeter wave range, i.e., high dielectric losses due to the material used and radiation losses due to the via holes, which do not provide a perfect metal shield, as shown in [13] and [14].

1.2.3 Gap Waveguide Technology

The gap waveguide is a new technology recently introduced [15, 16]. In gap waveguides the field is traveling in the air gap between parallel metal plates. The advantages compared to microstrip transmission lines, CPWs and SIWs, is that this structure can keep a planar profile as well as being low loss, since it can support waves in the air without need of dielectric. In addition, this technology can be realized without good metal contacts between the parallel metal plates, making fabrication process easy and cheaper. For these reasons, the gap waveguide is a promising alternative to hollow waveguides and microstrip lines for high frequency applications.
The key characteristic of this new technology is the use of a textured surface on one of the parallel plates, called Artificial Magnetic Conductor (AMC) [17], creating a high impedance condition forcing a cut-off of all parallel-



(a) Ridge Gap Waveguide (b) Groove Gap Waveguide

(c) Microstrip Gap Waveguide

Figure 1.3

plate modes [18]. Therefore, the field is guided only along desired paths, and it is in cut-off along other directions, avoiding the problem of radiation loss which affects conventional technologies at high frequency.
The gap waveguide can be made in different versions based on the type of path and propagation characteristics desired. In ridge and groove gap waveguides, shown in Fig. 1.3(a) and (b), the field is propagating along metal ridges and grooves, respectively [19, 20]. These two designs do not need any dielectric and can be realized using a texture of metal pins [21]. The third version in Fig. 1.3(c) is called inverted microstrip gap waveguide because it is similar to inverted/suspended microstrip lines, but the field propagates in the air gap between the strip line and the upper metal plate, forced by the AMC placed below the substrate of the microstrip line [22].

1.3 Aim and Outline of the Thesis

The design challenges for the next generation millimeter wave communication systems are to realize complete transceivers with low area, low loss, including integration between passive and active components, antenna arrays and advanced packaging techniques, which can be at the same time cost effective. The gap waveguide has been recently introduced as promising candidate for these kind of applications since it can overcome the problems experienced with traditional technologies.
This thesis presents the development of the gap waveguide technology for millimeter wave applications. In particular the study is focused on passive components design, losses study, packaging characteristics and integration with antenna arrays. Measurement results and experimental validation are provided for the designs presented as well as comparisons with standard microstrip transmission lines and hollow rectangular waveguides in terms of losses. The frequency range used is 10 - 20 GHz, but we also show possible applications of the gap waveguide packaging at lower frequencies (1 - 6 GHz). Moreover, we extend the study at high frequency, presenting a losses study and measurement results for gap waveguide circuits realized above 200 GHz in micromachining technology.
This thesis is separated in two main parts. The first part introduces the subject with the background needed in order to understand the contributions of the author in the appended papers, presented in the second part.
This first part of the thesis is divided as follows: Chapter 2 provides an overview of the gap waveguide technology and its evolution. Chapter 3 shows traditional packaging techniques and the gap waveguide packaging concept. Chapter 4 presents a preliminary study of the gap waveguide at millimeter waves, with transitions and fabrication techniques. Chapter 5 deals with the integration between gap waveguide and antennas. Finally, Chapter 6 is dedicated to the list of contributions and to the future work.
In the second main part of the thesis, the contributions of the author are included with five appended papers.

Chapter 2

Overview of the Gap Waveguide Technology

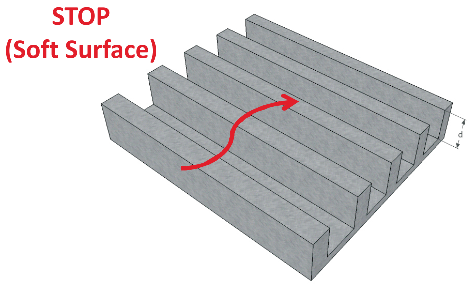
2.1 Soft and Hard Surfaces

The gap waveguide is based on the concept of *metamaterials* and on the definition of *hard* and *soft* surfaces, presented in [23] and [24]. Metamaterials are artificial surfaces that exhibit electromagnetic properties that are not found in nature. In particular, one property that is most desirable and does not exist in nature is the magnetic conductor. Researchers have worked a lot in the last years to create metamaterial surfaces which could artificially generate magnetic conductivity, therefore called Artificial Magnetic Conductors (AMCs), or ideally a Perfect Magnetic Conductor (PMC). Soft and hard surfaces are metamaterials satisfying this condition, being so-called *soft* and *hard* from acoustics theory. Generally, a soft surface stops the waves from propagating, whereas a hard surface supports propagating waves. A typical soft surface is realized by transverse corrugations, as shown in Fig. 2.1(a). When the length d of the corrugation is quarter wavelength, the short circuit is transformed to an open circuit at the aperture of the corrugation, and the surface impedance will be infinite along the direction of propagation, for narrow smooth corrugations, stopping all the waves from propagating. Soft surfaces are typically used to avoid undesired radiations along a certain

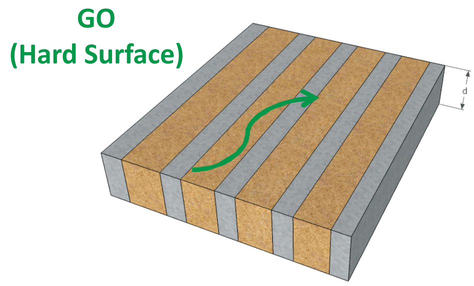
surface, e.g., to reduce the side lobes in E-plane of microstrip and aperture antennas [25, 26], for mutual coupling reduction [27, 28], as hat feed for reflector antennas [29], and for horn antennas [30].
On the other hand, the hard surface can be obtained by filling with dielectric material longitudinal corrugations, shown in Fig. 2.1(b), with a depth

$$d = \lambda/(4\sqrt{\varepsilon_r - 1}), \tag{2.1}$$

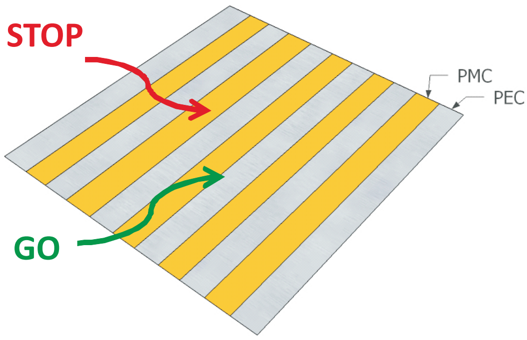
being ε_r the permittivity of the dielectric material and λ the free space wavelength. A hard surface can be used when a strong radiation is needed and it is mostly applied within the concept of hard waveguides, in which quasi-TEM modes can propagate without being perturbed by the waveguide vertical walls, realized with longitudinally dielectric filled corrugations. This concept is mainly used in horns, so-called hard horns, to improve aperture efficiency [31, 32] and in miniaturized array elements for multifrequency applications [33, 34]. However, these works showed that hard waveguides are typically lossy and narrowband.
Ideally, a soft-hard surface can be realized of PEC (Perfect Electric Conductor) and PMC strips [35], representing a hard surface when the strips are longitudinal, i.e., oriented in the same direction as the wave propagates, and a soft surface when they are transverse, i.e., orthogonal to the direction of propagation, as it is illustrated in Fig. 2.1(c). The PEC/PMC strips can be realized with a dielectric substrate with transverse (soft) or longitudinal (hard) metal strips.
In [36] it was demonstrated that local quasi-TEM modes can propagate along the ridges of corrugations when a metal plate is placed above the corrugations, at a distance smaller than quarter wavelength. The operation principle is the same as the PEC/PMC strips with a metal plate at the same distance above them, in which the waves are propagating only along the longitudinal direction whereas are attenuated after crossing the PEC/PMC strips along the transverse direction, due to the anisotropic characteristic of the PEC/PMC strips.
The gap waveguide concept has been finally derived from this discovery [15].



(a) Soft surface realized with transverse corrugations



(b) Hard surface realized with longitudinal dielectric filled corrugations



(c) Soft-hard surface ideally realized with PEC/PMC strips.

Figure 2.1

The improvement compared to the initial discovery done in [36] is that in gap waveguides the waves are not forced to follow straight paths defined by the ridges of corrugations. The field is propagating along a central metal ridge/strip and it is surrounded by the high impedance surface on its lateral sides, which ideally can be the PMC surface or the PEC/PMC strip grid. Therefore, the gap waveguide can be defined as a new type of hard waveguide with the advantage of being low loss and wideband compared to typical hard waveguides, as shown in the study in [37].

2.2 Basic Theory of the Gap Waveguide

The basic theory deriving the gap waveguide is illustrated in Fig. 2.2. Ideally considering two parallel plates, one PEC plate above a PMC plate (Fig. 2.2(a)). If the distance between these two plates is smaller than quarter wavelength, then no waves are allowed to propagate and all parallel-plate modes will be in cut-off, according to the boundary conditions on both surfaces. This situation changes if the parallel plates are both PECs. Hence, it is well known that parallel-plate TEM waves will propagate in the gap between them. If the bottom PEC plate is instead surrounded by a PMC plate on both sides, as shown in the illustration on the right of Fig. 2.2(a), then there will be no waves propagating in the gap between the PEC-PMC plates, confining only a local TEM mode propagating in the center, in the gap between both PEC layers, thus generating the gap waveguide [15, 16]. The PEC plate is easily realized by using metal conductors. To realized the PMC condition in reality, an Artificial Magnetic Conductor (AMC) must be used creating a high impedance on the surface [38].
Hence, a real gap waveguide can be realized with a metal ridge, strip or groove, embedded on both sides by a textured surface which provides a high impedance, allowing only a local quasi-TEM mode to propagate along the metal strip, as shown in Fig. 2.2(b).

