THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Gap Waveguide: Low Loss Microwave Passive Components and MMIC Packaging Technique for High Frequency Applications

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To my beloved family

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Abstract

The heavy congestion at the existing radio frequency spectrum allocated for the today's wireless communications motivates and accelerates the research work at mmWave bands or even higher frequency range where more spectrum space is available for massive data rate delivery. The inclination of modern wireless system research and development is towards small size, reliable, high-performance and high-yield microwave multifunctional products. Interconnect problems, packaging problems and the mechanical assembly issues related to radio front-end components have been the major limitations towards using the mmWave technology for regular commercial applications.

There are some key issues to be considered while using conventional microwave technologies such as planar microstrip line or the metal waveguide for building up high frequency microwave modules or systems. At first, this thesis explains these factors briefly and put forward the existing performance gap between the planar transmission lines such as microstrip or coplanar waveguide and the non-planar metal waveguides in terms of losses, manufacturing flexibility and cost. The packaging problems in conventional microwave circuitry are also brought up from practical view point.

After that, the newly proposed gap waveguide technology is presented as a promising solution for high frequency microwave problems. Chapter 2 explains the operating principle of the proposed gap waveguide technology along with design of the parallel plate stop-band. Measurement results for the manufactured gap waveguide demonstrators are also provided with emphasis on loss analysis.

Chapter 3 presents mechanically flexible design of high Q resonators and bandpass filters based on groove gap waveguide. Narrowband filter design with Chebyshev response is presented at Ku-band and Ka-band. The filter in Ka band has been designed with commercial specifications in mind and this opens up the whole new idea of designing filters without problematic electrical contact between split blocks and sidewalls.

In chapter 4, ridge gap waveguide planar slot array has been described. One 4×1 element linear array and one 2×2 element array have been designed, manufactured and measured. Good agreement has been obtained between simulated and measured reflection coefficient for both slot array antennas. Obtained radiation patterns are also in agreement with the simulated patterns.

Chapter 5 shows how the parallel plate stop-band obtained from PMC surface and smooth metal surface can be utilized as a new packaging solution for high frequency RF circuitry. The basics of new

PMC packaging along with some experimental verification for passive structures as well as active MMIC amplifier chain are detailed in this chapter.

Chapter 6 deals with crucial transition design for gap waveguide structures. One microstrip to ridge gap waveguide transition has been designed and measured at Ka-band. This transition is compact and utilizes only mechanical pressure contact between the microstrip line and ridge gap waveguide line instead of soldering or epoxy gluing process. The ridge waveguide to rectangular waveguide transition is also designed in two different approaches. In one approach, the ridge height is reduced in several steps to match the height of rectangular waveguide. In the other approach, the ridge gap waveguide is fed from the bottom by a rectangular waveguide and the width of the ridge section is tuned at the rectangular waveguide opening.

Thus, the topic of this doctoral dissertation is concerned with research tasks to validate the concept of gap waveguide technology and to investigate its potentials for high frequency microwave applications. All the studies presented in this thesis are proof of concepts and accomplished mainly in Ku-band or Ka-band. Nevertheless, the gap waveguide technology is quite suitable for mmWave frequency or even higher frequency applications.

Keywords: PMC surface, parallel plate stop-band, Quasi-TEM mode, gap waveguide, PMC packaging, high Q resonators, narrowband filter, fractional bandwidth, slot array antenna, corporate feed network.

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This acknowledgment would be incomplete without referring to our Bangladeshi friends in Göteborg whose presence made our stay a pleasant experience in Sweden. Special thanks to Risat vai and Shafiq vai with whom I had many long conversations on a variety of issues especially after each Friday prayer.

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Göteborg, Sweden.

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List of Figures

Acronyms and Abbreviations

AMC	Artificial Magnetic Conductor
CBCPW	Conductor Backed Coplanar Waveguide
CPW	Coplanar Waveguide
GaAs	Gallium Arsenide
LTCC	Low temperature co-fired ceramic
MMIC	Monolithic Microwave integrated circuit
mmWave	Millimeter wave
PEC	Perfect Electric Conductor
PIM	Passive Intermodulation
PMC	Perfect Magnetic Conductor
PP mode	Parallel plate mode
SIW	Substrate Integrated Waveguide
SOLT	Short-Open-Line-Thru calibration
TRL	Thru-Reflec-Line calibration
TFMS	Thin Film Microstrip
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network

Preface

This report is a thesis for the degree of Doctor of Philosophy at Chalmers University of Technology, Gothenburg Sweden. The thesis is divided into four main parts: validation of the concept of gap waveguide technology, design of critical passive microwave components such as filters and planar antennas, utilizing gap waveguide packaging for MMIC and active RF circuits and design of different transitions for gap waveguide components.

The work was carried out between August 2008 and May 2013 at Signals and System Department of Chalmers.

During the first years, the work has been supported by Swedish Foundation for Strategic Research (SSF) via the CHARMANT antenna systems research center at Chalmers, and by the Swedish Governmental Agency for Innovation Systems (VINNOVA) within the VINN Excellence Centre Chase at Chalmers. Over the last three years, the works is mainly supported by Swedish Research Council VR via a 12 MSEK so-called "ramprogram" on gap waveguides. The research continues with funding from a 2.5 M€ advanced investigator grant from European Research Council (ERC) given to Professor Kildal.

The basic intellectual property of the gap waveguide technology belongs to Gapwaves AB. Gapwaves AB is member of the Chase Center and partner in a Chase project on exploring industrial applications of gap waveguides at 38 and 60 GHz. The other industrial partner is Arkivator AB.

The examiner at Chalmers is Professor Per-Simon Kildal, who has also been the main supervisor. In addition, Prof. Ahmed Kishk was a co-supervisor when he was a guest Professor at Chalmers from June 2009 to July 2010. Associate Prof. Eva Rajo-Iglesias from Carlos III University in Madrid has also been involved as supervisor during her regular visits to Chalmers, almost every autumn, since this project started.

Part -I

Chapter 1
Introduction

Recently, there is a significant growth in wireless telecommunication applications. In near future telecommunication or RF applications will shift more and more to the higher frequency spectrum due to large available bandwidth, smaller component size, less interference etc. Potential high frequency commercial wireless applications include point to multipoint services, chip to chip high speed links, satellite communications, automotive radars, radiometers, imaging and security systems [1-8]. As a result, significant research activity has been going on around mmWave frequency range (or even higher) to validate different microwave system aspects.

On the other hand, there are plenty of technological and mechanical challenges in designing high frequency microwave RF front ends. These factors are cost pressure, smaller size requirement, increased system density, packaging and cross-talk suppression, lower power loss dissipation etc. Usually, RF front-ends are composed of both integrated circuits (ICs) and passive devices including antennas and filters that are not integrated on the semiconductor substrate. While the progress in active components in RF systems has propelled with the advancement of monolithic microwave integrated circuit (MMIC) technology, resulting in the fact that the active components of RF systems occupy only a small segment of the board space area, passive components on the other hand have not advanced in a similar manner due to the fabrication tolerance issues associated with geometrical scaling governed by operating frequency. There is a need for re-thinking in design techniques in terms of manufacturing flexibility and improved performance with continued affordability for RF front-end passive components (e.g., antennas and filter/diplexer). In this regard, having upcoming high frequency applications in mind, some new technology development seems to be important.

1.1 Metal waveguide problems

Classical metal waveguides shown in figure 1.1 have existed in microwave operation for a long time in the form of circular and rectangular waveguides. These waveguide based passive components can be very low loss even at mmWave spectrum and are very suitable for low loss applications. However, traditional machining techniques for manufacturing metal waveguides operating at mmWave frequencies, specifically above 60GHz, are complicated and costly [9-11]. This mature technology is not very suitable for low-cost mass-production since tedious and expensive post fabrication modification and mechanical assembling presents a bottleneck problem for manufacturers and commercial companies. Also, when realized as components and manufactured in two blocks, it is difficult to achieve the low loss and high Q values at high frequencies. The reason is usually the field leakage through the tiny gaps between two split blocks (originated due to manufacturing imperfections or metal deformations caused by thermal expansion). Also, poor electrical contact between the conductors is one of the most common sources of passive intermodulation (PIM) [12] which is considered as a hidden threat in many microwave applications.

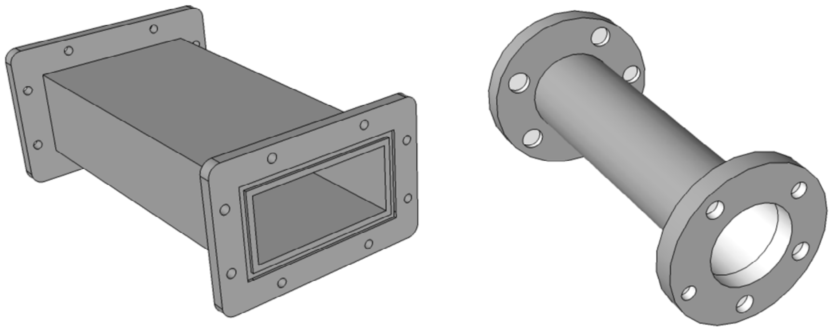


Fig.1.1 Typical metal waveguides.

Apart from these manufacturing problem issues at high frequency, the integration of the active microwave electronic circuitry with metal waveguide is not very easy and often challenges the engineers. Today's planar MMICs are incompatible with non-planar metal waveguides and require the use of different transitions which add more complexity in the overall system. Often at higher frequency, these transitions show degraded results and overall performance of the whole microwave module deteriorates. So, in spite of numerous indisputable advantages of metal waveguide components such as low loss and high power handling capacity, there are still some issues related mainly to the manufacturing cost and integration problem that should be considered while designing mmWave systems and modules.

1.2 Printed planar transmission line problems

Mircrostrip and Coplanar lines are the most representative planar transmission lines and are shown in figure 1.2. These are robust, low cost solutions and very suitable for integrating active microwave components on circuit boards. Especially, the CPW is widely used in monolithic microwave integrated circuits (MMIC) capable of a very high metal pattern resolution. But, the transmission properties of both microstrip and CPW lines greatly depend on the substrate parameters. Both lines suffer from high insertion loss at mmWave frequency spectrum due to the presence of lossy dielectric material. Published studies in [13-15] show that significant power leakage exists on various printed circuit transmission lines, often related to surface waves in the dielectric substrate causing serious cross-talk and interference problems. Particularly in the case of top-covered microstrip line, this leakage begins at a much lower frequency than expected and become a matter of serious concern for power loss as well as cross-talk issue [14]. Similarly, conventional packaging of CPW modifies the CPW into a conductor- backed CPW (CBCPW), and this thereby generates power leakage in the form of coupling to parasitic parallel-plate (PP) modes. This unwanted radiation can cause unexpected cross-talk problems, isolation problems and packaging problems [16]. Even for antenna applications, this unwanted or spurious radiation from feed lines can produce a dramatic degradation on radiation patterns and efficiency [17-18].

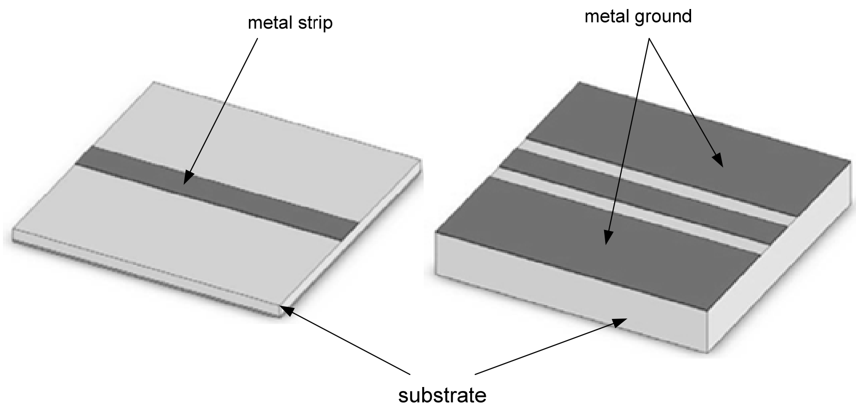


Fig.1.2 Typical microstrip and the CPW lines.

1.3 High Frequency high-gain planar antennas

Usually, planar waveguide-type slot antennas shown in figure 1.3 are very attractive candidate for high frequency high- efficiency antenna because the lower losses in the feed line are directly linked with the efficiency of the antenna. One of the key problems in this case has been the high manufacturing cost of 3-dimensional waveguide feed network. The feeding networks in this concern can be classified in two major categories: series-feed type and corporate-feed type. The series-type array is a simple structure but suffers from the narrow bandwidth problem (4 -5%) due to long line effect and beam squinting problems [19-20]. In corporate feed network larger bandwidth (8-10%) can be achieved but, the distance between the adjacent elements is difficult to maintain smaller than one wavelength in a single waveguide layer and grating lobe problems arise. Published studies suggest the possibility of using complex multilayer structure to solve the issue [21]. But in all cases, manufacturing costs are high at high frequency due to the requirements of electrically tight contacts between the slotted plate and the feed structure.

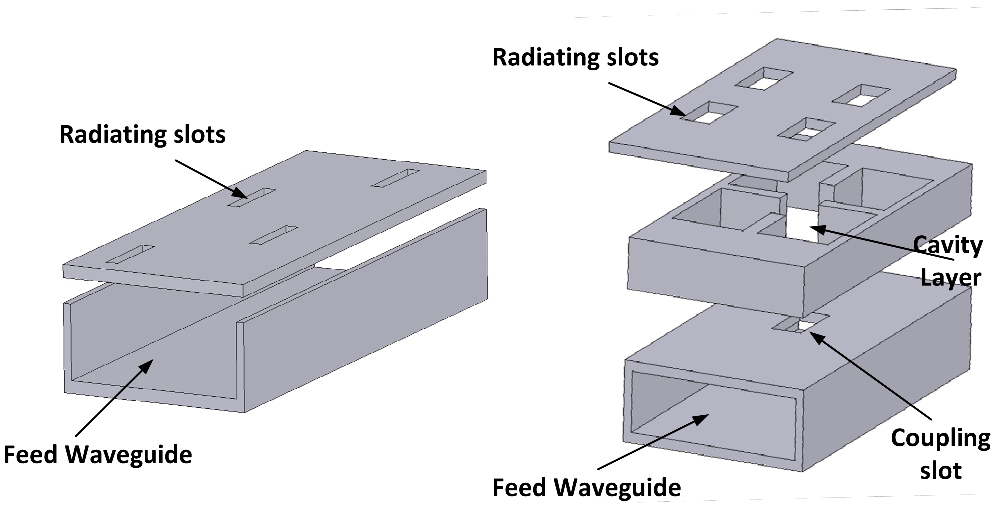


Fig.1.3 Single layer and multi-layer waveguide slot array antenna.

1.4 High frequency narrow band filters

The successful commercialization of broadband wireless links at mmWave frequencies depends to a large extent on the availability of low-cost components. Among them, filters and diplexers are of particular concern since they are in many cases the single most expensive component in a mmWave system. The number of research contributions devoted to the design and analysis of microwave filters and diplexers is enormous. One of the fundamental problems in filter realization is to overcome dissipation losses as sensitivity of a wireless receiver is determined by noise and nonlinearity in the RF front-end. The insertion loss in the passband is inversely proportional to the filter bandwidth and the resonator Q-factor and is proportional to the number of resonators used. Thus, for very narrow band channel selection applications, very high resonator Q-factors must be used in order to achieve low passband loss [22-24]. Typically, H-plane iris filters and E-plane metal insert filters shown in fig. 1.4 are used extensively. But the Q value decreases in H-plane iris filters due to leakage of energy through tiny gaps between the top metal plate and filter body which results from thermal expansion and metal deformation. Also, high quality surface finishing over the whole metal contact area is required for good mechanical assembly. In E-plane filters, tolerances associated with the thickness of metal inserts become critical as the dimensions of millimeter-wave circuits reach the limits. These strict mechanical requirements lead to very high precision metal machining technique which increases the cost of manufacturing and cause much delay in production chain.

