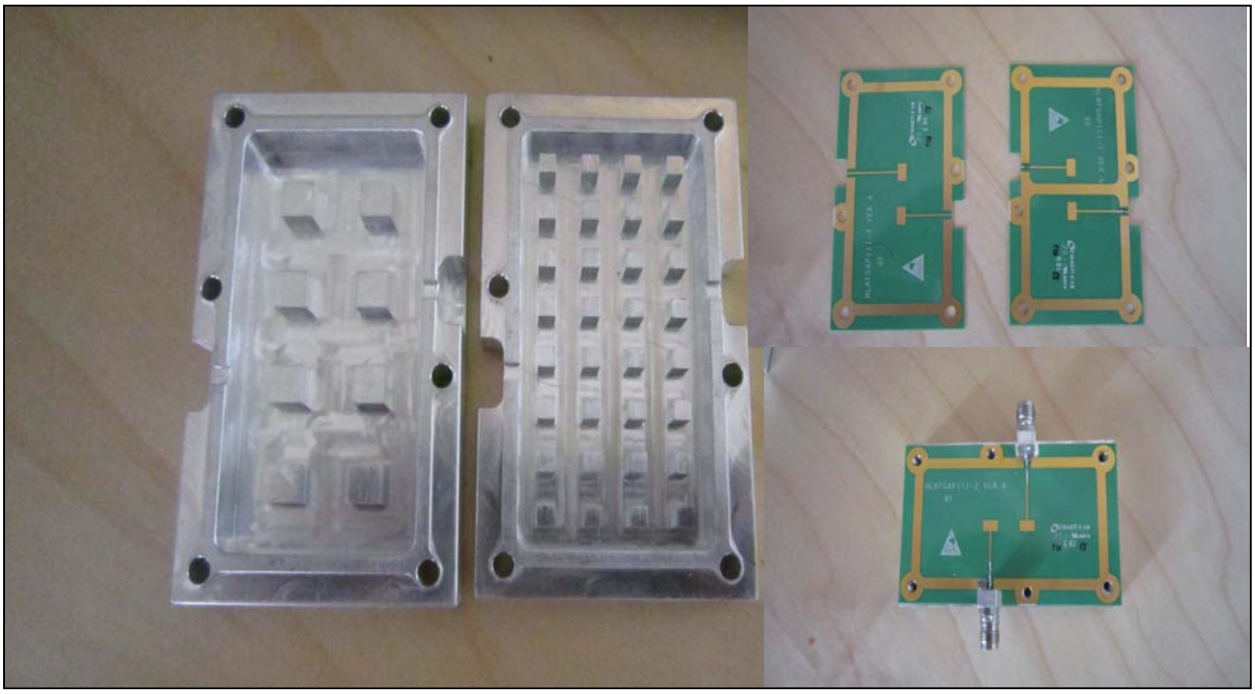

MICROWAVE GAP WAVEGUIDE SHIELDING COVER

Master of Science Thesis Wireless and Photonics Engineering 2011

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Göteborg, Sweden, August 2011

Microwave Gap Waveguide Shielding Cover
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ABSTRACT

This report presents a better and efficient way to package a microstrip circuit board in order to suppress cavity modes, stop unwanted radiation and improve isolation. This can be achieved by employing the concept of gap waveguide.

In this thesis, the gap waveguide concept has been used to replace an existing shielding concept which involves the use of via holes and metal walls across the entire area of a printed circuit board. The purpose of the the vias and metal walls is to shield one circuit component from the other. The limitations to this shielding concept is the that; the vias and metal walls take up a lot of space and suffers from metal contact problem, thereby making the entire circuit vulnerable towards field leakage, crosstalk and interference issues. Also, unwanted radiation, and cavity modes are also present in the circuit board with this shielding solution. The proposed gap waveguide technology is proven to be better in solving the above mentioned problem areas and therefore, it is worth applying the concept in this case.

The operating principle of the proposed gap waveguide technology is explained in this report along with the design of the packaging solution. Measurement results for the manufactured gap waveguide packages are also provided in the final chapter of this thesis.

AKNOWLEDGEMENT

I owe a great deal of appreciation to a number of people who helped me with this project;

Prof. Per-Simon Kildal who gave me the opportunity to work in the Antenna group and also gave me the opportunity to work for an esteemed company like Huawei.

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Finally to the Sani Ellis family and all my friends for their support and prayers.

Contents

PREFACE

This thesis is submitted in partial fulfillment of the requirement for a master degree in Wireless and Photonics engineering at Chalmers University of Technology. It contains work done from September 2010 to June 2011. My supervisors on the project were Prof. Per-Simon Kildal, Ashraf Uz Zaman and Ou Jian. This thesis has been made solely by the author; most of the text however is based on research of Prof. Per-Simon and Ashraf Uz Zaman. I have done my best to provide references for these sources.

This Thesis work has been done in collaboration with Huawei AB.

CHAPTER 1

1. INTRODUCTION

Different microwave components like mixers and amplifiers on a circuit board need to be shielded from one another to avoid unwanted signals from leaking from one component to the other through coupling. This makes shielding a very important and crucial part of a microwave circuit system.

In this project, a way to shield and package a PCB board with installed microwave components is discussed. State of the art methods of shielding circuit components involves the use of via holes and metal walls as shown in fig. 1. The purpose of via holes is to reduce effect of substrate modes and the purpose of metal wall is to stop the leakage or radiation through the air.

As much as this approach helped with isolating circuit components, it makes the entire circuit bulky. While the metal walls are heavy and occupy lots of space, a lot of via holes are needed on the PCB to stop the substrate travelling wave. This approach takes up a lot of space which can otherwise be used for more circuit components. To solve the aforementioned problems, a solution which doesn't involve metal walls and via holes is investigated. To achieve this, the gap waveguide concept is used.

The *gap waveguide* is a recent type of waveguide introduced [1-4]. This waveguide is based on the use of a textured surface in one of the plates of a conventional parallel plate waveguide, designed to stop the propagation of modes in any direction within a given frequency range, except the local quasi-TEM wave [1]. The propagation of the local quasi-TEM wave is achieved by means of a conducting ridge in the textured surface or a narrow metal strip above it.

In principle, the textured surface basically creates a high surface impedance to generate cut-off of normal parallel plate modes. In our case, the textured surface is termed the lid of nails. This textured surface is ideally a Perfect Magnetic Conductor (PMC) placed at some distance from a Perfect Electric Conductor (PEC). This PEC-PMC combination is what makes up the soft and hard surfaces [5], which is the research that resulted in the evolution of gap waveguides.

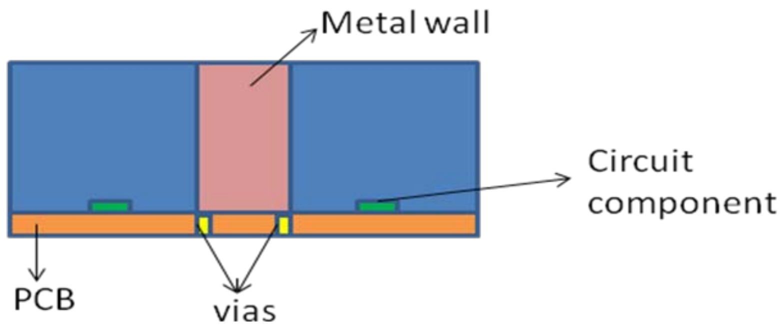


Fig.1 Existing shielding solution using metal wall and via holes

1.1 Design Requirements

The test board and shielding cover were designed to meet the following criteria:

Shielding frequency = 6 GHz – 42 GHz

Microstrip spacing $\leq$ 10 mm

Microstrip impedance = 50 Ohm

Isolation = 60 dB

Test board substrate = Rogers 4350

Testboard thickness = 10 mil

Air gap height = 3mm

CHAPTER 2

2. BASICS OF GAP WAVEGUIDE

As explained in [1], hollow rectangular waveguides were commonly used to realize low-cost antenna system components for frequencies between 3GHz-30GHz. Problems with manufacturing above 30GHz were faced because of the small dimensions of the air-field hole in the waveguide. The hollow structure can be manufactured in two parts joined together, but large problems occur due to the difficulty in ensuring good electrical contact in the joints. Microstrip lines are commonly used as well, but they become more lossy with increase in frequency which makes their power handling ability degrade as a result. There is therefore a need for new waveguides or transmission lines operating at high frequencies; above 30GHz.

There already exist waveguides specifically intended for such high frequencies called substrate integrated waveguides (SIW) described in [6]. The SIW is basically realized with metalized via holes made in the substrate of a printed circuit board. The SIW still suffer from losses in the substrate and metalized via holes are difficult to manufacture. This chapter discusses basic principle of operation of gap waveguide and the basics of its evolution.

2.1 Metamaterials

In the last couple of years, researchers have tried come up with artificial electromagnetic materials that have abnormal characteristics. These materials are called metamaterials. Metamaterials are basically materials engineered to have properties that may not be found in nature. One of the most desirable abnormal characteristics to achieve is magnetic conductivity or its equivalent, which doesn’t exist naturally. To realize magnetic conductivity, the first conceptual attempt was soft and hard surfaces.

2.2 Soft and Hard Surfaces

The soft and hard surfaces were based on transversely corrugated surface previously used in horn antenna design to feed large reflectors, and the main application foreseen for the hard surfaces was also horn antennas [7]. The soft and hard surfaces are conveniently described ideally as PEC/PMC strip grid. The PEC/PMC strip grid is a strip of parallel strips, where every second strip is perfectly electric conducting (PEC) and perfectly magnetic conducting (PMC), respectively [8]. The PMC strips can be realized with metal grooves with quarter-wavelength depts. or equivalent means. The characteristics of the PMC/PEC (soft and hard surfaces) grid strips are that the anisotropic boundary conditions allow waves of any polarization to propagate along the strip in the hard surface case, whereas in the soft case, they stop wave propagation in other directions along the surface, particularly orthogonally to the strip grids. The electromagnetic band gap (EBG) surface works in a similar way as the soft surface by stopping wave propagating along it but for all directions due to its isotropy. The PEC/PMC strip grids and EBG surfaces (or PMC surfaces) can be used to realize a new high frequency waveguide in the gap between parallel metal plates.

Horn antennas for instance, have used the design corrugations for a number of ways and have achieved good performance. The reason for this good performance is that, the corrugations make the field component orthogonal to the wall, almost zero at the wall, and therefore equal to the value of the transversely tangential field component. This polarization independent boundary condition makes one often refer to corrugated horns as soft horn antennas, as the corrugations of the surface give the same type of boundary condition as that of the soft surface in acoustic.

2.2.1 Realization of soft surfaces

Consider the figure 2 below, i.e., a transversely corrugated surface where $\mathrm{w} \ll \mathrm{w} + \mathrm{v} \ll \lambda/2$, where w is the width of corrugations and v is the width of the edges between them. There will be only one nonevanescent mode present within the corrugation. This mode (TE_n) will have only a tangential component, E_t, and no longitudinal variation within each corrugation. The E_t field is accompanied by H_t *and* H_n, the tangential and normal component of the magnetic field respectively, but by choosing a correct length of the slot depth, d, the field on the *surface* can be transferred as described in [5] as;

$$H_t = 0, \qquad |Z_t| = \infty \qquad \ldots\ldots\ldots.. \quad on\ the\ surface$$

On the edges between corrugations, $H_t = 0$ as well since there are no longer longitudinal currents when $v \rightarrow 0$ so the E_t and H_t components at the outer surface are short circuited between the edges of the corrugations. i.e.

$$E_t = 0, \qquad |Z_t| = 0$$

To achieve these conditions, the slot depth d should be;

$$for\ \frac{dE_t}{dn} = 0\ \ at\ the\ surface, slot\ depth, d = \frac{\lambda}{4}$$

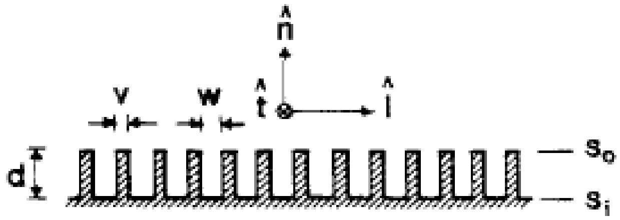


Fig.2 Transverse corrugation [5].