2.3 Artificial Magnetic Conductors and Electromagnetic Bandgaps

In the realized gap waveguide an AMC is needed in order to prohibit all parallel-plate modes from propagating. Soft surfaces can be used for this purpose. However, a soft surface is anisotropic, i.e., stops the waves from propagating only along one direction (transverse to the strip/ridge) and allows the propagation in the directions parallel the strip, destroying the local gap waveguide performance. Therefore, it is important that all global parallel-plate modes are in cut-off in the frequency range of operation of the gap

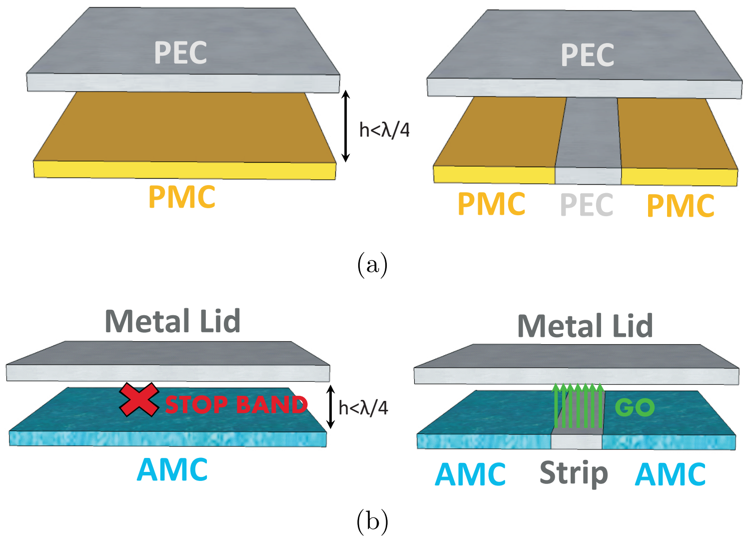
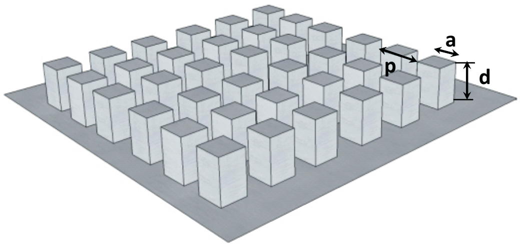


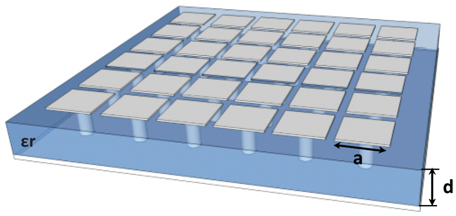
Figure 2.2: (a) Basic principle of operation of gap waveguides with ideal PEC-PMC parallel-plates (left) and PEC-PEC parallel plates, one of which is embedded by a PMC on both sides (right). (b) Realization of the same concept with a real metal lid and a AMC surface around the strip.

waveguide. Electromagnetic Bandgap (EBG) surfaces are high impedance surfaces [38] which forbid propagating waves (typically, surface waves) in all directions within a frequency range due to their isotropic characteristics. The most common EBG realizations used in gap waveguides are a textured surface made of periodic metal pins, so-called bed of nails [21], and mushrooms-type EBG textures proposed in [38], both illustrated in Fig. 2.3. The characteristics of the parallel-plate stopband provided by these structures are presented in [18].

The bed of nails can be easily realized with milling techniques and it is made of only metal, being suitable for high frequency applications. The pins work as a high impedance surface within a stopband defined by a lower and a upper cut-off frequency. The height of the pins must be approximately $d = \lambda/4$, to transform a short circuit (PEC) to an open circuit (PMC) and the period p must be small. The lower cut-off frequency is then defined by the height of the pins, while the upper cut-off limit is defined as the frequency at which



(a) Bed of nails.

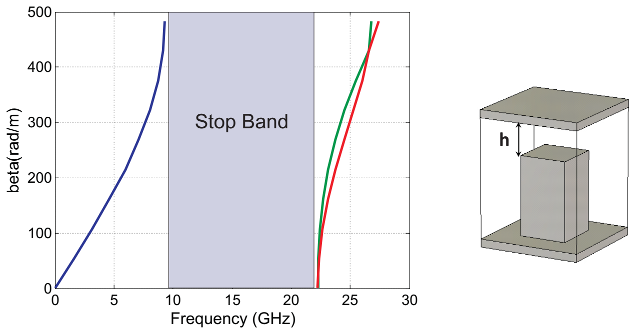


(b) Mushroom-type EBG surface.

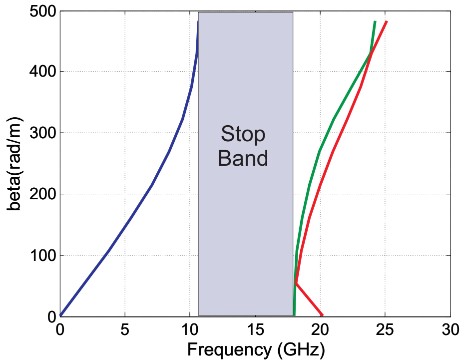
Figure 2.3

$d+h = \lambda/2$, where h is the height of the air gap, which must be smaller than $\lambda/4$, as already said.
The dispersion diagram for a periodic infinite unit pin cell is presented in Fig. 2.4(a). The pin has height $d = 5$ mm, period $p = 6.5$ mm, width $a = 3$ mm and the air gap to the upper metal lid is $h = 1$ mm, providing a stop band of all parallel plate modes from about 10 GHz to 22 GHz. Indeed, it can be seen that the first basic TEM parallel-plate mode starts at zero frequency, and then it deviates from the light line and goes into cut-off below 10 GHz, appearing again above 22 GHz. The width of the stopband depends on the air gap h, the larger the air gap between the pins and the upper metal plate and the narrower the stopband. This is shown in Fig. 2.4(b) and (c), where the dispersion diagrams are plotted for a larger h, i.e., $h = 2.5$ mm and $h = 4$ mm, respectively. The stopband decreases in both cases, being approximately 10.5 - 18 GHz in the first case and even narrower in the second case, 10.5 - 15 GHz.
The mushroom-type EBG surface is realized with printed circuit board technology and metal patches on the top of the substrate connected to the ground by via holes. For this reason this structure can be made in a compact way, thus being suitable also for low frequency applications. The mushroom surface works as a resonant parallel LC circuit with a surface impedance equal to the impedance of the parallel LC circuit, which becomes very high at the resonant frequency [38]. Fig. 2.5 shows the stopband provided by a mushroom-type EBG infinite periodic unit cell inside a parallel-plate structure, with the following dimensions: width of the patch $a = 6$ mm, radius

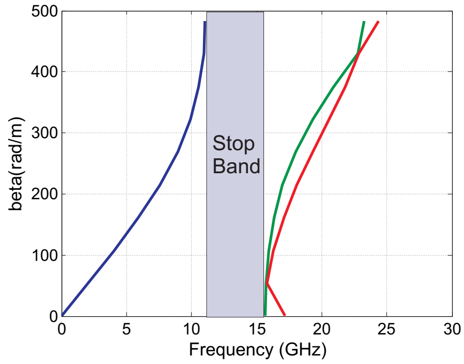
of the via $r = 0.75$ mm, thickness of the dielectric $d = 3.2$ mm and air gap from the patch to the upper plate $h = 1$ mm. The substrate has permittivity $\varepsilon_r = 2.2$ and tan$\delta = 0.0009$. The numerical study performed in [18] shows that the main design parameters affecting the parallel-plate stopband are the thickness and the permittivity of the dielectric used, and the height of the air gap. Basically, the thicker the substrate material (or the height of the vias), the wider the stopband. For the permittivity: the lower the ε_r, the wider the stopband. The air gap height has the same effect as for the pins, i.e., the stopband is wider for smaller h.



(a) h = 1 mm.



(b) h = 2.5 mm.



(c) h = 4 mm.

Figure 2.4: Dispersion diagrams of an infinite periodic pin cell varying the air gap h between the pin and the upper metal plate. The pin has height $d = 5$ mm, period $p = 6{,}5$ mm and width $a = 3$ mm.

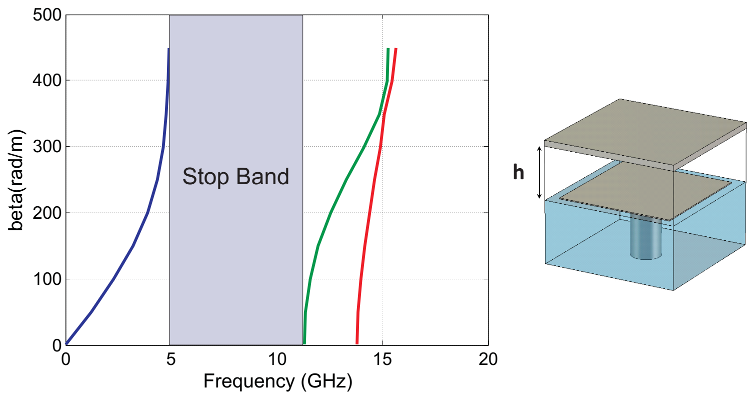


Figure 2.5: Dispersion diagram of a mushroom-type EBG infinite periodic unit cell with air gap $h = 1$ mm from the patch to the upper plate. The following dimensions are used: $a = 6$ mm, $r = 0.75$ mm and $d = 3.2$ mm.

2.4 Ridge Gap Waveguide

The ridge gap waveguide is realized with two parallel plates, an upper metal smooth lid and a lower plate, provided of a central metal ridge surrounded by the bed of nails. The bed of nails realizes the high impedance surface which stops all parallel-plate modes, confining only a local quasi-TEM mode allowed to propagate along the ridge. This structure does not need any dielectric because we are using a lid of metal pins, but also other types of AMCs can be used around the ridge if desired [39]. Fig. 2.6 shows the dispersion diagram of a row of pins with a central ridge, separated from the upper lid by the air gap h, infinite along the z direction. The dimensions of the pins are the same as the ones used in Section 2.3, the height of the ridge is the same as the height of the pins, i.e., $d = 5$ mm, the width of the ridge is $w = 3.5$ mm and the air gap is $h = 1$ mm. When the ridge is present, a quasi-TEM mode is established and propagating within the stopband. All other higher order modes are forced to be in cut-off by the bed of nails.

The ridge does not need to be straight, the field follows its path even if it has bends or if it is split in several branches. Hence, standard passive components, such as power splitters and bent transmission lines can be designed in ridge gap waveguide, as demonstrated in several studies [19, 40, 41, 42]. Fig.

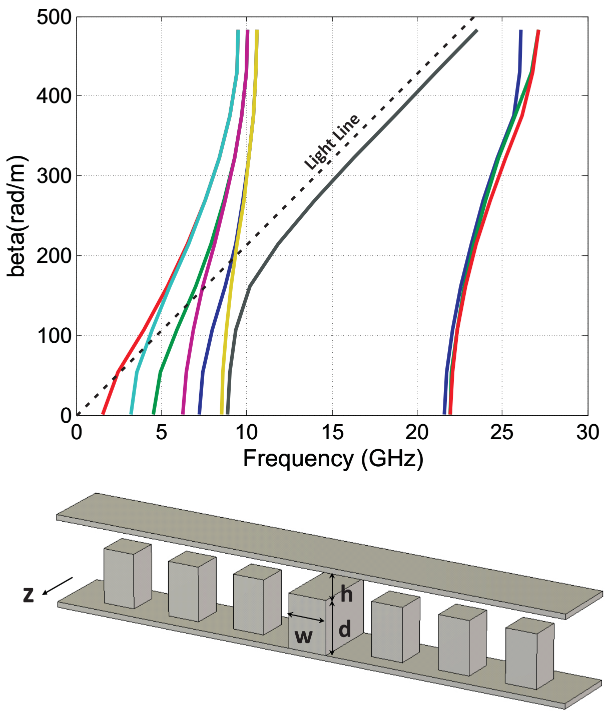


Figure 2.6: Dispersion diagram of a row of pins with central ridge infinite along z direction. The following dimensions are used for the ridge: $d = 5$ mm and $w = 3.5$ mm. The dimensions of the pins are the same as the ones used in Section 2.3 and the air gap is $h = 1$ mm.