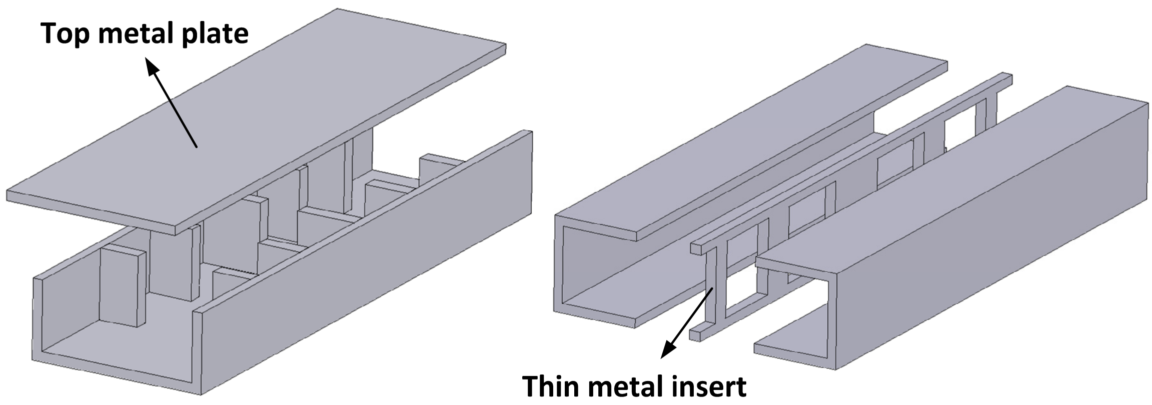


Fig.1.4 H-plane Iris filter and E-plane metal insert waveguide filter.

1.5 Packaging problems in high frequency microwave module

Electronic circuits must be enclosed both to protect the circuit from metal contamination, harsh weather and also to provide electrical isolation. Also, to comply with the smaller size requirements and compactness for mmWave microwave modules, large amount of electronic components must be placed into a confined area. For such high density microwave modules, RF packaging is more and more important in terms of isolation and interference suppression. Packaging of high frequency microwave modules has some challenges due to several issues. At high frequencies, circuit features and components can have dimensions that are an appreciable fraction of wavelength. There are some additional complex issues to deal with such as coupling and feedback due to surface mode and radiation from minor bends or discontinuities. The conventional way of doing the circuit package is to use rectangular metal wall cavity to isolate each critical circuit component. The size of the cavity is maintained to be lower than the half guided wavelength $\lambda_g/2$ to avoid cavity modes within the module. Also, lossy absorbers can be used to dampen the high Q cavity modes otherwise even a weak coupling of the desired signal and cavity modes can destroy the RF performance. The absorbing materials with metal walls are shown in figure1.5. However, the cavity size reduction becomes impractical at mmWave frequencies. The half guided wavelength $\lambda_g/2$ for a GaAs substrate at 80GHz is 0.52 mm. Also, the dampening absorbers with high value of permittivity and permeability do not work well enough at high mmWave frequencies. So, there are still some concerns left regarding packaging of RF electronic circuit at high frequencies.

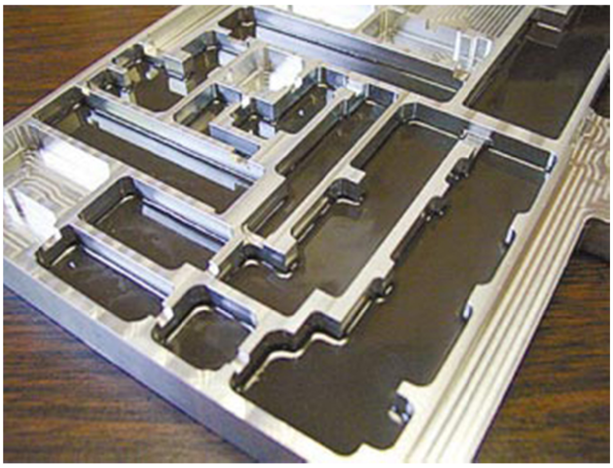


Fig.1.5 Microwave absorbers and metal walls used in metal package [85].

1.6 Motivation and objective of the thesis

There exists a big performance gap between the planar transmission lines such as microstrip or CPW and the non-planar metal waveguides in terms of loss, manufacturing flexibility and production cost. One of the main high frequency microwave research challenges to date is to narrow down the above mentioned performance gap. Researchers aim at finding a solution which is as low cost and flexible as microstrip and also as low loss as metal waveguide. In the context of the above mentioned examples, the design of high gain single layer antennas and narrow-band channel filters with more degrees of manufacturing flexibility are of great interest. It would add an extra advantage if these two critical passive components can be put together and be produced as a single unit to reduce the production time and cost. The other research challenges are related with integration and packaging issues such as suppression of cavity modes and unwanted radiation in case of integrated high frequency microwave modules or systems.

The prevailing idea throughout this dissertation is to exploit a new low loss transmission line technology known as gap waveguide to design the critical passive components. Gap waveguide technology has much lower loss than microstrip or CPW. Losses in gap waveguide are comparable to those of conventional metal waveguides and are in the same order. Also, gap waveguide structures are more flexible and easy to assemble than the conventional metal waveguides. Thus, this newly proposed solution gives a very good trade-off between two opposing factors such as low loss and manufacturing flexibility. Another aspect of the thesis is to propose new packaging method for high frequency microwave modules by using the parallel-plate mode suppression capabilities of gap waveguide technology.

1.7 Organization of the thesis

The entire work is organized in seven short chapters. Chapter 2 starts with the basic overview of the gap waveguide technology. It presents the experimental validation of the first gapwaveguide prototype. Also, it describes the loss performance of the gap waveguide demonstrator after TRL calibration has been performed.

Chapter 3 describes high Q gap waveguide resonators and narrow band filter design based on groove gap waveguide technology. Two different coupling techniques between adjacent resonators are verified and narrow band filters are designed at Ku-band and Ka-band.

Chapter 4 provides a summary of gap waveguide slot antenna design. Description of a 4×1 linear slot array antenna and a 2×2 planar antenna are presented with measured results. The antennas are designed in two metal plates; one of the plates has a ridge placed in between texture of metal pins and the other one is a smooth plate which contains the radiating slots.

Chapter 5 explores the packaging aspect and parallel plate mode suppression capabilities of gap waveguide technology. This packaging technique is applied to various passive circuits and has been used for improving isolation of circuit components in high frequency microwave module. Experimental results are presented, demonstrating the effectiveness of gap waveguide packaging technique.

Chapter 6 describes a back-to-back transition from microstrip line to ridge gap waveguide technology. The transition is designed around Ka band and is quite compact and suitable for MMIC to ridge gap waveguide antenna integration. This chapter also includes description about ridge gap waveguide to standard rectangular waveguide transitions.

Chapter 7 contains general conclusions, and possible future work.

Chapter 2
Overview of Gap Waveguide Technology

It is expected that high-density integration techniques, combined with a low-cost fabrication process, should be able to offer widespread solutions for future high frequency microwave or mm-Wave commercial applications. Lot of research has been done in microwave community to meet these requirements. Researchers have come out with technologies such as substrate integrated waveguide (SIW) [25-27], low loss thin-film microstrip lines (TFMS) [28-29], LTCC [30-31] etc. Each of the proposed techniques has their own merits and demerits. Recently, a new transmission line technology known as gap waveguide has been proposed in [32-33]. This new technology is free from dielectric losses and more flexible than metal waveguide in the sense of modular assembly. Thus, gap waveguide is a suitable candidate for critical components such as high gain antennas and narrow band filters.

2.1 Fundamentals of gap waveguide technology

Gap waveguide technology is an extension of the research about hard and soft surfaces [34]. Gap waveguide uses the basic cut-off of a PEC-PMC parallel-plate waveguide configuration to control the electromagnetic wave propagation between the two parallel plates. As long as the separation between the PEC and PMC plates is less than λ/4, no wave can propagate between the plates. But if a PEC strip is now placed on the PMC plate, wave can propagate along the strip. This is shown in figure 2.1. As PMCs are not available in nature, the PMC condition must be emulated by artificial magnetic conductor (AMC) in the form of periodic structures such as metal pins [35] or mushroom structures [36].

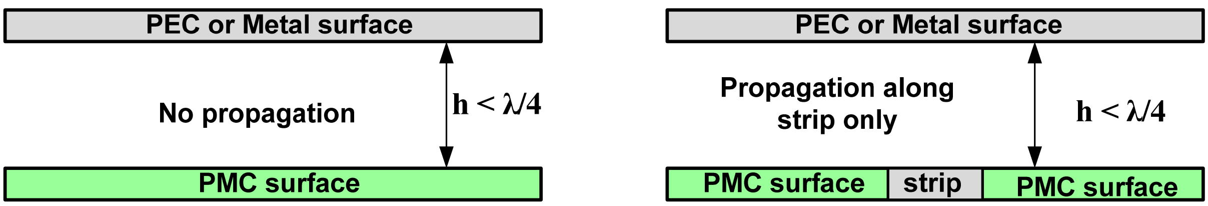


Fig.2.1 Basic concept of gap waveguide technology.

All the global parallel-plate (PP) modes are in cut-off within the frequency band where the AMC has high enough surface impedance to create a stop-band of the PP modes and thereby allows only the desired waves along ridges or grooves to propagate within the gap waveguide structure. Gap waveguide technology exists in three versions depending upon the guiding structure: ridge gap waveguide, groove gap waveguide and microstrip gap waveguide [37- 40]. These three configurations are shown in figure.2.2 where periodic metal pins are used as AMC surface. Out of these versions, the ridge gap waveguide and microstrip gap waveguide both support quasi TEM mode of propagation. On the other hand, the groove gap waveguide supports a mode very similar to TE_{10} mode of rectangular waveguide

[41]. The main advantage of the gap waveguide is that it can be realized without any requirement of metal contact between the upper metal surface and the lower metal surface allowing cheap manufacturing of low loss waveguide components in high frequency bands.

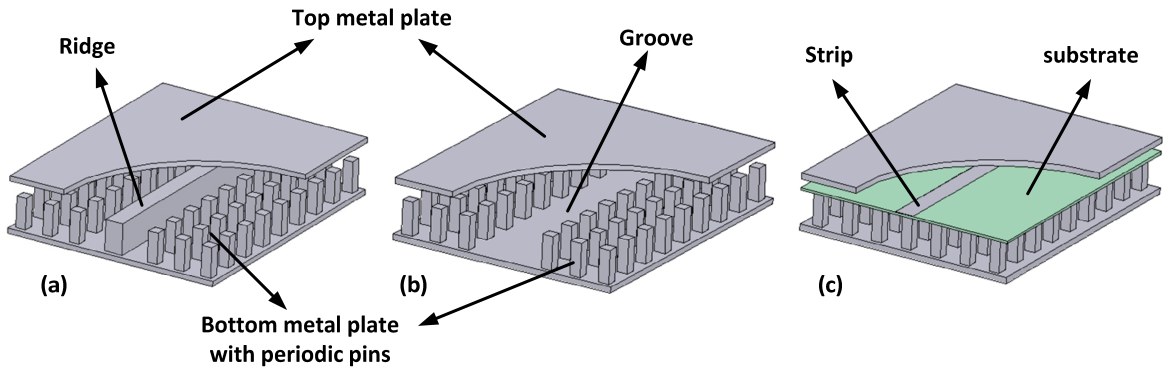


Fig.2.2 Three versions: (a) Ridge gap waveguide (b) Groove gap waveguide and (c) Microstrip gap waveguide.

2.2 Design of parallel plate stop-band with pin surface

As mentioned in section 2.1, the main performance of the gap waveguide is determined by its ability to create parallel-plate stop-band for wave propagation in the undesired direction. This stop-band is usually achieved by a periodic texture located around the metal ridge, groove or the strip. The periodic structure functions as a high impedance surface when placed closely (with an air gap smaller than λ/4) to a metal plate and is often referred to as AMC surface. The most important thing in designing the stop-band is to obtain the lower and upper cut-off frequency of this stop-band. Usually, the cut-off study is performed as a function of the geometrical parameters of the periodic structure to be used. This kind of study is well described in [42]. For the first gap waveguide demonstrator, a textured surface made of square pin is designed to emulate the AMC surface for a frequency range of 10-20 GHz. The figure 2.3 shows the details of the pin surface. The computed dispersion diagram for this corresponding structure is shown in figure 2.4. A large stop-band is created by the pin surface after 10 GHz where no waves can propagate without the presence of the ridge. But in presence of the ridge, there is a mode propagation which follows the light line and is considered as the desired Quasi-TEM mode.

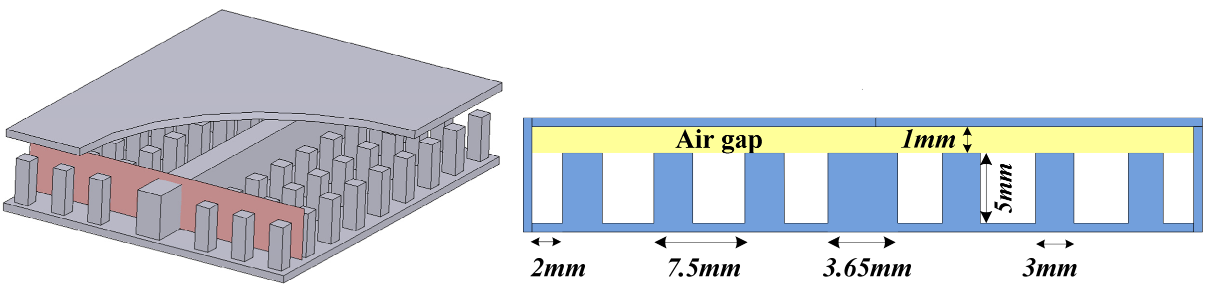


Fig. 2.3 Detailed dimensions of the periodic metal pin.

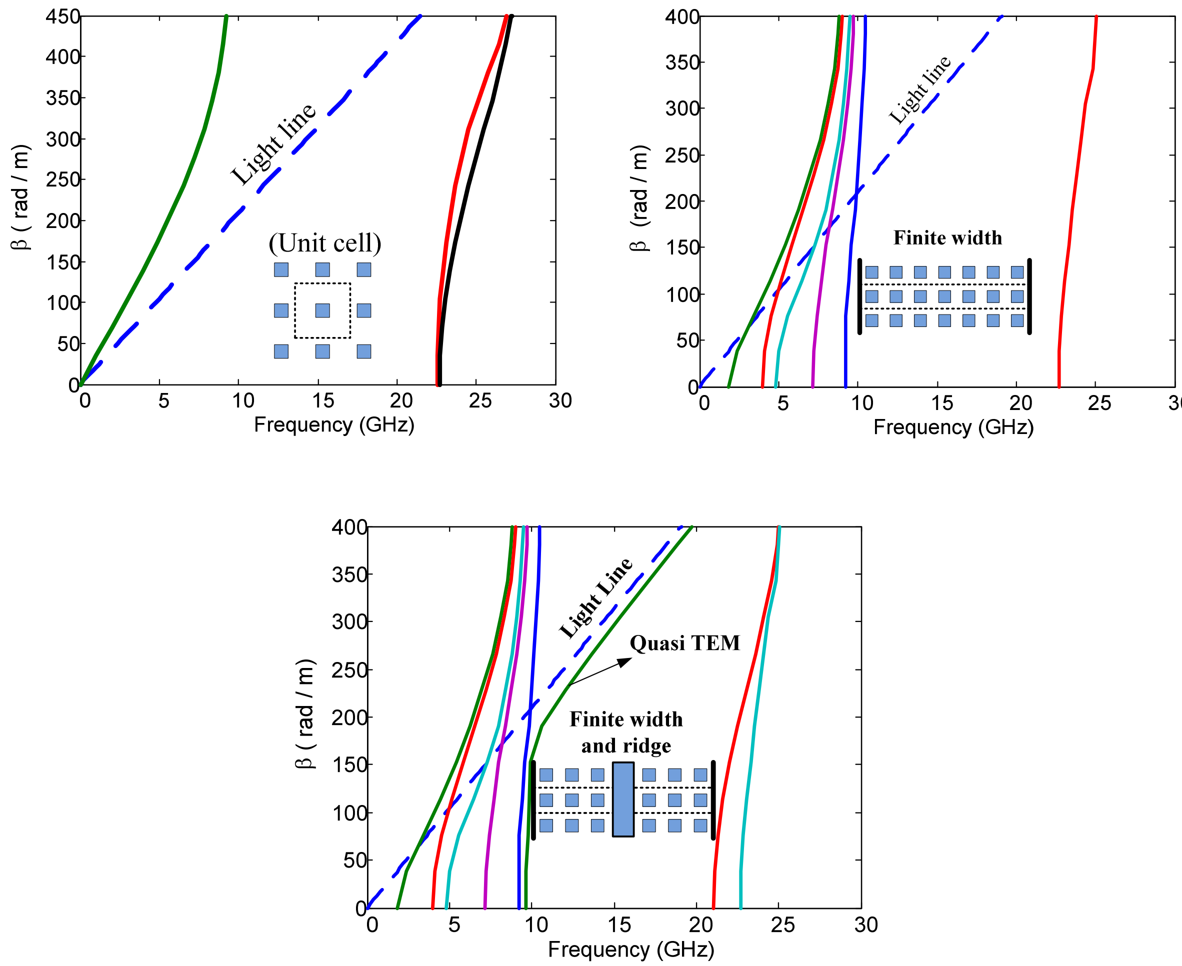


Fig. 2.4 Dispersion diagram for different cases.