2.2.2 Summary on soft and hard sufarces

It is safe to describe a soft surface as that which has traverse corrugations with λ/4 depth. Similarly a hard surface can be made using longitudinal corrugations of certain depth. These artificial corrugations of surface can also be called high impedance surfaces as they assume $|Z_t| = \infty \ (infinity)$.

2.3 Physical Theory of Gap Waveguide

The gap waveguide comprises two parallel conducting surfaces, either plane or curved. The two surfaces are separated by a small gap, and the gap waveguide is formed inside the gap between the two surfaces. The gap is usually filled with air but can also be partly or fully filled with dielectric. Effectively, the gap size is usually smaller than 0.25 wavelengths.

The new waveguide has a smooth upper metal surface and a ridge surrounded by a bed of nails as the lower surface with an air gap smaller than λ/4 between the upper plate and the ridge. The pin surface in the bottom metal plate serves as an artificial magnetic conductor (AMC) surface. When the distance between the pin surface and the top metal surface is close, a very wide parallel-plate stop band is obtained and electromagnetic waves cannot propagate in any direction within the stop band. But when a narrow metal ridge is placed along with the pin surface, the wave can only propagate in a desired direction along the ridge. This concept of gap waveguide is shown in figure 3. With the help of the new gap-waveguide concept, it is possible to refine the local waves between parallel plates in such a way that they become more confined and exist over a large bandwidth without the presence of global parallel plate modes [9]. The proposed gap waveguide can be realized without conducting metal contact between the upper metal surface and the lower metal surface which allows for cheap manufacturing of waveguide components in high frequency bands. The high impedance surface also does not need via holes as the bed of nails can be realized by milling or casting of metals. Thus the new gap waveguide technology visions for manufacturing flexibility and better RF performance as no lossy dielectric substrate is required [9].

Many transmission line equations related to microstrip lines also apply as a good approximation to the ridge gap waveguide, but only within the frequency band in which the artificial surface creates a cutoff for waves propagating in directions other than along the ridge. The characteristic impedance of the gap waveguide is therefore given approximately by that of a microstrip line;

$$Z_k = \frac{Z_o h}{w} \qquad [1]$$

Where Z_k is the wave impedance in air, w is the width of the ridge and h is the height of the gap between the ridge and the PEC surface. The formula is an approximation when $w >> h$, same as for microstrip lines. The propagation constant will also be the same as in air. A metal conductor can be replaced by a PEC but an exact value for the characteristic impedance for the ideal PMC would be twice the characteristic impedance of a strip line. This is illustrated below.

$$Z = 2Z_{stripline}$$

$$Z_{stripline} = \frac{\eta}{2}\left(\frac{W_e}{2h} + 0.441\right)^{-1} \quad [6]$$

Where $\frac{W_e}{2h}$ $can\ be\ defined\ as\ follows:$

$$\frac{W_e}{2h} = \frac{W}{2h} - \begin{cases} 0 & if\ \frac{W}{2h} > 0.35 \\ \left(0.35 - \frac{W}{2h}\right)^2 & if\ \frac{W}{2h} < 0.35 \end{cases}$$

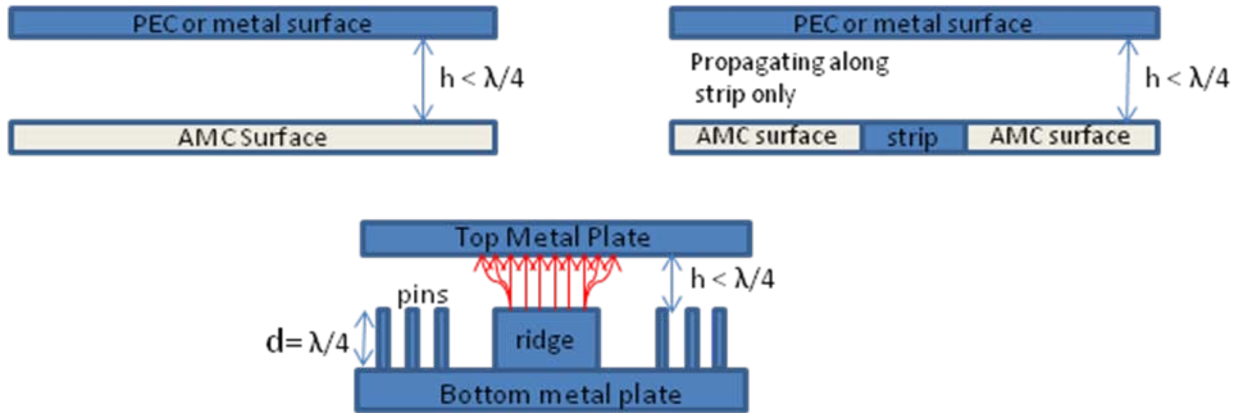


Fig.3 Basic concept of Gap Waveguide

The new waveguide is located in the gap between the metal surfaces. Smooth parallel metal surfaces will guide vertically polarized TEM waves in the gap between them, in any direction without any low cutoff frequency. This TEM wave which fills the gap is the global parallel-plate mode, whereas the quasi-TEM waves on the ridge gap waveguide are local waves following one ridge. When the spacing is smaller than half a wavelength, the global TEM wave will be the only propagating mode present between the smooth parallel metal plates. If present, they will destroy the performance of the local gap waveguide. It is therefore crucial for the performance of the gap waveguide that all kinds of global parallel-plate modes don't propagate at all. To achieve this, the metal surface on both sides of the ridge is textured in such a way that it becomes a high impedance surface and provides cutoff for the global parallel-plate modes.

2.4 Principle of Operation

The principle of operation of the gap waveguide explained in [1] is based on the following facts that are either well known or can be derived from Maxwell's equations [1]:

a) No waves can propagate in any direction in the gap between a PEC and a PMC if the gap height h < λ/4.

b) No waves can propagate in any direction between a PEC and an EBG surface if the gap height is smaller than a specific height that depends on the geometry on the band gap surface. The height is normally less than λ/4. Most practical EBG surfaces work for vertical polarization (i.e., TM_n case with respect to the surface normal) as an artificial PMC for all angles of incidence in the elevation plane. For horizontal polarization (i.e.,TE_n), they work as a PMC for normal incidence and as a PEC for grazing incidence and it's this property that provides the band gap for horizontal polarization. Between parallel plates, the PEC boundary condition for horizontal polarization provides cut-off whenever h < λ/2, i.e., a weaker cutoff condition than h < λ/4 valid for a PMC boundary condition on the lower plate.

c) Waves in the gap between a PEC/PMC strip grid surface and a PEC can only follow the direction of the PEC strips. Waves in other directions are in cutoff when h < λ/4 for vertical polarization (TM_n) and when h < λ/2 for horizontal polarization (TE_n). Therefore such an ideal gap waveguide works for all frequencies up to a maximum of h = λ/4.

CHAPTER 3

3. DESIGN RULES OF PARALLEL PLATE STOPBAND

This chapter will be dedicated to PMC packaging. Firstly, the stop band when the parallel plate waveguide consists of a metal surface and an ideal PMC will be discussed. This is necessary as a reference to compare when the ideal PMC is realized with lid of nails, as will be introduced later in the chapter. The latter part of the chapter will describe an example where the lid of nails has been applied to package a microstrip line. This chapter is purely based on research conducted in [11].

3.1 Parallel Plate Waveguide with Ideal PMC.

Firstly, a parallel plate waveguide consisting of a metal surface and ideal PMC, separated by a gap h will be studied. This ideal example is important for understanding the significance of h, of which reason it's included as a reference in several other graphs to follow. Theoretically, there is one physical limit for the start frequency and two physical limits for the end frequency of the stop band. The lower cut off limit comes from the frequency at which the textured surface starts exhibiting a high-enough surface impedance. The upper cut off, on the hand, comes from the frequency at which the surface impedance becomes too small. However, there is a second upper cut off determined by the gap h. The gap must be smaller than $\lambda/4$ in order to avoid propagation of all types of parallel plate modes and allow the propagation of the dominant TEM mode. The lower cutoff frequency is zero and the upper cutoff frequency which is determined by the surface impedance never appears. The ideal analytical upper cut-off limit is shown together with simulated results in the Fig. 4.

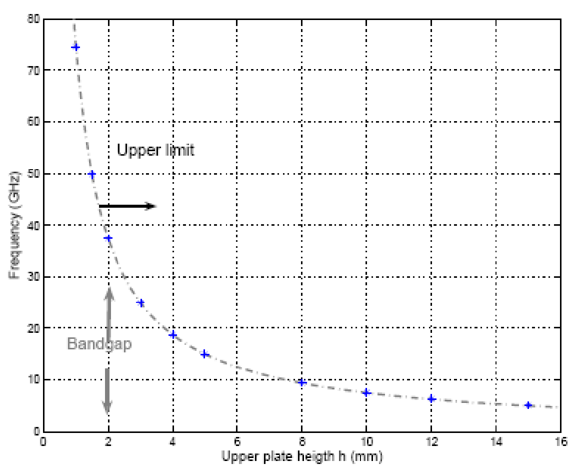


Fig. 4 Analytical (grey line) and computed (*) upper cut off limit of a parallel plate waveguide with ideal PEC and PMC walls.

3.2 Parallel Plate Waveguide with Bed of Nails

The lid of nails will be studied here. The geometry is shown below in Fig. 5. The geometrical parameters that may have effect on the cut-off bandwidth of the parallel plate waveguide described in [11] are:

- The distance to the upper plate, i.e., "the gap height" h.
- The length d of the pins, representing the thickness of the surface layer generating the AMC.
- The period p of the pins.
- The radius r of the pins.
- The geometry of the lattice, i.e., how the pins are regularly disposed.

Fig.5 Geometry of a parallel plate waveguide with lid of nails

Figure 6 represents the cut-off limits as a function of the gap height, for an example where d = 20mm, p = 3mm and r = 0.2mm. The start frequency of the band gap is defined by the frequency at which the wave propagation is stopped and the end frequency represents where the waves can propagate again, represented by a dashed blue line and solid red line, respectively.

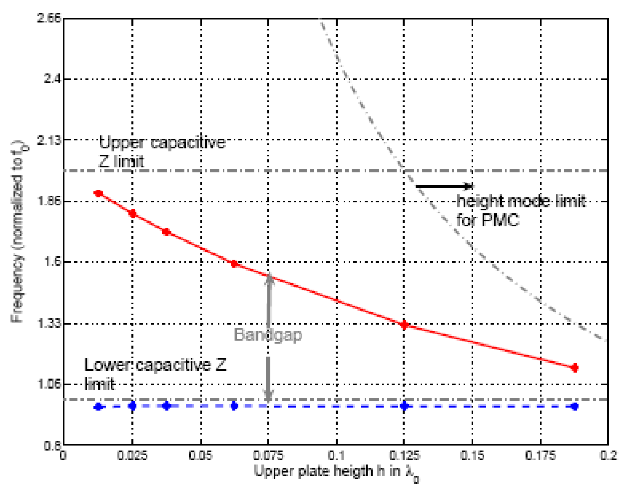
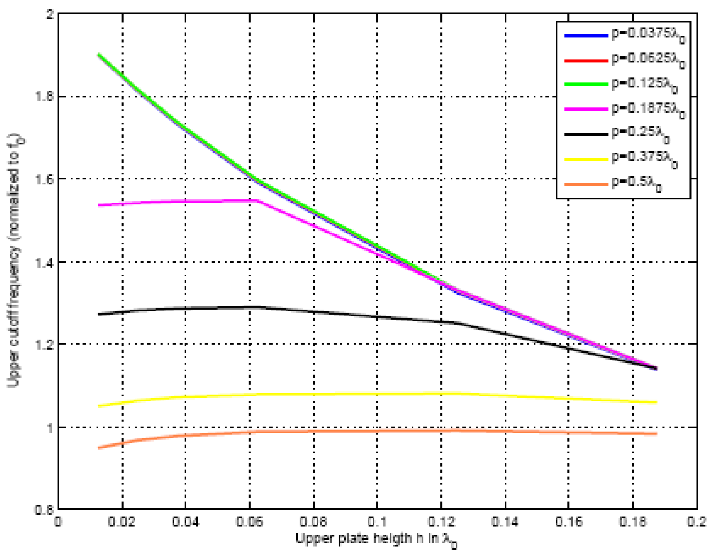


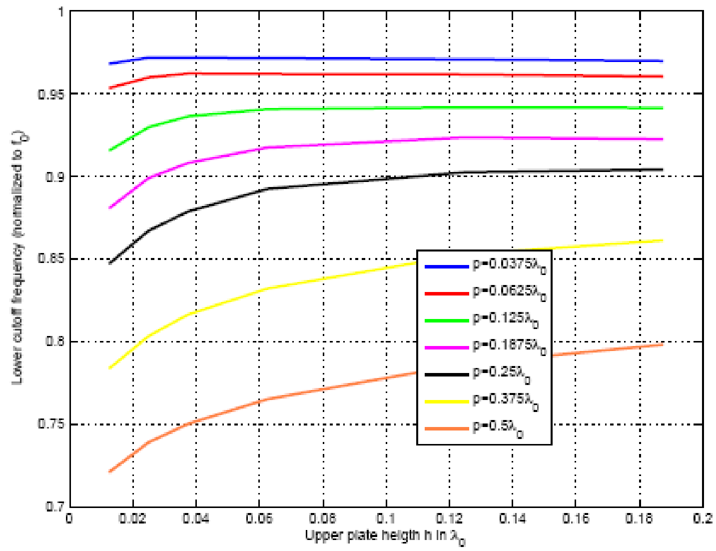
Fig.6 Computed relative start (dashed line) and end line (solid line) frequencies of the stop band of parallel plate waveguide with lid of nails in one plate as shown in fig 5 [11].