2.7 presents the simulated 2-D color plots of the absolute value of the E-field along a ridge gap waveguide with two 90° bends, for each frequency points, with a photo of the first prototype shown on the right. The field follows the ridge within the frequency range defining the stopband, i.e., from 11 GHz to 21 GHz. Before the lower cut-off frequency and after the upper cut-off frequency, the bed of nails does not work as an AMC and all parallel-plate modes can propagate spreading all around, as it can be seen in the plots at 9 and 22 GHz. The standing wave than can be noticed along the ridge above 18 GHz is due to the coaxial transitions used to feed the circuit, which work up to 18 GHz [43]. The measured S-parameters for the first ridge gap waveguide prototype realized are shown in Fig. 2.8(a), with a return loss below -10 dB within the band of 13-16.3 GHz.

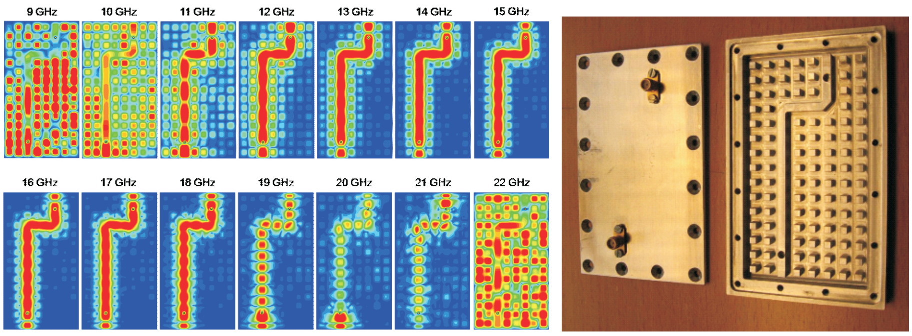
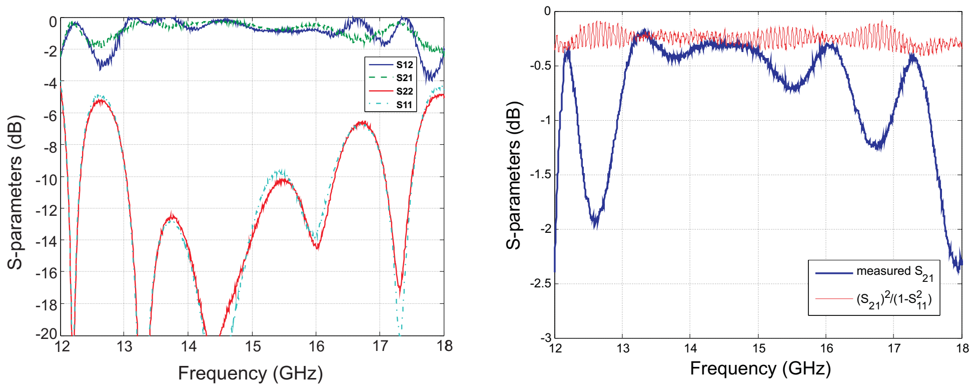


Figure 2.7: 2-D color plots of the absolute value of the E-field for each frequency point along the ridge gap waveguide, with a photo of the realized prototype.



(a) (b)

Figure 2.8: (a) Measured S-parameters for the first ridge gap waveguide demonstrator. (b) Zoom of the S_{21} with and without mismatch factor.

The measured S_{21} with and without mismatch factor is zoomed in Fig. 2.8(b), showing that there is certain amount of loss due to the absorptions in the coaxial transitions, besides the loss due to the circuit itself. A TRL calibration kit was later realized to measure the S-parameters excluding the absorptions due to the transitions [19], [44]. Measurements results, presented in these works, showed that the loss due to the gap waveguide is smaller than the measurement accuracy. Therefore a more accurate approach was needed in order to determine the losses in gap waveguides. For this reason a losses study was performed afterwards. This study is presented in the second part of the thesis, as contribution of the author in [Paper C].

2.5 Groove Gap Waveguide

In the groove gap waveguide, the ridge is replaced by a groove embedded by the pins on both sides, as it can be seen in Fig. 2.9 where a prototype is shown. The difference with the ridge gap waveguide is that the groove case allows propagating TE/TM modes, thus working similarly to rectangular waveguides with the additional benefit of having contactless metal plates [20, 45]. In addition, the groove gap waveguide has less losses than the ridge case because there is more volume for the current density and the ridge is removed.
For these reasons, the groove gap waveguide is very suitable for high Q-factor filter designs, as shown in the works in [46, 47].
The dispersion diagram of a row of pins with a central groove, infinite along z direction, below a smooth lid is presented in Fig. 2.10, together with a 2-D plot of the absolute value of the E-field. The E-field is vertically polarized with a distribution similar to the TE_{10} of a rectangular waveguide. The same behavior can be noticed from the dispersion diagram, with the groove gap waveguide mode propagating within the stopband created by the pins. In the study in [20] it is shown that this mode almost coincides with the one of an ordinary rectangular waveguide with same dimensions as the groove. The groove gap waveguide can also be designed for horizontal polarizations, or for dual-polarizations, suitable for example for horn antenna applications.

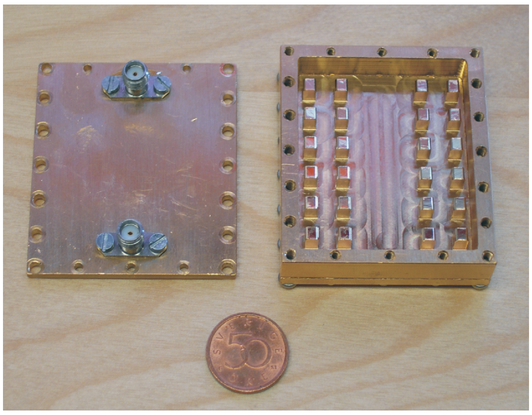


Figure 2.9: Groove gap waveguide prototype.

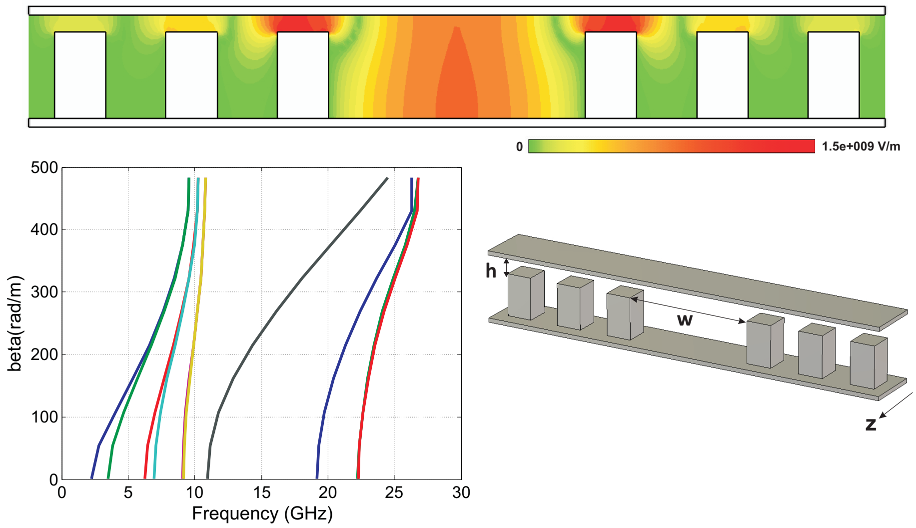


Figure 2.10: Dispersion diagram of a row of pins with central groove, infinite along z direction, below a smooth lid, and 2-D color plot. The dimensions chosen are h = 1 mm, w = 15 mm and the same used in previous sections for the pins.

2.6 Microstrip Gap Waveguide

The microstrip gap waveguide geometry is presented in Figure 2.11 and it works similarly to inverted/suspended microstrip lines with the difference that the substrate is supported by the artificial magnetic conductor. The AMC forces the field to propagate in the air gap, between the printed microstrip line and the upper ground plane. The AMC used to realize this structure can be either the bed of nails or the mushroom-type EBG surface. The advantage of this gap waveguide version is that it can be easily adapted to printed circuits and it has less dielectric losses because of the propagation in the air, and less conductive losses because wider lines can be used to match the 50 Ω line impedance in the air, compared to typical microstrip lines. Plus, there is no problem with surface waves and radiation losses. Thus, the microstrip gap waveguide can be applied as feed network for antenna arrays, as it will be shown in the second part of the thesis, in [Paper E].

The microstrip gap waveguide can be realized in different versions, depending on the AMC used and on the desired design. Three possible geometries are shown in Figure 2.12. In the first, the lid of nails supports the dielectric on which the microstrip line is printed. In the second, the microstrip line is placed above a mushroom-type EBG surface. In the third, mushrooms and microstrip line share the same dielectric. The stopbands are computed for the following dimensions: air gap $h = 1$ mm, substrate thickness $t = 1$ mm, pins height $d_1 = 7$ mm, vias height $d = 3.2$ mm, vias radius $r = 1$ mm, patches width $w = 6$ mm and the separation between each patch is $g = 1$ mm. The substrate used is Duroid 5880 with $\varepsilon_r = 2.2$ and $\tan\delta = 0.0009$. Dispersion diagrams computed with CST Eigenmode solver are presented in Figure 2.13 together with 2-D color plots of the absolute value of the E-field for each geometry. The color plots of the E-field are taken in the middle of the stopbands and show how the quasi-TEM mode is mainly propagating in the air (between the microstrip line and the upper plane).

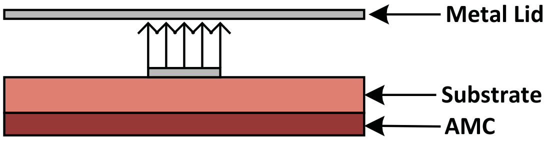


Figure 2.11: Geometry of the microstrip gap waveguide.