2.3 Field attenuation in the pin region and measured attenuation

One very important aspect to know for such oversized parallel plate structures is the level of field attenuation in the periodic structure which has been designed to act as high impedance surface or AMC surface. This gives also an indication of the parallel-plate stop-band achieved by the periodic structure. Throughout this thesis, the periodic structure which is considered as an AMC surface for the gap waveguide is the 'bed of nails' or periodic metal pins with specific dimensions. The modal field is computed in the transverse plane inside ridge gap waveguide to determine the level of decay in the pin region. The computed field distribution is shown in figure 2.5. As shown in figure 2.5, field distribution is nearly constant over the ridge and then it falls almost at a rate of 18-20 dB per row of pins (within the stop-band), most rapidly near the upper end of the frequency band. The periodic variations in the field pattern coincide also with the period of the pins. This attenuation has been measured also by placing two ridge gap waveguide sections and separating them by three rows of pins. The measured isolation is shown in figure 2.6. The measured results correspond well with the computed attenuation level. The measured isolation between two lines placed side by side has been found better than 60dB for the entire Ku- band.

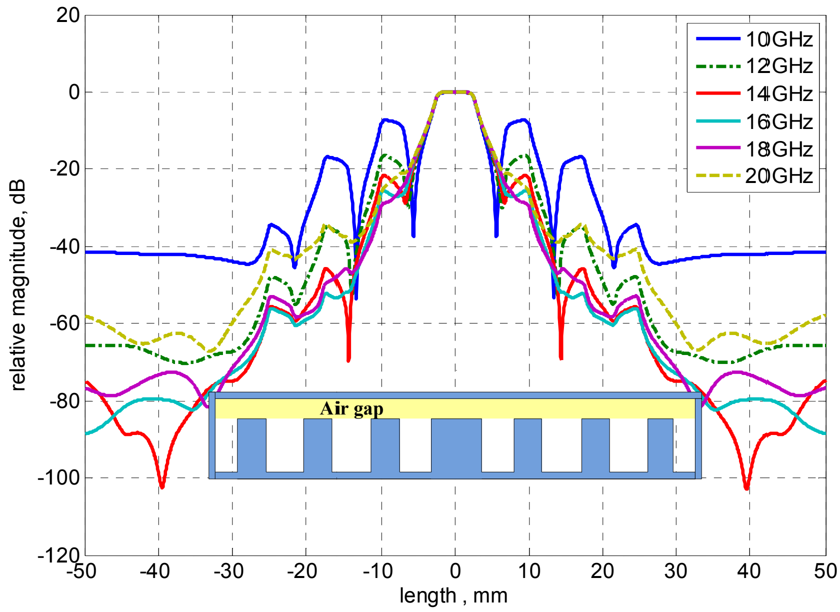


Fig. 2.5 Field distribution in transverse plane within the gap waveguide structure.

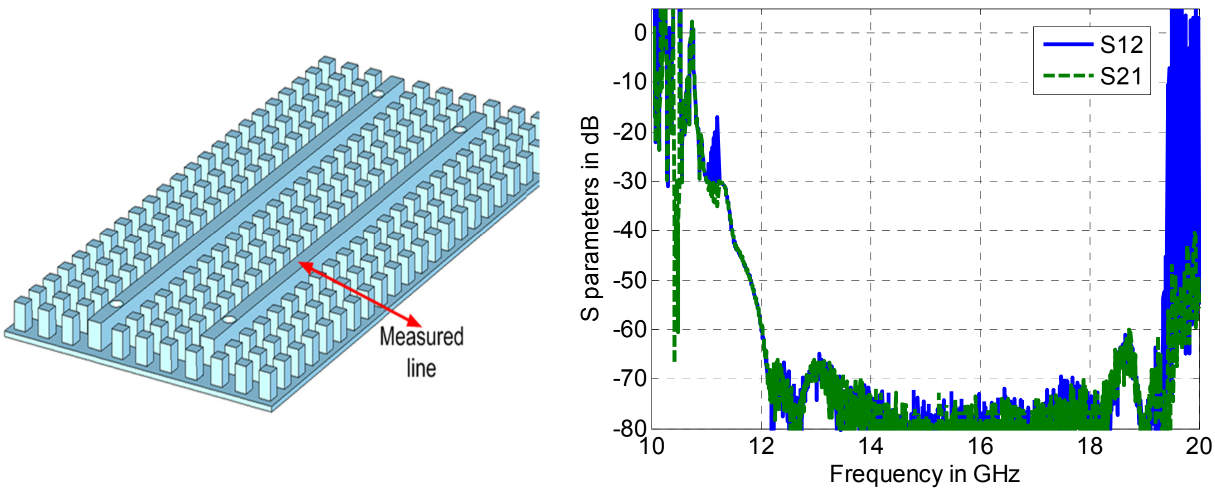


Fig. 2.6 Measured isolation between two lines within the gap waveguide structure.

2.4 Measurements of the first gap waveguide demonstrators

The first ridge gap waveguide demonstrator has been designed based on the textured pin surface and uses a coaxial to ridge gap waveguide transition as discussed in [43]. Two prototypes are manufactured: one with a straight ridge and the other one with a ridge having two 90^o bends. The prototype with a ridge having two 90^o bends is manufactured just to validate the guiding property of gap waveguide. The bends are designed very similar to the metered bends of microstrip line. The simulated vertical field plot for this bended line is shown in figure 2.7. This figure shows that- the field follows very well the ridge over the range from 12-18GHz. Even after introducing the discontinuity such as 90^o bends, the electromagnetic wave is guided very clearly along the ridge within this frequency range. The measured S-parameters for the two prototypes mentioned earlier are shown in figure 2.8. In this case the network analyzer is calibrated up to the VNA ports. So, the effects of the SMA connectors are not de-embedded at this point.

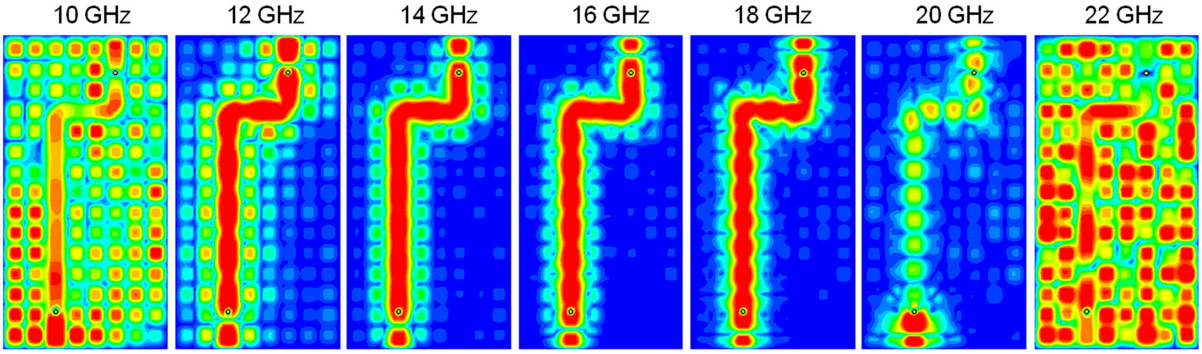


Fig.2.7 Simulated vertical field plot for a ridge with two 90° bends.

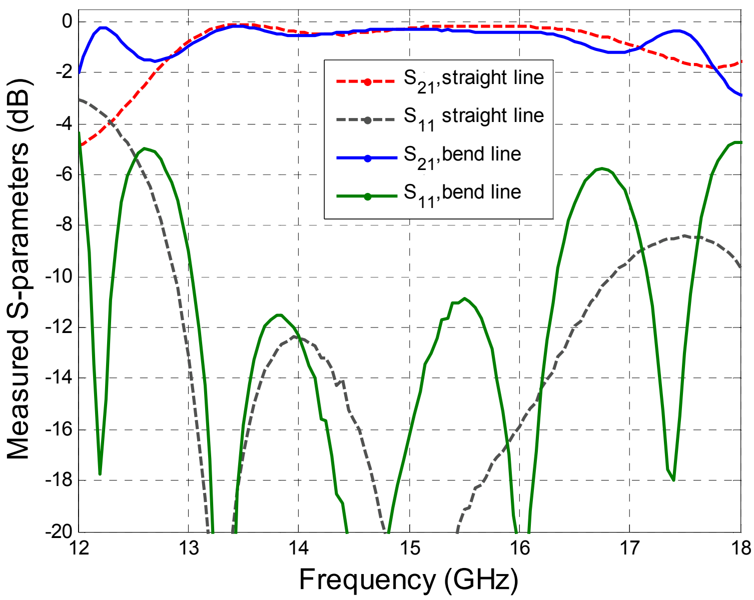


Fig.2.8 Measured S-parameters for the two prototypes with SOLT calibration.

When the VNA is calibrated at the coaxial interface using standard SOLT calibration kit with sliding load, the measurements include the test fixture and coax-gap waveguide transition effects. To de-embed the influences of the transitions, a second tier calibration was performed using the 'Thru-Reflect-Line' or TRL calibration technique. Unlike coaxial measurements, a set of three distinct well characterized impedance standards (open, short & load) are often difficult to produce for non-coaxial transmission medium. For this reason, TRL is very useful as is mentioned in [44-45]. TRL usually refers to the three basic steps in the calibration process: '*Thru*' is connection of port 1 and port 2 directly or with a short length of transmission line; 'Reflect' is connection of high reflection coefficient devices such as short or open to each of the ports and '*Line*' is connection of a certain length of transmission line between port 1 and 2. The resulting S-parameters of both the straight ridge and ridge with two bends after using TRL calibration is shown in figure 2.9. It is found that, S_{11} of the straight line is 20 dB down over most of the frequency band. The ridge with the two 90° bends has larger S_{11}, but it is still below –13 dB over most of the band. The pictures of the manufactured bended ridge gap waveguide and the straight ridge gap waveguide along with the TRL calibration kit is shown in figure 2.10.

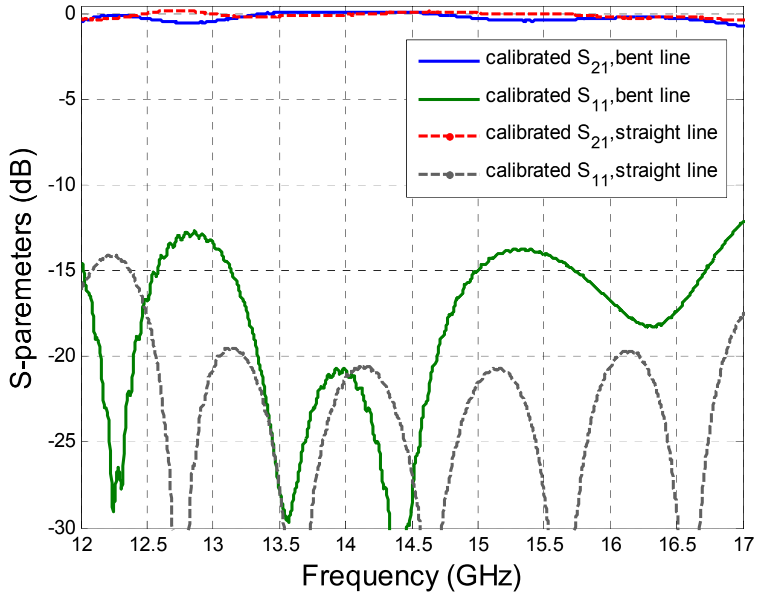


Fig.2.9 Measured S-parameters for the two prototypes with TRL calibration.

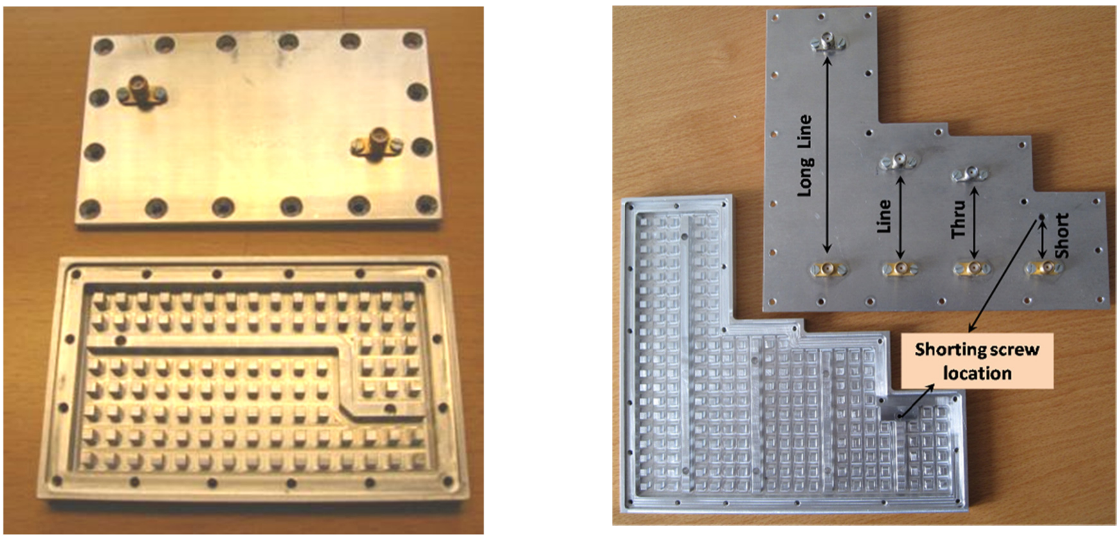


Fig.2.10 Manufactured prototypes of ridge gap waveguide and TRL calibration kit.

2.5 Summary

In this chapter, the basic operating principle of the gap waveguide is discussed along with the design of the pin surface for emulating the AMC surface. Also, the low loss performance of the ridge gap waveguide is validated by designing two prototypes and TRL calibration kit. By using the TRL calibration technique, it is shown that ridge gap waveguides work as transmission line with very low loss over a relatively large bandwidth. However, such lower values of losses are hard to quantify due to the fact that- measurement and calibration uncertainty become comparable to the losses.

Chapter 3
Gap Waveguide Narrow-band Filters

A full duplex communication wireless link consists of transmitters and receivers. In such links, narrow band RF filters are required after high power amplifiers (HPAs) and prior to low noise amplifiers (LNAs). Usually, such full-duplex communication systems transmit and receive simultaneously. The transmitted power in the system is far too high in comparison to the received power. So, the transmitter filter must have very high attenuation in the receive band to stop the intermodulation noise and wide band thermal noise to be fed into the receiver. Also, the loss of the transmitter filter needs to be low due to the linearity and efficiency constrains of power amplifiers. In the receiver case, the noise figure of the receiver is dictated by the losses in the receiver filter as this filter sits before the LNA in the receiver chain. So, the receiver filter should also have a low insertion loss and very high selectivity in the transmitting band. As the number of resonators in a filter is increased in order to increase the selectivity, the insertion loss increases [46-47]. For a specific insertion loss, a narrow band filter usually requires resonators with higher unloaded Q than a broad band filter. Apart from the electrical performance requirement, the filters have to be mass producible and low cost. For this reason, H-plane iris coupled filters and E-plane metal insert filters are extensively used in narrow band waveguide filter design.

