Thesis for the degree of Licentiate of Engineering

Gap Waveguide for Packaging Microstrip Filters & Investigation of Transitions from Planar Technologies to Ridge Gap Waveguide

by

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Abstract

Gap waveguide technology has proved to constitute an effective alternative for the design of microwave passive components, due to its advantages with respect to traditional planar technologies and standard waveguides. There is no requirement for conductive contact between the two different metal pieces making up a gap waveguide prototype, since one of these pieces makes use of a textured surface that eliminates any possible leakage of the field through the gap to the surface of the other metal piece above it. The textured surface provides together with the opposite surface a cutoff of parallel-plate modes, so cavity modes are suppressed for any extent of the gap between the two surfaces. It is also less lossy than microstrip and coplanar waveguide, because there is no need to use dielectric in the design of gap waveguide components.

The packaging of electronic circuits has become a critical factor, and it is important to study the effects on the performance when packaged. The first part of this thesis is focused on the study of packaging using gap waveguide technology, as a promising packaging method of microstrip passive devices such as filters. The gap waveguide packaging is in this thesis realized by using a lid of nails. Planar technologies, such as microstrip lines, are open structures that need to be electrically shielded and physically protected. One of the main drawbacks of the traditional packaging in metal boxes with a smooth metal lid, is the appearance of cavity resonances when two of the dimensions of the box are larger than half wavelength. It is possible to dampen these resonances by attaching absorbers to the lid of the metal cavity. The problem with this is the uncertainties in locating the absorbers in the package, and the additional losses introduced by the absorbing material. The present thesis investigates a microstrip coupled line filter by employing different types of packaging, including gap waveguide technology in Ku-band. Numerical results are also presented for the ideal case of using a Perfect Magnetic Conductor (PMC) as a lid.

There is a stronger potential for advantages of the gap waveguides at higher frequencies, approaching and including the THz range. Therefore, the second part of this report deals with gap waveguide components that have been numerically analyzed at 100 GHz. At these frequencies, there is in particular a need for appropriate transitions that can ensure compatibility between the gap waveguide circuits and existing vector network analyzer ports and probe stations. For this reason, we have designed a transition from coplanar waveguide to ridge gap waveguide and another transition from microstrip to ridge gap waveguide. The integration of active components (MMIC) into the gap waveguides is challenging and can only be achieved with good transitions.

Keywords: Artificial magnetic conductor (AMC), perfect magnetic conductor (PMC), gap waveguide, microstrip circuit, coupled line filter, packaging, parallel plate mode, coplanar waveguide (CPW), transition.

Preface

This report is the thesis required for the degree of Licentiate of Engineering at Chalmers University of Technology.
The work is divided into two main parts: Packaging of microstrip filters by using gap waveguide technology, and design of transitions from planar technologies to ridge gap waveguide applied at 100 GHz. It has been performed within the Antenna Group, Department of Signals and Systems, at Chalmers between October 2010 and April 2013. The main supervisor and examiner is Professor Per-Simon Kildal, and the co-supervisor is Associate Professor Eva Rajo Iglesias.
The work has mainly been supported by a so-called "ramprogram" from the Swedish Research Council (VR), and by the Strategic Research Center on Microwave Antenna Systems (CHARMANT) supported by the Swedish Foundation for Strategic Research (SSF).

List of Publications

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

Paper I
A. Algaba Brazález, A. U. Zaman, E. Pucci, E. Rajo-Iglesias, P.-S. Kildal and A. Kishk, "Improving Microstrip Filters with Gap Waveguide Packaging", in *Proceedings of the 5th European Conference on Antennas and Propagation, EUCAP 2011*, Rome, Italy, 11-15 April 2011.

Paper II
A. Algaba Brazález, A. U. Zaman and P.-S. Kildal, "Improved Microstrip Filters Using PMC Packaging by Lid of Nails", *IEEE Transactions on Components, Packaging and Manufacturing Technology*, Vol 2, No. 7, pp. 1075 - 1084, July 2012.

Paper III
A. Algaba Brazález, A. U. Zaman and P.-S. Kildal, "Design of a Coplanar Waveguide-to-Ridge Gap Waveguide Transition Via Capacitive Coupling", in *Proceedings of the 6th European Conference on Antennas and Propagation, EUCAP 2012*, Prague, Czech Republic, 26-30 March 2012.

Paper IV
A. Algaba Brazález, A. U. Zaman and P.-S. Kildal, "Investigation of a Microstrip-to-Ridge Gap Waveguide Transition by Electromagnetic Coupling", in *IEEE Antennas and Propagation Society International Symposium (AP-SURSI)*, Chicago, U.S.A, July 2012.

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

- A. Algaba Brazález, E. Pucci, S. Rahiminejad, M. Ferndahl and P.-S. Kildal, “Evaluation of Losses of the Ridge Gap Waveguide at 100 GHz”, submitted to *IEEE Antennas and Propagation Society International Symposium (APSURSI)*, Orlando, U.S.A, July 2013.
- A. U. Zaman, A. Algaba Brazález, and P.-S. Kildal,, “Design of Bandpass Filter Using Gap Waveguide Technology”, in the *4th Global Symposium on Millimeter Waves*, Espoo, Finland, May 2011.
- S. Rahiminejad, A. Algaba Brazález, H. Raza, E. Pucci, S. Haasl, P.-S. Kildal and P. Enoksson, “100 GHZ SOI Gap Waveguides With High Aspect Ratio Structures”, *17th International Conference on Solid-State Sensors, Actuators and Microsystems*, Barcelona, Spain, June 2013.

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I would like to express my deepest gratitude to my co-supervisor Prof. Eva Rajo Iglesias. I consider myself very lucky to collaborate with such a brilliant and enthusiastic researcher. Your support, advices and help have meant a lot for me since the first moment we met. Your friendship, and all the special moments we have shared together, go way beyond what I can expect or even hope for.

My special acknowledgement goes to my former and current colleagues of the Antenna Group. It is really great to work with all of you in such a nice and multicultural environment. I feel very fortunate to belong to this work team, and I always enjoy our interesting chats, coffee breaks and group activities.

I am highly indebted to my friend Benjamin Klein for his help and advices, especially in relation to this Licentiate degree thesis. I really miss you and I hope we can meet very soon.

Furthermore, I would like to take this opportunity to sincerely thank all my colleagues and friends at the Department of Signals and Systems, for creating an extremely enjoyable and pleasant work environment.

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Astrid

Göteborg, April 2013

Contents

Part I
Introduction

Chapter 1

Introduction

Wireless communication has become an essential and critical part of daily life. The fast evolution of wireless systems has motivated the increased need of higher data rates and bandwidths. This has lead to a big interest in moving up in frequency, specially to the millimeter and submillimeter range. The design of electronic components and packaging at these frequencies has to confront similar problems as in microwave frequencies, but with extra complications. Low loss components and high interconnection capability are required, as well as efficient packaging features are needed. Planar technologies such, as microstrip, stripline and coplanar waveguide, are very appropriate for integration of active and passive components. The main drawback of these transmission lines is the high loss introduced due to the presence of dielectric material in the structure. Thus, conventional metal waveguides might be more suitable due to their low loss. However, the waveguide manufacturing is very complex at millimeter frequency bands, and very precise machining is required in order to get good metal contact between the different split blocks. Therefore, one of the biggest challenges is to find an alternative to traditional planar technologies and standard waveguides, that can overcome these weaknesses.

1.1 Packaging and integration of active components (MMIC) issues

A crucial aspect when designing electrical circuits is the inclusion of some kind of enclosure, in order to protect the electronic components from the environment and supply electrical isolation [1]. Open structures such as, microstrip and coplanar waveguide circuits, need to be properly covered to avoid radiation losses. At microwave and millimeter-wave frequencies the dimensions of the elements contained in a circuit become appreciable compared to the wavelength. Therefore, as the frequency increases, the effect of discontinuities present in the design can become very negative to the overall performance, provoking undesired radiation and excitation of cavity modes. This adds complexity to the design process since the effect of the discontinuities has to be taken into account in order to mitigate their possible negative impact in the system behaviour.
Traditionally, circuits are shielded by covering them with a metal housing. The main disadvantage of this type of packaging is the potential excitation of cavity modes inside the package, if this one has dimensions larger than half a wavelength in at least two orthogonal directions [2, 3]. These cavity modes might couple to the packaged circuit perturbing its behavior. One way to avoid the excitation of resonant cavity modes is to keep the dimensions of the enclosure smaller than half a wavelength, only feasible at low frequencies. Another possible solution is dampening the resonances using an absorbing material. Absorbers are usually very lossy materials and they attenuate the resonances, but with a considerable increase in the insertion loss of the overall circuit performance. Moreover, the location of the absorbers within the metal cavity is usually chosen by trial and error, since it is not easy to predict the optimum placement [4].
On the other hand, as the frequency reaches the millimeter-wave band the amount of electronic elements (including Monolithic Microwave Integrated Circuits (MMIC), passive components and interconnects in the way of transmission traces or bond wires) integrated in a small area is becoming considerably large in order to achieve high performance and cost effective solutions.

The possible interferences and parasitic coupling between adjacent elements can have as consequence instabilities and perturbation of the circuit behavior [5]. Hence, a more robust and effective packaging method that can provide good electrical isolation between the different components, is necessary for microwave and millimeter-wave applications.

1.2 Gap waveguide concept

The soft and hard surfaces concept [6] has been applied to artificially realize the Perfect Magnetic Conductor (PMC) condition in order to be employed in the design of horn antennas and reflectors. First local Quasi-TEM modes were observed in the air gap between a longitudinal corrugated hard surface and a smooth metal plate [7]. This geometry was modified and the result was the so-called *gap waveguide* technology, that constitutes a new planar metamaterial-based waveguide suitable for millimeter and submillimeter wave frequency ranges [8, 9, 10].
The gap waveguide is created in the gap between two parallel metal surfaces. One of these surfaces is formed by a metamaterial texture. This texture is a periodic structure made by means of metal pins [11], or mushroom-type EBG (for low frequency applications) [12]. The textured plate constitutes an Artificial Magnetic Conductor (AMC), that artificially emulates the effect of the ideal PMC. If the air gap between the parallel plates is smaller than a quarter wavelength, the AMC establishes a high impedance boundary condition and all the unwanted cavity or parallel-plate modes, as well as surface modes, are eliminated within a certain frequency band (called the stopband). The desired wave propagation is only allowed along metal ridges (*ridge gap waveguide*), strips (*microstrip gap waveguide and inverted microstrip gap waveguide*)[13], or grooves (*groove gap waveguide*)[14], that are located between the plates. These three different variants of the gap waveguide are shown in Figure 1.1.