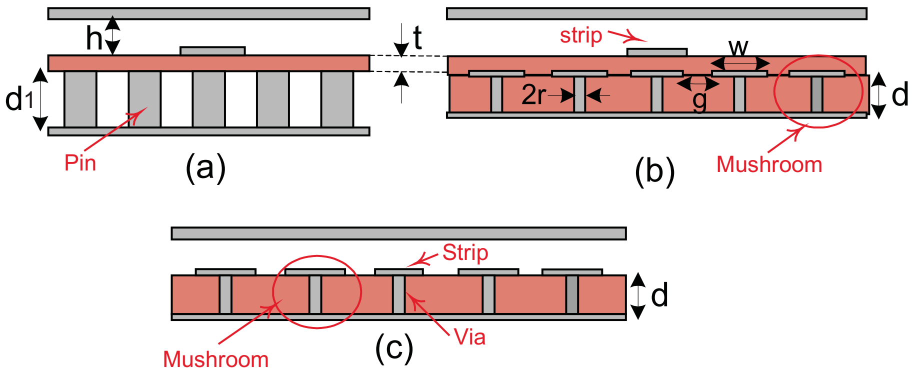


Figure 2.12: Three geometries considered. In the first the AMC surface is made with metallic pins, in the second with mushrooms-type EBG, in the third microstrip line and mushroom-type EBG share the same substrate.

The parameters affecting the bandwidth are the air gap height, the dielectrics chosen and the substrate thicknesses d and t [18]. In this case we have chosen a dielectric with low permittivity ($\varepsilon_r = 2.2$) and with thickness of 3.2 mm in order to enlarge the stopband. h is kept fixed to 1 mm to have a characteristic impedance of 50 Ω. Considering the designs in Fig. 2.12(a) and (b), by keeping h, d and d_1 constant, the upper frequency limit of the stopband increases as t decreases for both solutions with pins and mushrooms, as shown in the plot in Figure 2.14. This happens because for gap waveguides the stopband increases when the distance between the AMC boundary and upper metal plate is reduced. The substrate layer above the mushroom surface (and the pins) adds more space between the mushrooms (creating the high impedance condition) and the upper lid. Therefore, the smaller the t, the larger the stopband.

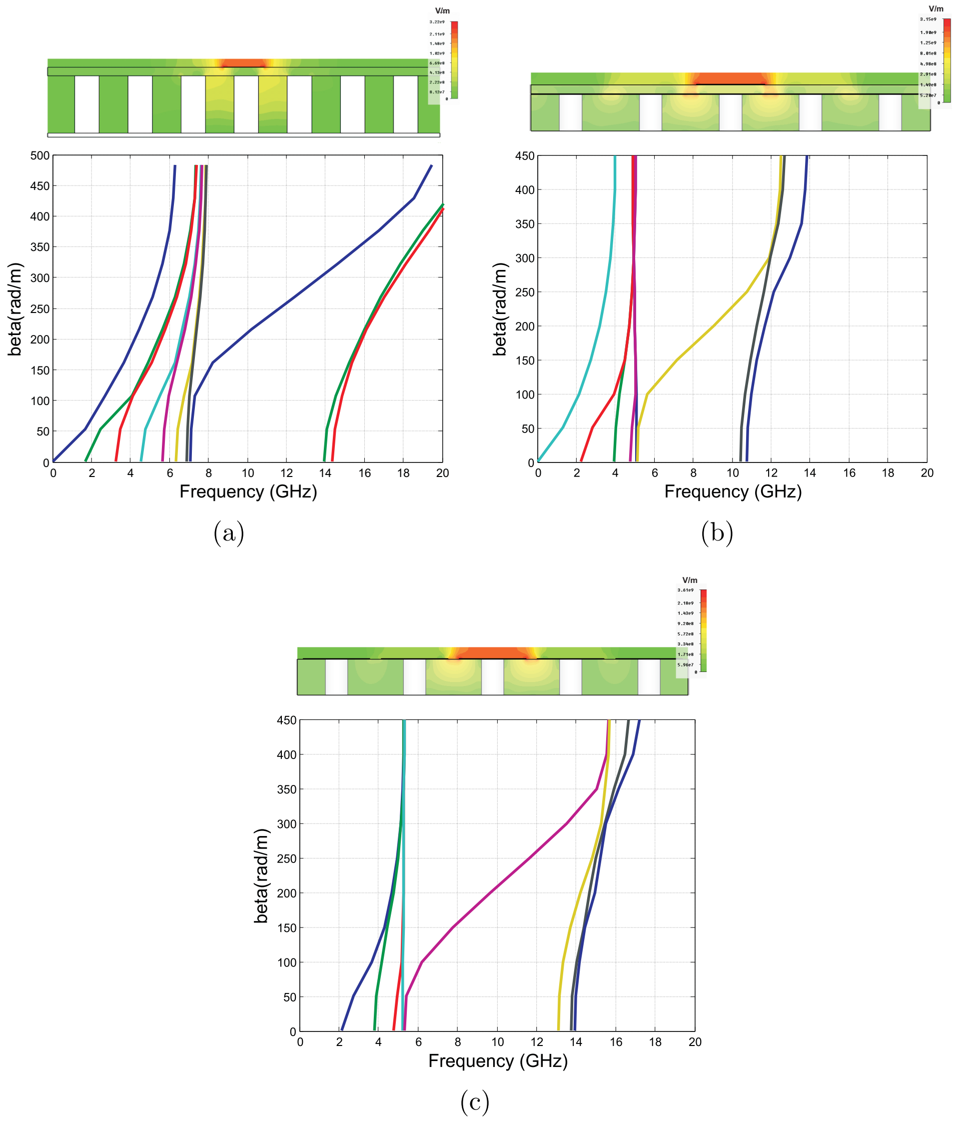


Figure 2.13: Dispersion diagrams of microstrip gap waveguides below 2-D color plots of absolute value of E-field. (a) Solution with lid of pins, (b) mushroom-type EBG surface and (c) mushrooms and microstrip line on the same layer.

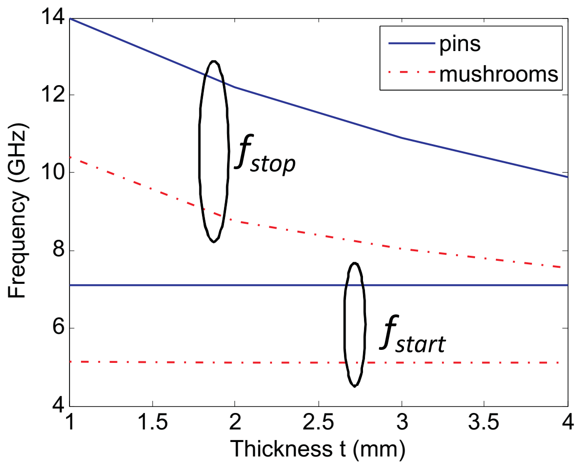


Figure 2.14: Start and stop cut-off frequencies of the stopband for the microstrip line above pins and mushrooms as a function of the substrate thickness t. Dimensions used for the mushrooms are: $d = 3.2$ mm, $r = 1$ mm, $w = 6$ mm, $g = 1$ mm. Pins length is $d_1 = 7$ mm and air gap is $h = 1$ mm for all cases.

For this reason the third design solution (Fig. 2.12(c)) gives a wider stopband compared to the previous ones, since the additional substrate is removed and the strip line is directly printed on the mushrooms layer. A study of this case is presented in [Paper A].
The solution with pins becomes bulky at the typical operation frequency range of microstrip lines. The version made with mushrooms is more compact and convenient for low frequency applications.

Chapter 3

Packaging Techniques

3.1 Microwave and Millimeter Wave RF Packaging

Electrical circuits need to be shielded from external disturbances that can deteriorate the system performance and the mechanical circuitry. To provide such isolation they are typically enclosed within a metal package. In addition, the current trend of moving up in frequency and integrating RF blocks, MMICs and passive components in one single module has led to the need of advanced packaging techniques. As the frequency moves into the microwave and the millimeter wave range, the physical dimensions of the metal package enclosing the circuit board become comparable with the wavelength, thus exciting cavity modes which can couple with the circuits causing undesired effects and instability of active devices [48]. This problem can be solved by reducing the size of the package so that the cut-off frequency of the cavity modes will be too high to interfere with the operation frequency of the circuits. However, at high frequency it is not always possible to reduce the dimensions of the cavity, taking also into account that the cavity must contain more interconnected circuits. Other solutions such as relocating the circuit to a different position or using absorbing materials that can dump the cavity modes would require a more complex design and manufacturing process. In particular, the absorbers are useful in reducing reflections from scattering objects and radiations from discontinuities, but as a drawback they add losses to the system, which are already a critical factor at such frequencies [49]. Also, it is difficult to predict the optimal position of the absorbers within the package and most of the time their placement is defined by a trial and error process during the measurement test which adds delays to the realization of the complete module.

Another problem occurring in the packaging process is that MMICs and passive components are placed on printed materials and surface waves can be generated in the dielectric causing leakage of energy and cross talk problems [50]. Coupling between different transmission lines as well as radiation from interconnected lines can also arise interference between integrated circuits at high frequencies.

Therefore, all these problems add more challenges to the overall packaging design complexity.

3.2 PMC Packaging Concept

The PMC packaging concept developed in gap waveguides can overcome the typical problems experienced when packaging circuits at high frequency and improve the isolation between interconnected components. The basic concept is shown in Fig. 3.1. A parallel-plate cut-off region is created in between two parallel ideal PMC-PEC layers when they are separated by a distance smaller than a quarter wavelength. When a microstrip line is placed above the PEC plate, the only mode allowed to propagate will be the fundamental microstrip mode along the strip. On the other hand, all other unwanted modes, i.e., cavity modes, radiations from discontinuities, unwanted reflections and surface waves, will be suppressed within the stopband created by the parallel PMC-PEC condition. This solution does not need metal walls separating different circuits to avoid the coupling over the air and it does not need the use of absorbing materials which add losses to the system. The unwanted substrate modes are also stopped from propagating with no problem of coupling via the substrate.

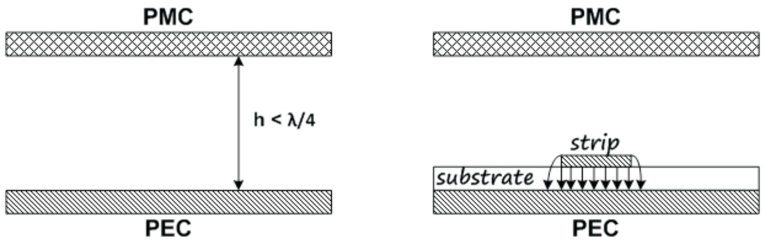


Figure 3.1: PMC packaging concept (left). The propagation is permitted only along the microstrip line within the PMC-PEC plates (right).