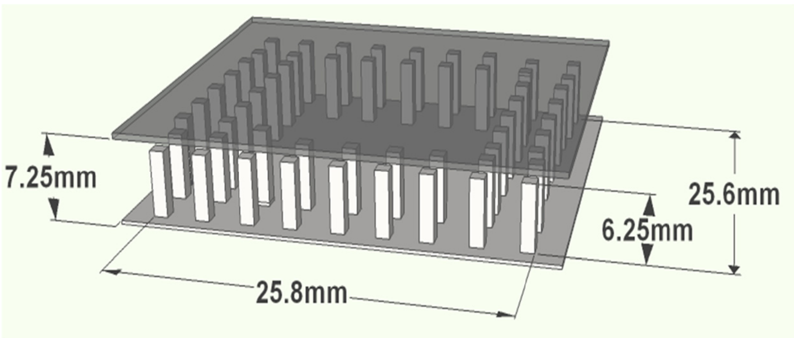
As mentioned in chapter 1, both these type of filters have certain drawbacks at high frequency. In case of H-plane filters, filter assembly will exhibit a transitional resistance between the top metal plate and milled waveguide section. As this transition occurs at location of high current density, this has to be taken care of by ensuring good electrical contact between the two parts; otherwise significant amount of energy will leak through tiny gaps leading to Q value degradation of the resonators [48]. Also, the milling process requires very small tools to manufacture rounded corners with smaller radius [49]. On the other hand, in case of E-plane filters, the electrical performance of filters is mainly determined by the pattern of the metal inserts. For example, the thickness of the metal insert needs to be thin enough (30–80 micrometer) for a moderate filter requirement at 38GHz. The thickness of the metal insert will have to be even thinner at mmWave frequency range to comply with the filter requirements. Also, these metal waveguide types of filters are very difficult to integrate in a single module with other passive components such as couplers or antennas.

In this concern, there is a need for developing new types of high Q filters which are more robust in terms of mechanical assembly and can be integrated with other modules of passive components such as antennas. The groove gap waveguide based high Q filters can be of interest in this case. These high Q filters can be built in an open parallel plate structure surrounded by periodic metal pins without any side walls. The electrical contact between the parallel plates will not play major role in the filter performance as the field leakage will be negligible after two or three rows of pins. Also, measured Q values for such groove gap resonator are similar to that of a rectangular waveguide [50].

3.1 High Q groove gap waveguide resonators

The gap waveguide resonator is a resonator that has very controlled leakage of EM energy through the gap between two metal blocks or plates. This type of resonator basically allows a leakage up to a certain level and traps the rest of the EM energy within the structure. By designing the AMC surface with square pins carefully and utilizing that pin surface to stop propagation of EM wave, the gap waveguide resonator stops the field leakage and traps the EM energy within the structure. It has been observed in previous studies of the gap waveguide that- after two consecutive rows of pins, the field leakage goes down up to a level of -40 dB over significant bandwidth. This motivates the design of the high Q resonator with much more manufacturing flexibility. The metal walls on each side of the resonator and the electrical contact do not play a significant role in trapping the EM energy.

Figure 3.1 shows the half wavelength short circuit groove gap waveguide resonator at Ku band. The resonator also has only some texture of pins forming a groove in the lower metal plate. The detailed design procedure of pin surface to be used as AMC is described in [42]. The pins are about $\lambda/4$ in height. The upper metal plate is a smooth plate and placed at a distance of 1 mm from the pin surface. It was chosen to have two rows of pins on each side of the resonator to make the field decay up to a level of about -40 dB.



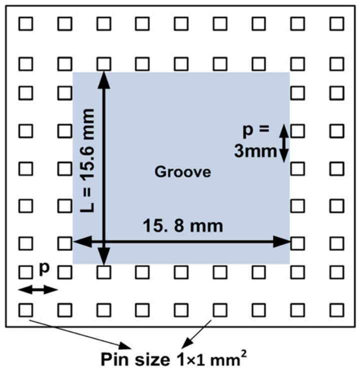


Fig. 3.1 Geometry of the groove gap resonator, perspective view and top view.

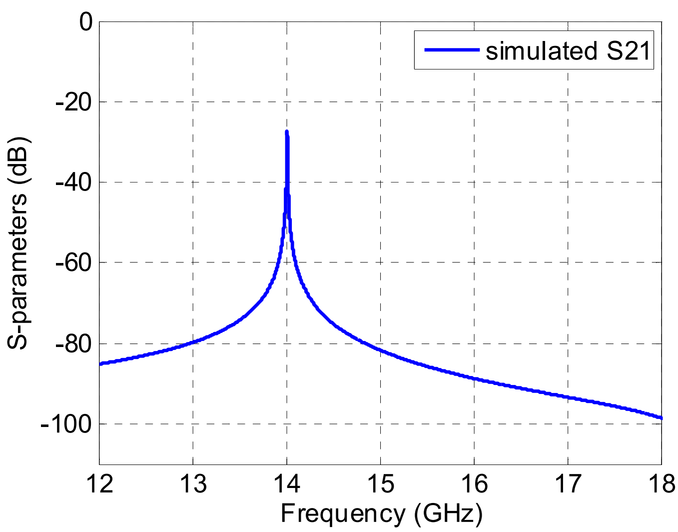


Fig. 3.2 Simulated frequency response of groove gap resonator.

The pins have a cross section of 1×1 mm^2, a height of 6.25 mm and a period of 3 mm. The width of the groove is 15.8 mm, similar to the width of standard Ku-band rectangular waveguide. The total length of the groove is about 15.6 mm. The frequency response of the resonator is also shown below in figure 3.2. The simulated vertical E-field distribution is shown in figure 3.3 for a groove gap waveguide resonator with two rows of pins and three rows of pins surrounding the resonator. The field distribution shows very clearly that after two rows of pins the field is decayed to a level lower than -40dB. The simulated Q value for this type of resonator with conductivity of aluminium is about 4605 which is 14% lower than the simulated rectangular waveguide resonator made with the same material at that frequency. Q factor of a practically realized groove gap resonator and a rectangular waveguide resonator having split in H-plane is compared more in details in [50].

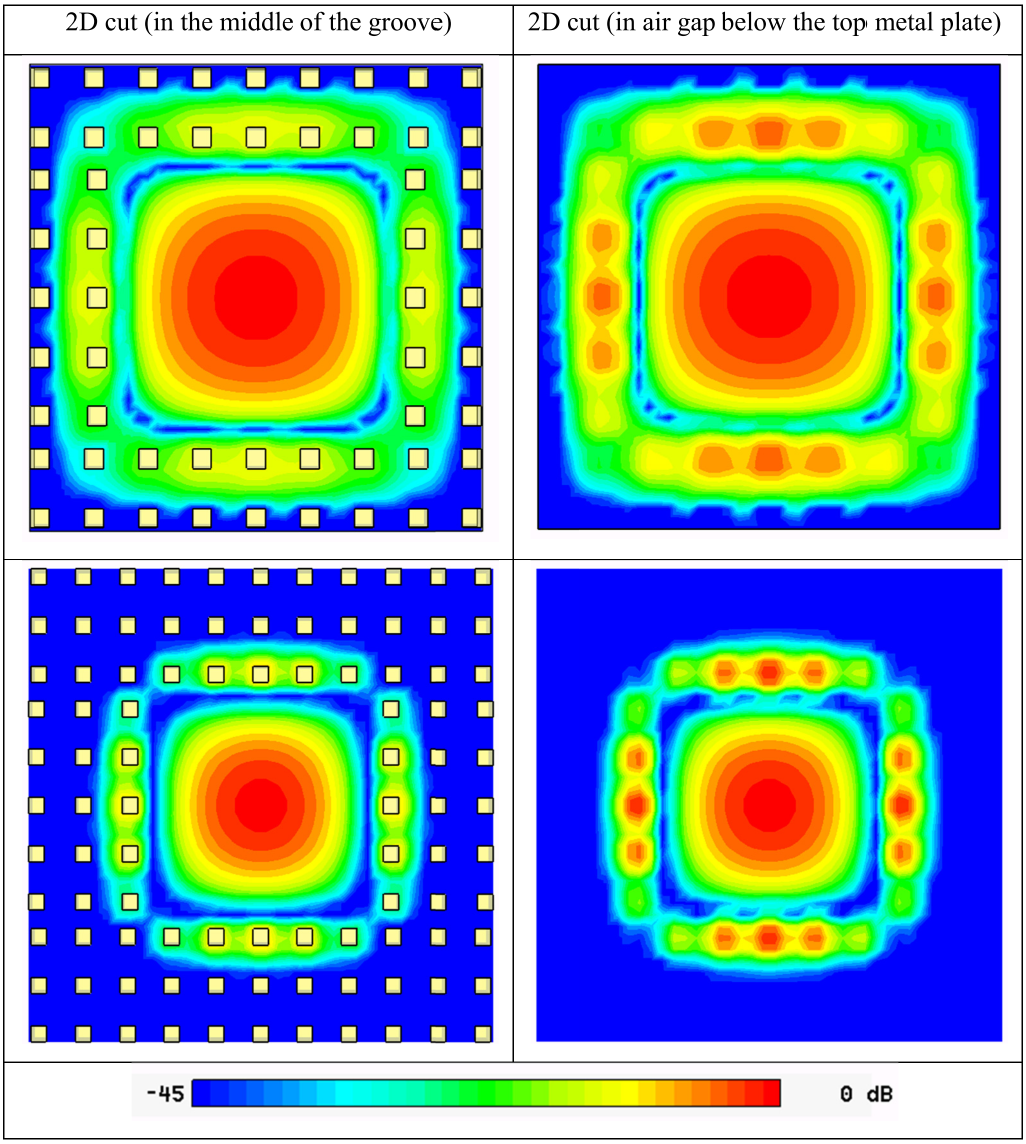


Fig. 3.3 Vertical E- Field distribution for groove gap waveguide resonator.

3.2 Coupling mechanism and narrow band filter design

Two coupling mechanisms are studied to achieve the required coupling between two adjacent groove gap waveguide resonators having different pin dimensions. These are shown in figure 3.4. In the case of ridge coupling, the pin dimensions for the resonators are 1.75×1.75×6 mm^3. The width, length and height of the ridge section can be varied to achieve coupling coefficient values varying over large range. For the other case, the pin dimensions for the resonators are 1.0×1.0×6.25 mm^3. For this case, only the periodicity of the pin rows and distance between the pin rows separating the two resonators are varied. Very low values of coupling coefficients are possible to obtain which is required for very narrow band filters.

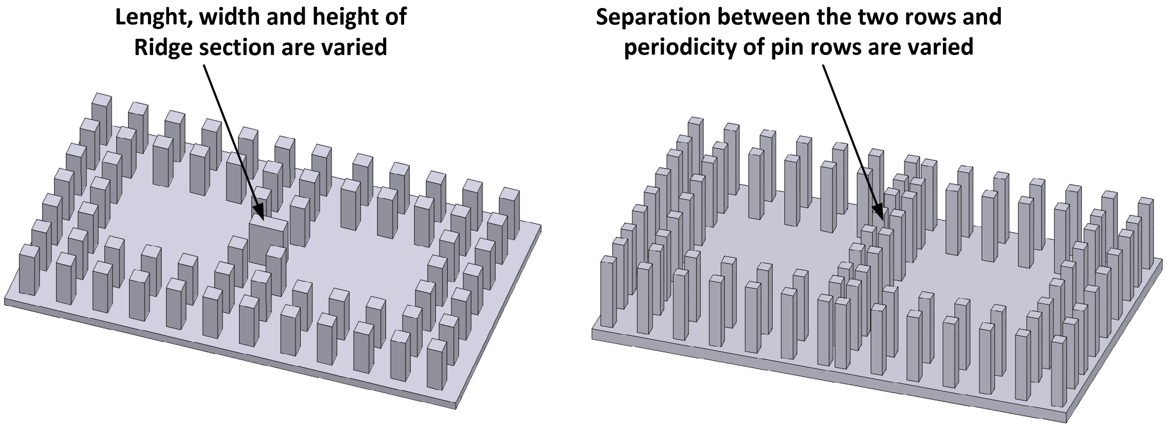


Fig. 3.4 Two types of coupling mechanism for groove gap waveguide resonators.

Based on these two coupling mechanisms, 3rd order and 5th order Chebyshev band-pass filters have been designed at Ku band. The excitation of the input and output resonators of the filters has been achieved by typical coaxial line using SMA connectors for simplicity of measurements with the help of available Vector Network Analyzer at Ku band. Two 3rd order filters having 1% relative bandwidth and pass-band ripple of 0.032dB and 0.1dB are shown in figure 3.5. The simulated results for the two 3rd order filters are shown in figure 3.6. Out of these two filters, the filter with 0.1dB pass-band ripple has been manufactured and tested. The measured results are presented in figure 3.7. The details of this filter design can be found in [48].

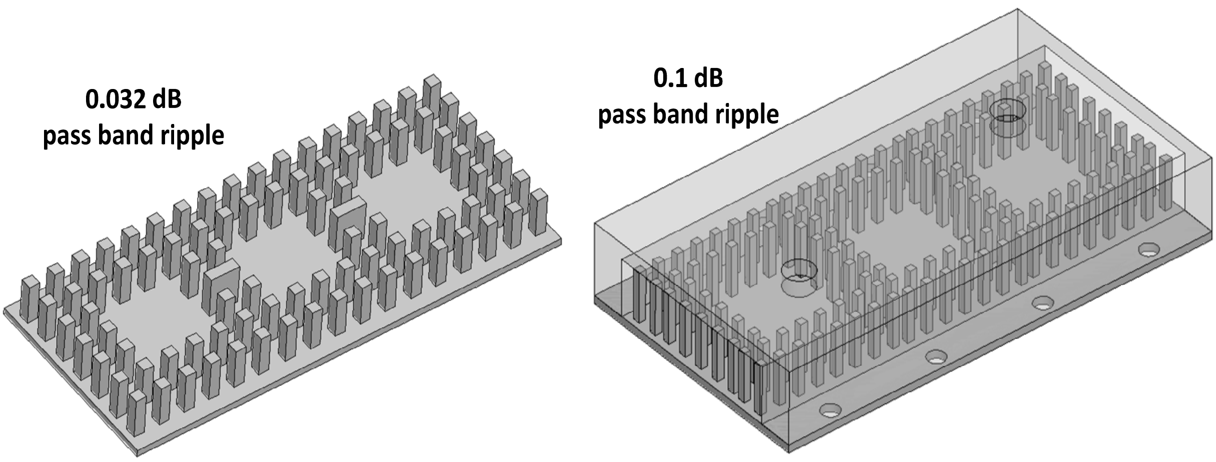


Fig. 3.5 Two different groove gap waveguide coupled resonator filters.

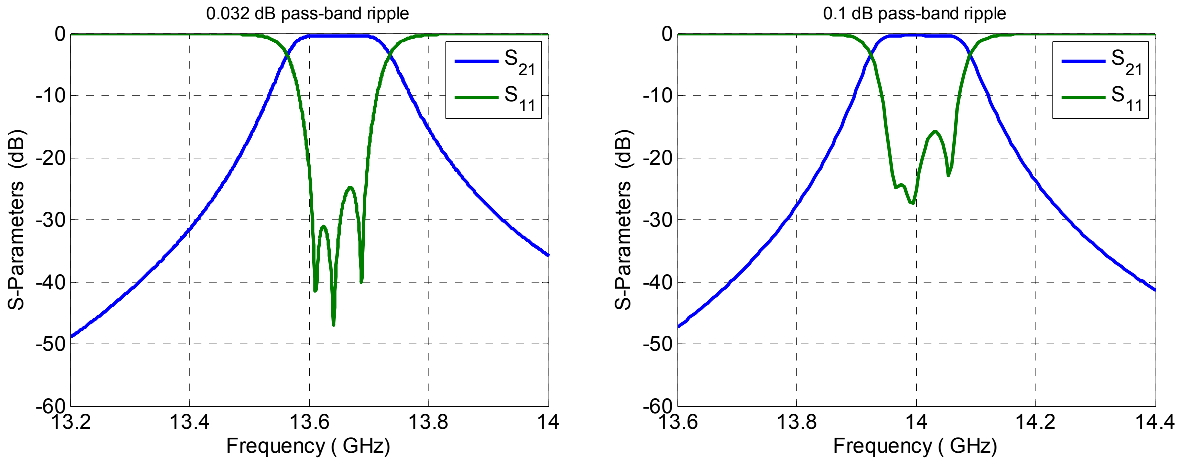


Fig. 3.6 Two different groove gap waveguide 3rd order filter simulated responses.