From this example, it is clear how the gap h is an important parameter which strongly affects the size of the upper band. This motivates the study of the effect of h when other parameters such as the period of the pins are also varied. Fig.7 below shows the effect of the gap size h on the start and end frequencies of the stop band. It is seen that for all periods the size of the stop band increases when the height h of the gap to the upper plate decreases.

The start frequency of the stop band reduces when the period of the pins increase due to some degree of increase of the electrical length of the pins. The end frequency on the other hand remains unaffected by the period as long as this is small enough. When the period increases, the upper limit is greatly reduced to the propagation of new modes. Moreover, for periods larger than $0.25\lambda_o$, the end frequency of the stop band remains fairly constant with gap size h, and the total increase of the stop band is only due to the change in the start frequency, which greatly reduces for small gap heights.



(a) End frequency



(b) Start frequency

Fig.7 Start (a) and end (b) frequencies of the stop band as a function of gap height h for different pin periods, for the parallel plate waveguide with bed of nails in Figure 3. Circular pins with length d = 20mm and radius r = 0.2mm [11].

The total relative bandwidth (f_{end}/f_{start}) as a function of period and gap height will be discussed next. Starting from the smallest period, this bandwidth increases with period for all gap sizes, up to a certain height-dependent period which corresponds to where a new mode appears in the dispersion diagram. The frequency at which this periodicity mode appears depends much more slowly on the gap height than the mode appearing when the gap height becomes larger. Therefore, the latter height limits the stop band for larger heights rather than the periodicity mode. It can therefore be concluded from these results that small periods as wells as small heights have to be used when a large bandwidth is required.

Now the radius will be considered. The radius was changed while keeping the period constant while changing the ratio between the radius and period (r/p). It is noted that a larger period moves the start frequency of the stop band towards lower frequencies but also affects the end frequency, particularly when the ratio between radius and period r/p is small. As a result, the largest stop band for small gaps is obtained for small periods. The relative bandwidth f_{end}/f_{start} has been computed and represented in figure 11. When the radius is much smaller than the period, only then does the structure with smaller period exhibits the largest relative bandwidth. When the radius is relatively thick, the structures with larger periods achieve larger bandwidths.

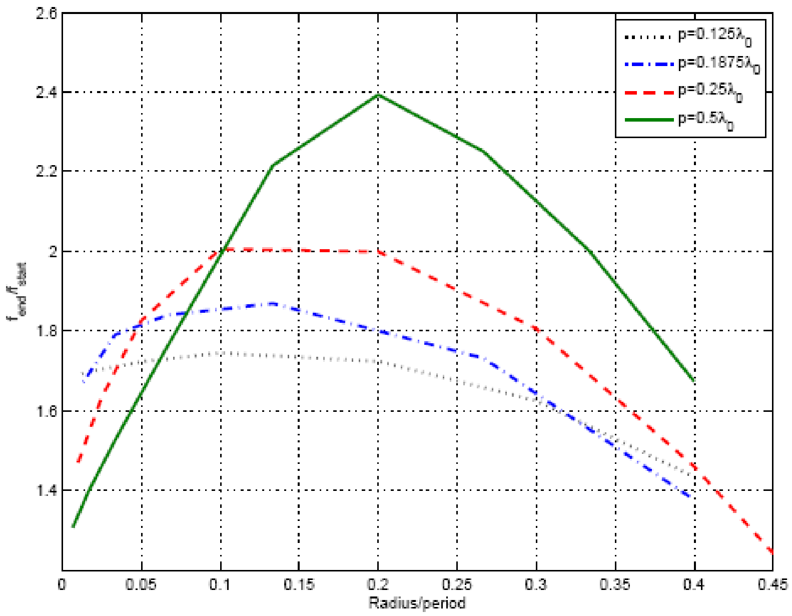


Fig.11 Relative bandwidth as a function of the radius/period for different periods for a pin surface with d = 20mm and h = 5mm [11].

A complete parametric study of the bed of nails evaluating the bandwidth in which the mode propagation is stopped when the surface is topped by a metal plate is presented. The main parameters affecting the stop band is the gap which gives the name to the waveguide. Also the period as well as the radius of the unit cell is of importance. The achieved stop bands are large enough for most of the applications, going up to 2:1 size [12].

3.3 Parallel plate Cavity Mode Suppression in Microstrip Packages Using Lid of Nails.

The lid of nails applied to package a microstrip line will be discussed now. The textured surface can have a periodic structure that provides high impedance to generate cut off of normal parallel plate waves. The lid of nails was previously shown to have high surface impedance over a large bandwidth and it was already proven in [1] to work in a ridge-type gap waveguide.

The concept of gap waveguide used to suppress parallel plate modes when microstrip circuits are packaged and shielded was published in [12-13]. The proposed geometry is shown in figure 13 below.

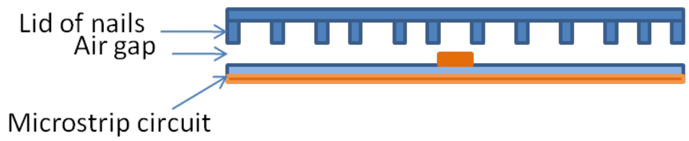


Fig.13 Sketch of the proposed mode suppression technique.

The microstrip circuit is covered by the nails with an air gap defined as the distance from the end of the pin to the microstrip substrate. As discussed previously, this air gap is the main parameter determining the bandwidth of the structure.

3.3.1 Cut-Off Study

The cut-off properties of lid of nails over a grounded substrate without microstrip lines were initially studied. Realizable stop band was chosen between 10 and 20 GHz. To achieve this, the length d of the pins was chosen equal to a quarter wavelengths at the middle frequency, i.e., 15 GHz. Hence the pins height d is 5mm. The other parameters radius r, period p and gap height h were determined to obtain the desired bandwidth. Finally an air gap height of 1mm gap was chosen to be sufficient for demonstration even thought smaller heights could have achieved larger bandwidth. The radius r and period p of the pins were finally chosen to be 1.5 mm and 7.5 mm respectively. The substrate material was AD450 ($\varepsilon_r = 4.4$) with thickness $t = 0.5$mm. The resulting dispersion diagram is shown in figure 14.

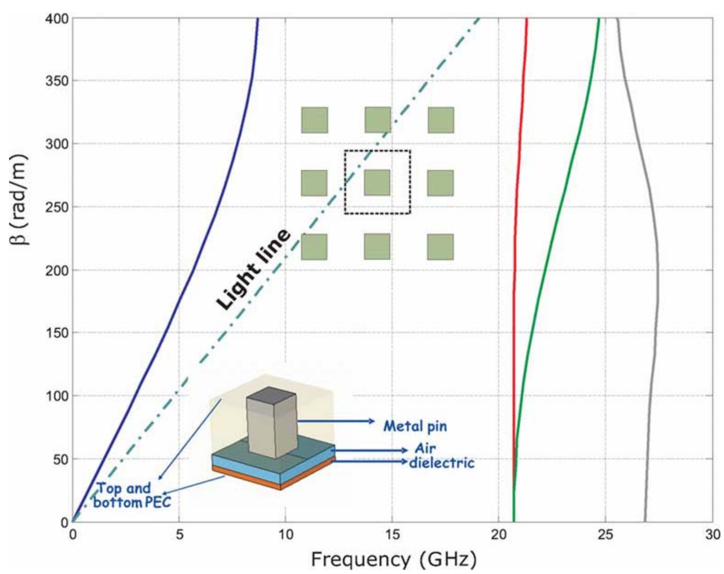


Fig.14 Dispersion diagram of the infinite lid of nails above grounded substrate of thickness 0.5 mm [13].

3.3.2 Simulated and Measured Results

A simple microstrip line was manufactured and tested as an example, as shown in figure 15 (left).

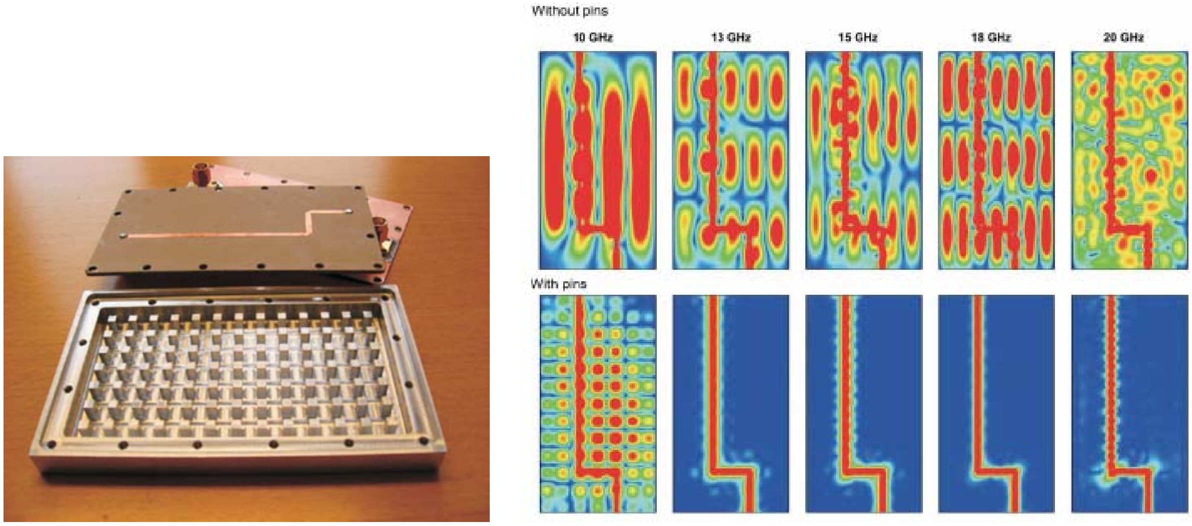


Fig. 15 Manufactured metal lid with pins (left), 2-D color plots of vertical E-field distribution (right) inside gap between microstrip board and lid of the metal box, both (a) with smooth metal lid (b) with lid of nails [13].

It consists of a microstrip line with two 90^{o} bends. Bends often cause undesired radiation, and will ensure excitation of cavity modes if present in our circuit. The line width of 1mm was chosen to provide 50Ω line impedance. To better illustrate the removal of cavity modes, the vertical electric field inside the gaps was computed for two cases, i.e., with smooth wall and with lid of nails at some selected frequencies where cavity modes appear. The 2D plots are shown in figure 15. It is clear how the different cavity modes and strong fields in the bends of the microstrip line are suppressed within the stop band when the lid of nails is used, and how the waves are confined on the microstrip line within the same stop band.

The gap waveguide concept has been proposed as a way to suppress parallel plate and cavity modes in a shielded microstrip circuit package [12].