Another advantage of the PMC packaging is the reduced computation time in the simulation process. Thus, it is possible to include the packaging characteristics in the design and to simulate and optimize their performance before the realization stage, as already discussed in [51].

3.3 Realizations of Gap Waveguide Packaging

In order to realize the ideal PMC concept, any type of Artificial Magnetic Conductor (AMC) can be use in real realizations. The AMC surface provides the parallel-plate stopband needed to remove all unwanted modes excited within the metal package in the frequency range of operation.
The bed of nails, sketched in Fig. 3.2, is mostly used for packaging at high frequency, because is made of only metal. Validation of the bed of nails for packaging of passive microstrip transmission line circuits has been presented in [52]. In particular, the plots in Fig. 3.3 show the E-field traveling along a microstrip line packaged first with a smooth metal lid and after with a bed of nails, for each frequency point, within the stopband provided by the pins. When the microstrip line is packaged with a smooth metal lid, cavity modes appear all around the circuit affecting the fundamental microstrip mode. On the other hand, they are totally removed when the bed of nails is used as a package, showing a clear propagation of the E-field along the microstrip line.

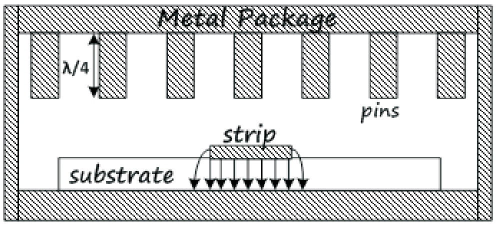


Figure 3.2: Gap waveguide packaging of a microstrip circuit by using bed of nails.

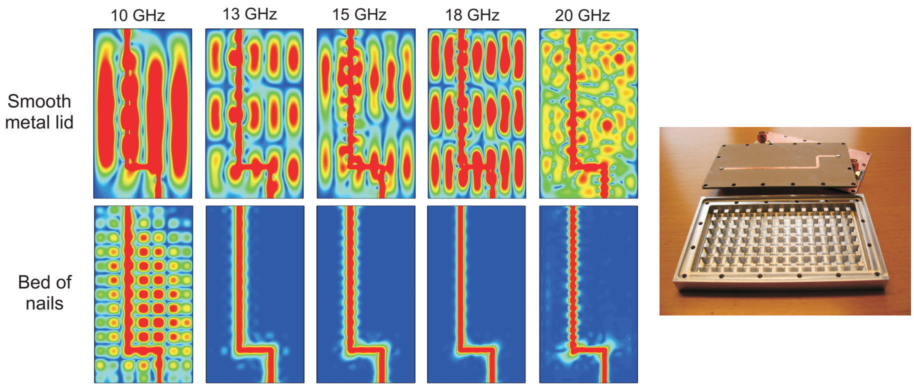


Figure 3.3: 2-D color plots of the vertical E-field traveling along the microstrip line shown in the photo, packaged with a smooth metal lid and with a bed of nails. The dimensions of the circuit and of the pins are provided in [52].

The lid of nails has also been utilized in [53, 54] to package classical microstrip coupled line filters to avoid the rise of cavity modes and radiations, and in [55] to improve the isolation between amplifier chains. Furthermore, the shape of the nails can be modified to enlarge their stopband. An example is provided in [56], where an inverted pyramidal shape geometry is adopted to provide a wider bandwidth, which can be suitable for integrating and packaging wideband MMICs.

The pins become too bulky at low frequency as they have to be quarter wavelength long, and other types of more compact gap waveguide packaging solutions are needed. In [57, 58] a new type of periodic structure is proposed which has similar characteristics as the pins, i.e., made of only metal, and it can also be used for packaging applications at low frequency. The design is realized by metallic helices, therefore called bed of springs, shown in Fig. 3.4. The total electrical length of the wire used for this solution is $\lambda/4$, but it is spiral-shaped so that it becomes more compact compared to regular pins. Another advantage of this design is that there is no strong capacitive effect from the end of the springs to the opposite plate, compared to the bed of nails and to the mushrooms-type EBG which have a flat surface in parallel with the corresponding metal plate creating a capacity with a clear effect on the stopband. Therefore, the air gap in this case is not a critical parameter affecting the stopband and more flexibility can be used in the choice of larger gaps to allow more space for capacitors or transistors on the circuit board.

However, the disadvantage of using the metal springs is that they can be more difficult and expensive to manufacture side by side. Therefore, a *zigzag* version of the springs has been proposed in which the zigzags are printed on vertical slices of a thin dielectric, placed side by side to create the periodic structure. The circuit is presented in Fig. 3.5.

Another type of packaging solution in printed technology is the mushrooms-type EBG surface which can be combined in the same substrate layer as the microwave circuits, as illustrated in Fig. 3.6. This and the zigzag design are described in details in [Paper A] and [Paper B], respectively.

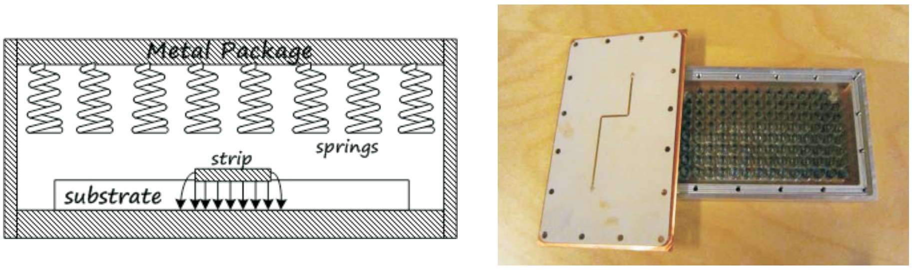


Figure 3.4: Packaging of microstrip line circuits by using a bed of springs.

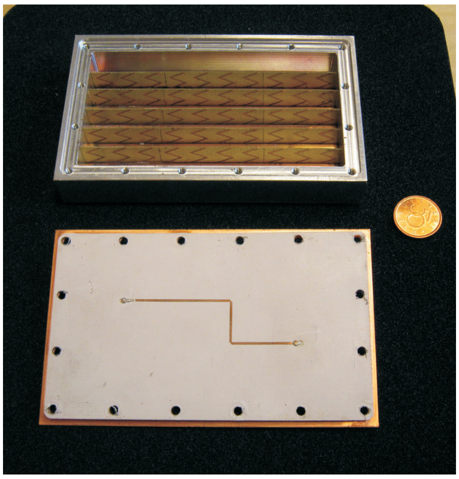


Figure 3.5: Packaging of microstrip line circuits by using printed *zigzag* wires.

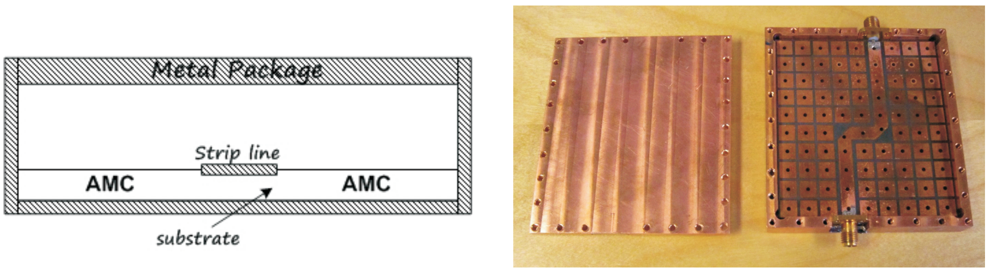


Figure 3.6: Packaging solution by using a mushroom-type EBG surface printed on the same substrate as the microstrip line.

Chapter 4

Gap Waveguide at Millimeter Waves

4.1 Challenges of Millimeter Wave Applications

The need of faster data rates and the spectrum scarcity have driven commercial communication applications and research to investigate the millimeter-wave bands. Guaranteeing the system performance and accuracy while keeping low costs is the main challenge of these new applications. Geometries are scaled down with the wavelength and become smaller at higher frequencies. The small circuit elements lead to the first challenge, i.e., facing a new design approach in terms of manufacturability and performance. The impedance matching is more difficult to maintain, losses are high and traditional assembly techniques are inaccurate. At these frequencies MMIC, passive components and interconnects are mounted on the same substrate as the active devices. One problem is that the passive elements, placed on the MMIC chip, suffer from lower Q-factors and limited power handling capability compared to the their placement in standard circuit boards or packages. In particular, microstrip transmission lines are easy to integrate on such chips but they present high losses. On the other hand, waveguides have higher Qs, but it is more difficult to combine them into a MMIC-based system and they need bulky transitions which are demanding to realize at such frequencies. Another challenge is the fabrication of these chips, which is complex and require long iterations. High precise machining is needed in order to assure a very good electrical contact between the split blocks and it is difficult to correct and discover the tiny gaps or imperfect joints, which can easily cause leakage of energy and radiation losses. In addition, measurement techniques can be affected by the signal attenuation which disturbs both the analyzer's internal circuits and the external signal connections, the latter also becoming expensive and inflexible at these frequencies. Also, the measurement equipments, i.e. millimeter wave instruments and probe stations, are expensive.

4.2 Micromachined Gap Waveguides

The advance of silicon-based micromachining technologies is due to the growing demand of micro-electro-mechanical systems (MEMS) [59, 60]. Traditional machining techniques to produce passive components refer to milling or drilling the metal or substrate materials to realize the required 3-D geometries. However, these techniques are limited by the smallest available milling cutter which is not enough accurate to realize micro circuits at high frequency. Therefore, a new approach must be developed to adapt to the needs of the MEMS. Micromachining is an emerging method to realize microscopic circuits on silicon wafers with etching techniques. The advantage of this procedure is that many circuits can be made simultaneously on one wafer, resulting in low costs and easy mass-production. The gap waveguide is well suited for this kind of fabrication process due to its planar topology. Ridge and groove gap waveguide circuits working at 100 GHz and above 200 GHz have been produced with micromachining by building the circuits on the silicon wafer and then etching away the unwanted parts. The detailed designs and measurement results are presented in [61, 62].

The general realization process of these circuits by micromachining is shown in Fig. 4.1. First, a thick aluminum (Al) layer is sputtered on a silicon wafer. A thin photoresist layer is placed above to define the pattern of the geometry, so that the unwanted Al parts can be etched away. The lateral walls and the height of the pins and ridge/groove are realized by a deep ion etching.