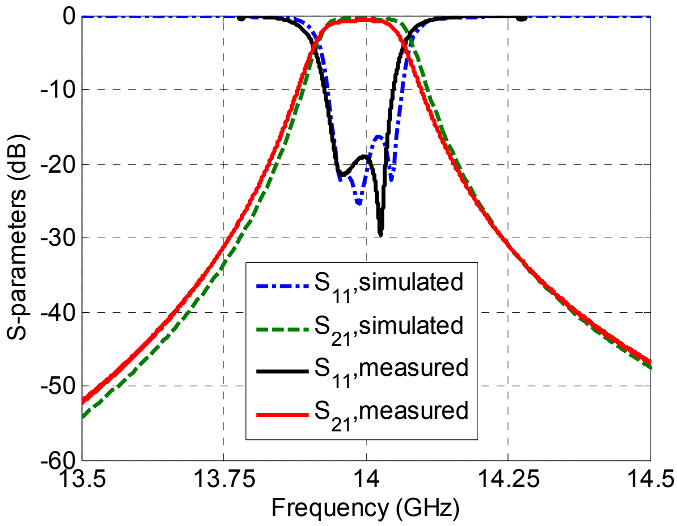


Fig. 3.7 3rd order groove gap waveguide filter measured results [48].

3.3 Ka band filter design for commercial diplexer application

Usually, diplexer filters require very low insertion loss in the passband and high selectivity to reject frequencies close to passband. The purpose of this section is to demonstrate the potential of gap waveguide technology to design filters with very stringent commercial specifications. The key filter specifications for commercial 38GHz diplexers are shown in the following table:

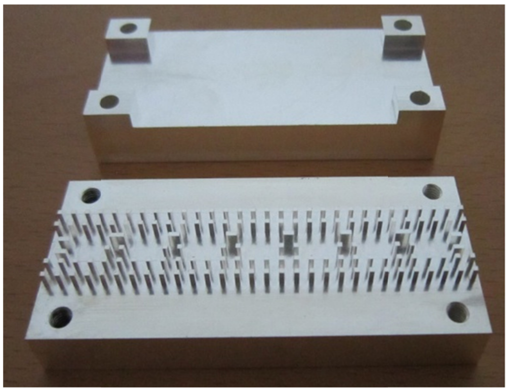
Table: I Specification for the 38GHz diplexer filter

Passband	37.058-37.618 GHz
Stopband	38.318-38.878 GHz
Passband Insertion loss	Max. 1.5 dB
Attenuation in the Stopband	70 dB
Return loss	-17 dB

The general bandpass filter design procedure utilizes the low-pass elements of the prototype filter to determine the required coupling coefficients between the adjacent resonators and the coupling to the external circuit; that is to the source and load. For a filter with $N = 7$, the low pass parameters are obtained from [51]. Once the low pass parameters are known, the coupling coefficients (K) and the external quality factor (Q_{ex}) are easily calculated by using following equations:

$$K_{i,i+1} = \frac{fractional\ bandwidth}{\sqrt{g_i\, g_{i+1}}} \quad ; \quad Q_{ex} = \frac{g_n\, g_{n+1}}{fractional\ bandwidth}$$

To design the filter, the ridge coupling scheme presented in section 3.2 have been chosen. The resonators are designed with pin dimension 0.7×0.7×2.3 mm^3. The periodicity of the pins has been chosen as 2.1mm. The manufactured 7th order filter and the measured response of the filter are shown in figure 3.8. Details of this filter are presented in [52].



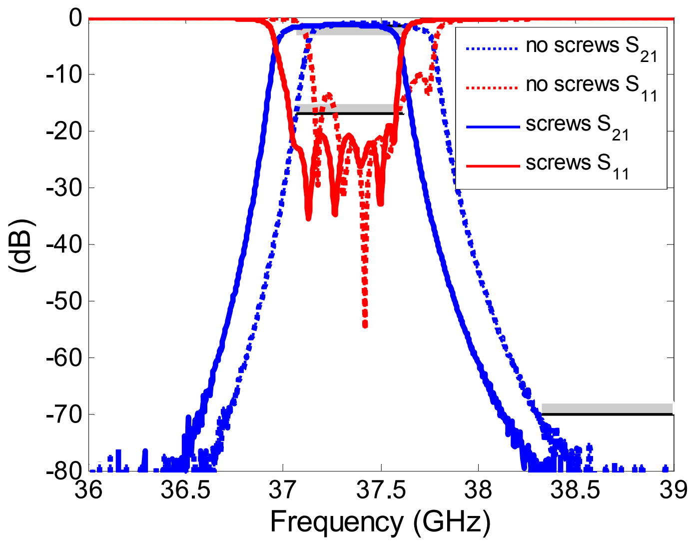


Fig. 3.8 Ka-band 7th order groove gap waveguide filter prototype and measured results [49].

3.4 Summary

Newly introduced groove gap waveguide technology is used to design high Q resonators and narrow band microwave filter with a fractional bandwidth of about 1-2%. Two different types of coupling mechanism have been described and used to design the filters. Good electrical performance has been achieved for manufactured filter structures even after removing all the sidewalls. These filters do not need any electrical contact between the split blocks and thus relaxes the tight mechanical restriction usually applicable to the standard waveguide cavity filters. Also, the measured performance for the filter at Ka band shows that these filters can meet very stringent commercial specifications.

Chapter 4
Gap Waveguide Slot Array Antenna

Wireless communication systems have evolved from cellular telephony with data rates of kilobits per second (kbps) to wireless local area networks (WLANs) and wireless personal area networks (WPANs) that communicate with megabits per second (Mbps). High-gain and large-aperture antennas with fixed beams are required to achieve high S/N ratio for point-to-point high-speed systems (e.g., network backhaul) in the mmWave frequency band.

Although high antenna efficiency can be obtained by using dielectric lens antennas or reflector antennas [53-56], it is difficult to realize planar structures because they essentially need focal spatial length. Microstrip array antennas can be light weight, low cost and low profile but they suffer from high dielectric losses and ohmic losses at high frequency bands [57]. Also, microstrip array antennas are associated with problems such as leakage via surface waves and undesired radiation [58-59]. Thus, realization of a high efficiency high gain microstrip antenna array is quite challenging especially at mmWave frequencies and above.

Slotted hollow waveguide planar array antennas are free from large feed-network loss and can be applied to design high-efficiency high-gain or moderate-gain antennas [60-61]. However, the production cost of waveguide antennas is generally very high because they usually consist of metal blocks with complicated three-dimensional structures. Usually, high precision manufacturing techniques are needed to achieve good electrical contacts between the slotted metal plate and the bottom feed structure in such waveguide fed slot array antennas [62]. Apart from the manufacturing costs and assembly complications, some limitations of waveguide slot arrays have been reported in literature. Single layer waveguide slot arrays (if the elements are series feed) are simple but have narrow bandwidth due to long line effect [19]. In single layer structure, it is difficult to feed each radiating element in parallel (fully corporate-feed) without having the element spacing close to one wavelength (λ_o) and avoiding grating lobe issues [63-64]. For wider bandwidth, multilayer antenna configuration has been considered in [21], [65] which add extra complexity in feed network and mechanical assembly.

The ridge gap waveguide technology mentioned in the previous sections of this thesis can be used to design low loss slot array antennas. The low loss feed network needed for an array can be built very easily with the help of ridge gap waveguide concept. In addition, radiating slots can be placed conveniently on the top smooth metal plate of ridge gap waveguide. It is possible to design slot antenna without having strict requirements of good electrical contacts between the slotted metal plate and the bottom feeding structure. Thus, the ridge gapwaveguide slot antenna with flexible mechanical assembly can be an attractive as well as cost effective solution for high gain and high efficiency applications. The corporate feed network (consisting of simple T-junctions) which is a key for wideband slot array application, can be designed in a fashion similar to that of a microstrip array.

4.1 Ridge gap waveguide slot element and 3-dB power divider

The slot array antenna design usually starts with a single slot element. Similar approach is followed in this work as well. The initial single slot antenna excited by ridge gapwaveguide is shown in figure 4.1(a). This single element is quite narrow band as is observed in simulated S_{11} results. Later on, this design has been improved with addition of a T-section ridge [66]. The length and the width of the slot element are also varied to have the S_{11} level below -10 dB over a significant bandwidth. The improved element design and obtained reflection coefficient for the element are shown in figure 4.1(b).

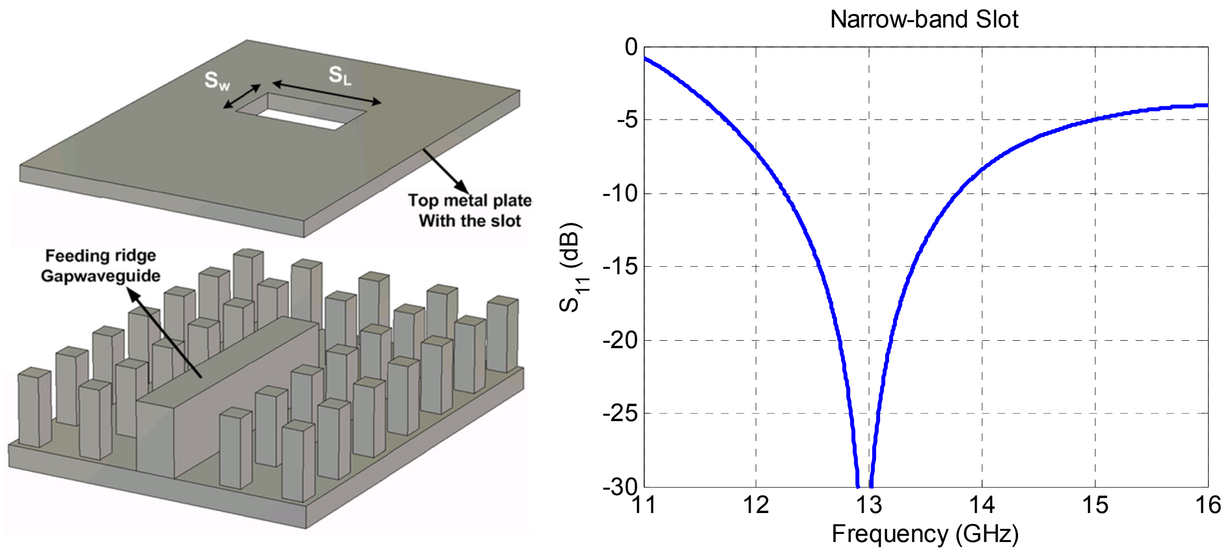


Fig. 4.1(a) Narrow band slot with dimension S_L = 11.5mm; S_W = 5.85mm and its simulated reflection coefficient.

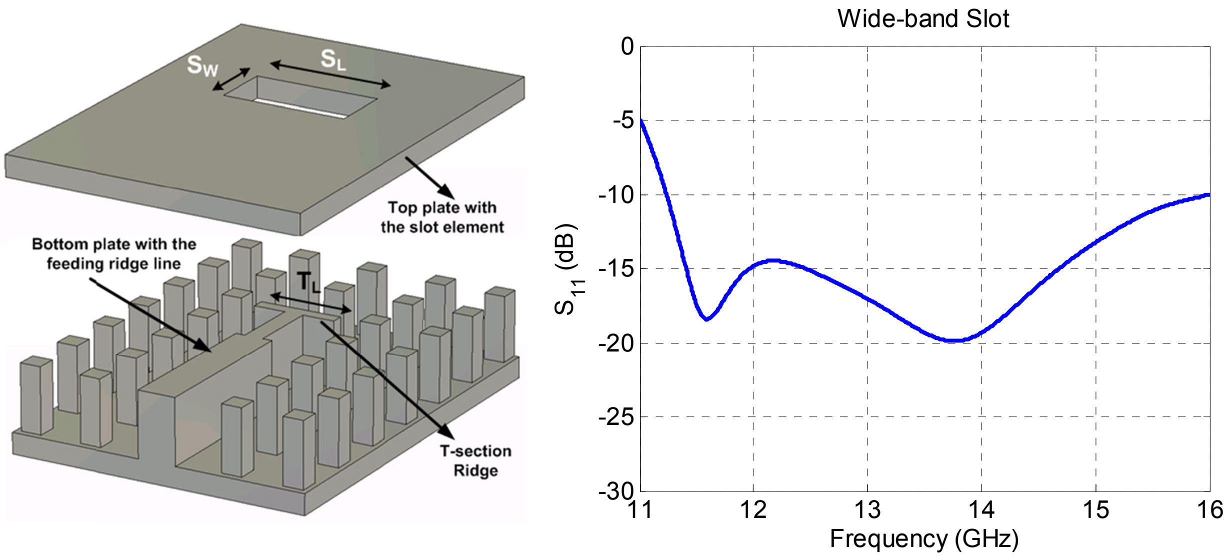
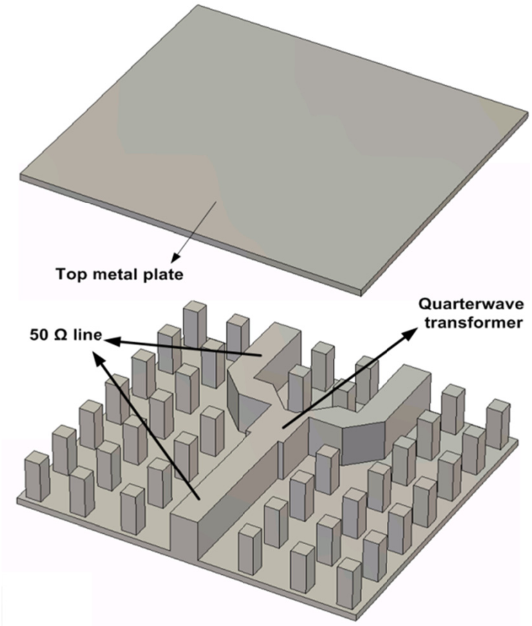


Fig. 4.1(b) Wide band slot with T-section and its simulated reflection coefficient; S_L = 11.75mm; S_W = 5.85mm; T_L= 8.25 mm.

Another important component for antenna corporate-feed network is the 3-dB power divider in the form of a T- junction. The T-junction usually consists of a quarter wave transformer section and three 50Ω lines. The ridge waveguide T-junction power divider and its simulated S-parameters are shown in figure 4.2. The simulation results show that it is possible to design a wideband feed network for a complete array antenna based on this T-junction.



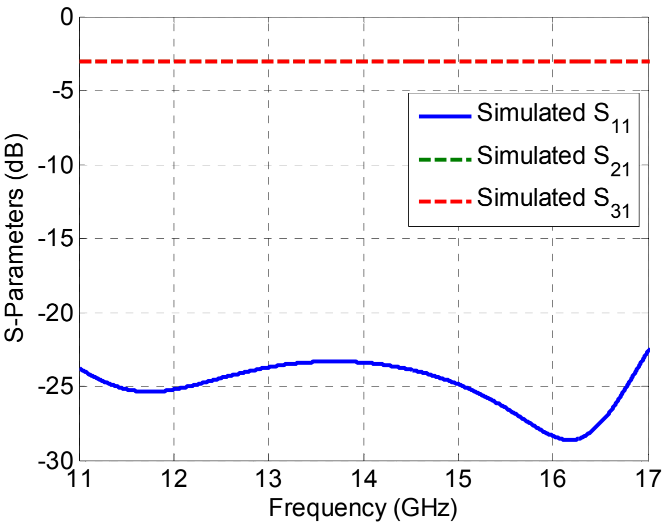


Fig. 4.2 Simulated S-parameters for ridge gap waveguide T-junction.