The first ridge gap waveguide demonstrator was designed and experimentally validated [15] at around 15 GHz. After this first gap prototype, other types of microwave components (power dividers, couplers, rat-race hybrids,

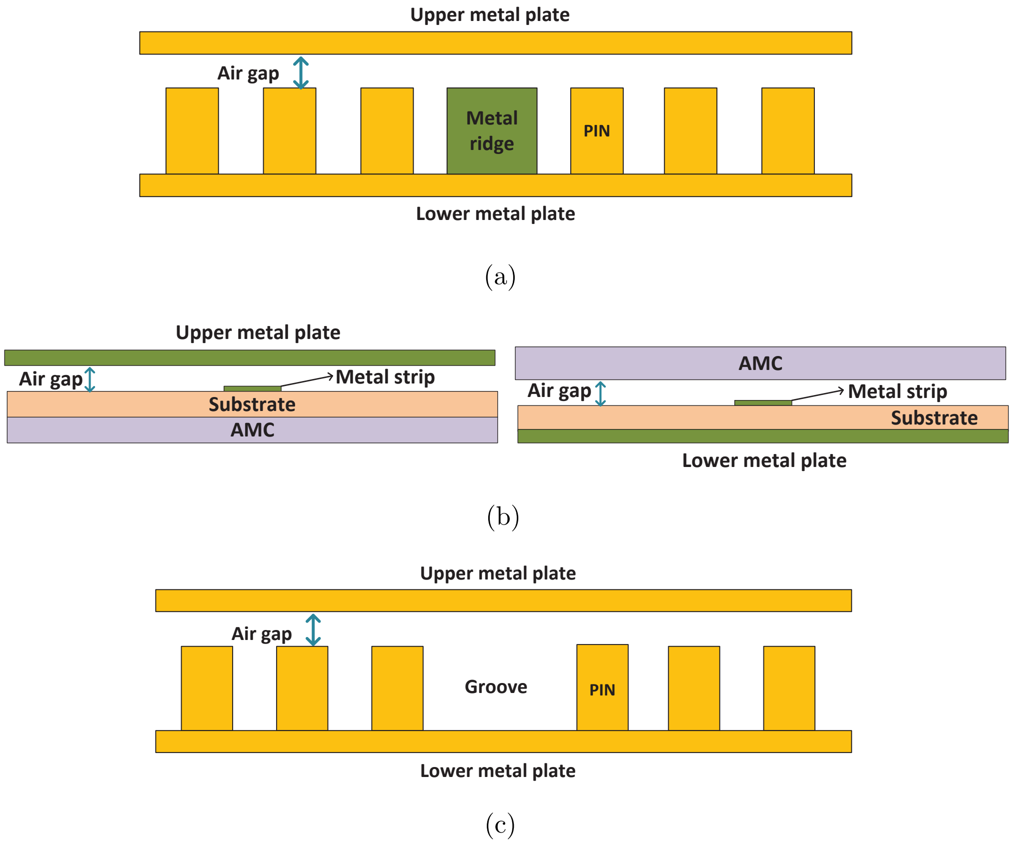


Figure 1.1: Front view of: (a) Ridge gap waveguide. A quasi-TEM mode is guided along the ridge. (b) Inverted microstrip gap waveguide (the field is confined in the air gap) and microstrip gap waveguide (the field is more concentrated in the substrate). (c) Groove gap waveguide. A TE or TM mode is allowed to propagate depending on the cross-sectional dimensions of the groove.

filters, etc.) have been developed in gap waveguide technology [16, 17, 18, 19]. A numerical study of the achievable stopbands for the bed of nails, corrugation and mushroom-type EBG cases is performed in [20]. One of the most remarkable features of the gap waveguide technology is its inherent low loss [21], since there is no dielectric material involved in the structure. Moreover, it is not required to provide good conducting joints between the different metal plates, making the manufacturing more flexible and less costly. These characteristics make the gap waveguide a very appropriate technology to be applied up to the THz band [22, 23, 24].

1.3 Goal and outline of the thesis

The aim of this work is to demonstrate the effectiveness of the gap waveguide as an advantageous way for packaging microstrip passive devices such as filters. The current packaging investigation is related to the microstrip gap waveguide approach. Moreover, the gap waveguide technology is expected to be very suitable for millimeter and submillimeter-wave frequencies and the integration of active components into gap waveguide becomes very challenging. The major complexity found at these frequencies is related to the measurement procedure. First ridge gap waveguide prototypes were manufactured at 270 GHz but proper measurements were difficult to be taken due to the not sufficiently good contact between the ridge gap waveguide circuit and the rectangular waveguide flange, through a transition made with steps. Therefore, we have designed ridge gap waveguide prototypes at 100 GHz in order to be able to measure them with the available probe stations at that frequency. The compatibility between Ground-Signal-Ground probes and the ridge gap waveguide circuit should be ensured. Hence, a transition from coplanar waveguide to ridge gap waveguide, and a transition from microstrip to ridge gap waveguide are investigated.

This thesis is partitioned into two main parts. The first topic of this work addresses to the packaging of microstrip filters. This is shown in chapter 2, where improved performance of well known microstrip coupled line bandpass filters, when employing PMC packaging and gap waveguide packaging is reported. Chapter 2 includes both simulation and measurement results. Chapter 3 presents an investigation of a transition between coplanar waveguide and ridge gap waveguide, including a numerical study of the prototype. Chapter 4 explains the design and simulation results of a transition from microstrip to ridge gap waveguide. The conclusions of this report and future work are given in chapter 5.

The second main part completes this thesis, and consists of four papers by the author. Paper I and II are related to Chapter 2. Paper III is a report about the transition discussed in Chapter 3. Paper IV concerns the transition design presented in Chapter 4.

Chapter 2

Gap Waveguide Packaging for Microstrip Filters

2.1 PMC and gap waveguide packaging basics

The packaging of open planar circuits like microstrip and coplanar waveguide is a matter of great interest for microwave designers. The first observation of parallel plate/cavity modes suppression, when packaging a single microstrip line with a bend of 90° by applying a lid of pins, is presented in [25]. From this initial research work comes the motivation to investigate more deeply the effect of packaging real passive microstrip circuits, such as filters, by using PMC packaging artificially realized by gap waveguide technology and conclude its advantages with respect to other types of packaging methods.
The ideal PMC packaging concept and its realization by lid of nails are illustrated in Figure 2.1.

The situation in which there is a PMC lid opposite to a PEC plate ensures the suppression of any higher order modes, as long as the separation between both plates is smaller than quarter wavelength. When the PEC layer is covered by a substrate material and a metal strip lies over this substrate (constituting a standard microstrip line), a local quasi-TEM mode follows

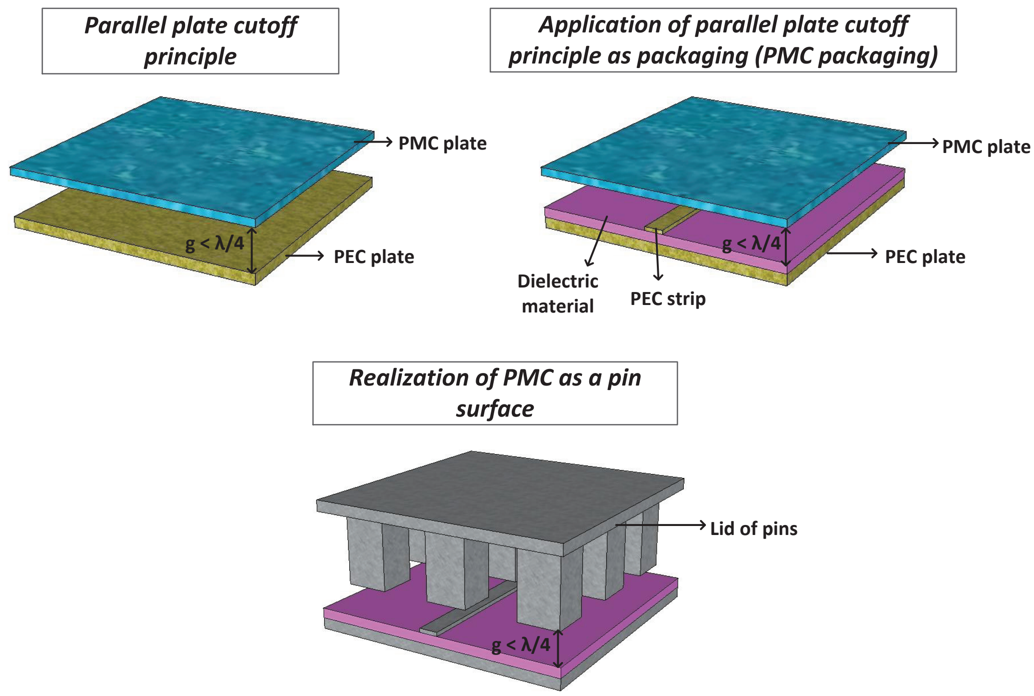


Figure 2.1: Parallel plate cutoff principle with ideal PMC-PEC situation, PMC packaging concept and realization by gap waveguide technology

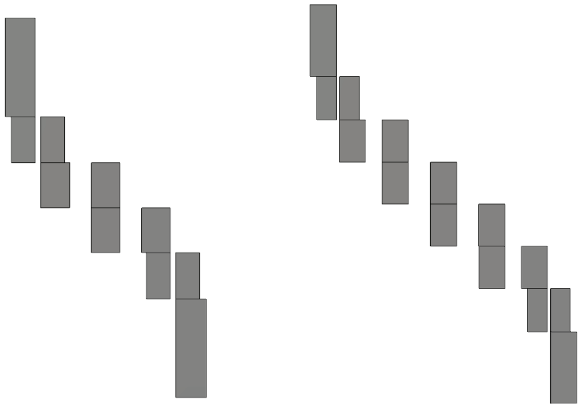
the conducting strip and all fields are forbidden to propagate outside this strip. The PMC packaging is an ideal case and it needs to be artificially realized, which is done here by using gap waveguide. The current work focuses on the PMC packaging realization by the lid of pins. However, another gap waveguide packaging solution has been developed by a bed of helices (springs) [26] for applications at lower frequencies.

2.2 Microstrip coupled line bandpass filter

Filters constitute important elements for RF/Microwave/Millimeter-wave communication systems, in both transmitter and receiver stages. They have the critical function of separating frequency components or rejecting unde-

sired signals. This is very crucial when non-linear components like mixers and amplifiers are integrated in the structure.
Microstrip is one of the most common technologies applied for the design of planar filters. This technology is low cost, simple to manufacture and suitable for series production. Microstrip circuits are inherently open geometries, and they need to be electrically shielded and physically protected from outdoor conditions. Therefore, the packaging is a critical feature to take into account during the filter design, in order to guarantee that the final filter performance is as expected.
We have designed a 3^{rd} and a 5^{th} order Ku-band coupled line bandpass filters, in order to study their behavior when they are packaged with different types of shielding methods. The center frequency is chosen to be $f_c = 15$ GHz and the fractional bandwidth is fixed as 10%. The designed filters are specified to have a Chebyshev response, with 0.5 dB ripple for the 3^{rd} order filter case and 0.1 dB for the 5^{th} order one. The substrate material is Rogers TMM4, with thickness $h = 0.762$ mm, dielectric constant $\epsilon_r = 4.5$ and loss tangent $\tan\delta = 0.002$.
A coupled line filter is composed of $n+1$ coupling sections where n is the filter order. Each section has an electrical length of a quarter wavelength at f_c. The even and odd mode impedances of each coupling section are calculated as explained in [27, 28]. From these impedance values it is possible to get the filter layout dimensions (width of each section and separation between coupled lines) by employing a transmission line calculator. The physical layout for both filters is shown in Figure 2.2.