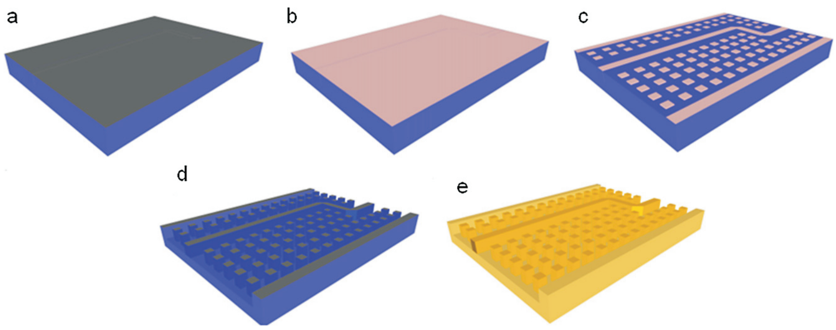
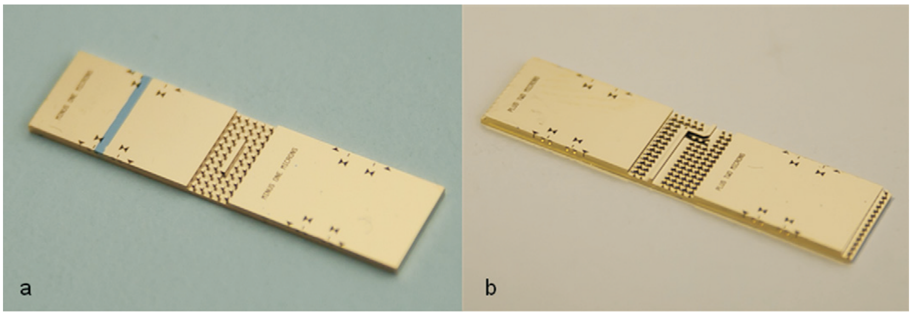


Figure 4.1: Micromachining process: (a) A thick Al layer is sputtered on a silicon wafer, (b) a thin photoresist layer is placed on top, (c) the pattern is created by etching away the Al layer, (d) deep ion etching is used to create the lateral walls, (e) electroplating is provided with a gold layer.

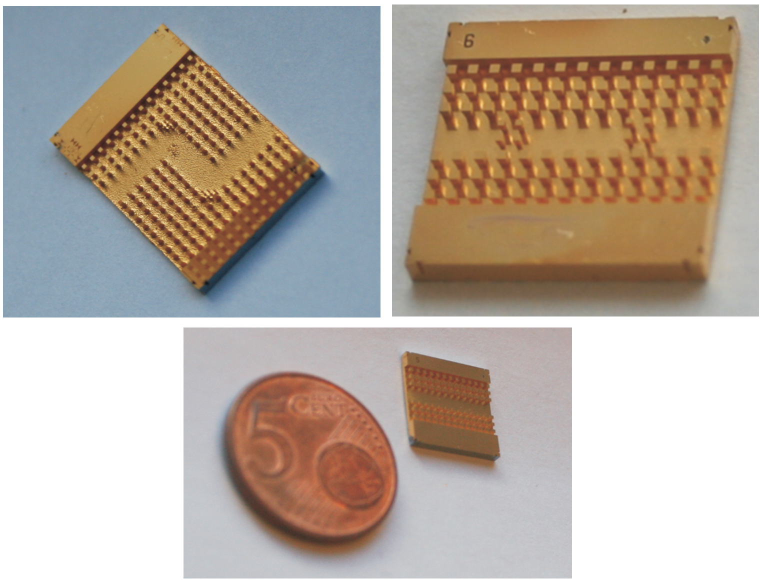
Finally, the circuit is electroplated by adding a thick layer of gold. The final chips are presented in Fig. 4.2. The circuits are then packaged within a metal box made in Copper, which provides also the needed upper metal lid. The field will propagate in the air gap between the ridge/groove and the upper metal cover. The waveguide flanges are then connected directly to the chips, through the holes made in the external package.

4.3 Losses

The loss in transmission lines can be easily determined from the Q-factors of resonators. This study has been done for a micromachined ridge gap waveguide at 230 GHz. A certain weak coupling has to be established between the transition and the resonator in order to lower the level of the S_{21} peak so that the Q of the resonator is not affected by the loading of the transitions, thus determining the unloaded Q. The 230 GHz resonator is measured by waveguide flanges connected directly to each side of the resonator, as shown from the sketch of the resonator in Fig. 4.3. The resonator has dimensions 3.175×2.281 mm. The field will propagate in the air gap, of height 167 μm, between the ridge and the upper metal cover. The waveguide flanges are then connected directly to the resonator, through the holes made in the external



(a)



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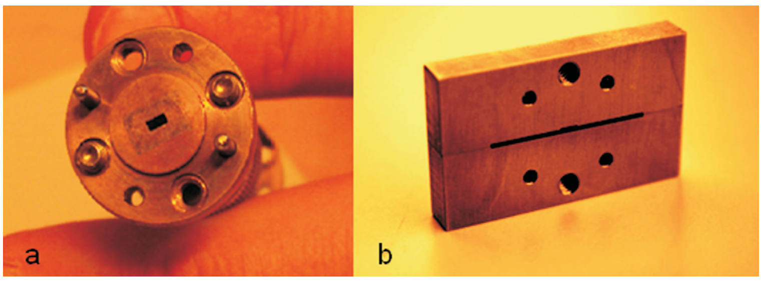


(c)

Figure 4.2: Gap waveguide chips: (a) Ridge gap waveguides. (b) Groove gap waveguides. (c) WR-3 waveguide flange and metal package for the chips.

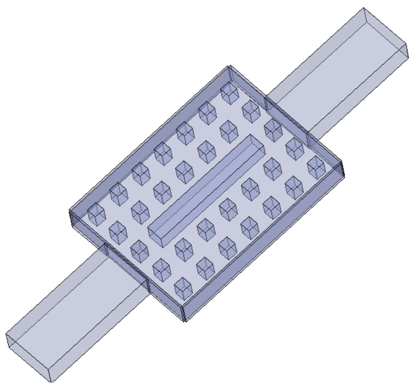


Figure 4.3: Design of the ridge gap waveguide resonator with waveguide transitions.

package. The weak coupling with the waveguide transitions is obtained by adding one pin row between the waveguide port and the ridge at each side.

Simulated and measured results are shown in Fig. 4.4. The resonator including waveguide transitions has been simulated in HFSS. Measurements have been carried out by using a Network Analyzer combined with a millimeter wave controller. The latter is then connected to the circuit under test via connectors with WR-3 waveguide flanges at their ends, working between 220-325 GHz. Simulated and measured resonance frequencies agree very well. The unloaded Q-factor, Q_U, can be calculated by the following equations [10, 63]:

$$Q_L = \frac{f_o}{\Delta f_{3dB}}, \tag{4.1}$$

$$Q_E = 10^{-[S_{21}(dB)/20]} \cdot Q_L, \tag{4.2}$$

$$\frac{1}{Q_L} = \frac{1}{Q_U} + \frac{1}{Q_E}, \tag{4.3}$$

and

$$Q_U = \frac{Q_L}{1 - S_{21}}, \tag{4.4}$$

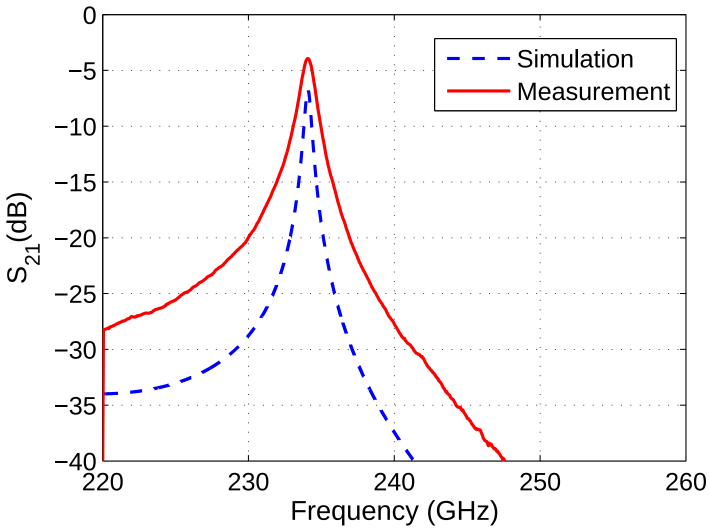


Figure 4.4: Simulated and measured results for the micromachined ridge gap waveguide resonator.

Table 4.1: Measured and Simulated Results

	Simulation	**Measurement**
f_o **(GHz)**	234.07	234.074
Q_L	465	218
Q_U	860	597
α **(dB/mm)**	0.0247	0.0357

where f_o is the resonance frequency, Δf_{3dB} is the 3-dB bandwidth of the resonance, Q_E is the external Q-factor (due to the loading effect), Q_L is the loaded Q (due to the effect of the loads plus the resonator), and Q_U is the unloaded Q (due to the only resonator). In addition, the attenuation constant can be also extracted by using:

$$\alpha = \frac{\beta}{2Q_U}, \tag{4.5}$$

being β the propagation constant.

The results are summarized in Table 4.1. The difference between simulated and measured unloaded Qs is probably due to the surface roughness, which was not included in the simulations.

4.4 Transitions

High frequency measurements are performed by using Vector Network Analyzers (VNA) with standard waveguide flanges or by mechanical probe stations which utilize thin needles on the surface of the circuit to acquire the signal. Therefore, new transitions are needed in order to connect the gap waveguide circuits with the conventional waveguide flanges and coplanar probes.

While the groove gap waveguide circuit can be directly connected to standard rectangular waveguides, a transition is needed to connect the ridge gap waveguide and the microstrip gap waveguide to standard waveguides or microstrip lines.

A coplanar waveguide (CPW) to ridge gap waveguide transition has been designed in [64], working at 100 GHz. However, radiations from the substrate and potential excitation of higher order modes have been experienced, making this CPW design complex and time consuming. For this reason, a microstrip to ridge gap waveguide transition has been also developed, showing good performance for both 100 GHz and Ka-band applications [65, 66]. Currently, studies are ongoing to investigate also possible transitions for microstrip gap waveguides.