CHAPTER 4

4. APPLICATION OF PMC LID FOR IMPROVING ISOLATION

This chapter will be dedicated to the application of the gap waveguide concept to improve isolation between microwave circuit components on a printed circuit board. The lid of nails concept described in chapter 3 will be employed. A solution which takes care of isolation between the different circuit components already exists. This existing solution makes use of via holes and metals walls between circuit components to isolate them. Even though this solution provides a pretty good isolation, a lot of circuit space is occupied which therefore limits the number of circuit components that can potentially be placed on the PCB. The gap waveguide shielding concept will be used in attempt to solve this problem.

4.1 Existing Solution in improving isolation

The top view of the existing solution with metal walls is shown in Figure 16. The two patch antennas represent two circuit components. Low efficiency patch antennas are used in design to ensure that we have undesired radiation due to the discontinuities in impedance between the patch and feed line. The vias and metal wall serve to stop substrate travelling and surface travelling waves respectively. This existing solution takes up a lot of space which can otherwise be used for other components or make the entire circuit less bulky.

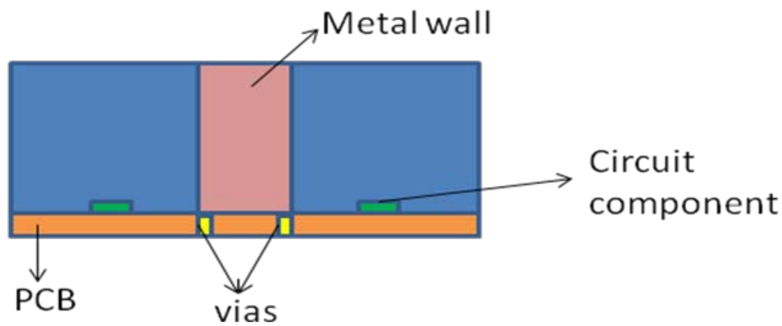


Fig.16 Existing shielding solution using metal wall and via holes

4.2 Gap Waveguide shielding cover solution

The gap waveguide solution will be used as an attempt to provide shielding to the circuit components without the use of via holes and metal walls. This solution will allow room, otherwise used for vias and metal walls, to be available for other circuit components. Figure 17 shows a picture of the gap waveguide solution.

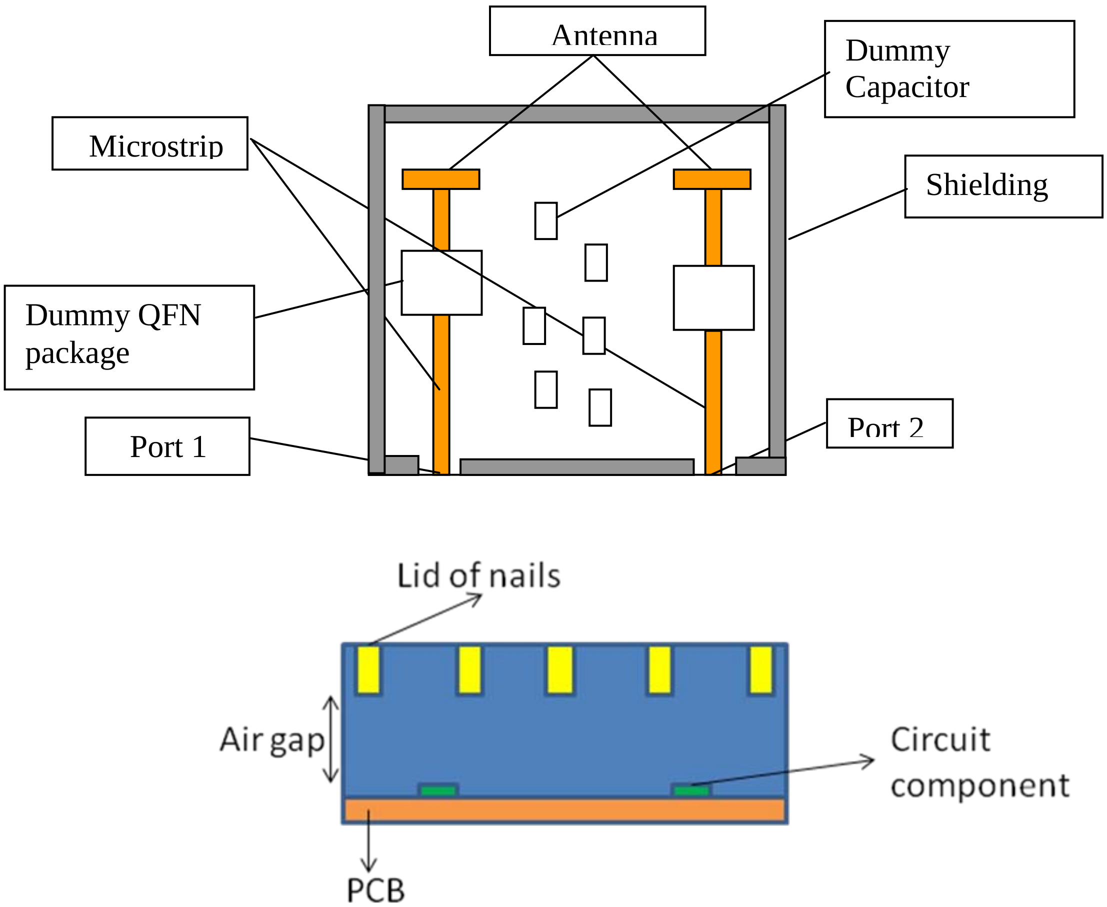


Fig.17 Isolation between components with Gap waveguide shielding cover

4.3 Isolation results of different shielding solutions

A cavity size of 60mm x 30mm was chosen. This size was chosen because it was big enough to ensure the presence of cavity modes since the number of modes in any cavity depends on the size of that cavity. A gap height of 3mm was chosen for design. This was chosen since one component was 2mm high and to allow for some tolerance in the manufacturing, a 3mm gap height was deemed appropriate. The design and simulation were run in HFSS.

4.3.1 Existing solution (with Metal wall and Vias)

Figure 18 below shows a plot of isolation between two components. From the figure, a pretty good isolation of below 50 dB is achieved for most part of the bandwidth, i.e., from 5 – 20GHz but with lots of resonances. These resonances are undesirable in our signal since they are a major cause of interference.

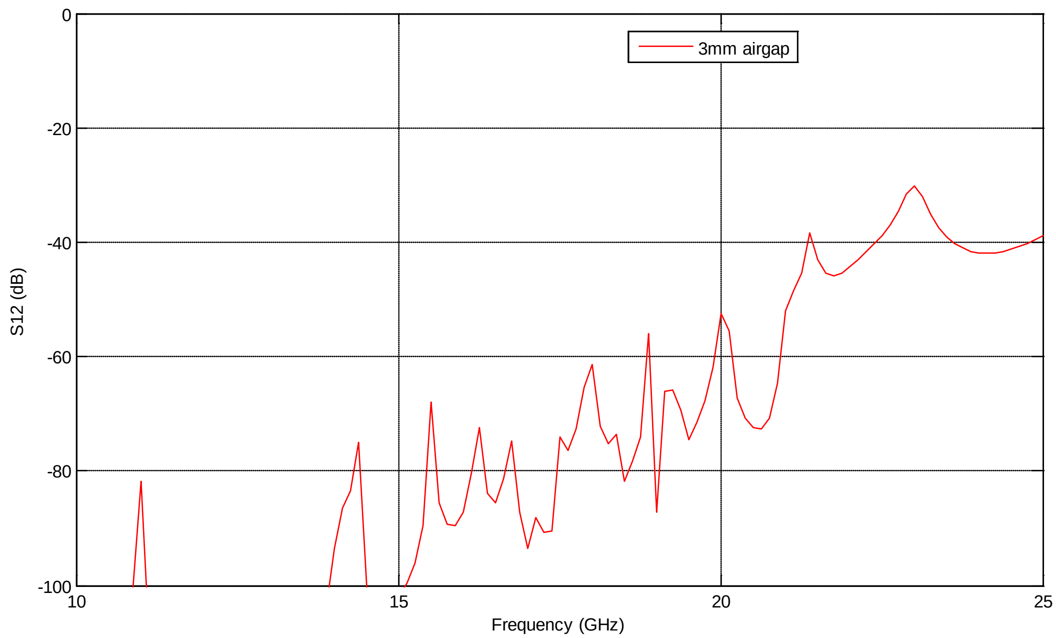


Fig.18 Plot of isolation (S_{12}) between port 1 and port 2 for metal wall and grounding vias.

4.3.2 Gap Waveguide Shielding Solution

Firstly, an ideal PMC will be used to realize the shielding cover. Then the lid of nails will be used to realize the PMC. The plots will be plotted together to see the disparity between the ideal case and the practical case.

4.3.2.1 Ideal PMC at 3mm

The ideal PMC cover was used to realize PEC/PMC grid or EBG discussed in chapter 2. The ideal PMC is represented as *perfect H boundary* in HFSS. This boundary was placed at 3mm from the top of the circuit components (realized by patch antennas). The isolation plot is shown in figure 19.

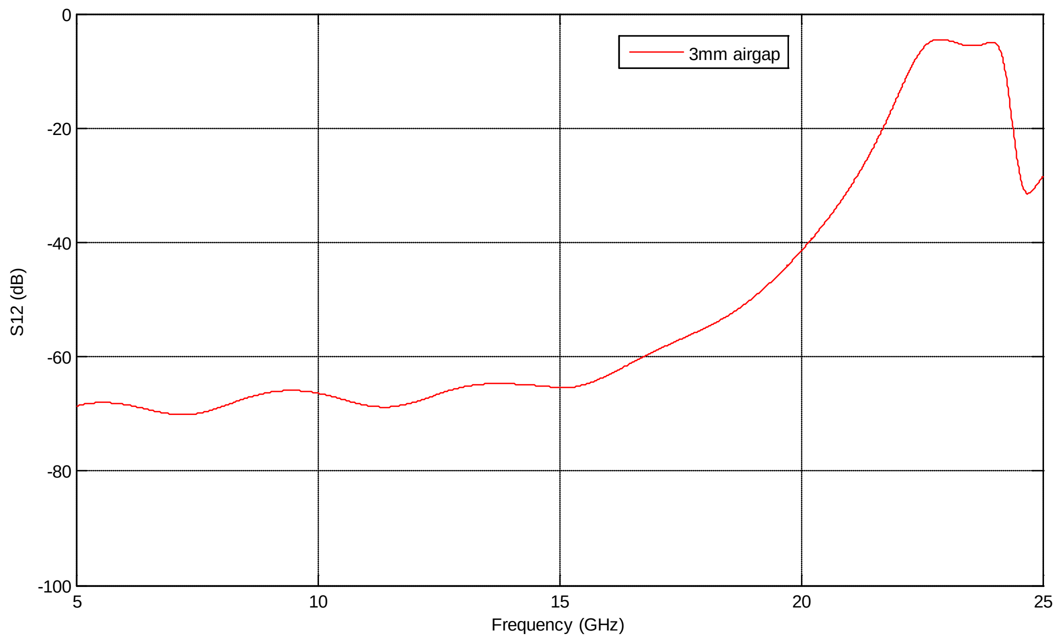


Fig.19 Plot of isolation with PMC at 3mm air gap.

4.3.2.2 Analyses of Ideal PMC cover

Fig. 19 shows the application of the gap waveguide concept explained in chapter 2. It's is seen in the figure that resonances (peaks) seen in figure 18 are not seen in here. This is because the PMC has removed those resonances up to a certain frequency. As discussed before, this frequency is the point where the distance between the PEC (the ground plane) and PMC is less than λ/4. Hence in this case, the frequency can be calculated as :

$$h < \frac{\lambda}{4}, \quad \lambda > 13.016mm \ldots\ldots for\ h = 3.254mm\ (distance\ between\ PEC\ and\ PMC),$$

$$f = \frac{c}{\lambda}, f = {3.10^8}/{13.10^{-3}} = 23GHz \ldots. Hence\ the\ PMC\ should\ work\ for\ frequencies \leq$$

$$23GHz.$$

We can see from Fig. S that the PMC stops working when the PMC starts to get close to 23 GHz and completely stops working at 23GHz and beyond. With this analogy, its obvious that higher bandwidths can be achieved with lower gap heights. To prove this, a parametric analysis of three different gap heights have being made for comparison in figure 20 below .