The reason to choose this type of bandpass filter is the fact that each coupling section has an open-end discontinuity. The presence of discontinuities can degrade the response of the filter in different ways depending on the packaging conditions. If the circuit is not properly packaged, any radiation caused by the discontinuities is free to propagate away from the structure. Radiation is specially critical within the proximities at the discontinuity, and its consequences are even more severe when the circuit is composed of resonant sections (like filters). Thereby, the radiation losses become an important contribution to the overall loss of the microstrip circuit. On the other hand, the



(a) (b)

Figure 2.2: (a) Layout 3^{rd} order filter. (b) Layout 5^{th} order filter.

existence of discontinuities in the geometry assures the excitation of cavity resonances, when the circuit is packaged with a conventional smooth metal lid. The radiated waves can be reflected in the metal enclosure and affect different parts of the circuit (like other discontinuities) causing spurious coupling and interferences. Waves can also propagate and reflect "downwards", between the upper conducting strip and the ground plane of the microstrip. This is explained in [29], where it is shown how these reflected waves can manifest in the form of leaky waves or surface waves, depending on the angle of incidence.

The effect of the open-end discontinuity is modeled as a parasitic parallel capacitance [28] and it can be reduced somehow by shorting the actual strip by a certain equivalent length Δl. There are some formulas to get a suitable value for Δl in [28] and [30]. However, if the condition in (2.1) (taken from [31]) is verified, any discontinuity (even if it has been corrected to reduce its effect) causes some radiation and affects the circuit response.

$$f\left\{GHz\right\} \times h\left\{mm\right\} > 2.14\sqrt{\varepsilon_r}, \tag{2.1}$$

The next sections demonstrate that the PMC packaging and its artificially realization by gap waveguide, can suppress all the cavity modes and surface modes as well as it eliminates efficiently the radiation due to the discontinuities, improving the performance of the designed coupled-line filters with respect to other packaging solutions.

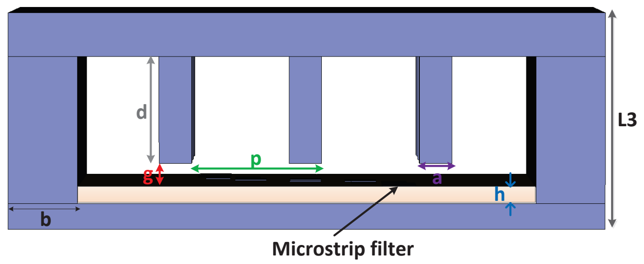
2.3 Design of gap waveguide packaging

The PMC packaging is going to be performed by means of a pin lid surface. The pin lid geometry is the same for both 3^{rd} and 5^{th} order coupled line filters, and it is presented in Figure 2.3. All the metal parts are made of copper and the metal sidewalls have thickness $b = 3.175$ mm to be able to fit the lid with screws. The dimensions of the metal box are shown in Table 2.1. The period for the pin surface is $p = 6$ mm, the pin height is $d = 5$ mm and the pin size $a = 1.5$ mm. The gap is settled as $g = 1$ mm (it should be smaller than $\lambda/4$ in order to prohibit propagation of higher order modes).

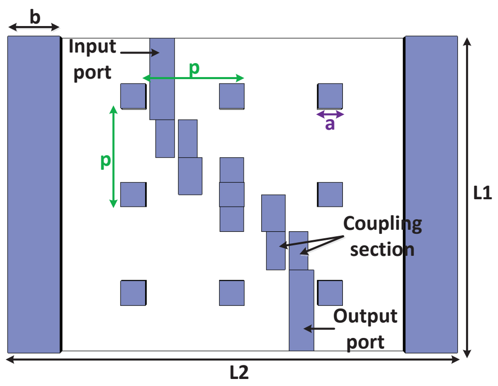
The corresponding dispersion diagram for this pin geometry has been computed with CST Eigenmode Solver [32] and it is ilustrated in Figure 2.4. This dispersion diagram shows a stopband from 10.6 to 21 GHz, ensuring a cutoff of higher order modes within that frequency range. This stopband is considered sufficient for the current investigation about packaging of microstrip filters. However, wider stopbands can be achieved by using other geometrical shapes instead of rectangular pins, for example mushrooms or inverted pyramidal shaped nails [33]. The chosen dimensions for the lid of pins are a result of a parametric investigation carried out with CST Microwave Solver [32]. It is found that depending on the lid of nails dimensions, the filter response varies. Therefore, it is important to design the gap waveguide packaging in such a way that the stopband becomes sufficient and the filter performance is optimal.

Table 2.1: 3D Dimensions of the metal box containing the circuit and lid of nails packaging

	L1	L2	L3
3^{rd} order filter	19.258 mm	27.35 mm	9.962 mm
5^{th} order filter	22.24 mm	33.85 mm	9.962 mm



(a)



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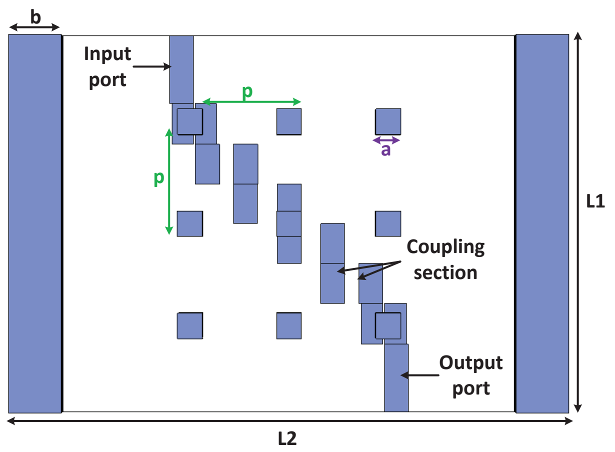


(c)

Figure 2.3: (a) Front view of filter packaged with lid of pins. (b) Top view of the 3^{rd} order filter packaged with lid of pins.(c) Top view of the 5^{th} order filter packaged with lid of pins.

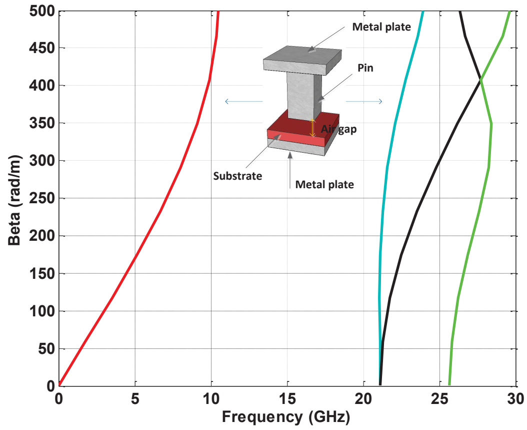


Figure 2.4: Dispersion diagram of the infinite lid of nails with substrate covering the lower metal plate.

2.4 Simulation results for different types of packaging

We have numerically analyzed each coupled line filter taking into account four packaging cases: unpackaged or open case, smooth metal lid packaging, ideal PMC lid packaging and lid of nails packaging. When the filter is unpackaged, an open boundary condition over the microstrip circuit is defined. The smooth metal lid packaging is the conventional way of shielding microstrip circuits and it consists of covering the Printed Circuit Board (PCB) with a metal lid and metal side walls. The lid is located 3.9 mm above the PCB (around five times the thickness of the substrate) as shown in Figure 2.5.

The ideal PMC lid packaging can be simulated by establishing a PMC boundary condition 1 mm over the microstrip geometry (the same distance as the air gap between the lowest side of the pin and the circuit). The lid of nails emulates the PMC packaging within a certain frequency range defined by the stopband.

We have considered an additional situation for the packaging study of the 5^{th} order filter in which a thin layer of absorbing material (ECCOSORB MCS with 1 mm of thickness) is attached to the metal lid that covers the circuit.

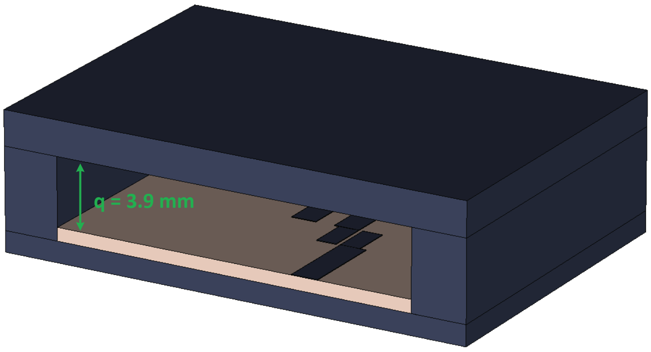


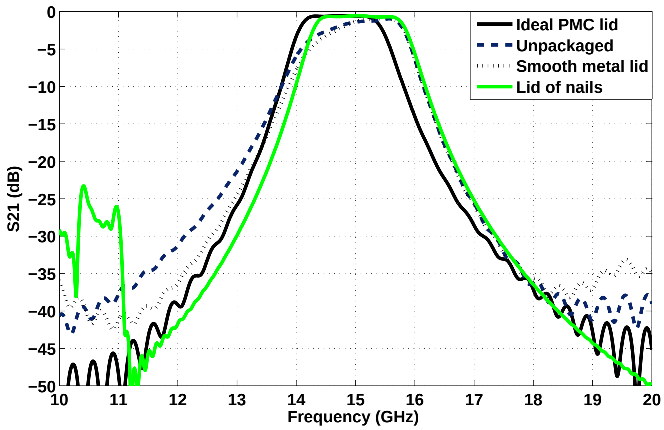
Figure 2.5: Smooth metal box as packaging.

Thereby, the separation between the absorber and the substrate becomes 2.9 mm.

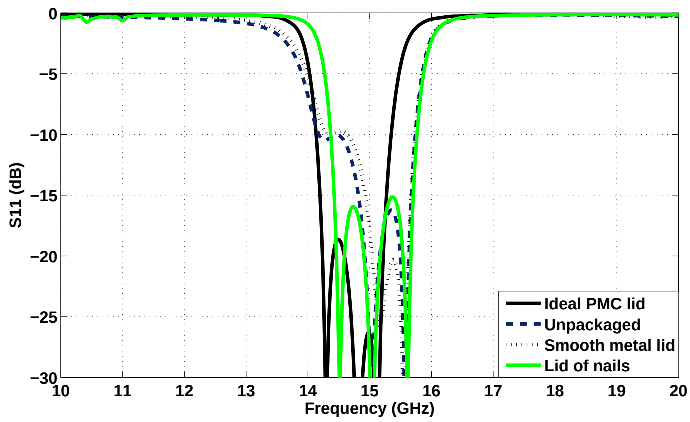
The S parameters for the previously explained conditions of packaging were calculated and compared. The comparison of both S_{21} and S_{11} parameters, for the 3^{rd} order and 5^{th} order coupled line filters packaged in four (five in the 5^{th} order case) different ways, are presented in Figure 2.6 and 2.7 respectively.