4.2 Design of linear array antenna

Based on the above mentioned slot element and the 3-dB power divider, a 4×1 linear slot array has been designed. At this point, the linear array is designed for a fixed beam in mind. So, the element spacing can be kept 0.85λ to avoid grating lobes and all the slot elements are excited with equal amplitude and phase. The complete array is shown in figure 4.3 and it is designed to operate between 11.5-14.5 GHz frequency band [67]. As shown in figure 4.3, the bottom plate with ridge and texture pin structure holds the feeding network for the array. On top is placed a smooth metal plate with four radiating slots at a distance of 1 mm from the bottom plate. It is important to mention that- no electrical contact between the radiating layer and bottom feed layer is needed in the array which is a significant advantage of this technology.

As expected, the array has more directive beam and symmetric pattern in H-plane. In H-plane, the first side-lobe is 11.8 dB lower from the beam peak value which is also common for uniform arrays. On the other hand, in E plane the beam is wider and is not really symmetric as the slots are close to the edge on one side. In E-plane, there is a possibility of back radiation as the slots are close to the edge. To avoid this back radiation, three corrugations are added. It is needed also a transition from ridge gap waveguide to the standard transmission line for measurement of the entire antenna. This transition can be a simple interface consisting of steps in ridge which allows the Quasi TEM mode to convert to a groove gap waveguide mode (similar to that of standard rectangular waveguide mode). Then the antenna can be excited with an SMA connector with extended inner conductor. The measured S_{11} and measured radiation patterns in the main planes are shown in figure 4.4 and figure 4.5 respectively.

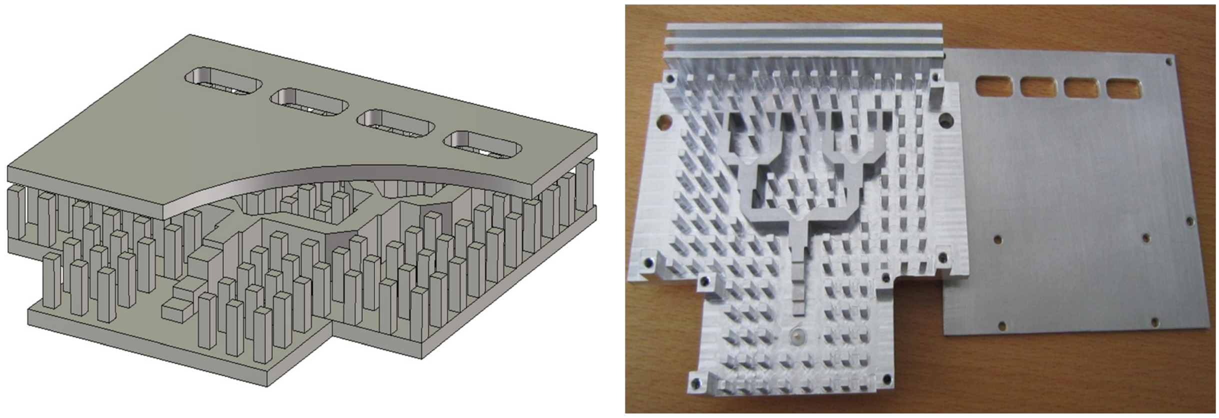


Fig. 4.3 CST model of the linear array and manufactured array.

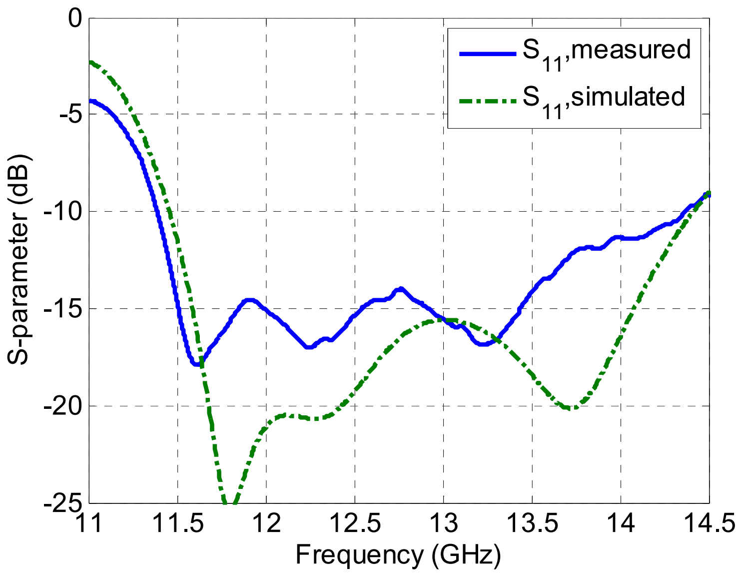


Fig. 4.4 Measured and Simulated S_{11} for the linear array.

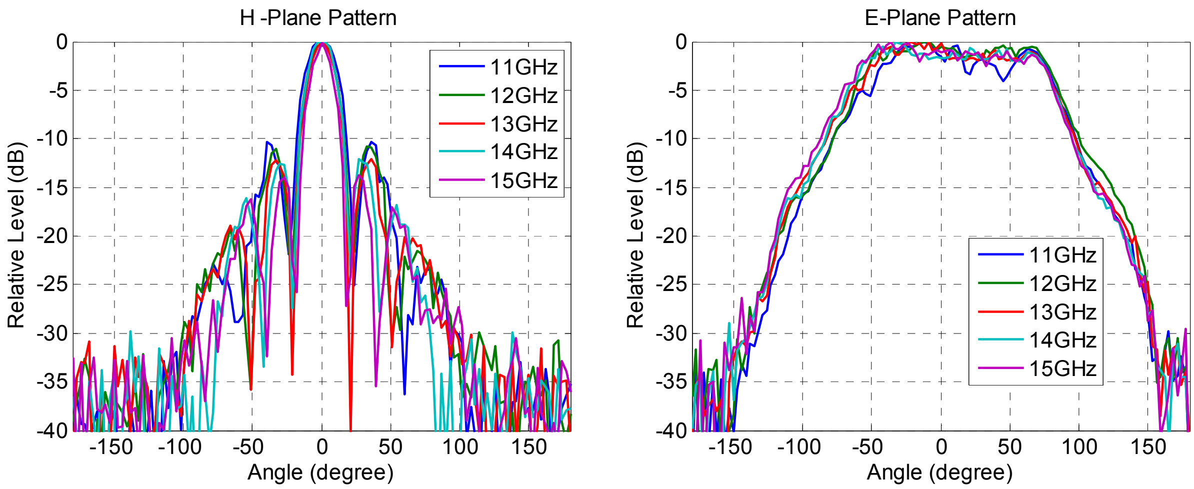


Fig. 4.5 Measured E and H plane radiation patterns for the linear array.

4.3 Design of 2×2 element planar array antenna

After designing the linear array, a simple 2×2 element planar array has been designed with ridge gap waveguide technology to operate over the band 12-15 GHz. The 2×2 element array is excited in phase and with equal amplitude by a corporate feeding. The element spacing is about 0.88λ at highest frequency of interest. The slot length 'S_L' and slot width 'S_W' are chosen to be 11.45mm and 6.25mm for this particular design. The antenna is excited with a standard Ku-band rectangular waveguide from the bottom plane using a transition that will be described in chapter 6. Figure 4.6 shows the model of the antenna and the manufactured antenna. The figure 4.7 and figure 4.8 presents the measured reflection coefficient and measured principle plane radiation patterns respectively. It is evident that more than 20% impedance bandwidth is achieved for this antenna.

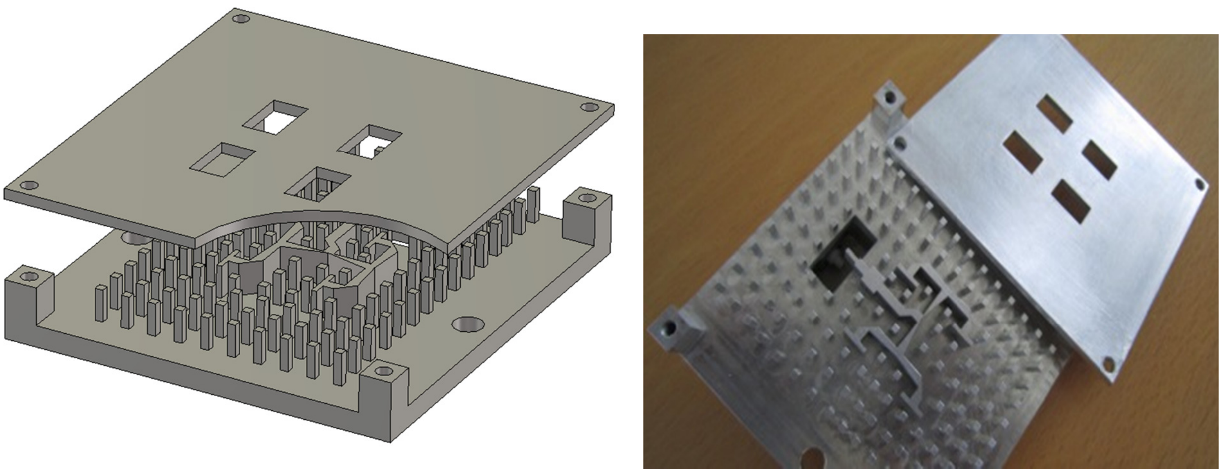


Fig. 4.6 CST model of the 2×2 element array and manufactured array.

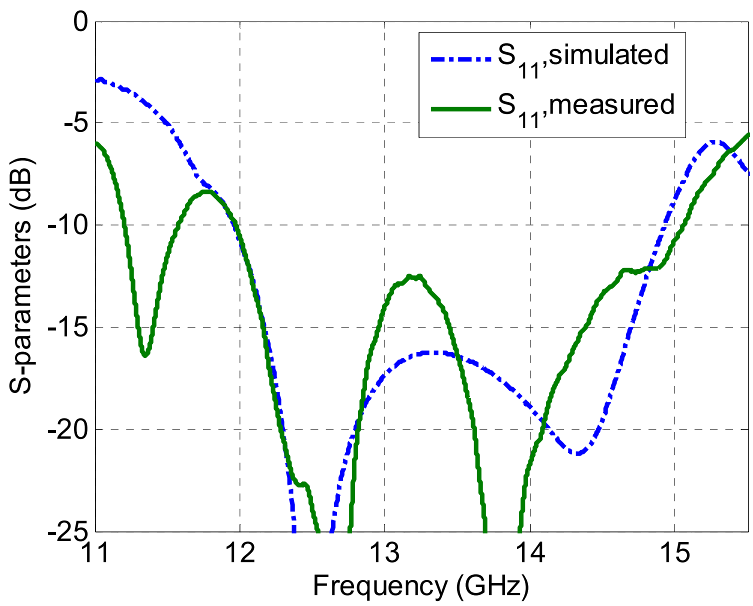


Fig. 4.7 Measured and simulated S_{11} for the planar array.

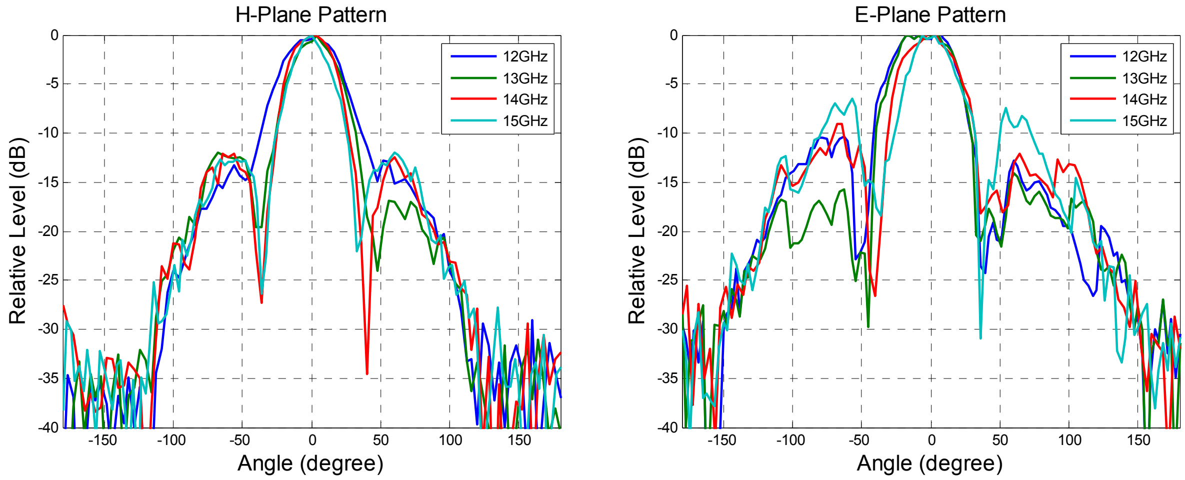


Fig. 4.8 Measured E and H plane patterns for the planar array.

4.4 Summary

A 4×1 element linear slot array and 2×2 element planar array antenna based on ridge gap waveguide technology have been presented in this section. For both antennas, the low-loss corporate feed network has been designed on the bottom metal plate with guiding ridge and periodic pins, and above the ridges there are radiating slots in the top metal plate. There is absolutely no need for electrical contact between these bottom layers and top radiating layers of these antennas, thus making them cost effective to manufacture and very simple to assemble mechanically. The simulated and measured results also show reasonable agreement for both the antennas.

Chapter 5
Gap Waveguide Packaging Solution

Most of mmWave microwave systems have to operate at outdoor, under harsh weather conditions and therefore have to be shielded, i.e., *packaged* in a proper way to provide protection against mechanical stress and environmental condition. Also, to comply with the smaller size requirements and compactness for mmWave microwave modules, large amount of electronic components are to be placed into a confined area. For such high density microwave modules, RF packaging is more and more important in terms of isolation and interference suppression.

In a common microwave module, circuit components such as MMICS are placed on a dielectric substrate which can carry the necessary interconnecting lines, the passive components etc. Enclosing the complete circuitry in a metal package usually degrades the RF circuit performance because of the onset of package resonances and more, in general, due to the interactions of electromagnetic fields (produced by the signal propagating in the electronic circuitry) with the package itself. Published studies show that significant power leakage exists on various printed circuit transmission lines, often related to surface waves in the dielectric substrate causing serious cross-talk and interference problems. Apart from this problem of surface wave or PP mode leakage and radiation, at mmWave frequencies, interconnects and transitions between different components or even the interconnecting signal lines may produce spurious radiation or standing waves. This can easily get coupled (over the air) to the neighbouring circuit elements resulting in interference and cross-talk. Figure 5 displays some of the possible ways of electromagnetic field coupling and unwanted energy leakage between the adjacent circuit elements and also shows the conventional prevention techniques mentioned in [68-69].

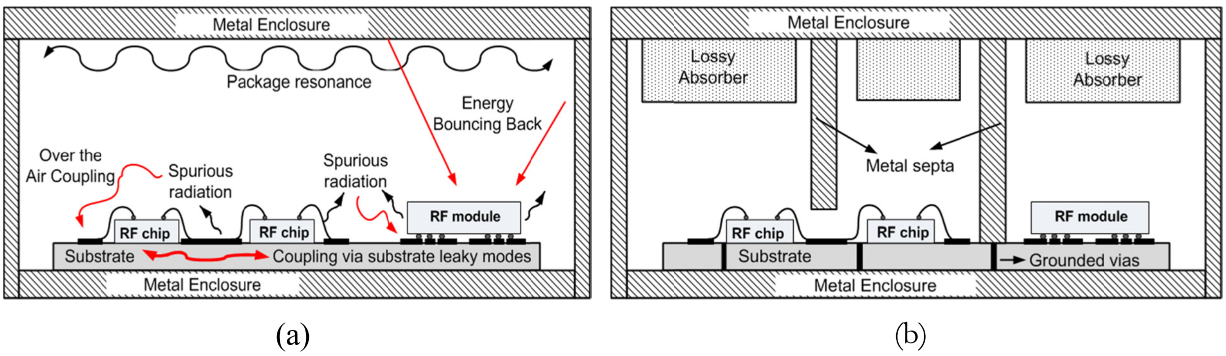


Fig. 5: a) Various undesired coupling phenomena; b) traditional prevention techniques.