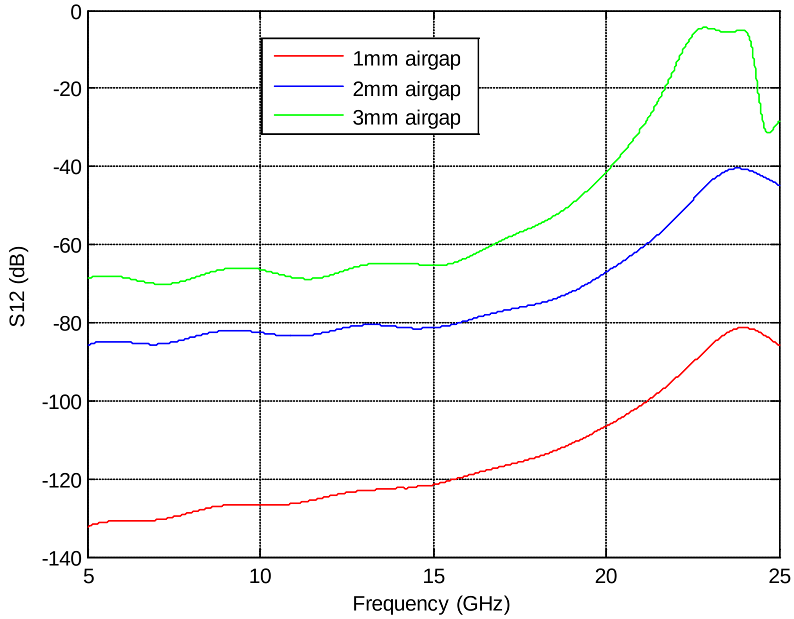


Fig.20 A plot showing isolations for different PMC heights

The red lines represent a PMC cover 1mm above the patch antennas, blue and red green lines represent 2mm and 3mm gap sizes respectively. The red line shows a better overall isolation. Even at 25GHz, an isolation of 80 dB is achieved unlike the blue and green line which shows -40 dB and 0 dB isolation respectively. Hence we can conclude from the above plots that at low PMC heights, a higher bandwidth and better isolation can be achieved.

4.3.3 PMC Realization with Lid of Nails

Now we realized how much bandwidth can be achieved at 3mm gap size using an ideal PMC. As discussed earlier, we have to realize this theoretical PMC with lid of nails explained in chapter 3. Two sets of frequency of are interest in this project, i.e., 8GHz and 15GHz. It should be noted that the stated frequencies are center frequencies of the achievable bandwidth.

4.3.4 Lid of nails @ 15GHz

To dimensions of the pins needed to achieve a bandwidth of around 15GHz has being investigated in [6]. The same dimensions have being used but for 3mm gap size in this case. The pins dimensions are *height (d) = 5mm, period (p) = 7.5mm, width (w) = 3mm* for 15GHz. To investigate the bandwidth that can be achieved with this design, the dispersion diagram was made in CST with infinite row of pins. The plot is shown below.

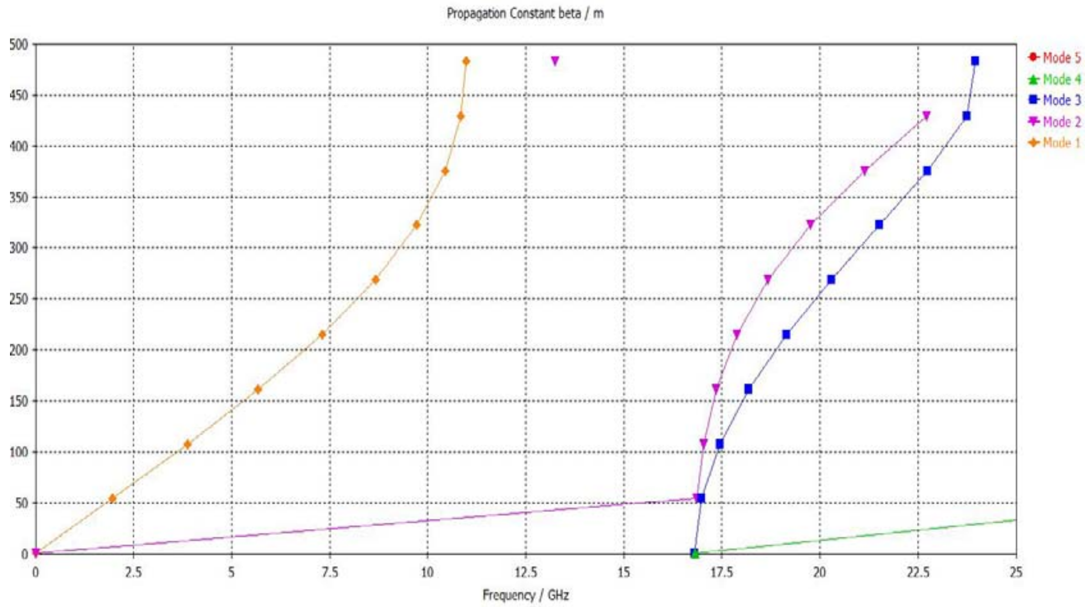


Fig.21 Dispersion diagram of infinite row of pins at 15GHz plotted in CST.

A bandgap of around 11GHz – 16.5GHz is achieved with infinite number of pins as seen in Figure 21 above. Knowing this, a limited number of pins were put in the actual design to see how close we could get to the bandgap. The plot is shown in Fig. 22 below

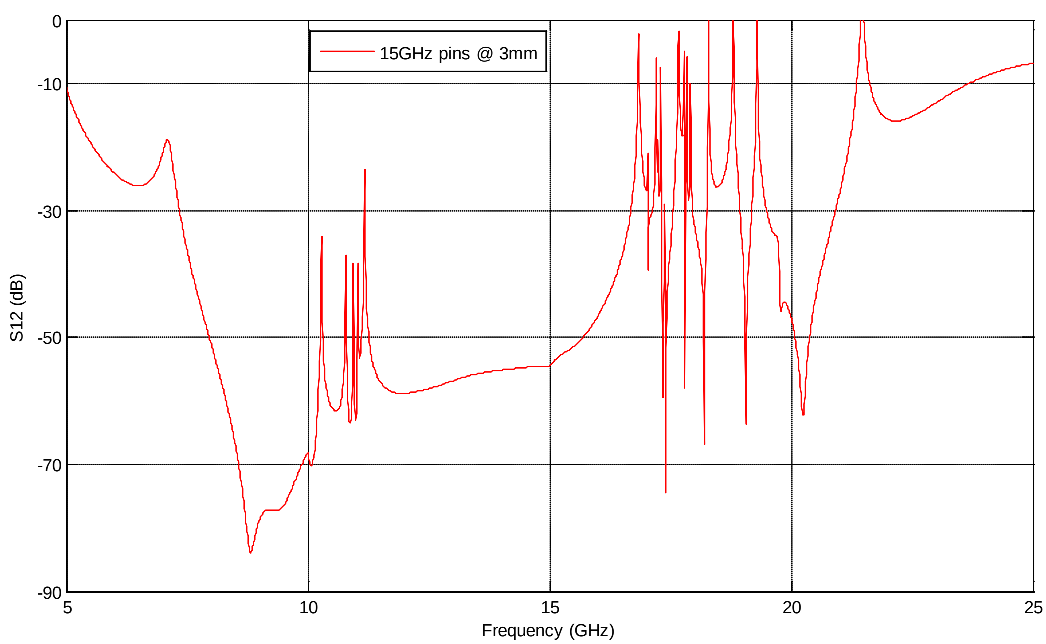


Fig.22 Plot of isolation when lid of nails for 15GHz is used.

Figure 22 above shows that at frequencies around 11.5GHz – 16GHz, the cavity modes are removed because the modes are in cut off in this frequency range and an isolation close to 60dB is achieved.

4.3.5 Comparison between 15GHz pins lids and Ideal PMC

In Figure 23 below, the ideal PMC and the pins at 15GHz have being plotted together to comparison and analysis.

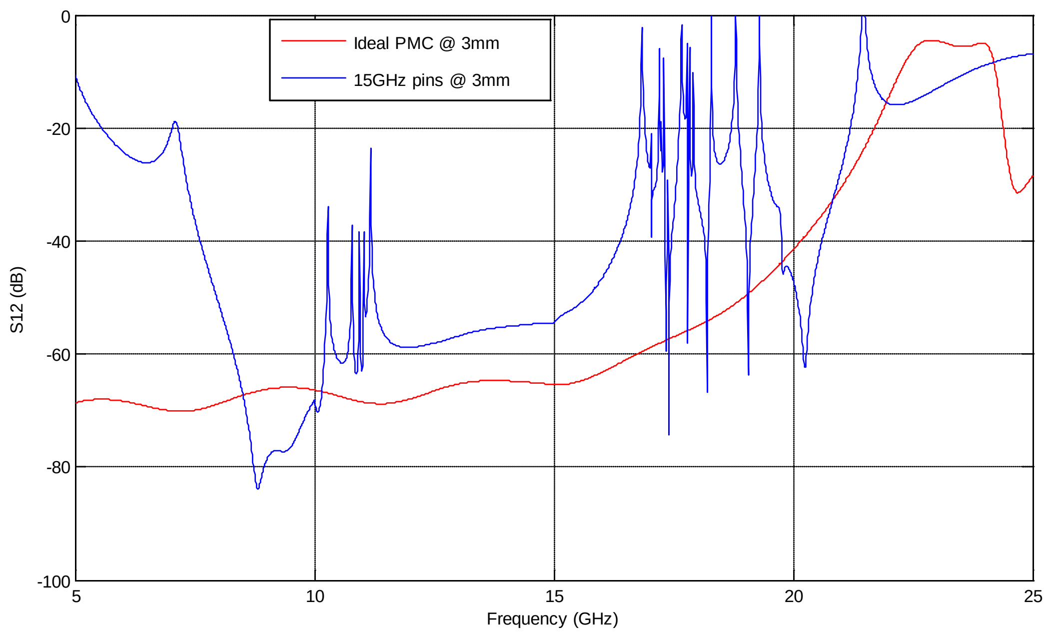
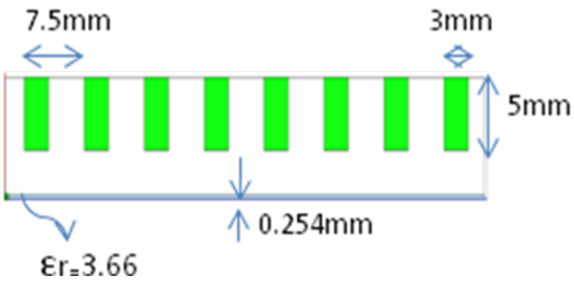
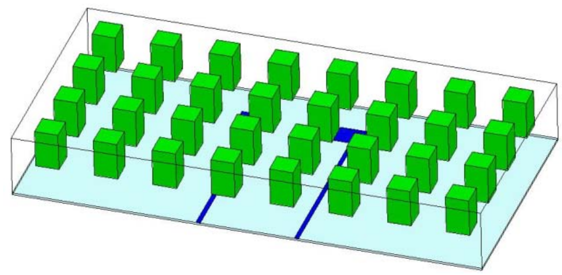


Fig. 23. A combined plot of ideal PMC cover and 15GHz lid of nails cover

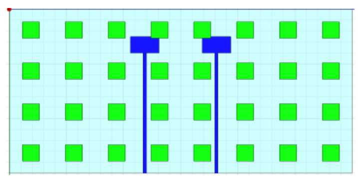
It is realized that from figure 23 that, at frequencies around 11GHz-16GHz, the lid of nails act as a PMC. After 16GHz, it stops acting as such and the modes reappear. Even thougth the pins lids act as PMC in this frequency (11 – 16GHz), the two lines are not exactly in line since the lid of nails is not as ideal as the PMC.

A figure showing how the pins @ 15GHz are arranged is as shown in figure 24 below.





a) crossection



b) top view

Fig.24 Different views of 15GHz pins placed on PCB

4.3.6 Lid of Nails @ 8GHz

A center frequency of 8GHz was also investigated. To achieve dimensions at this frequency, the dimensions for 15GHz were scaled down to 8GHz, using a scaling factor of $^{15}/_{8}$. Since frequency is inversly proportional to wavelength, bigger dimensions of pins were gotten for 8GHz. These dimensions were *period = 14.1mm, width = 5.63, height = 9.4mm*. The airgap was maintained as 3mm. The dispersion diagram retrieved from CST is shown below.