The unpackaged and metal lid packaging cases do not show good filter behaviour. In the unpackaged situation the radiation losses are so high that the S_{21} does not present a flat filter passband. In the smooth metal packaging, the presence of cavity modes degrades the circuit performance, especially in the 5^{th} order filter. The packaging including absorbing material eliminates the possible resonances, and the performance is similar to the unpackaged case, but with an increase in the insertion loss due to the utilization of the absorber.

However, the obtained behaviour for the ideal PMC packaging and its realization by lid of pins, is very close to the theoretical Chebyshev bandpass filter response. In both cases all cavity resonances and radiation losses are removed efficiently, showing much better filter performance than the other packaging cases. Return and insertion loss have similar values for PMC and lid of nails packaging which means that the gap waveguide packaging performs approximately as the ideal PMC one. As shown in Figures 2.6 and 2.7, the lid of pins eliminates the parallel plate modes completely from 11.5



(a)



(b)

Figure 2.6: Comparison filter response for four different packaging methods. (a) S_{21} parameter for 3^{rd} order filter. (b) S_{11} parameter for 3^{rd} order filter.

to 20 GHz approximately.

Some transmission peaks appear below 11.5 GHz. This is due to the fact that the pin lid geometry establishes a high impedance boundary condition within a certain stopband (see the dispersion diagram in Figure 2.4). These resonant peaks cannot be avoided but can be moved away from the desired frequency band, if the geometrical shape of the periodical pattern is modified [20, 33].

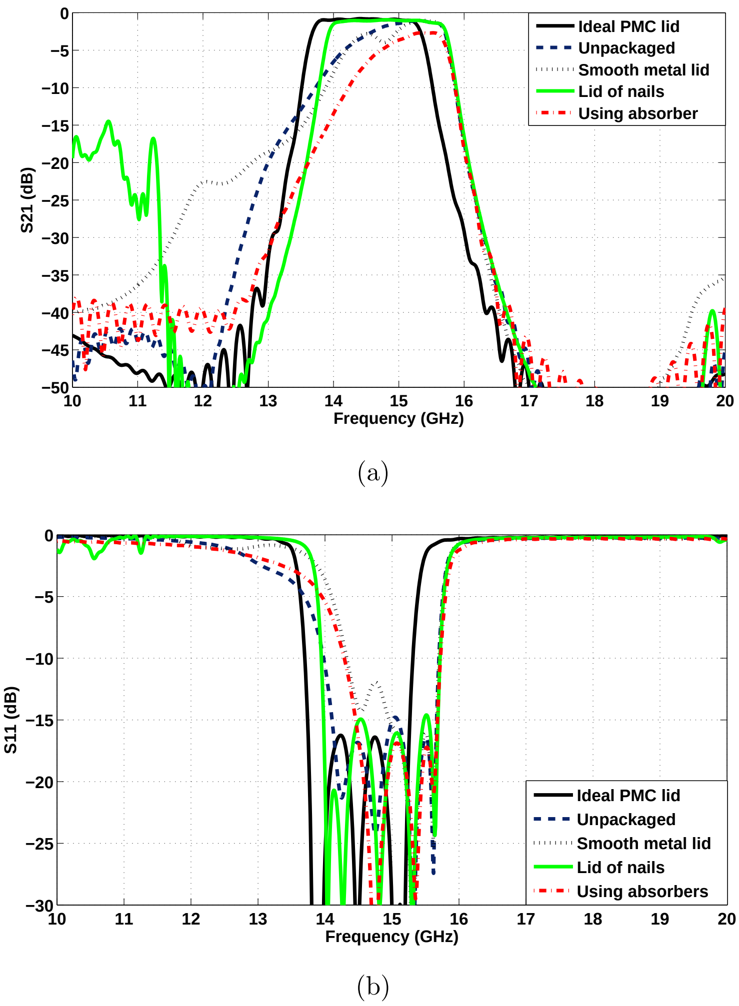


Figure 2.7: Comparison filter response for four different packaging methods. (a)S_{21} parameter for 5^{th} order filter. (b) S_{11} parameter for 5^{th} order filter.

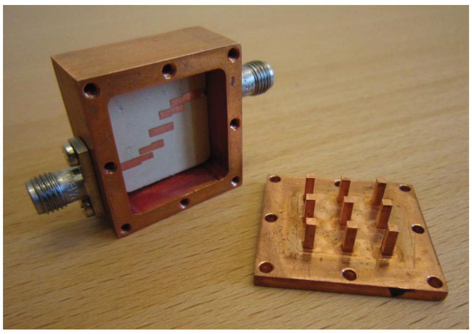
On the other hand, the idealized PMC lid is advantageous in initial numerical simulation because the computation time is much smaller than for realizations such as pin lids, and the accuracy is still quite good within the stopband of the parallel plate modes when using the actual textured surfaces. Therefore, the required computational time to carry out a full optimization of the main filter parameters in order to find the best response, is much shorter than the optimization procedure by using other packaging situations.

We have designed the coupled line filters as explained in section 2.2, and their dimensions are optimized considering PMC packaging. When the optimization finishes, the PMC lid is replaced by the lid of nails and the results are still much more satisfactory than the unpackaged and metal lid cases. Thereby, the PMC packaging can be already taken into account during the filter optimization making this process much simpler and more efficient.

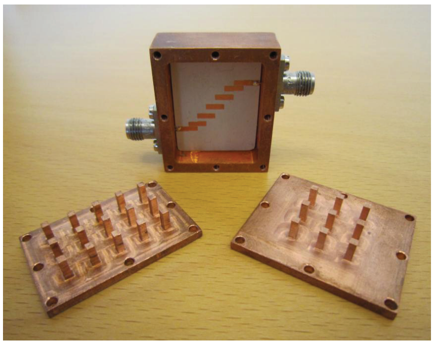
2.5 Measurement results for different types of packaging

In order to experimentally validate the gap waveguide packaging concept when packaging microstrip filters, the two described coupled line filters and the different lids used for the packaging have been manufactured and measured using a vector network analyzer (see manufactured prototypes in Figure 2.8).

For the packaging study of the 5^{th} order filter, two different lid of nails have been fabricated. One of these has 3 rows of 3 pins (pin period $p = 6$ mm), and the other one has 3 rows of 5 pins (pin period $p = 5.5$ mm).



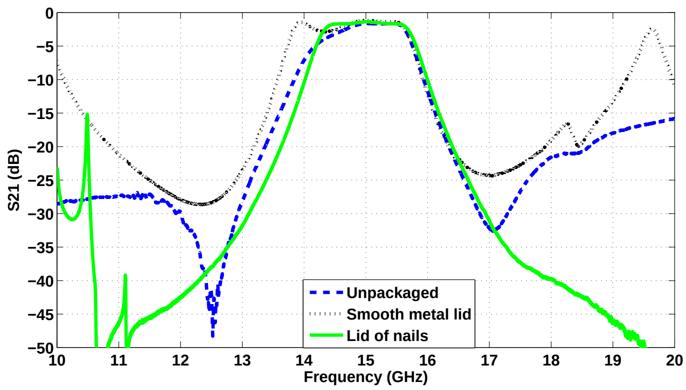
(a)



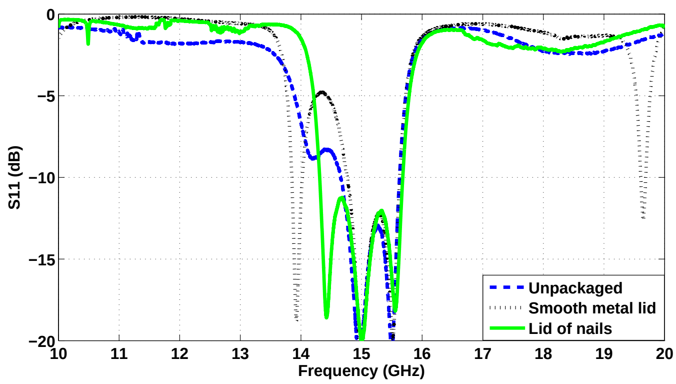
(b)

Figure 2.8: Manufactured filter prototypes and respective lid of nails. (a) 3^{rd} order filter and lid of nails with 3 rows of 3 pins. (b) 5^{th} order filter and lid of nails with 3 rows of 3 pins, and another one with 3 rows with 5 pins.

We have found out that the position of the pins, with respect to the strips composing the filter, affects the filter response. The more symmetric the pins are in respect to the center coupling section, the better is the overall circuit behaviour. The motivation of manufacturing two types of lid of nails to package the same filter is to test if the displacement of the pins with respect to the circuit, affects in the same way if there are more pins present in the lid. It is also interesting to compare the results of packaging with different versions of gap waveguide packaging, in terms of losses and low transmission peaks outside of the filter passband. Figures 2.9 and 2.10 present the measurement results for both filter prototypes respectively.

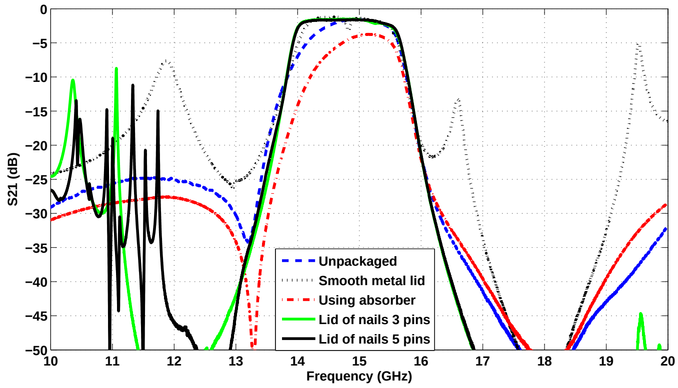


(a)

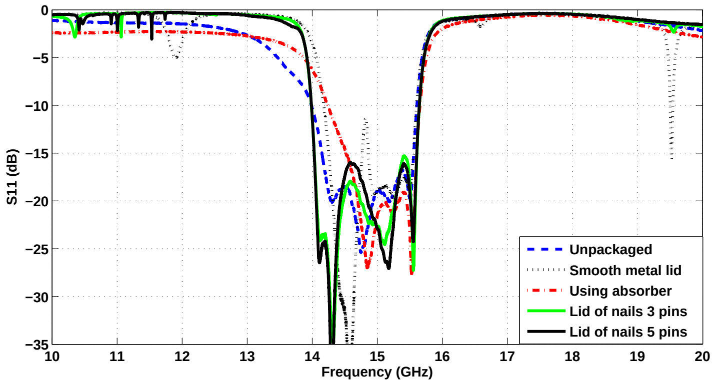


(b)

Figure 2.9: Measurements of 3^{rd} order filter. (a) S_{21} parameter. (b) S_{11} parameter.