4.4.1 Contactless Gap Waveguide Flange

When performing high frequency measurements using rectangular waveguide interfaces, it is critical to control the alignment and to obtain good electrical contacts between the flanges of the VNA and the circuit under test. Alignment pins and tightening screws are normally used to ensure good contacts between the two opposing flanges, being laborious to use in practice. Hence, the idea of a contactless flange made by bed of nails has been introduced in [Paper D] and developed in [67]. The design is shown in Fig. 4.5. Two rows of pins can be milled (or micromachined) on the face of a standard WR-3 waveguide flange around the waveguide opening, as shown in Fig. 4.5. The pins are quarter wavelength long and create a stopband of all parallel plate modes occurring between the pin surface and the opposite smooth flange surface, located at a distance smaller than quarter wavelength from the opposite textured flange. In this way, it is possible to keep an air gap between the two flanges avoiding any possible leakage. In addition, we found it advantageous to keep a circular region around the waveguide opening, of the same height as the pins. This is about quarter wavelength long in radial direction and will approximately create a short circuit at the waveguide wall, thereby improving the reflections from the transition. The prototype is shown in Fig. 4.6. The simulated and measured S-parameters are presented in Fig 4.7 for the back-to-back configuration. The circuit under test is made of a thick waveguide disc with pin flanges attached on both sides, connected to the standard waveguide flanges of the VNA. The prototype has an actual air gap of 56 μm between the waveguide opening and the opposite flanges of the VNA.

Measurements are also performed with the waveguide disc connected directly to the inputs of the VNA with standard WR-3 flanges without pins, for comparisons. Both configurations considered are illustrated in Fig. 4.8, where on the right the waveguide disc is connected to the waveguides of the measurement setup with standard WR-3 flanges, whereas the pin flanges are used in the configuration on the left. The measured S-parameters for these two cases are shown in Fig. 4.9. The measurements are performed for two different situations: first when the flanges of the VNA are tightened well with screws to waveguide disc with or without pin flanges, and second when they are placed in a touching position next to each other without any screws. The plots on the right represent the S_{21} parameters zoomed between 0 dB and -4 dB for each case.

The cases with pins (red curves) show a much better transmission coefficient than the standard WR-3 flanges (blue curves), when the screws are not used, as expected because the leakage is stronger for the waveguides and the disc when they are not tightened to each other with screws. Furthermore, this difference can also be noticed when screws are used. The insertion loss is larger for the standard WR-3 flanges than for the case with pin flanges, being due to the leakage even though in this situation screws were used.

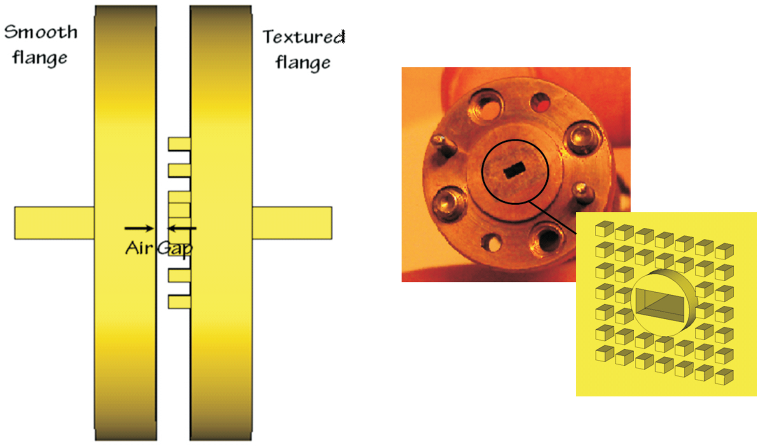


Figure 4.5: Design and sketch of the contactless flange made by bed of nails. A standard WR-3 flange is shown in the photo.

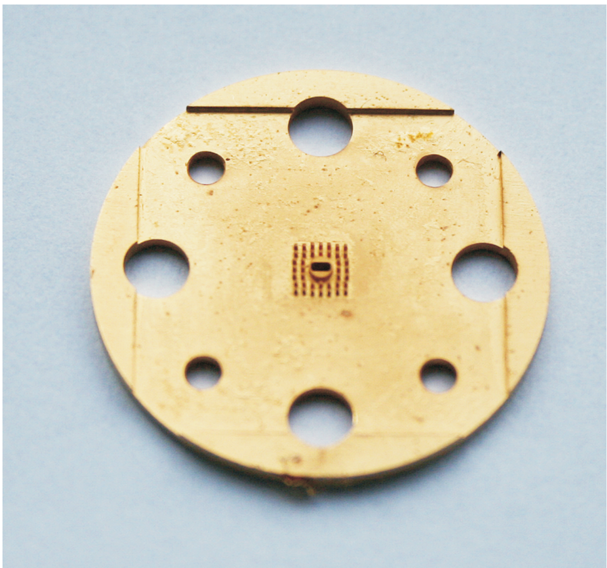


Figure 4.6: Pin flange prototype.

This work shows the potentials of the contactless pin flange to make more accurate measurements at high frequencies and ongoing studies are investigating the possibility of realizing unisex pin flanges.

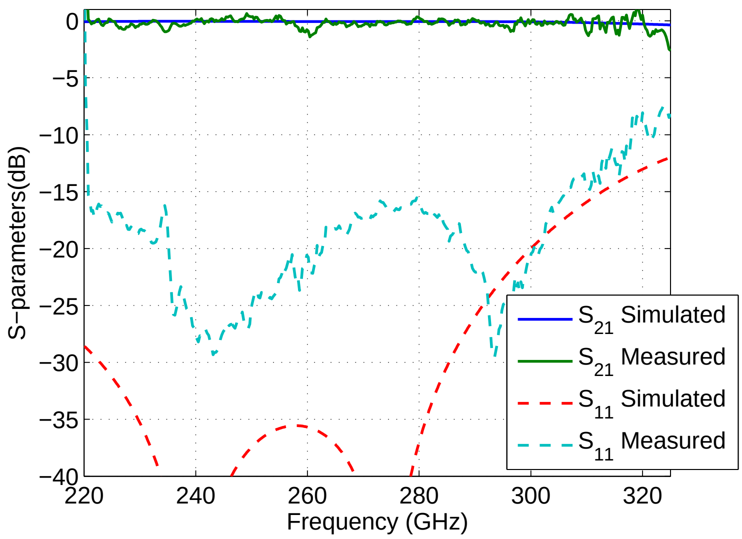


Figure 4.7: Simulated and measured S-parameters of the back-to-back pin flange.

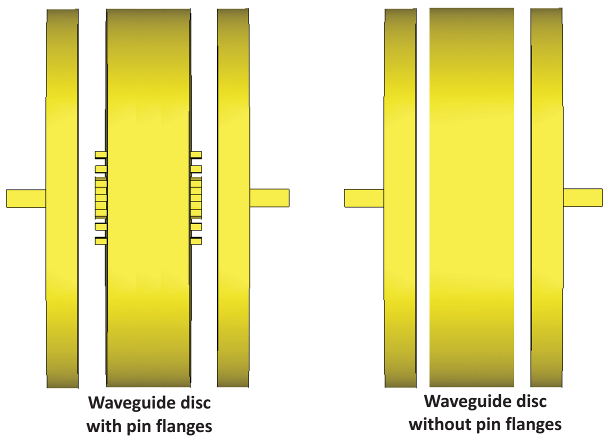
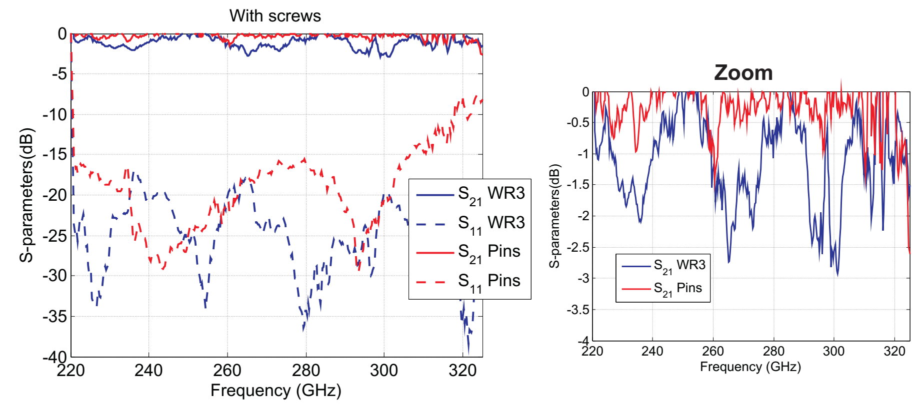
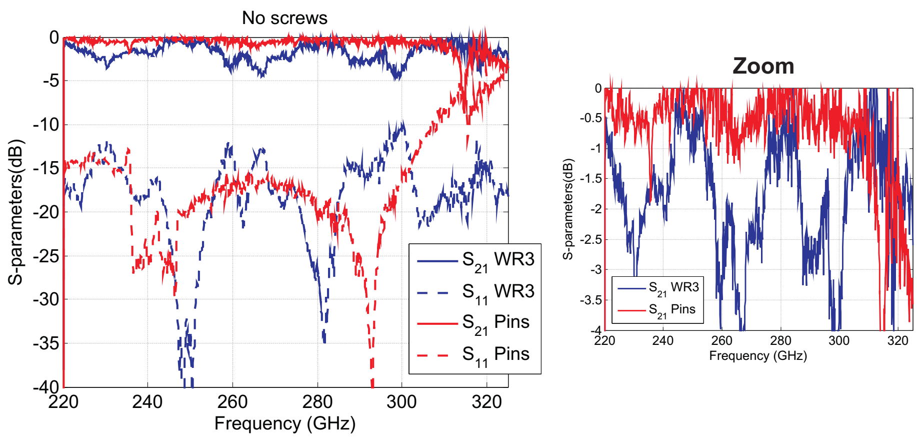


Figure 4.8: Waveguide disc with pin flanges (left) and without pin flanges (right) connected to the waveguides of the measurement equipment.



(a)



(b)

Figure 4.9: Measured S-parameters when the circuit under test is connected to the waveguides of the measurement setup (a) with screws and (b) without.

Chapter 5

Integration with Antennas

5.1 Antennas for High Frequency Applications

Planar antennas and their feed networks are very crucial for millimeter wave receivers and transmitters and for the advance of short range high data rate applications. WPAN applications, outdoor mm-wave point-to-point backhaul and future cellular systems need very directive antennas with high efficiency, symmetrical main beam and low side lobes.

In addition, the possibility of integrating antennas directly on-chip makes it possible to avoid all the connections with the RF circuits, leading to cost reductions and compact designs. While planar antenna arrays integrated on a dielectric substrate present low cost and easy integration with planar circuit technologies, their losses are large due to substrate absorption and conductive currents [68, 69]. These problems induce to poor radiation patterns and low efficiency. In large arrays, which are needed to obtain a high gain, feed line losses can be substantial, in particular when a corporate feed system is used. Mm-wave microstrip antennas can be realized by using electrically thicker substrates, which provide a broader bandwidth. However, surface waves can be excited in thick substrates creating unwanted radiations and deteriorating the radiation pattern. Furthermore, the spurious substrate modes increase the mutual coupling between the elements of the array.