In practice, the efficiency of the different techniques available for reducing packaging problems and reduction of cross-talk goes down with frequency; the higher the frequency, the lower is usually the effectiveness of the techniques mentioned so far. So, there is a need for new packaging technology to be used at high frequency and gap waveguide based PMC packaging can be a real good solution to overcome the packaging related problems.

5.1 Gap waveguide packaging concept

The gap waveguide packaging solution is based on the concept shown in figure 5.1. Here the parallel plate cut-off is achieved by a Perfect Magnetic Conductor (PMC) surface when the opposite surface is a Perfect Electric Conductor (PEC) and as long as the spacing between these two surfaces is smaller than quarter wavelength. Once a substrate and the microstrip line are placed, the dominant microstrip mode can propagate along the strip only. Field propagation in all other directions is stopped by the above mentioned PEC-PMC concept. As PMC is not naturally available, the periodic structure of square pins (having height equal to quarter wavelength) is used to obtain the artificial magnetic conductor.

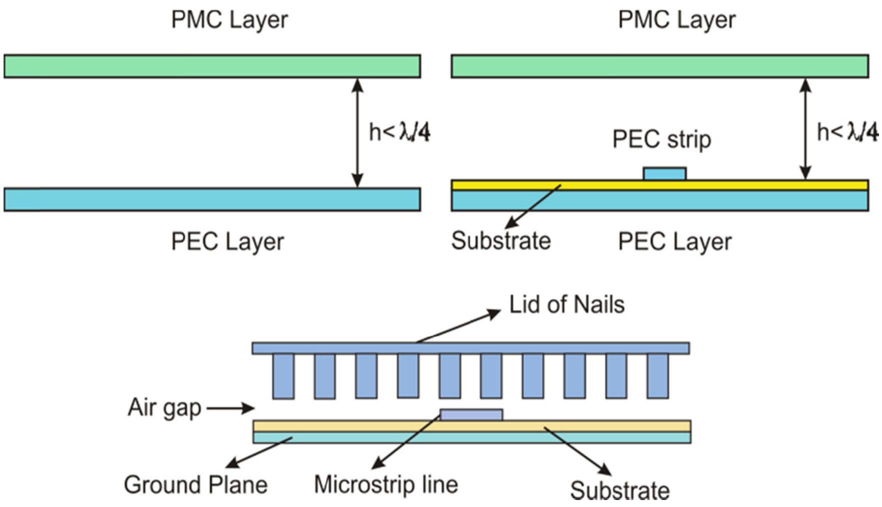


Fig. 5.1 Gap waveguide packaging concept.

The application of gap waveguide for packaging was first demonstrated successfully for a passive microstrip line in [70]. Later it was applied to a multi-port antenna feed network in [71] and to improve the performance of well-known coupled line microstrip filter [72]. In all these cases, it was observed that unwanted cavity modes and surface waves were efficiently suppressed within the band of interest. In the above mentioned references, periodic pin structures have been used to realize the AMC. But recently, several other periodic structures such as periodic metal springs [73] or, periodic zigzag lines printed on a substrate [74] have been used to obtain the AMC condition for such kind of work. Also, wider resonance free packaging bandwidth is of immense interest in designing multi-purpose MMICS as the complete chain of MMIC is active over a very wide frequency band. In this regard, new inverted pyramidal shape geometry is studied and this new geometry offers a very large parallel plate stop band [75].

Apart from the improvements in electrical performance, this new packaging technique offers an advantage while doing circuit design using full wave simulations based on FTTD or FEM. With this new technique, the designer can reduce the computational domain by using an ideal PMC surface instead of several matching layers. This saves computer time and requires no major modification afterwards (when the circuits are practically realized) as the packaging effects are already considered during the full wave design [76].

5.2 Gap waveguide packaging for improved isolation within microwave modules

Instability in a mmWave amplifier (if biasing circuit is properly designed) is mainly the result of unwanted feedback across the amplifier and such feedback is normally introduced during the packaging [77-79]. Engineers are left with options such as placing lossy absorber material in the packaged cavity or relocating a particular circuit element to a different position in the cavity, in order to solve problems with cavity resonances and other package phenomena. These particular approaches are effective if the amplifier gain in each cavity is not very high, typically below 20~22dB, and they become less effective if larger gains are required of the amplifiers in every cavity. This section describes the performance (stability, oscillation tendency etc.) improvement in case of a Ka band high gain amplifier chain when the proposed gap waveguide packaging technique is used in comparison to the standard metal wall and absorber based solution. The two isolation cases investigated in this work are shown below in figure 5.2.

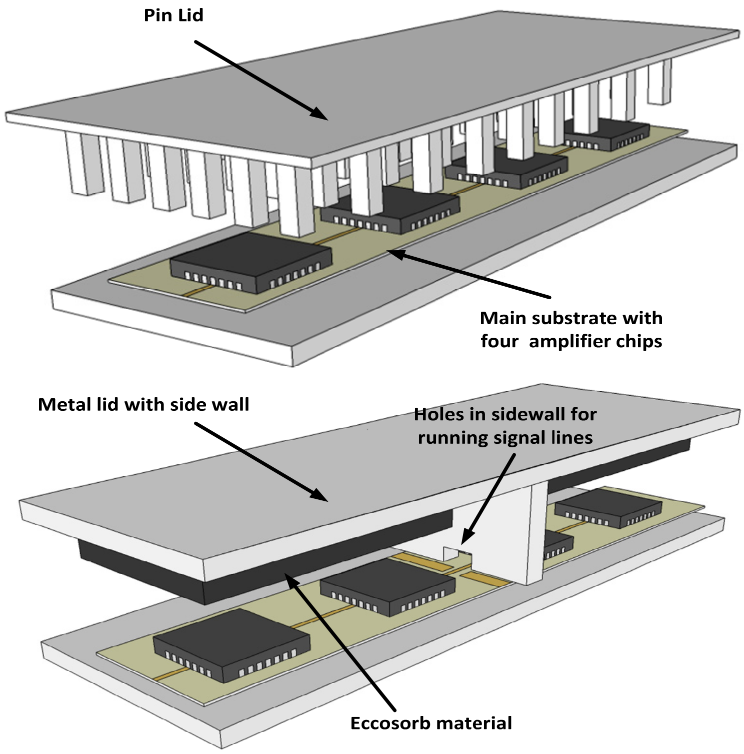


Fig. 5.2 Test circuits for isolation evaluation of a single amplifier chain (side walls not shown).

The amplifier chains used in the test circuits consisted of four variable gain amplifiers from UMS (CHA3694-QDG) and have been placed on the Arlon main substrate. This main substrate is attached to a smooth metal plate by using silver epoxy. Passive components such as capacitors and resistors, as a part of the biasing network, and DC-connectors are placed in another FR4 substrate and are attached on the other side of the same metal plate. DC and RF sides are interconnected using Samtec's through-hole headers. Two experimental approaches have been followed to test the isolation performance of the single chain amplifier: stable forward gain test and self-oscillation test. This has been explained in details in [80]. The measured results for only the self-oscillation test are presented in this section in figure 5.3. As shown in the figure, no oscillation peaks have been observed for gap waveguide packaging (pin lid packaging) even after 65~70 dB of forward gain. On the other hand, for traditional metal wall packaging with absorbing material, resonance peaks appeared at around 40dB of total forward gain.

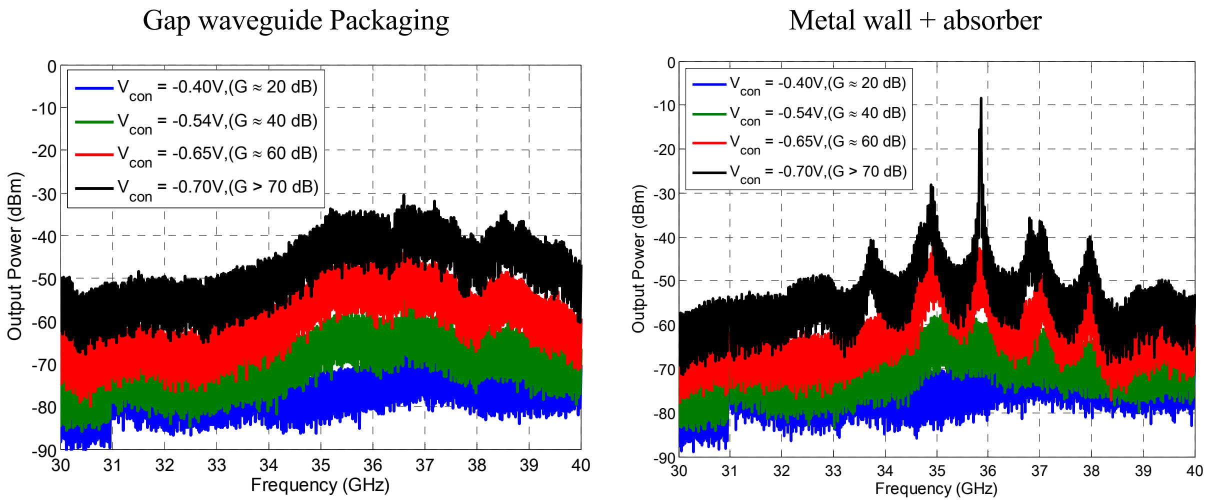


Fig. 5.3 Measured results for self-oscillation test.

5.3 Summary

The gap waveguide technology represents hereby, a new and advantageous way of packaging high frequency microwave circuits. The performance of the complete microwave system can be destroyed due to the packaging problems such as cavity resonance, spurious radiation, dominant mode coupling to substrate modes etc. This chapter clearly shows that- the proposed gap waveguide technology is a very suitable technology which can overcome the problems of packaging of RF circuits and can improve the electrical performance of the overall system.

Chapter 6
Gap Waveguide Transitions

The transitions between gap waveguide and other standard transmission line such as microstrip and rectangular waveguide are very important constituent related to gap waveguide components. Most often, other transmission lines have standardized cross-sections (e.g., rectangular waveguide) or characteristic impedance (e.g., microstrip line). In order to reduce the reflections from the interface between gap waveguide and standard transmission lines, impedance transformers or matching sections are required. This chapter deals with one microstrip to ridge gap waveguide transition and two ridge gap waveguide to standard rectangular waveguide transitions.

6.1 Microstrip to ridge gap waveguide transition

This transition is based on the fact that the E- field of dominant mode in a microstrip line can be transformed easily to a standard ridge waveguide mode [81-82]. In case of ridge gap waveguide, it is even simpler as the dominant mode is also a Quasi-TEM mode. This is shown in figure 6.1.

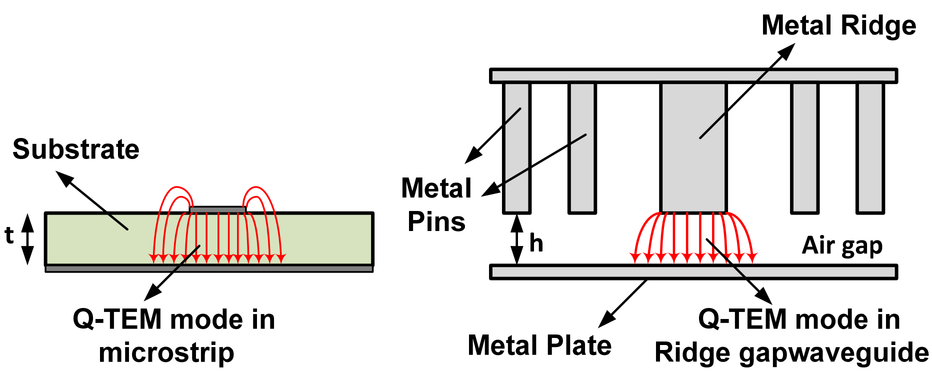


Fig. 6.1 E-field distributions of dominant mode of microstrip line and ridge gap waveguide.

Due to such similar field distribution, only requirement for a good transition between these two different transmission lines is an interface for transforming E-fields in the dielectric to E-fields in the air. This can be done by tapering down the width of the ridge section in several steps. In the proposed design, the narrower ridge section is viewed as an extended section of the regular ridge section and is placed just above the microstrip line. The width of the ridge at this section is kept similar to that of the metal strip in microstrip line. In this way, this tapered ridge section needs to be in electrical contact with the microstrip line and the substrate. This can be achieved by soldering, gluing or simply by pressing the ridge section down. In this work, the electric contact is achieved only by mechanical pressure contact. Schematic of the designed transition between the microstrip line and ridge gap waveguide is shown in figure 6.2. A standard Chebychev transformer based on several $\lambda_g/4$ sections of different width can also be employed to improve the transition. But in this work, only one tapered section of the ridge has been used in a way to keep the overall transition compact. The manufactured transition and the measured results are shown in figure 6.3. The measured return loss is 14.15 dB for the 23-43 GHz band which means that a single transition will have even lower return loss over the entire Ka band of interest. The maximum insertion loss over the same 23-43 GHz band is found to be 0.32 dB for the back-to-back transition including the losses of the ridge gap waveguide section meaning a loss smaller than 0.16 dB per single transition over the entire Ka band.

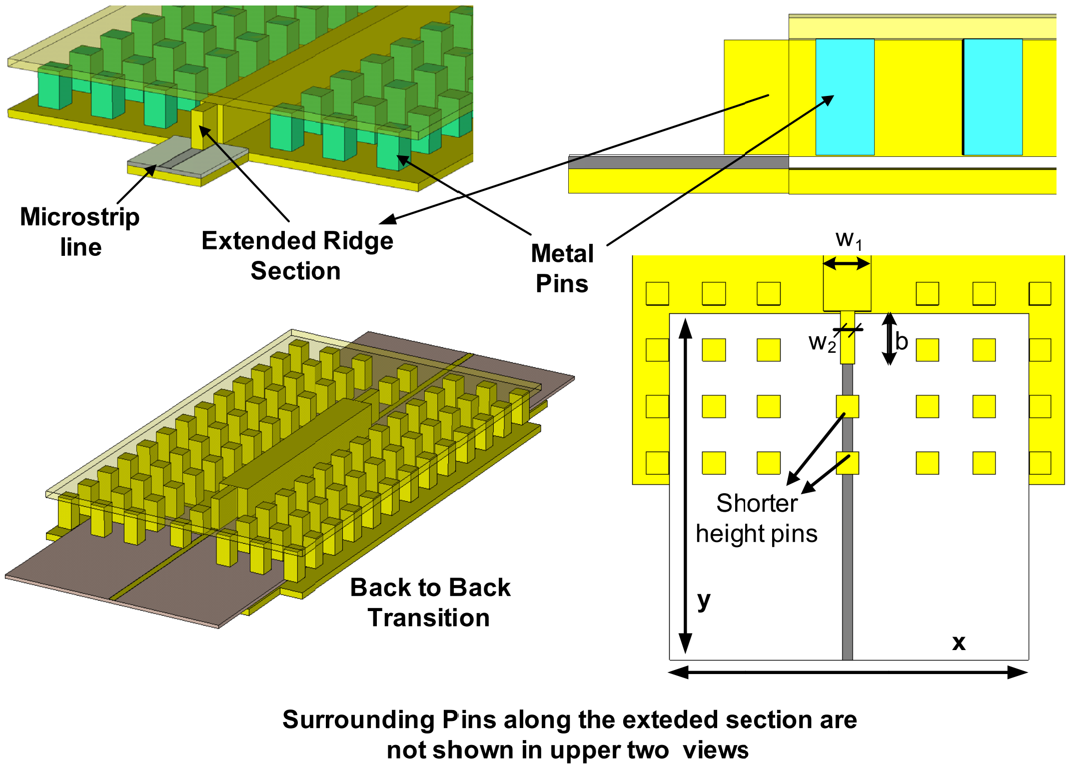


Fig. 6.2 Schematic details of the proposed transition, $W_1 = 2.65$ mm, $W_2 = 0.72$ mm, $x = y = 20$ mm and $b = 2.75$ mm.