(a)



(b)

Figure 2.10: Measurements of 5^{th} order filter. (a) S_{21} parameter. (b) S_{11} parameter.

When the filter is unpackaged the response is neither flat nor sharp in the passband, due to high radiation losses. The filter passband is a bit flatter when it is packaged with smooth metal lid, but the return losses are still high and moreover, cavity modes are excited and resonances even affect the passband (see Figure 2.11). These resonances are suppressed when the filter is packaged using an absorber attached on the inner side of the metal lid. However, there is an important deterioration of the passband response due to the high insertion loss.

All the weaknesses of the previous packaging methods are overcome by employing gap waveguide packaging. The microstrip filter response is clearly

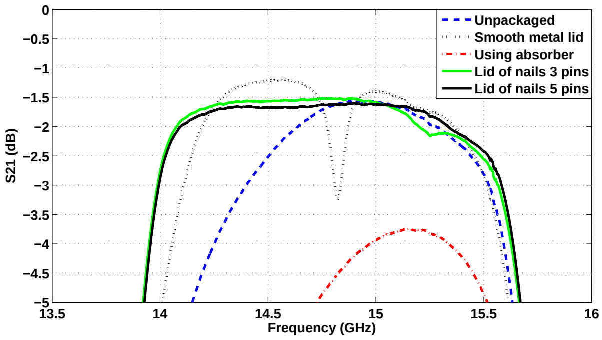


Figure 2.11: Measured S_{21} parameter for 5^{th} order filter (zoomed).

improved, presenting a much flatter passband and sharper behaviour as well as more satisfactory return loss. The resonances presented in the metal lid packaging case also have been eliminated. Regarding the employment of a lid of nails with less or more number of pins, the conclusion is that the filter response is sensitive to the location of the pins, with respect to the packaged circuit for both types of lids. The homogenization of the pin lid to reduce the dependence of the resultant circuit response from the location of the pins, is an issue that should be studied in the future. So far, we can conclude that a symmetrical position of the pins with respect to the central section of the circuit give better overall performance.

Chapter 3

Transition from Coplanar Waveguide to Ridge Gap Waveguide

3.1 Gap Waveguide for millimeter and submillimeter-wave applications

The manufacturing of standard rectangular waveguides at frequencies above 100 GHz is very complex. One important reason is that it is difficult to get sufficiently good contact between the different metal blocks. The so-called gap waveguide technology overcomes this problem and it has potential to be applied at frequencies up to the THz range. Using this technology there is no need to provide very good conducting contact between the metal plates, because all the possible leakage of fields is removed by the gap waveguide itself. The first gap waveguide prototypes designed to operate at 270 GHz have been fabricated by micromachining (MEMS) technology, which is a more accurate and precise manufacturing method than milling, for frequency bands above 100 GHz.

At first, a transition from a rectangular waveguide to a 270 GHz ridge gap waveguide [22] made by means of steps was designed. Proper measurements turned out to be difficult to obtain, due to the poor contact between the transition and the rectangular waveguide extension used in the measurement

setup. Another alternative is to measure the prototypes by using Ground-Signal-Ground (G-S-G) probe stations but that would require the design of new transitions.
The goal of Chapter 3 and Chapter 4 is to study suitable ways to interconnect the gap waveguide components with available coplanar probe stations at 100 GHz. The design of good transitions from planar structures like microstrip and coplanar waveguide, is crucial to facilitate accurate measurements of gap waveguide prototypes at millimeter and submillimeter-wave frequency ranges. Such transitions will enable the integration of MMICs with gap waveguide technology. Moreover, suitable transitions are needed to act as feeding network of gap waveguide antennas that are currently being investigated.

3.2 Coplanar Waveguide basis

The Coplanar Waveguide (CPW) is a structure that supports the propagation of a Quasi-TEM mode and results to be a suitable alternative to microstrip technology. The main advantages of CPW compared to Microstrip [34] are:

1. Lower dispersion.
2. It consists of a signal pad and two ground pads at both sides of the signal. They are all located at the same side of the substrate, facilitating the integration of passive and active components.
3. No need of vias if components are required to be connected to ground.

There are two types of CPW:

- Ordinary CPW: No ground plane below the substrate.
- Conductor backed CPW (CBCPW): There is an additional ground plane in the bottom side of the substrate in order to provide mechanical support and efficient heat dissipation.

There are also concerns related to the utilization of CPW, and these drawbacks are different depending on the type of CPW. CBCPW has problems with the potential presence of parallel plate modes. These modes can be suppressed by placing vias between the upper ground pads and the lower conducting plane. On the other hand, a drawback with the conventional CPW is the mode coupling between the even and odd mode [35]. This mode coupling becomes very critical with the presence of asymmetries in the circuit, and in the vicinity of discontinuities. Usually, the effect of the mode coupling can be decreased by using bond wires to short the ground pads. These bond wires introduce a reactance and cause mismatch, thus degrading the circuit performance as the frequency increases. Therefore, the effect of the bond wires should be taken into account during the circuit design, which may increase the complexity of that task.

In this work, we have designed and numerically analyzed a vialess transition from conventional CPW-to-Ridge Gap Waveguide via capacitive coupling and without employing any air-bridges. Radiation leaking away from the dielectric material was observed. This is probably due to the previously mentioned mode coupling problem. A solution by gap waveguide technology is also presented in order to eliminate this radiation phenomena.

3.3 Transition design

The transition is designed to operate at a center frequency $f_c = 100$ GHz. The geometry consists of two different layers. One layer is the ridge gap waveguide circuit located upside down. The second part is the CPW layer that is placed under the ridge. The side-ground pads of the CPW circuit are extended in such a way that they act as the opposing metal plate to create the gap of the ridge gap waveguide. Both layers are separated by an air gap $g = 0.15$ mm which has to be smaller than $\lambda/4$ in order to meet the high impedance condition.

The complete geometry and the different circuit parts are presented in Figure 3.1. The ridge gap waveguide dimensions are chosen to provide a stopband between 55 and 134 GHz. Figure 3.2 shows the layout for the front view of the ridge gap waveguide layer.

The substrate material employed for the CPW layer is TACONIC TRF-45 with dielectric constant $\epsilon_r = 4.5$, thickness $h = 0.2$ mm, loss tangent

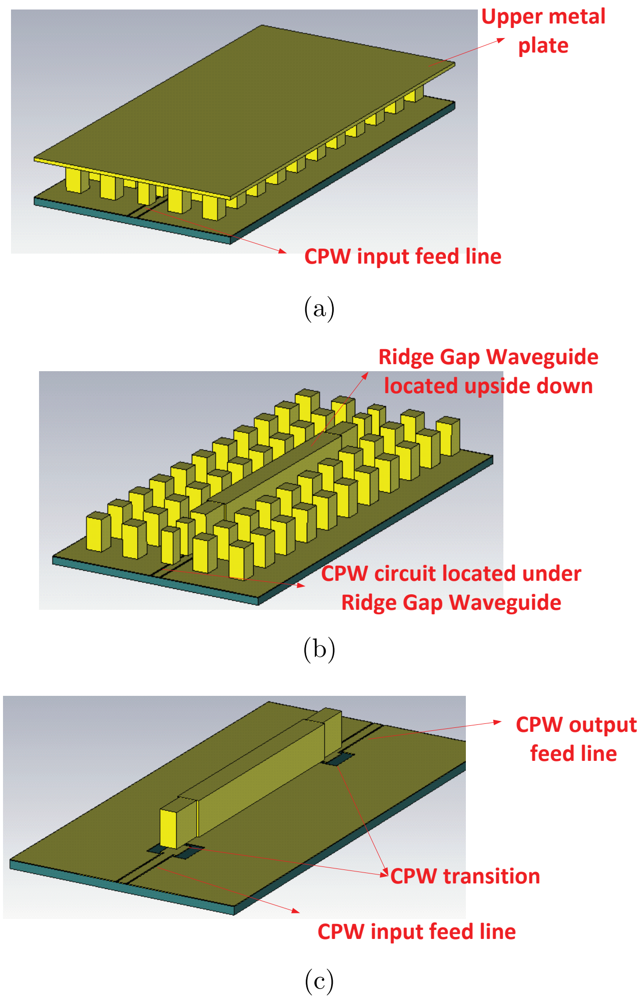


Figure 3.1: (a) Complete geometry of two back-to-back CPW-to-Ridge Gap Waveguide transitions. (b) Upper metal plate is removed and the ridge gap waveguide layer is visible.(c) Pins are hidden in order to distinguish the CPW transitions located under the ridge gap waveguide layer.

$\tan\delta = 0.0035$ and the copper thickness is 0.018 mm. The reason to choose this material is its good mechanical characteristics (rigid and not easily breakable). The CPW input and output feeding lines are designed to have a characteristic impedance of $Z_c = 50\ \Omega$.

The transition design contains a CPW rectangular patch which is separated from the upper ridge by a distance equal to the air gap g. Initially,

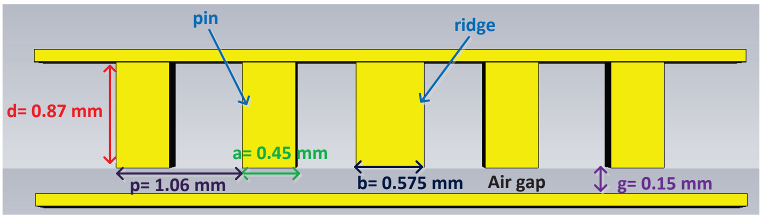


Figure 3.2: Front view of ridge gap waveguide layer, located upside down.

the rectangular patch length is set to $\lambda_g/2$ where λ_g is the corresponding guided wavelength of the CPW. The signal is coupled from the CPW patch to the upper ridge through the air gap without using vias. The different patch dimensions are optimized in order to improve the matching.
On the other hand, the upper ridge is divided into three sections. A central ridge section (with a length of 2λ) guides the coupled signal to the other side of the circuit. There are two additional ridge sections located at both sides of the central ridge. These side ridge sections receive/couple the signal from/to the CPW rectangular patches. Moreover, the transition performance is improved if the width of these two ridge sections is reduced to the same size as the CPW patch. The top view of the circuit is shown in Figure 3.3.

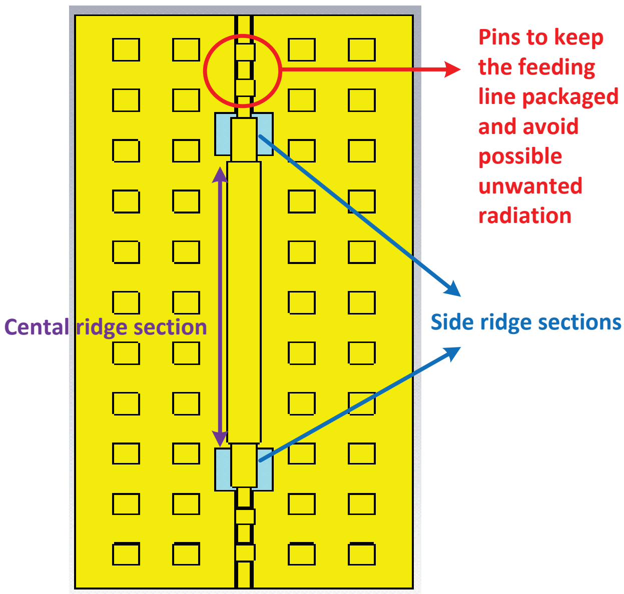


Figure 3.3: Top view without including the upper metal lid.