Hollow waveguides can provide instead low loss feed networks, but their combination with the planar integrated systems is difficult and require high precision assembly process which is expensive at high frequency and not suitable for mass production.
Some different approaches, so-called hybrid arrays, try to join a microstrip array with a waveguide feed network to combine the advantages of both technologies [70, 71]. Although these structures have lower losses in the feed network, they are still bulky and have the problem of integration with the mm-wave planar circuits.
Planar waveguides, in the form of Substrate Integrated Waveguides (SIWs), are waveguides made in printed technology and can be easily integrated with planar microstrip circuits. Still, they are more lossy than conventional hollow metallic waveguides. SIWs slot arrays have been presented in several studies [12, 72, 73, 74]. However these solutions present single layer slot array designs which are narrow band and suffer of grating lobes. A multilayer structure is instead developed in [75] to achieve wide bandwidth with high efficiency, but the multilayer solution require a more complex design and manufacturing at high frequency.

5.2 Gap Waveguide Antennas

The gap waveguide technology presents some benefits when it is used for high frequency antenna applications. It has a planar profile and it can be used as low loss feed network for array antennas. The field is traveling in the air rather than in the substrate, thus having low dielectric losses. The width of the lines can be increased to reduce the conductive losses and there is no problem of excitation of surface waves which affect common microstrip feed networks. In addition, there is no need of good electrical contacts between the feed network and the antenna block.
High gain antennas are mostly realized with reflectors and arrays. A parabolic cylindrical reflector with feed line in gap waveguide technology has been designed and proposed in [76]. The reflector presents high efficiency and low losses but the structure has a non-planar design and can be bulky.

A multi-layer phased array in gap waveguide technology has been realized for 76 GHz in [77]. The multi-layer solution has as a drawback a more complicated design compared to the single-layer array.
In [78] a slot antenna placed on the top metal lid is excited by a ridge gap waveguide with a T-shaped feed line, showing an achievable bandwidth of more than 15%. A four-element planar slot array excited by a ridge gap waveguide single-layer corporate feed network is then developed in [79, 80] with 20% bandwidth at 13 GHz and element spacing smaller than one wavelength to avoid grating lobes. However, the realization of this design at high frequency is more difficult because of non-uniform pin locations around the feed network and a very thin milling tool would be needed to realize the pins and the ridges.
The microstrip gap waveguide is an attractive solution for high frequency array applications. The design is planar and the feed network can be easily made in printed technology, still keeping the propagation in the air. In addition, a uniform lid of pins, or any other type of AMC, can be used below the microstrip feed line, making manufacturing simpler at high frequency, and cheaper because the layer containing the uniform periodic surface can also be re-used for other similar designs at the same frequency of operation [81].
The work in [82] presents the design of a slot-coupled dual-mode horn element fed by a microstrip gap waveguide. This concept is then evolved in [Paper E] which shows the design of a sixteen-element dual-mode horn array with low loss corporate feed network realized by inverted microstrip gap waveguide.

Chapter 6

Summary and Contributions

The new gap waveguide is a promising technology suitable to solve some of the challenges experienced when working at high frequency with standard microstrip transmission lines and waveguides.
This thesis presents the development of the gap waveguide focusing on different aspects: packaging capabilities, losses validations, progress at millimeter waves, and integration with antennas.
An introduction is given in the first part of the thesis, in order to provide the reader with the background needed to understand the work described in the five appended papers, listed below and included in the second part of the thesis.

Paper A: New Microstrip Gap Waveguide on Mushroom-type EBG for Packaging of Microwave Components

In this paper, we present a new design of a microstrip gap waveguide made on a mushroom-type EBG surface. This design is suitable for low frequency applications where the metal pins become too thick. The proposed geometry is made in two layers: one upper metal lid and a lower layer, where the mushroom-type EBG surface and a microstrip line are printed on the same substrate. The EBG periodic surface prohibits the propagation inside the dielectric, forcing the field to travel in the air gap, along the microstrip line. This is short-circuited to the ground plane with via holes, in order to reduce the leakage of the field into the dielectric and to avoid other propagating modes in between the line and the ground plane. Simulations and experimental validations are provided, showing a good agreement, with a 2:1 bandwidth. In addition, comparisons with a standard microstrip line are presented in two cases: unpackaged circuit and packaged with an upper metal lid. Measurements results show that the proposed solution has low losses and can easily remove cavity modes and unwanted radiations compared to a packaged microstrip line with a smooth metal lid.

Paper B: Suppression of Parallel Plate Modes in Low Frequency Microstrip Circuit Packages Using Lid of Printed *Zigzag* Wires

The paper is a follow-up of previous papers on packaging using gap waveguide with a lid of pins and with a lid of springs. In this case, the packaging of a microstrip line circuit is done using narrow PCBs with zigzag-shaped metal strips, mounted to the lid of the box in such a way that a 2-D grid of zigzag strips is formed. This solution is an alternative to the lid of springs, which can be difficult and more expensive to realize. The application is for packaging of low-frequency circuits where metal pin lids become bulky. The paper provides simulation results and experimental validation. Cavity modes in the box were effectively removed. In addition, measurement results of the relative radiated power are shown for the microstrip line circuit in different cases: unpackaged, covered with a smooth metal lid, and packaged with the zigzag lid. The measurements are done in Reverberation Chamber and show how the radiation loss is very low for the zigzag case, compared to the open and smooth lid case.

Paper C: Study of Q-Factors of Ridge and Groove Gap Waveguide Resonators

This paper presents the study and experimental validation of losses in ridge and groove gap waveguides at 13 GHz. Losses can be easily characterized in terms of Q-factors of resonators. In addition, the attenuation can be directly calculated from the unloaded Q values when dealing with TEM transmission line resonators. The resonator design for each gap waveguide version is presented, together with a study of the parameters affecting the Q-factor. Experimental validation is provided for all prototypes. It is shown that the Q increases with the height of the air gap, therefore the groove gap waveguide provides the highest Q-factor, becoming a promising alternative to standard waveguides for high frequency applications. In addition, it is demonstrated that the lid of pins, surrounding the ridge and the groove, stops the field from leaking out when there is a poor conductive contact between the circuit blocks. This is the main difference with rectangular waveguides which suffer from leakage problems at high frequency when they are realized in different metal blocks.

Paper D: Contactless Non-Leaking Waveguide Flange Realized by Bed of Nails for Millimeter Wave Applications

The paper shows a new idea for a contactless waveguide flange for high frequency applications. Waveguide flanges are typically used for measurements at millimeter and sub-millimeter waves. At these frequencies, high precision is needed in order to assure a good alignment between the waveguide flanges. Mismatch and leakage can be generated if a proper electrical contact is not provided between the blocks. The proposed contactless flange is designed by adding two rows of pins on the flange face, around the waveguide opening. The periodic surface made of bed of nails provides a stopband region in the air gap created in between two opposite flanges. Simulations show promising results, presented for the waveguide WR-3 in the frequency band 220 - 325 GHz.

This paper was supposed to be extended in a larger manuscript including different flanges designs and measurements results. However, it was not possible to finalize the manuscript and include it in this thesis due to the lack of time. Although, some additional measurement results regarding this idea are added in the first part of the thesis, in Chapter 4.

Paper E: Planar Dual-Mode Horn Array with Corporate-Feed Network in Inverted Microstrip Gap Waveguide

In this paper, we present an extensive study on the electromagnetic design, simulations and experimental verification of a gap waveguide horn array antenna. This is the first time so-called inverted microstrip gap waveguides are used in antenna designs, and the results are very promising. The advantage compared to other technologies lies in the low-loss and low-cost distribution network. The paper shows the design of a 4 by 4 dual-mode horn array, excited by a microstrip gap waveguide corporate feed network. The dual-mode radiating elements are designed to be compact and to decrease the power loss due to the grating lobes, being the distance between the elements 2λ, to have space for the wide feed lines. A good agreement is found between simulation and measurements. The antenna is first realized at 10 GHz, but later the antenna can be produced at higher frequency where the technology may be more advantageous.

6.1 Future Work

This thesis is a collection of the contributions of the author regarding the development of the new gap waveguide technology. This work contributed to provide the concept validation, fundamental limitations in terms of losses, components and antennas designs, underlying the advantages for low and high frequency applications.
The next main steps within the gap waveguide project are the following:

• Realization of 60 GHz antennas. The main issue regards developing a new transition from waveguide to microstrip gap waveguide in order to use the low loss corporate feed network in microstrip gap waveguide for antenna arrays at high frequency.

• Further investigations will be done in to methods to package and integrate MMICs and active devices in gap waveguides.

• Numerical tools suitable for gap waveguides will be developed to obtain a faster and more efficient response compared to commercial simulation tools.

• Transitions to test micromachined gap waveguides antennas and components above 100 GHz will be realized. In particular, we are developing new types of unisex gap waveguide flanges, which may improve the measurement practices in the THz domain.

The future vision is to realize complete gap waveguide systems for radio links to create and interconnect passive components, to package active devices and MMICs as well as antennas on the same module, as shown in the sketch in Fig. 6.1.

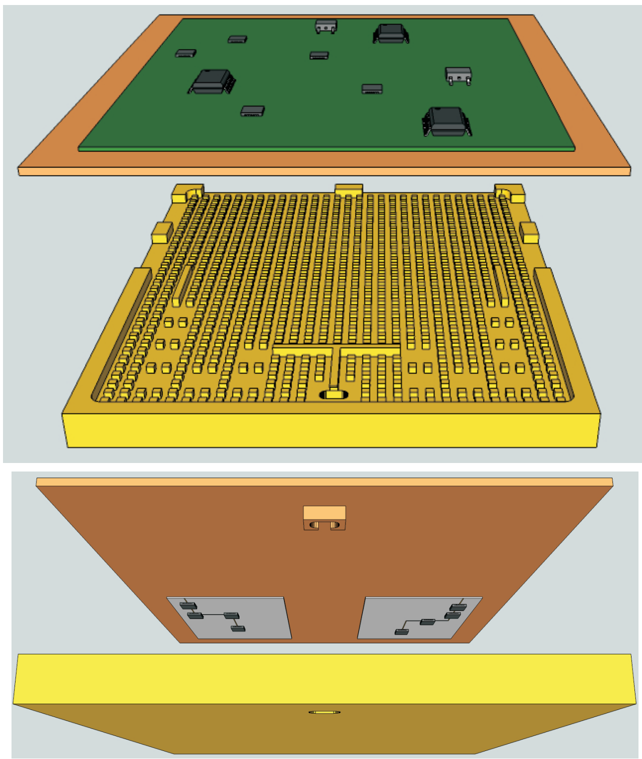


Figure 6.1: Sketch of microwave transceiver frontend demonstrator with integrated branching filter (diplexer) in gap waveguide technology.

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