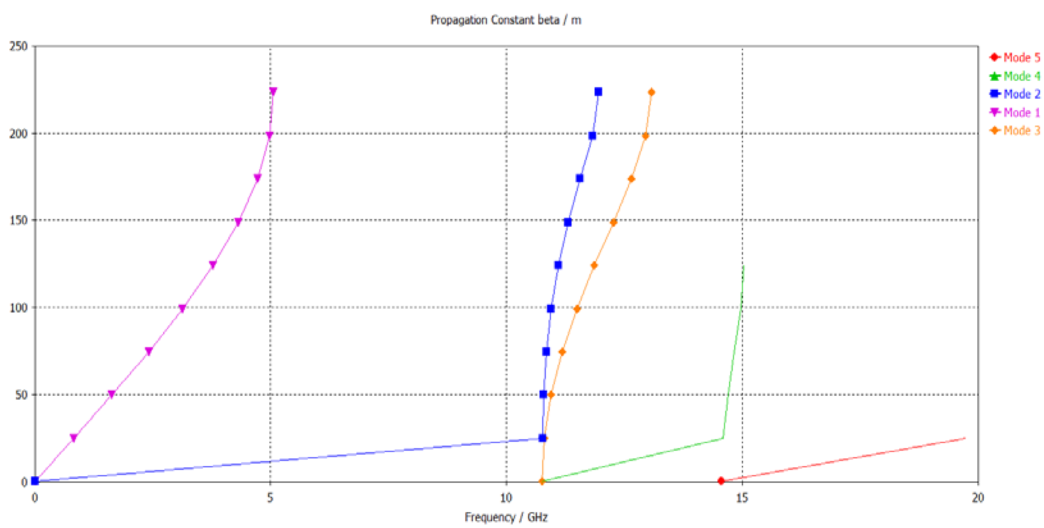


Fig. 25 Dispersion diagram of infinite row of pins at 8GHz plotted in CST

A bandgap of around 5GHz – 11GHz was achieved with infinite number of pins with the dimensions for 8GHz. Knowing this, we put a limited number pins in our actual design as shown below.

a) crossection

b) Top view

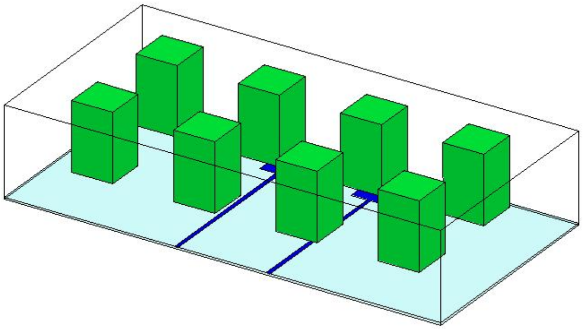


Fig.26 Different diagrams of 8 GHz pins

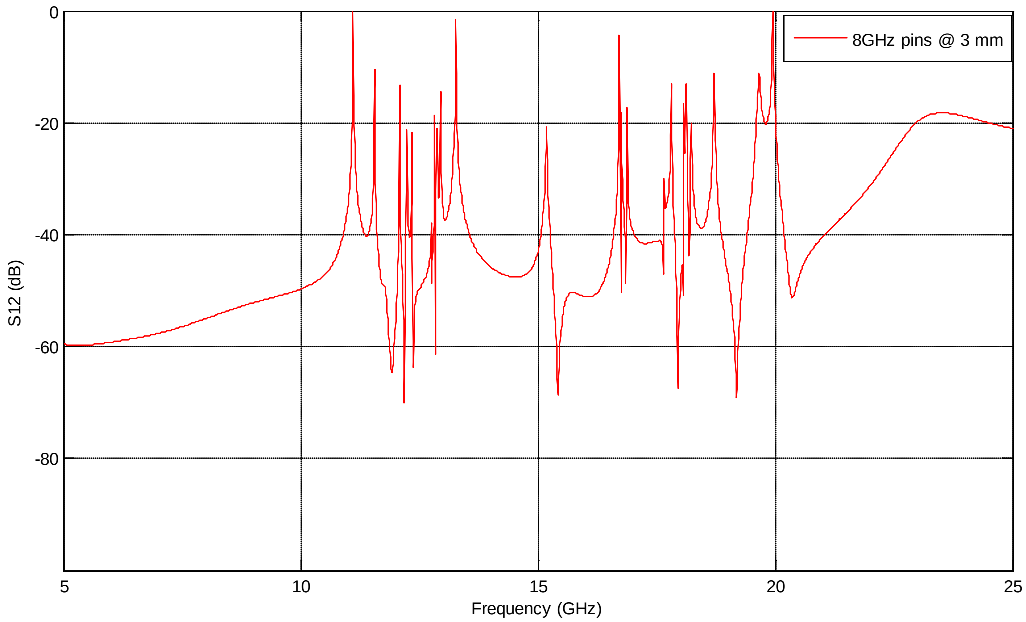


Fig.27 Plot of isolation when lid of nails for 8GHz is used.

Figure 27 above shows that at frequencies around 5GHz – 10GHz. The cavity modes are removed because the modes are in cut off in this frequency range and an isolation of around 50-60dB is achieved.

4.3.7 Comparison between 8GHz pin lids with Ideal PMC

The figure below shows the simulated plots between using an Ideal PMC as a plot and using the lid of nails at 8GHz as lids for the circuit.

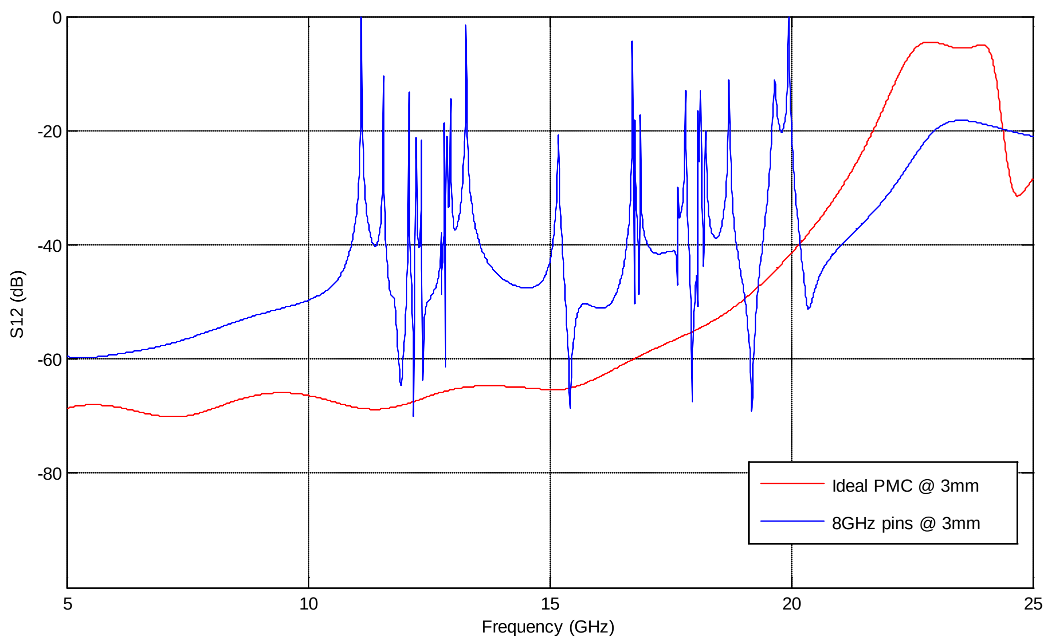


Fig.28 A combined plot of ideal PMC cover and 8GHz lid of nails cover

It is realized that from figure 28 that, at frequencies around 5GHz-10GHz, the lid of nails act as a PMC. After 10GHz, it stops acting as such and the modes reappear. Even thougth the pins lids act as PMC in this frequency, the graph is not exactly in line since the lid of nails is not as ideal as the PMC.

4.4 Comparing between the existing solution and gap waveguide cover solution

Figures 29 and 30 below show combined plots of the existing solution and the gap waveguide solution. We described earlier that the existing solution comprises both via holes and a metal wall to prevent the surface and substrate travelling waves from coupling between the two circuit components. The graph shows that better overall isolation is achieved with the existing solution but the presence of resonances is unwanted and this is removed using the gap waveguide solution. It is also noted that, the gap waveguide solution here is defined for a 3mm air gap. Better isolation can be achieved with lower heights as proven earlier.

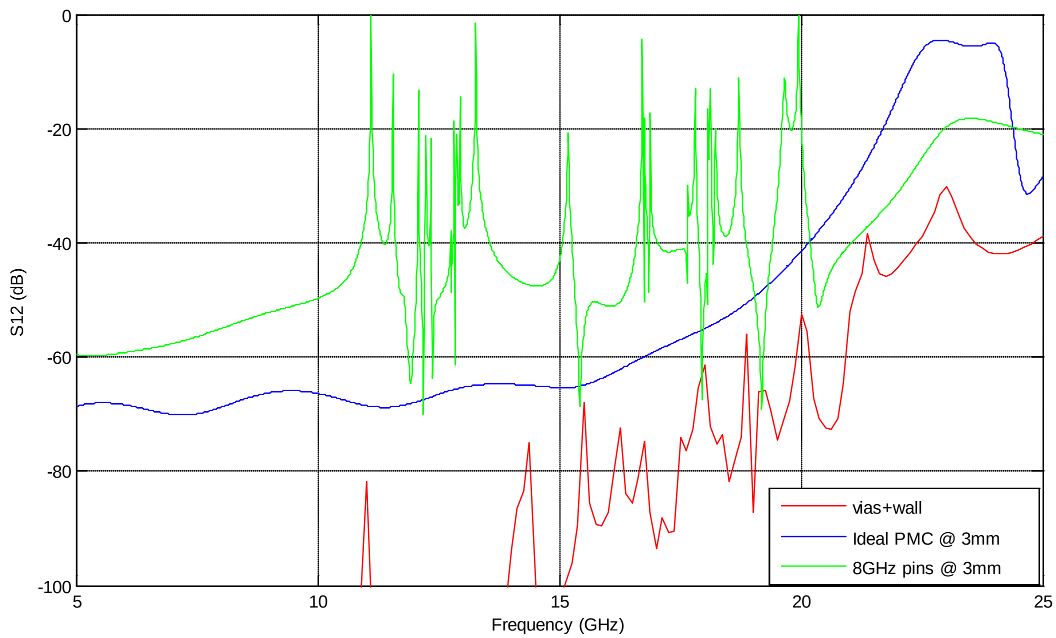


Fig. 29 Combined plots of Existing solution (wall+vias) and lid of nails solution @ 8GHz

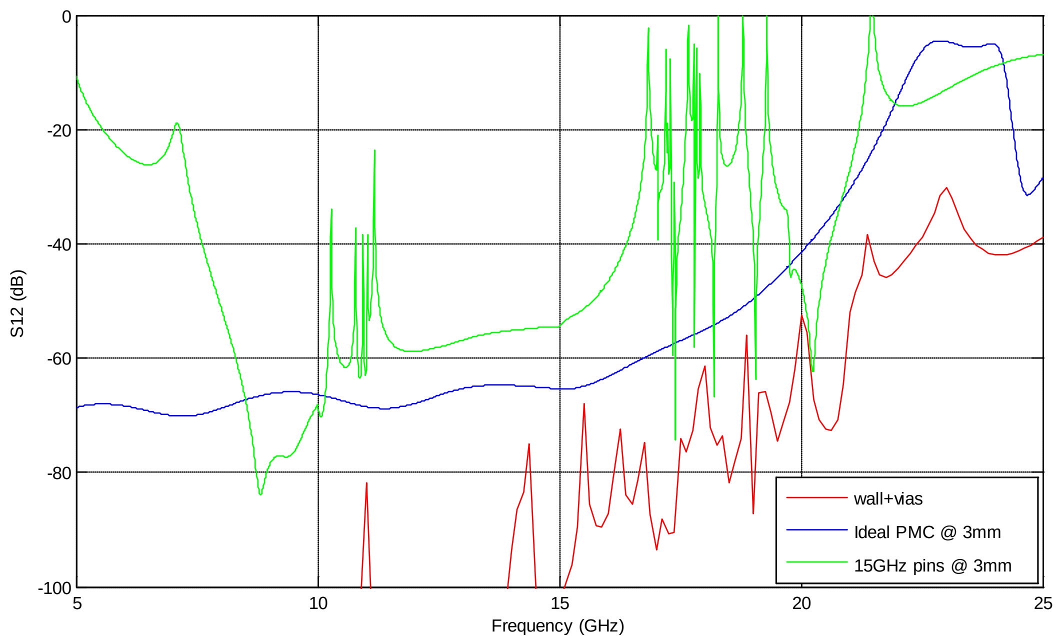


Fig. 30 Combined plots of Existing solution (wall+vias) and lid of nails solution @ 15GHz

CHAPTER 5

5. PROTOTYPE DESIGN OF GAP WAVEGUIDE SHIELDING SOLUTION

The 8GHz and 15GHz designs already discussed were sent in for manufacturing. Manufacturing the structure in the workshop is quite different from designing in software. The software design is usually changed a little bit in order to accommodate addition of screws and connectors. The picture of the initial design ready for manufacturing is shown in fig. 31.