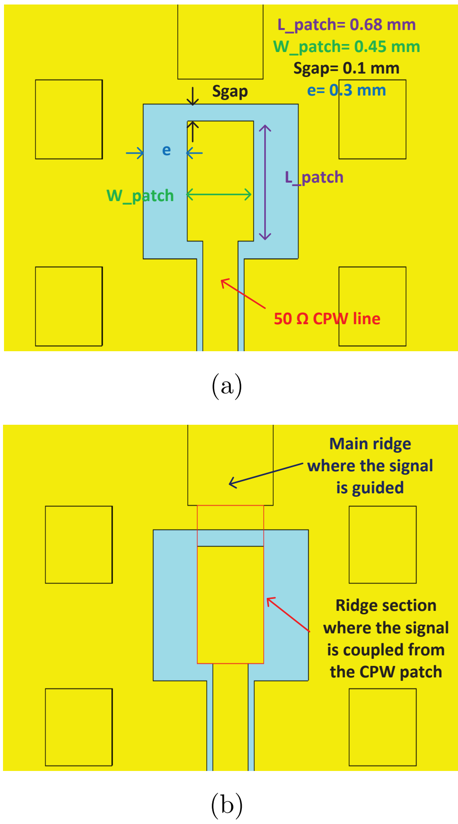


Figure 3.4: (a) Layout of the CPW rectangular patch. (b) Ridge side section follows the shape of the CPW rectangular patch.

We have placed two additional pins before and after the ridge. The function of these pins is to package the CPW feeding lines and eliminate any undesired radiation from the CPW circuit. Figure 3.4 presents the transition dimensions that have resulted from the optimization process.

3.4 Simulation results

The transition under study has been numerically analyzed by using CST Microwave Studio [32]. We can extract several conclusions from these preliminary simulation results:

1. If the boundary condition considered below the substrate is open, radiation leaking away from the substrate material is observed and the

transition performance is severely degraded (presence of resonances and deterioration of return and insertion loss).

2. If the boundary condition considered underneath is PMC, any possible unwanted radiation is suppressed and the transition works well. Computed S parameters are presented in Figure 3.5. These simulation results show that S_{11} is lower than -15 dB over 10 % bandwidth. Insertion loss is approximately 1 dB between 100 and 108 GHz. Therefore, the loss contribution corresponding to each transition is around 0.5 dB.
3. Since the PMC boundary condition corresponds to an ideal situation, it needs to be artificially realized somehow. The radiation issue can be solved by a gap waveguide solution (see section 3.5).

3.5 Removal of radiation by a gap waveguide solution

The leakage of radiation away from the substrate material of the conventional CPW when there is an open boundary condition underneath, is a problem that needs to be solved. The gap waveguide packaging, based on the PMC

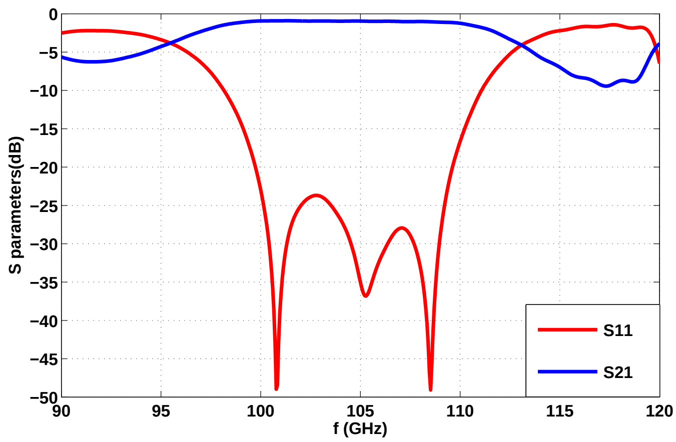


Figure 3.5: Computed S parameters for two back-to-back CPW-to-Ridge Gap Waveguide transitions with PMC boundary condition considered below the dielectric material.

packaging principle explained in the previous chapter, has been demonstrated to be a very suitable solution to suppress radiation losses for high frequency microstrip circuits. We can apply the same PMC packaging concept to overcome the radiation problem reported in this transition study.
Figure 3.6(a) shows the ideal situation taking into account PMC boundary condition, whilst Figure 3.6(b) presents the realization of the ideal case entirely by means of gap waveguide.

The design shown in Figure 3.6(b) is based on the study of the operating bandwidth of the upper ridge gap waveguide layer and the bed of nails located under the CPW structure. If both operating frequency bands overlap, the whole structure works properly. The corresponding dispersion diagrams for both gap waveguide layers appear in Figure 3.7. The dimensions chosen for the lower pin structure are: pin width $a = 0.2$ mm, pin period $p = 0.9$ mm, and pin height $d = 0.87$ mm. The lower bed of nails provides a stopband from 43.8 to 124 GHz, overlapping the corresponding stopband of the upper ridge gap waveguide.
It has been noticed that when the pin elements composing the lower bed of nails are wider than the CPW line, the characteristic impedance of the

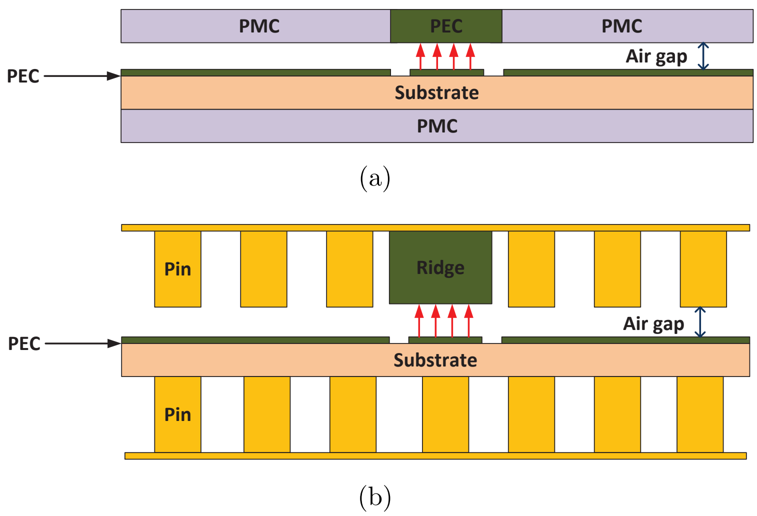
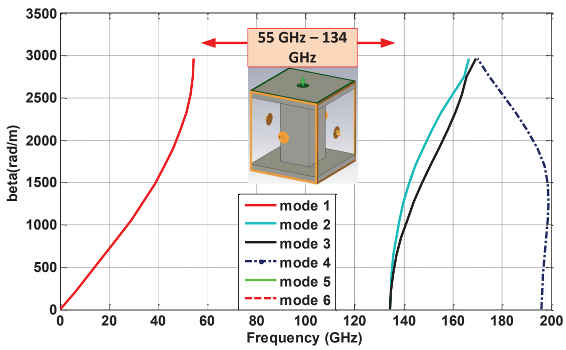


Figure 3.6: (a) Ideal situation with PMC. (b) Real situation with ridge gap waveguide in upper layer and bed of nails located under substrate material.

CPW line changes dramatically. Furthermore, the characteristic impedance is also dependent on the location of the pins with respect to the CPW. Similar conclusions were reported in [36]. In order to avoid this dependence, a denser bed of nails is needed. The central pin row of the bed of nails is centered with respect to the CPW feeding line, and the pin width is set to be 0.2 mm which is smaller than the CPW feeding line. The complete transition geometry, including the gap waveguide solution to eliminate the radiation problem, is shown in Figure 3.8 (the upper metal plate is hidden in order to visualize the whole structure).



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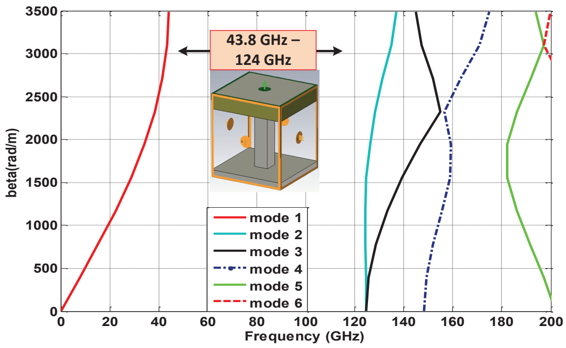


(b)

Figure 3.7: (a) Dispersion diagram of the upper ridge gap waveguide layer. (b) Dispersion diagram of the lower bed of nails layer.

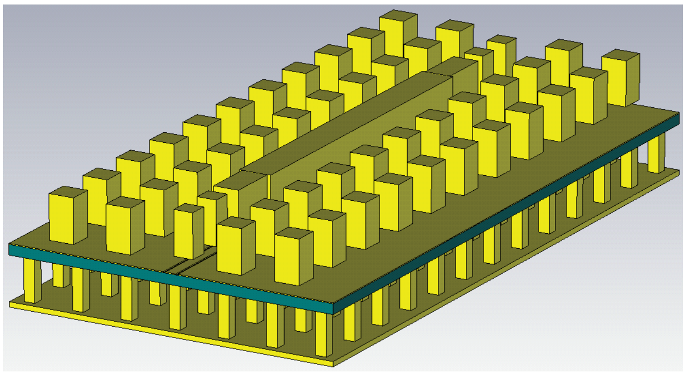


Figure 3.8: Perspective view of the complete transition geometry including bed of nails underneath.

3.5.1 Simulation results

The complete transition structure has been simulated and the resulting S parameters are shown in Figure 3.9. The return loss is better than 15 dB over 9.5% bandwidth approximately, and the insertion loss is 1 dB for almost the same frequency band. Since we consider two back-to-back transitions, one single transition introduces 0.5 dB to the overall insertion loss. Therefore, these simulation results are very similar to the obtained values with the ideal PMC situation (see Figure 3.5).

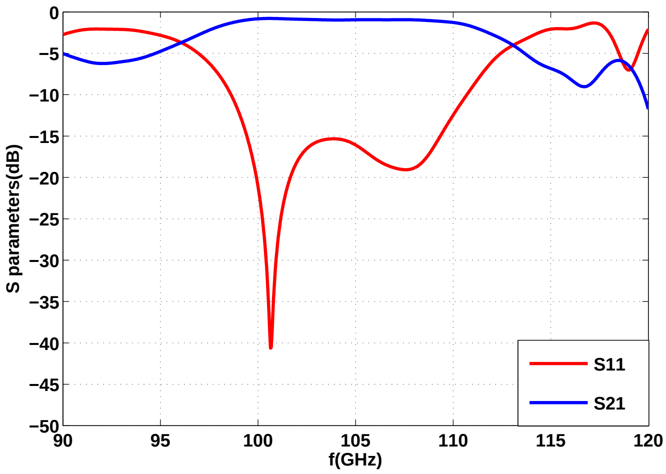


Figure 3.9: Computed S parameters of two back-to-back transitions from CPW-to-Ridge Gap Waveguide with bed of nails underneath.