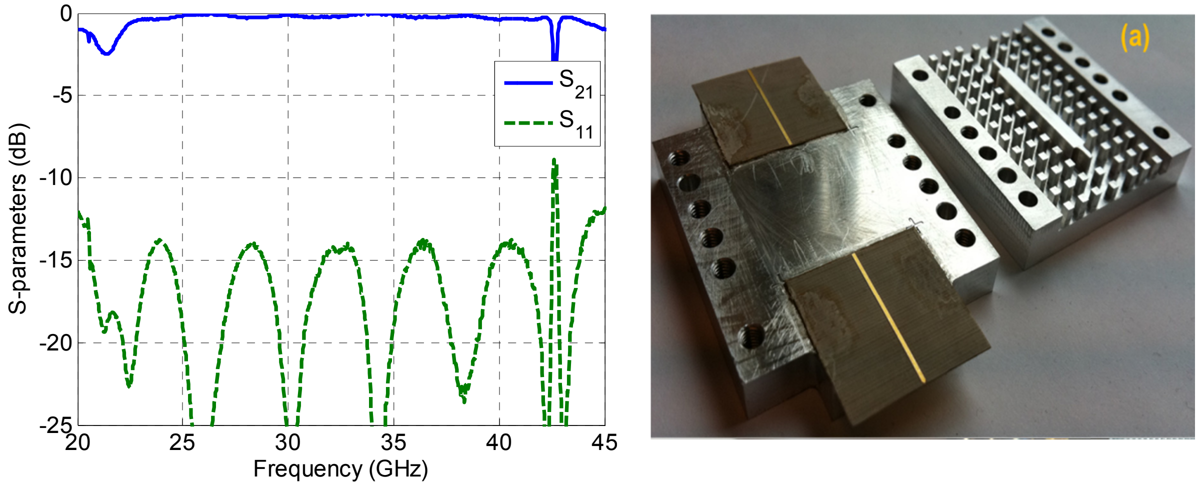


Fig. 6.3 Manufactured back-to-back transition and measured S-parameters for the transition.

6.2 Ridge gap waveguide to rectangular waveguide transition

Two transitions from ridge gap waveguide to rectangular waveguide have been designed recently. One is the inline transition where the height of the guiding ridge is reduced in several steps to match the height of the empty rectangular waveguide. In the other transition, the ridge gap waveguide is excited by a rectangular waveguide from the bottom. The first transition with stepped ridge sections is designed at Ka-band and is shown in figure 6.4 where the critical dimensions are as follows: L_1 = 2.46mm; L_2 = 2.27mm; L_3 = 2.17mm; L_4 = 1.78mm and S_1= 0.22mm; S_2= 0.52mm; S_3= 0.76mm, S_4 = 0.53mm and S_5= 0.42mm. The simulated performance of this back to back transition is shown in figure 6.5. We can observe a good performance in the whole waveguide band.

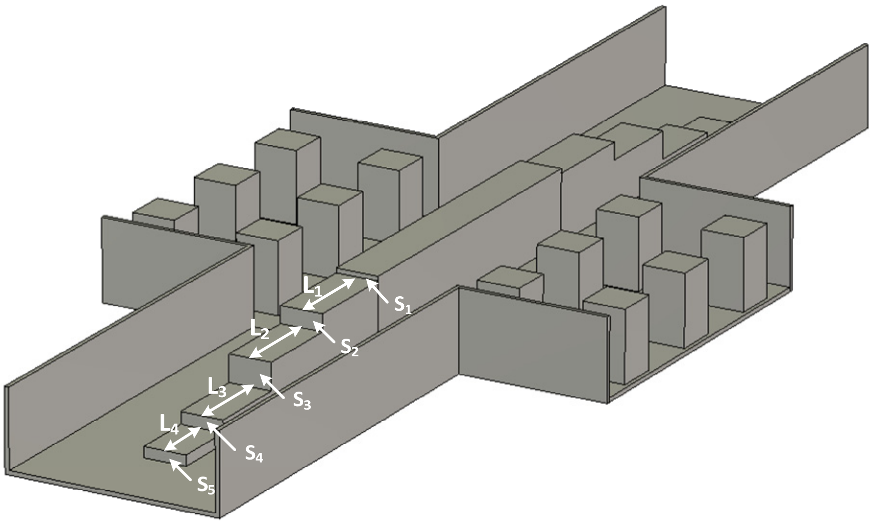


Fig. 6.4 Back-to-back transition with stepped ridge section, top metal plate not shown here.

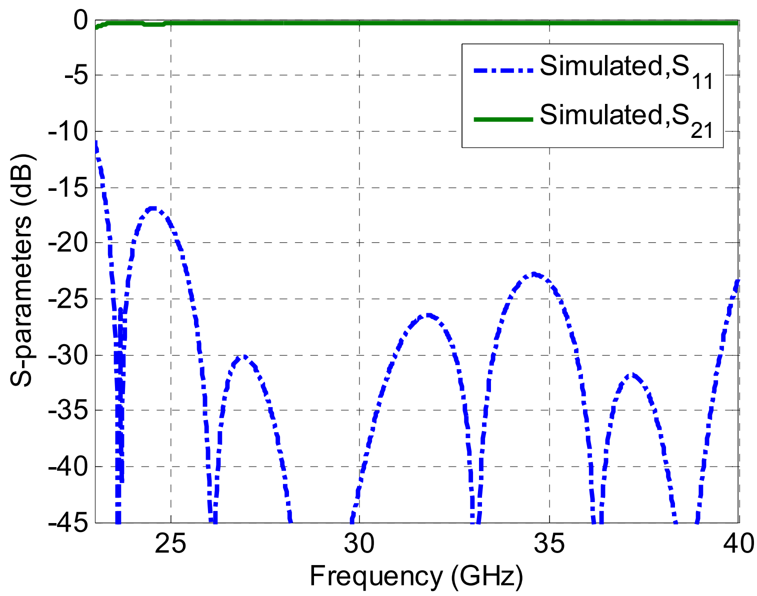


Fig. 6.5 Simulated S-parameters for the stepped ridge back-to-back transition.

The other transition is also a simple transition where the rectangular waveguide is feeding the ridge gap waveguide from the bottom. This type of transition is needed for measuring the ridge gap waveguide antenna where the feeding waveguide has to be placed below the antenna. The transition is designed at

Ku-band and is shown in figure 6.6 where all critical dimensions for this transition are as follows: P_L = 3.65mm; P_w = 1.25mm; P_s = 4.25mm; R_w = 4mm; R = 2mm. The simulated performance of the single transition is shown in figure 6.7.

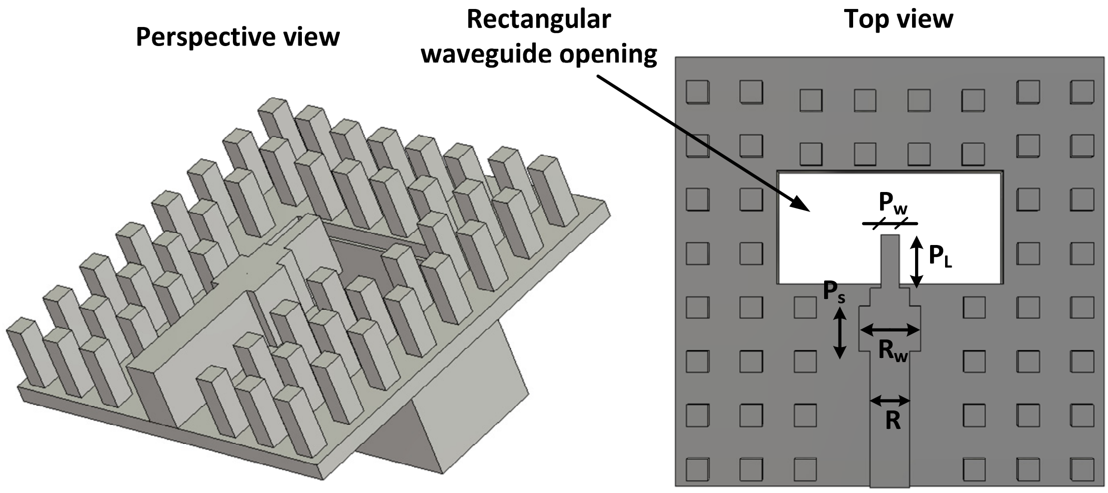


Fig. 6.6 Ridge gap waveguide to rectangular waveguide transition (fed from bottom).

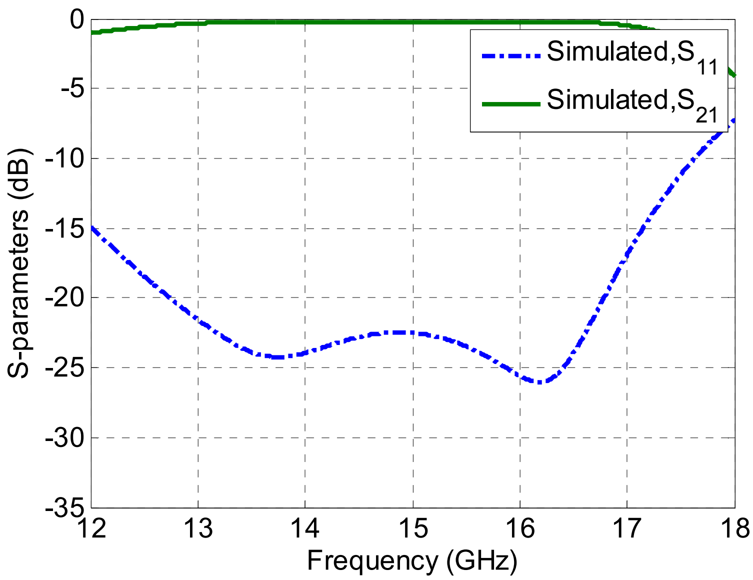


Fig. 6.7 Simulated S-parameters for the single transition of ridge gap waveguide to rectangular waveguide (fed from bottom).

6.3 Summary

Three important transitions have been presented in this chapter. The microstrip to ridge gap waveguide transition has been manufactured and measured. The other two ridge gap waveguide to rectangular waveguide transitions have been used in the two ridge gap waveguide slot array antenna presented in chapter four. All these transitions worked over considerable bandwidth and measured results remain within acceptable limits and are in reasonable agreement with the simulated results.

Chapter 7
Conclusion and future work

To leverage the vast unlicensed bandwidth available at mmWave frequencies, wireless and microwave designers have begun developing high frequency system architectures, circuits, antennas and packages. But as expected, they face enormous challenges to design, develop and integrate components cost effectively. As for example, a simple interconnect that works very well at 5GHz may have unacceptable loss above 60GHz and can become a source of unwanted radiation. Due to the increasingly short wavelengths, power dissipated along straight lines can be of lesser importance in comparison to the influence of discontinuities that become electrically large and cause reactance, radiation and excitation of surface waves. Also, power generation at these high frequencies is difficult and designers cannot afford this hard-fought-for RF power to lose in interconnects, discontinuities or components. Thus, the challenges are many at mmWave frequencies, making this an incredibly rich and deep area of research in the coming years. Surely, microwave engineers will come up with streams of new concepts, ideas and technologies around all the problem areas and will reinvent the wireless industry.

The gap waveguide technology presented in this thesis is a similar new concept with lots of potential in it to be used at high frequency spectrum. It is much lower loss than microstrip or CPW and has very flexible mechanically assembly compared to metal waveguide. It also solves the difficult problems of unwanted radiation, excitation of surface waves, cavity modes and isolation and can easily be applied for packaging high frequency modules and circuits. In fact, this new technology can be used to design all critical passive components (e.g., filters, antennas etc.) and the packaging lid for the active circuits in a single module. This single unit will become a more robust and compact module providing improved electrical performance, reduced cost and will cause less delay in production chain.

The scope of this dissertation focuses on the gap waveguide passive components and packaging solutions for RF front-ends. This thesis deals mainly with ridge gap and groove gap waveguide and uses periodic metal pins as AMC surface. Major contributions from this work can be summarized as follows:

- Firstly, validation of gap waveguide concept has been done by designing and manufacturing first ridge gap waveguide demonstrator. Theoretical and experimental work has been done to confirm the low loss property of the first demonstrator by designing in house TRL calibration kit and characterizing losses of ridge gap waveguide. For such oversized parallel plate structures, the level of field attenuation in the periodic structure is very significant. This field attenuation has been carefully investigated and measured for gap waveguide structures.
- Secondly, narrow band filters with high selectivity have been designed at Ku-band and Ka-band based on groove gap waveguide technology. Good electrical performance is achieved for manufactured high Q filter structures even after removing the sidewalls. Two different

types of coupling mechanisms have been investigated and used to design these filters. For these groove gap waveguide filters, the spit-block assembly is not critical at all, thus making these filters much more flexible to manufacture and integrate with other critical components such as antennas.

- Thirdly, planar slot array antennas have been designed as a proof of concept for gap waveguide based high gain antenna. Initially, a wideband single slot element has been developed. Later on, a 4×1 element linear array and a 2×2 element planar array have been designed and manufactured at Ku-band as a demonstrator. These two slot array antennas work over 20% of relative bandwidth. Both the antennas have the feeding network in the bottom metal plate consisting of guiding ridge and periodic pins, and above the ridges there are radiating slots in the top metal plate. Thus, these antennas have very simple single layer feeding network which is of great advantage considering the mechanical assembly and manufacturing complexity of the 3-D structure.
- Fourthly, the parallel-plate mode suppression quality of gap waveguide technology is applied in microwave modules to package microstrip circuits. By using the gap waveguide package, many critical package related phenomena such as onset of cavity modes, leakage to substrate modes, radiation from discontinuity, feedback issue due to over the air coupling etc. have been prevented within the band of interest. Gap waveguide packaging technique has been successfully utilized to improve the performance of passive circuits such as microstrip filters and active amplifier chains yielding high forward gain. The main advantage of the proposed packaging technique is that- it is scalable to any frequency range. Also, packaging performance does not depend on mechanical issues such as stress and corrosion, joint reliability, surface properties, and deformations or apertures caused by thermal expansions or contractions.
- Lastly, transitions between ridge gap waveguide and other standard transmission lines such as microstrip and rectangular waveguide have been designed and tested. The microstrip to ridge gap waveguide transition has a compact design with a transformation of EM fields from typical microstrip mode to air-filled ridge gap waveguide mode. The transition works even without soldering which is quite an advantage in some systems where large number of transitions is needed in separable modules or split-blocks. On the other hand, one of the ridge gap waveguide to rectangular waveguide transition is a typical inline transition where the height of the guiding ridge is reduced in several steps to match the height of the empty rectangular waveguide. In the second transition, the ridge gap waveguide is excited by a rectangular waveguide from the bottom which is very suitable for antenna measurements.

In summary, this research work lays the foundation for promoting and investigating the gap waveguide technology for the development of a broad range of high frequency and mmWave devices or systems. This dissertation will help in exploration and development of future generation high-volume and mass-producible high frequency microwave components based on gap waveguide technology.

Future work

Following the work and studies described in this dissertation, a number of technical issues are still waiting to be resolved. Some of these issues are mentioned below:

- The work presented in the thesis serves as a proof of concept for gap waveguide technology and its potential, but its applications in the field of mmWave frequency or even higher frequency wireless systems need more system level evaluation. More efforts will be needed to accomplish a well-developed academic/industrial project.
- This thesis mainly deals with ridge gap waveguide and groove gap waveguide technology. The potential of microstrip gap waveguide technology needs to be investigated more at high frequency and mmWave frequency range.
- High frequency active components need to be integrated in a good way with the gap waveguide structures to exploit the full benefit of this technology. New wideband transition design is necessary to be able to do so.
- Fabrication tolerances associated with commonly used CNC milling or molding techniques have to be investigated more in depth to realize the gap waveguide components at mmWave frequency range. Apart from the fabrication tolerance issue, the conductor losses for gap waveguide have to be characterized well at mmWave frequency, in particular, for frequency ranges where the skin depth is comparable with the surface roughness.
- Fabrication techniques such as silicon based micromachining have been tried recently for realizing gap waveguide structures at a frequency of 100 GHz and above [83-84]. However, there are other manufacturing techniques such as laser milling and 3D printing process in metal, etc. These fabrication techniques can also be suitable for realizing high frequency gap waveguide structures and needs more thorough investigation.

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