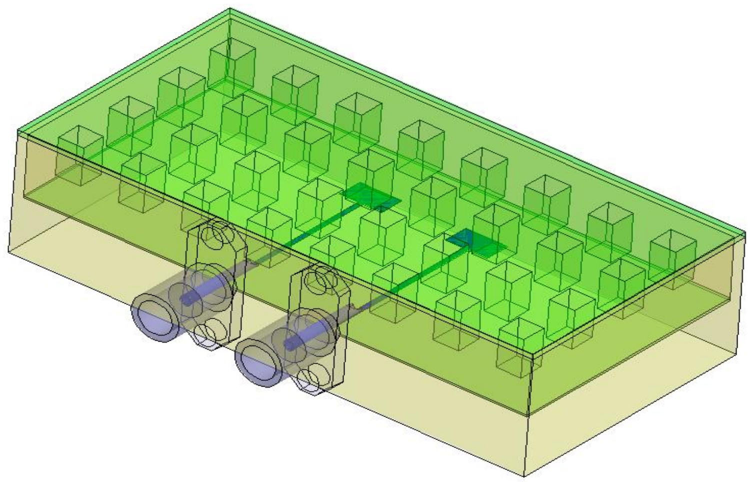


Fig.31 Initial prototype design with attached SMA connectors

5.1 Modifications of initial prototype design

In figure 32 , it can be noticed that one of the patch antennas has being turned around (180 degrees) from its previous position. This is because it enables the attached SMA connectors to be used efficiently without causing problems in measurements. If kept the same as in Fig. 30, the sma connectors will be too close to each other and this will affect our return loss values which will in turn affect our overall measurements in one way or another.

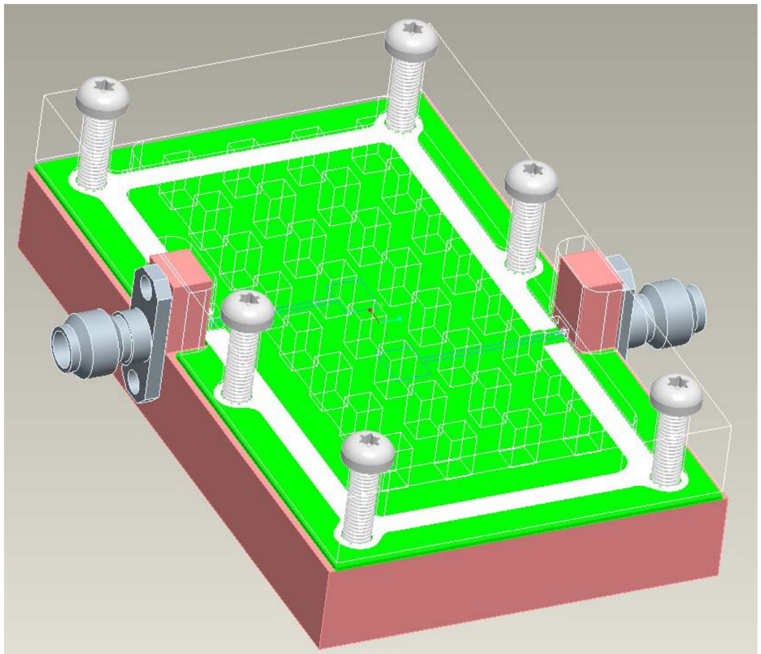


Fig.32 A picture of the modified structure ready for manufacturing

5.2 Calibration and measurements of the various design prototypes

Measurements were performed on the different prototypes with a network analyzer. The network analyzer was calibrated with Short-Open-Load-Through (SOLT) calibration kit. After calibration the return loss (S_{11}) of -50 dB was obtained for a frequency range of 5 – 22 GHz. This frequency is suitable since our gap waveguide works in this frequency range.

In measurements, we demonstrated different prototypes, i.e. 15GHz pins at 3mm, 15GHz pins at 1mm, *wrongly fabricated* 8GHz pins at 3mm, a shielded metal lid and a smooth metal lid. Each of these were compared with two different substrate types, i.e. a substrate with or without via holes. Figure 33 below shows the different prototypes measured.

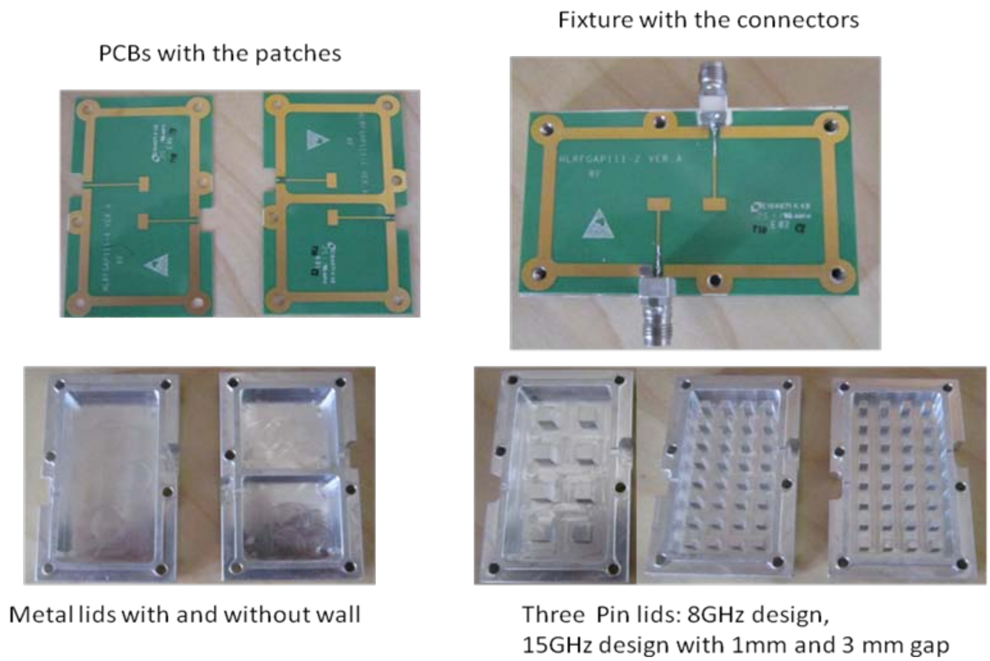


Fig. 33 Prototype design of the different PCB's and lids

5.3 Analysis of measured results

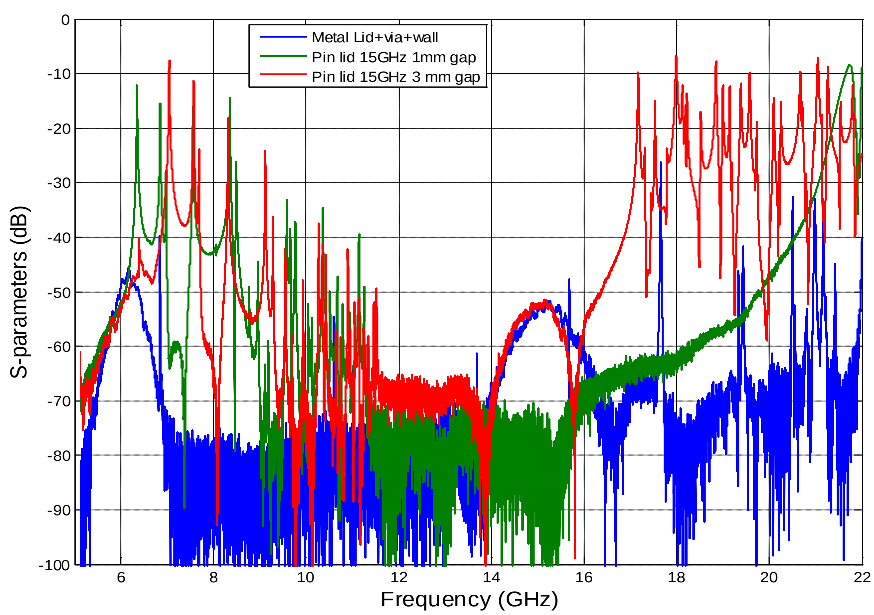


Fig.34 Measured S_{21} of the circuit components with via holes in three different situations: metal lid with wall, 15GHz pin lid with 1mm gap and 15GHz pin lid with 3mm gap.

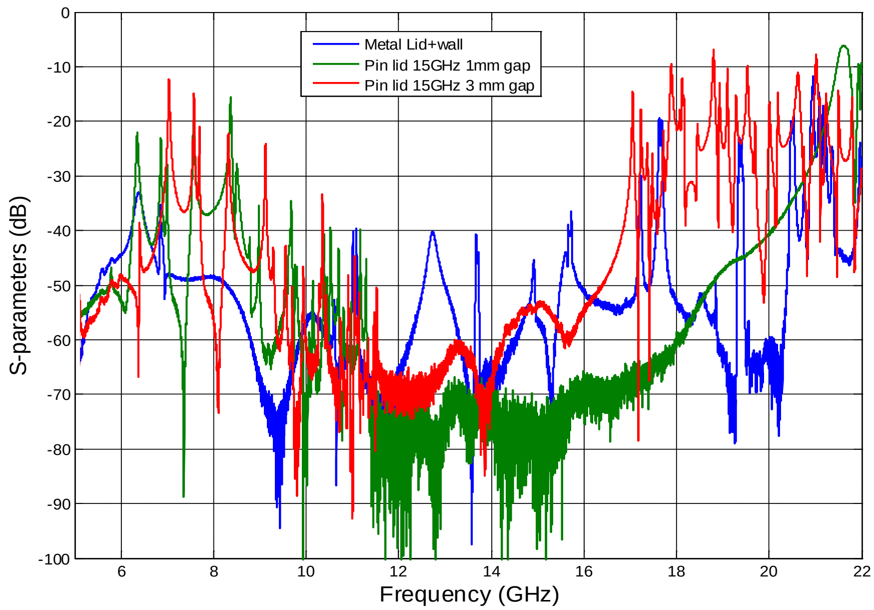
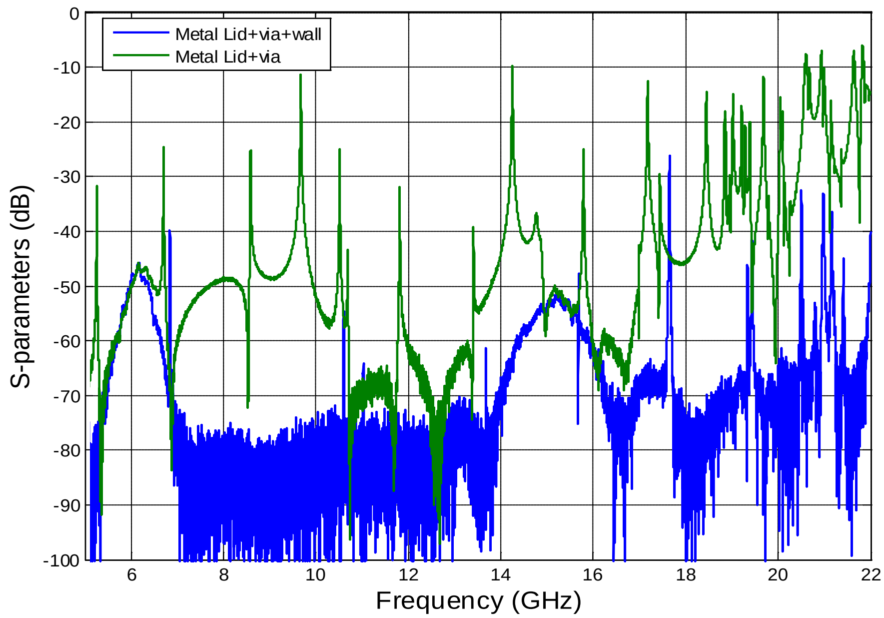


Fig.35 Measured S_{21} of the circuit components without via holes in three different situations: metal lid with wall, 15GHz pin lid with 1mm gap and 15GHz pin lid with 3mm gap.