The bed of nails has removed the leakage of radiation away from the substrate material, and the transition behaviour is approximately as good as with the ideal PMC boundary condition. Moreover, the bed of nails also provides mechanical support to the structure.

Chapter 4

Transition from Microstrip to Ridge Gap Waveguide

In the previous chapter, a vialess transition from CPW-to-Ridge Gap Waveguide was investigated. The potential excitation of higher order modes if CBCPW is used, the mode coupling problem between the even and odd mode if conventional CPW is chosen, and the consequent leakage of radiation away from the substrate material, set up the motivation to study a new transition from Microstrip to Ridge Gap Waveguide by electromagnetic coupling. This transition should ensure compatibility between the micromachined ridge gap waveguide components and the available G-S-G probe stations at 100 GHz, allowing good measurements of those prototypes.

4.1 Transition design

The geometry of the new transition is composed by two different parts. The first part is the ridge gap waveguide circuit, which is located upside down. The second part is a microstrip PCB which contains the transition, and it is attached to a lower metal lid placed opposite to the ridge gap waveguide. Figure 4.1 presents the front view of the structure, including corresponding dimensions.

We have selected alumina as substrate material to constitute the mi-

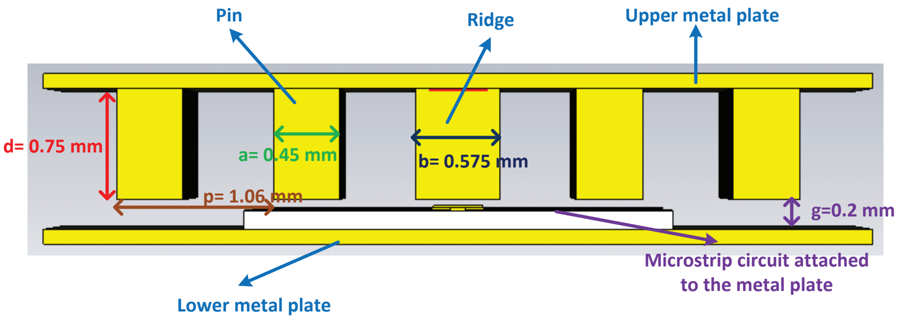
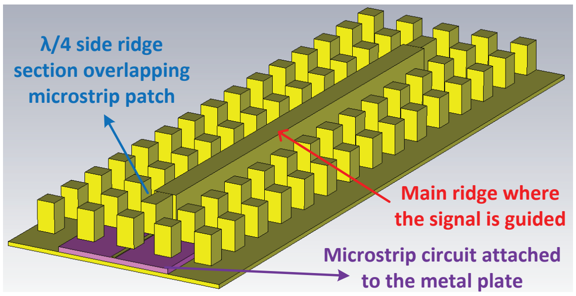


Figure 4.1: Front view and dimensions of the ridge gap waveguide, the PCB is also included and it is attached to the lower metal plate.

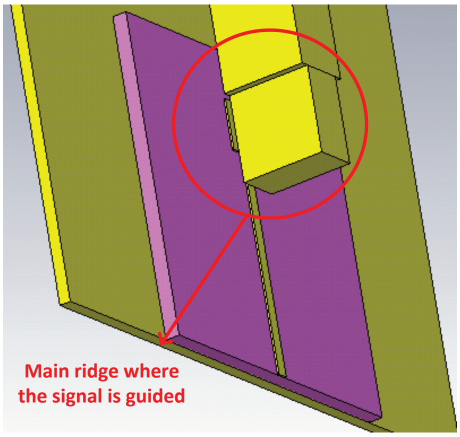
crostrip circuit. This material is less lossy than TACONIC TRF-45 which was chosen to create the CPW transition explained in the previous chapter. The dielectric constant is $\epsilon_r = 9.9$, the substrate thickness is $h = 0.127$ mm and the loss tangent value is $\tan\delta = 0.0001$.

There are two types of vertical transition approaches: via direct physical contact between the different segments, and through electromagnetic coupling (contactless). A good vertical transition should propagate the signal from one layer to another with the least possible degradation. The microstrip-to-ridge gap waveguide transition design is based on overlapping $\lambda/4$ transmission line segments, which is the basic principle of electromagnetic coupling. Several transition examples based in this principle are explained in [37] and [38], where the coupling between different transmission lines is achieved through a dielectric media. In the current case, the coupling is realized through the existent air gap between a microstrip rectangular patch and the ridge. The gap between the ridge and the lower metal plate is designed to be $g = 0.2$ mm. This is different to the space between the microstrip patch and the upper ridge section, which is 0.056 mm

The ridge is divided into three segments: a central ridge with a length of approximately 4λ, and two additional ridge sections located at both ends of the main ridge. The perspective view of the entire structure, without including the metal upper layer, is illustrated in Figure 4.2(a). An extra pin is added at both end sides of the ridge gap waveguide. Its function is to keep the



(a)



(b)

Figure 4.2: (a) Perspective view of Microstrip-to-Ridge Gap Waveguide transition. (b) Overlapping area zoomed.

microstrip feeding line packaged and avoid any possible unwanted radiation. Figure 4.2(b) shows the zoomed area where the side ridge portion overlaps the microstrip patch (pins are occulted).
The main parameters of the microstrip rectangular patch, as well as the ridge width, have been tuned in order to optimize the matching and get the best overall transition performance. The final layout is shown in Figure 4.3.

4.2 Preliminary simulation results

We present simulated S parameters of two back-to-back Microstrip-to-Ridge Gap Waveguide in Figure 4.4. Metal walls surrounding the structure are

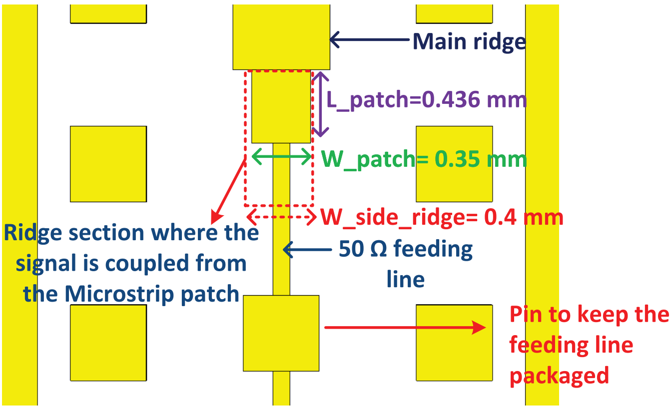


Figure 4.3: Layout of microstrip rectangular patch.

considered. A closer look reveals that the S_{11} parameter is lower than -15 dB in 25.4 % bandwidth, and S_{21} shows values above -0.85 dB in the same frequency range. Therefore, the insertion loss contribution corresponding to a single transition is 0.425 dB. No problem related to radiation leakage was observed, hence avoiding the important weakness with the transition from CPW-to-Ridge Gap Waveguide. The new transition approach is simpler and less time consuming than the explained in the previous chapter.

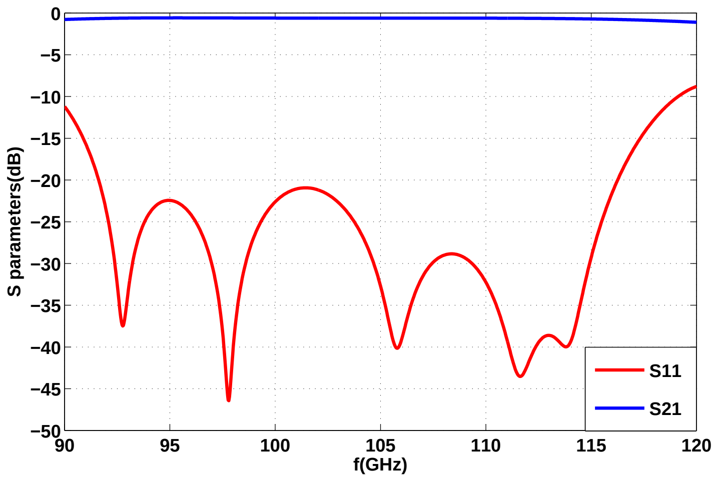


Figure 4.4: Computed S parameters for two back-to-back Microstrip-to-Ridge Gap Waveguide transitions.

4.3 Modifications in the preliminary transition design

The previous design has to be adjusted in several ways due to the requirements related to the measuring procedure of the prototypes. It is necessary to add small pads at both sides of the input and output microstrip line in order to fit the G-S-G probes employed in the measurement setup. These pads need to be shorted with vias to avoid the excitation of higher order modes. Following the via specifications from the PCB manufacturer, two small pads and vias are designed and shown in Figure 4.5.
The probes are fitted from the sides, thus an open boundary condition is considered in order to make the simulations more realistic (see simulations in subsection 4.3.1). Another modification in the design concerns the upper metal lid. A distance of 0.5 mm in the input and output sides is required to keep open, in order to enable us to study the position of the probes by using a microscope.

Furthermore, at millimeter-wave frequencies the mechanical tolerances due to the manufacturing and assembling can be critical and affect the overall circuit behaviour. Attaching the small PCB in the exact location of the lower metal plate might be difficult. Therefore, we have redesigned the PCB with the purpose of avoiding misalignments between the ridge gap waveguide layer

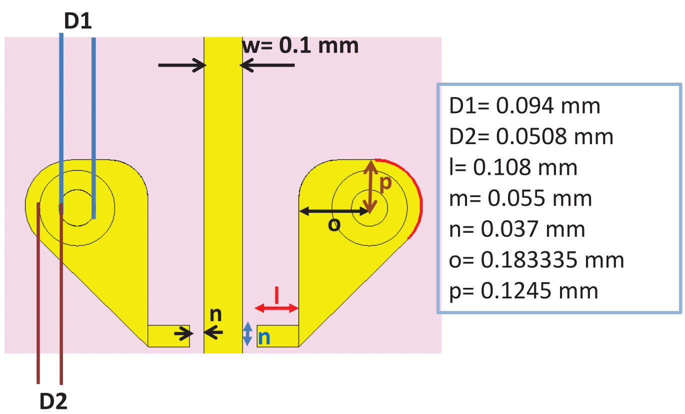
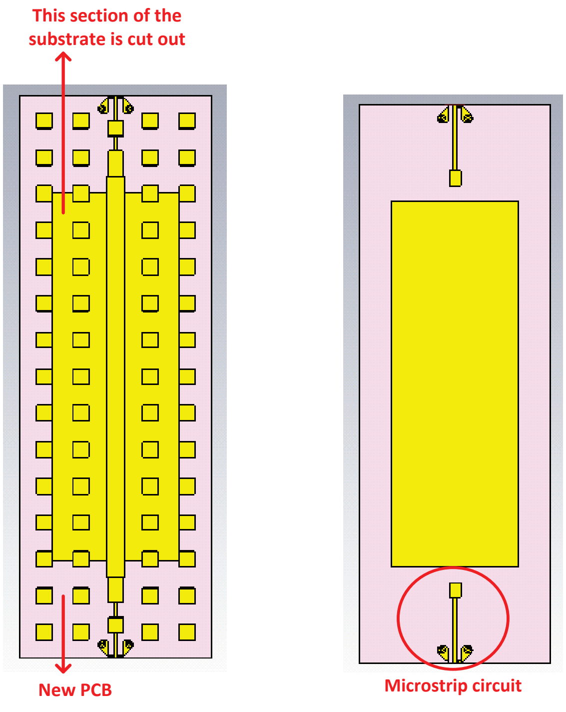


Figure 4.5: Layout of the additional pads and the via.

and the microstrip circuit. Instead of having a metal plate and attaching a PCB, a bigger PCB with the same dimensions of the lower metal plate is created. It is important to point out that the microstrip patch dimensions are not modified, only the area that the PCB occupies is varied. Since the central part of the substrate is cut out, the ridge "sees" a metal plate below (which is actually the ground plane of the microstrip circuit) and the coupled signal from the microstrip patch is suitably guided along the ridge to the output port. The layout of the new structure is shown in Figure 4.6.

4.3.1 Simulation results

After applying all the mentioned adjustments of the transition design, we perform a simulation study. Two prototypes are numerically analyzed: a

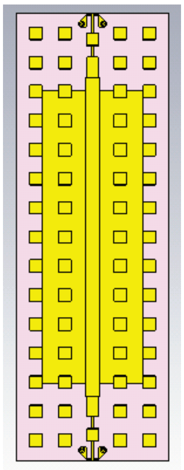


(a) (b)

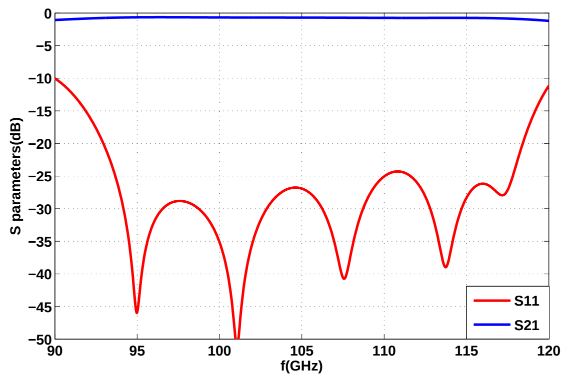
Figure 4.6: (a) Top view of the transition structure with new PCB (upper metal lid is hidden). (b) Top view of the PCB (ridge gap waveguide layer is hidden).

straight ridge gap waveguide (see corresponding S paramenters in Figure 4.7), and a ridge gap waveguide with two 90° bends (S parameters shown in Figure 4.8).

In both cases return losses are better than 15 dB in approximately 25.9 %

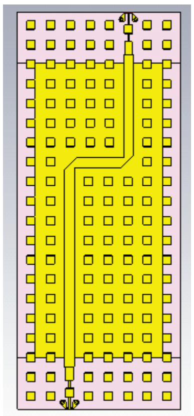


(a)

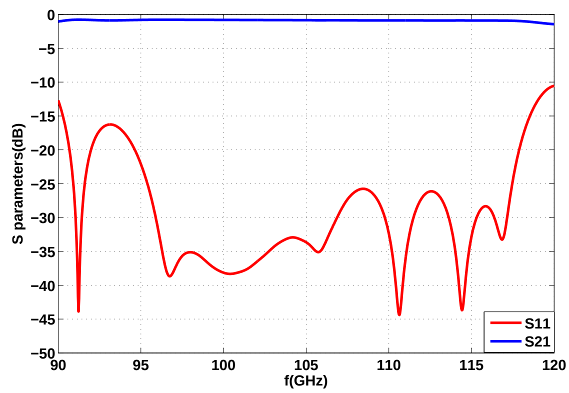


(b)

Figure 4.7: Straight ridge gap waveguide (a) Top view of the prototype. (b) Computed S parameters for two back-to-back Microstrip-to-Ridge Gap Waveguide transitions for this prototype.



(a)



(b)

Figure 4.8: Ridge gap waveguide with two 90° bends (a) Top view of the prototype. (b) Computed S parameters for two back-to-back Microstrip-to-Ridge Gap Waveguide for this prototype.

bandwidth. Insertion loss is less than 1.1 dB over the same frequency band. A single transition thus introduces 0.55 dB of insertion loss to the circuit. Therefore, in spite of the settings applied in the PCB, the transition from Microstrip-to-Ridge Gap Waveguide via electromagnetic coupling still works well.

Chapter 5

Conclusions and Future Work

5.1 Conclusions

In this thesis we have proposed a more robust and effective packaging solution for real microstrip filters, based on the PMC packaging concept and its artificial realization via gap waveguide technology. We have investigated the packaging of two coupled line bandpass filters by employing different types of packaging methods, and presented both simulations and measurements.
The gap waveguide packaging made by a lid of nails, emulates the behaviour of the PMC lid packaging within a certain operating band. Both solutions applied to the coupled line filter show almost theoretical Chevyshev bandpass behaviour (see Figure 5.1). The suppression of cavity/parallel plate modes and the efficient removal of unwanted radiation losses when the filter is packaged with PMC lid and lid of nails, have been numerically and experimentally validated. Simulation and measurement results show improved insertion loss when the microstrip filter is packaged with PMC lid and gap waveguide packaging solution, compared to the other analyzed packaging methods.
Moreover, the filter optimization procedure is much faster if the circuit is packaged with a PMC lid instead of considering the unpackaged condition, smooth metal lid packaging or by using an absorber attached to the metal lid. Therefore, we can design a preliminary filter by using the equations in

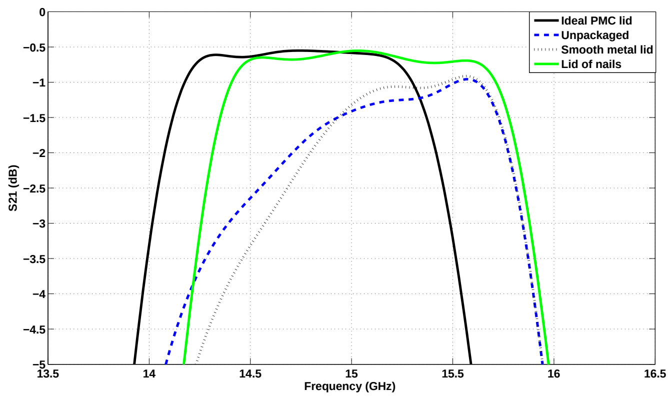


Figure 5.1: Bandpass response (zoomed) in 3^{rd} order coupled line filter case.

[27, 28], and afterwards, carry out a full optimization by considering PMC packaging. Once the optimum filter response is achieved, the PMC packaging is replaced by the lid of nails and the final performance turns out to be significantly better than using the other analyzed packaging cases.
The gap waveguide packaging is an advantageous way of packaging microstrip passive devices such as filters. It is easy to scale to other operating frequency bands and there is no need to have a good metal contact between the lid of nails and the rest of the metal enclosure since the possible undesired leakage is removed by the gap waveguide.

On the other hand, we have presented in Chapter 3 a vialess back-to-back Coplanar Waveguide-to-Ridge Gap Waveguide transition via capacitive coupling operating at around 100 GHz. Radiation leaking away from the substrate has been reported when the boundary condition underneath is set as open. This radiation is due to the mode coupling between the even and odd mode in the conventional CPW. The utilization of air bridges might overcome the mode coupling. However, it also introduces a reactance in the circuit that can cause serious mismatch as the frequency increases.
We have analyzed two transitions in order to solve the radiation issue. One of them had ideal PMC boundary condition below the dielectric material. In the second transition, the PMC boundary is replaced by a bed of nails. Both PMC and bed of nails solutions suppresses the leakage of radiation and

transition performance results to be very similar. Furthermore, the bed of nails provides mechanical support to the whole structure.
The drawback of the mode coupling for the conventional CPW, and the potential excitation of higher order modes in the CBCPW case, make the transition design complex and time consuming. Therefore, an alternative transition from Microstrip-to-Ridge Gap Waveguide via electromagnetic coupling has been proposed in Chapter 4. The simulation results show that this transition has low return and insertion losses in a wider operating bandwidth than the transition explained in Chapter 3. Furthermore, no problem of radiation leakage has been observed. Thereby, the proposed transition from microstrip-to-ridge gap waveguide is very promising to allow proper measurements of gap waveguide prototypes working at millimeter-wave frequency ranges.

5.2 Future Work

The integration of active/passive components and antennas in a unique module with good packaging capability at the same time, is very challenging at millimeter and submillimeter-wave frequency ranges. The gap waveguide approach is a low loss technology that has enormous potential to achieve this integration and overcome the weaknesses of traditional technologies. We have presented a transition from microstrip-to-ridge gap waveguide that will enable to take measurements of ridge gap waveguide components at millimeter-wave frequency bands, and will open up the path to start investigating the integration of active components into the gap waveguide technology. Moreover, gap waveguide antennas are currently under investigation and this transition can be very useful to be employed as feeding network.
Our main goal is to create a complete front end demonstrator in gap waveguide technology in which transitions are very critical since we need to interconnect active and passive elements of different characteristics. Figure 5.2 shows a sketch with a possible way to interconnect active/passive components with gap waveguide by using the transition concept explained in this thesis. No bond wires are required and the gap waveguide keeps the RF chips properly packaged and electrically isolated from each other. Further-

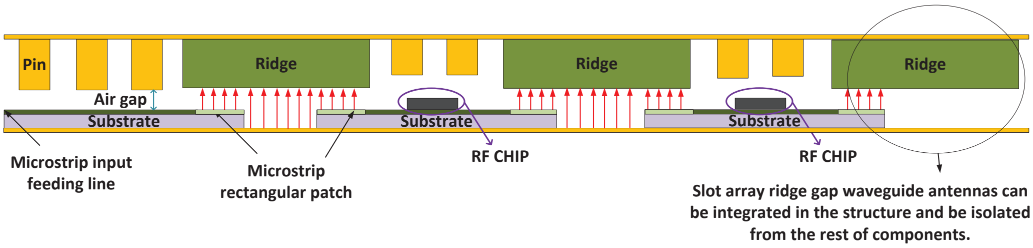


Figure 5.2: Integration of active/passive components into gap waveguide technology (cross section).

more, recently investigated slot array ridge gap waveguide antennas [39] can also be integrated in the structure.

Mechanical tolerances are critical at millimeter and submillimeter-wave frequencies. For this reason, we have carried out a preliminary tolerance study of the possible influence of misalignments and displacements in the transition behaviour. This study has been made by sweeping the different geometry parameters separately. However, we can realize a more complete tolerance investigation via a Monte Carlo analysis in which all the involved parameters are described as random. Therefore, this will constitute a further step in the transition investigation.

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