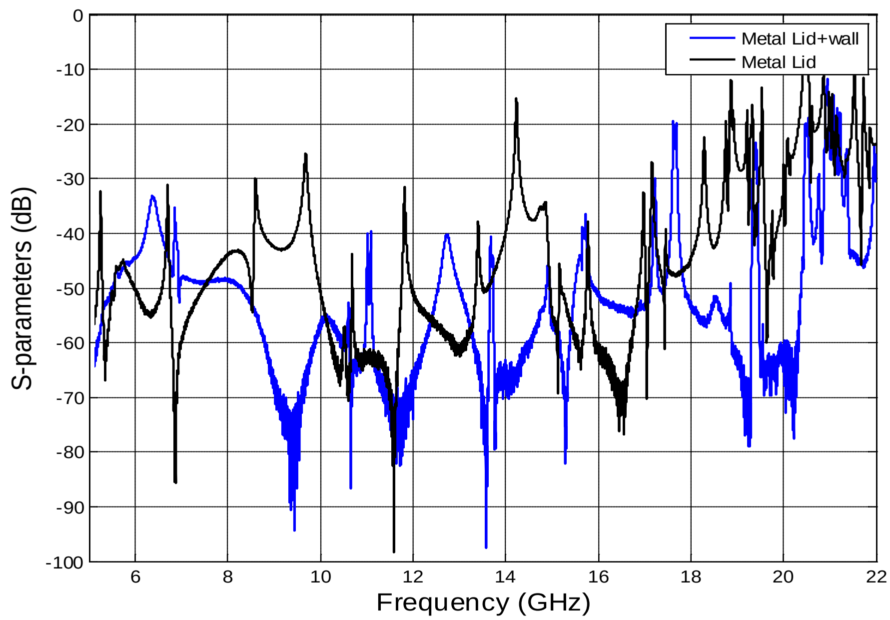
It is clearly seen from figs. 34 and 35 that the 15GHz pin lid covers take out the resonances present when the metal lid + via + wall and the metal lid + wall are used. For example, in fig. 33, the resonances appearing at around 12.5GHz, 13.5GHz, 15GHz and 15.5GHz are all removed by the 15GHz pin lid 3mm gap. Even much more resonances are removed with the 15GHz pin lid 1mm gap.

Results of figures 34 and 35 also show that the vias has no effect on shielding when the gap waveguide covers are used, since the plots are exactly the same with and without them. It can be seen that the 15GHz pin lid1mm gap provides a better isolation over a wider bandwidth than with 15GHz pin lid 3mm gap, as the theory proves.

The smooth metal lid shows almost no shielding at all, with and without vias. A lot of resonances appear inside the circuit which makes it undesirable as a shielding cover, as shown in Figure 36 below.



(a)



(b)

Fig.36 Measured S_{21} of the smooth metal lid (black) and metal lid + wall (blue): (a) with vias (b) without vias

The 8GHz pin lids 3mm was also manufactured. As described in chapter 4, the dimensions of the pins were *period = 14.1mm, width = 5.63, height = 9.4mm* .In manufacturing, a mistake was made and the length was manufactured with a *height = 5mm* while the other dimensions were kept correct. With the correct dimensions, an isolation of 50-60 dB over a bandwith of around 5 – 10GHz was expected. With a wrongly manufactured height, the pin lids were not expected to work since it didn’t follow the principle of the gap waveguide, but it suprisingly did, as shown in fig. 37 below.

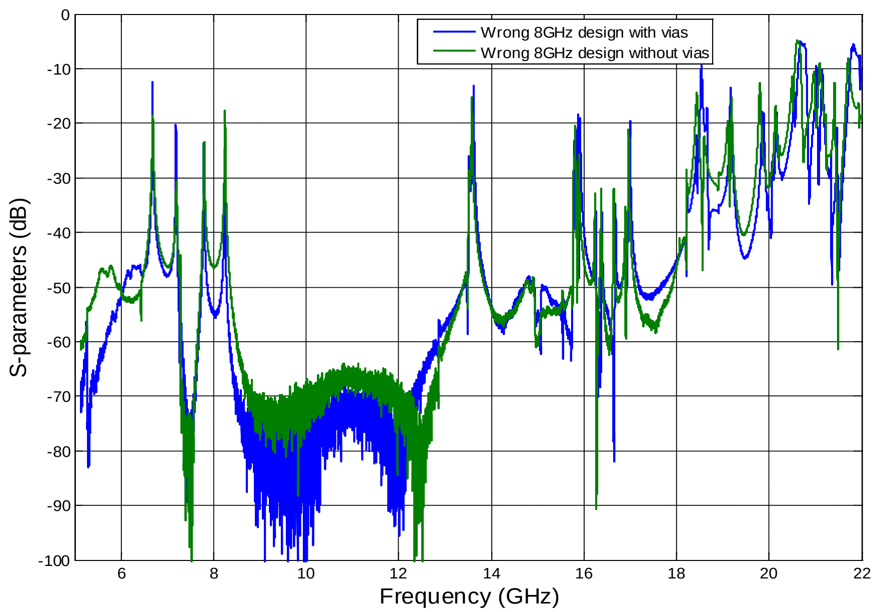


Fig.37 Measured S_{21} of the 8GHz pin lids with wrongly manufactured pin height

The wrongly manufactured 8GHz pin lids provides an isolation of around 65 - 70 dB over a bandwidth of 8.5 – 13GHz. The presence or absence of the vias doesn’t affect the results as we noticed with the 15GHz pin lids.

From the measurements above, it is realized that both pin lids designs work as expected from simulations. Therefore we can safely package our PCB board with both 15GHz and the wrongly manufactured 8 GHz pins without making use of the old packaging with vias and metal walls.

CHAPTER 6

6. Comparison between simulated and measured results

This chapter compares the results achieved from measuring the prototypes designs with what we achieved from software simulation. It is important that they are compared to determine if there is agreement between them. Since software simulation is usually done in ideal conditions while actual fabrication and measurements are rather done in practical conditions. It is crucial that we compare the two conditions to see how well our prototypes perform under practical conditions.

6.1 Metal Lid + Via

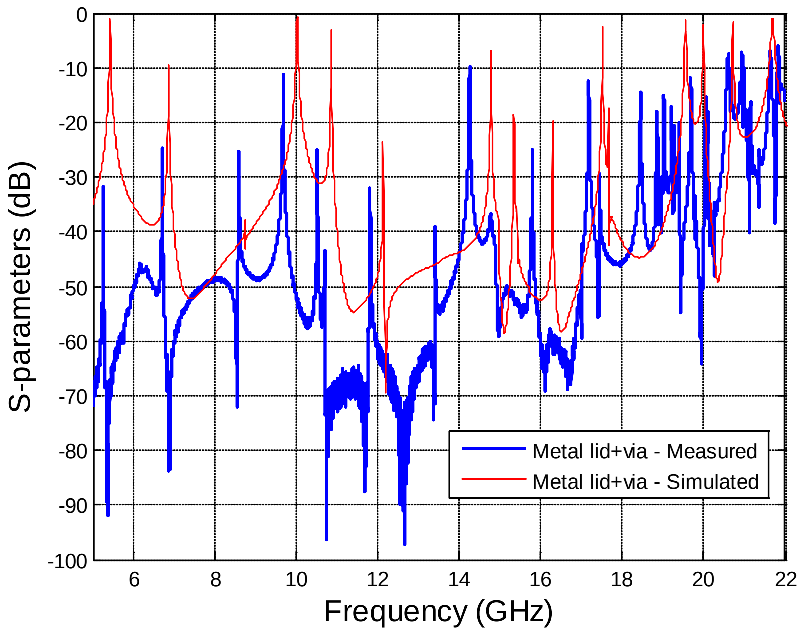


Fig. 38 Measured and simulated plot of metal wall lid + via

6.2 Metal Lid + Wall

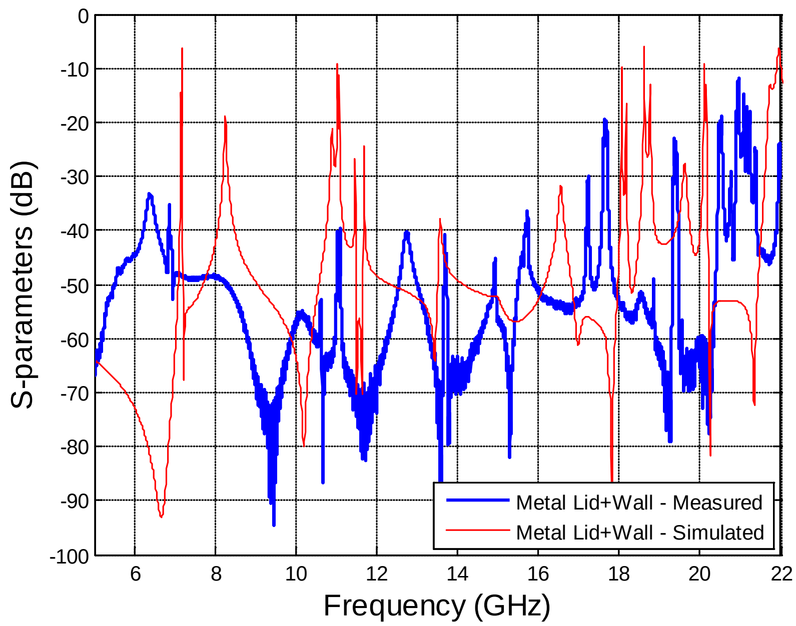


Fig. 39 Measured and simulated plot of metal wall lid + wall

6.3 Metal Lid + Wall + Via

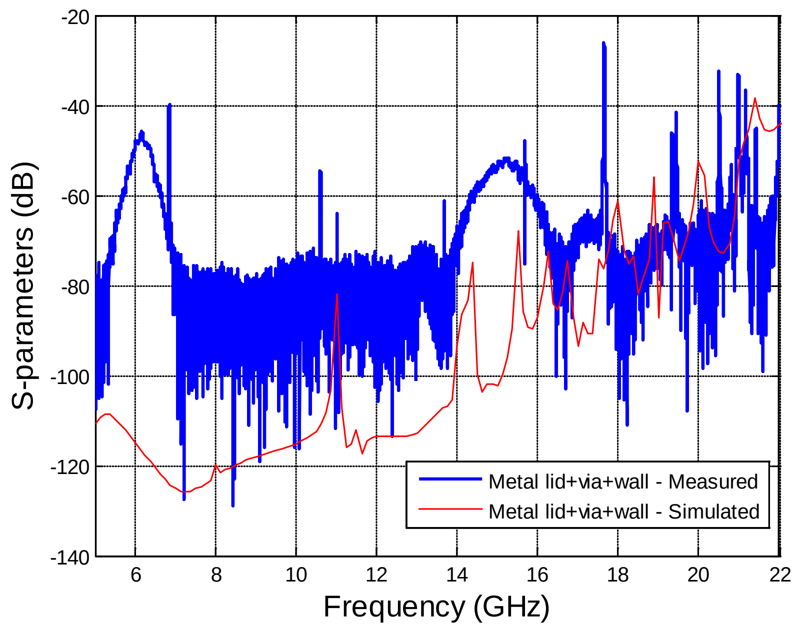


Fig. 40 Measured and simulated plot of metal wall lid + wall + via

6.4 15 GHz Pin Lid @ 1mm

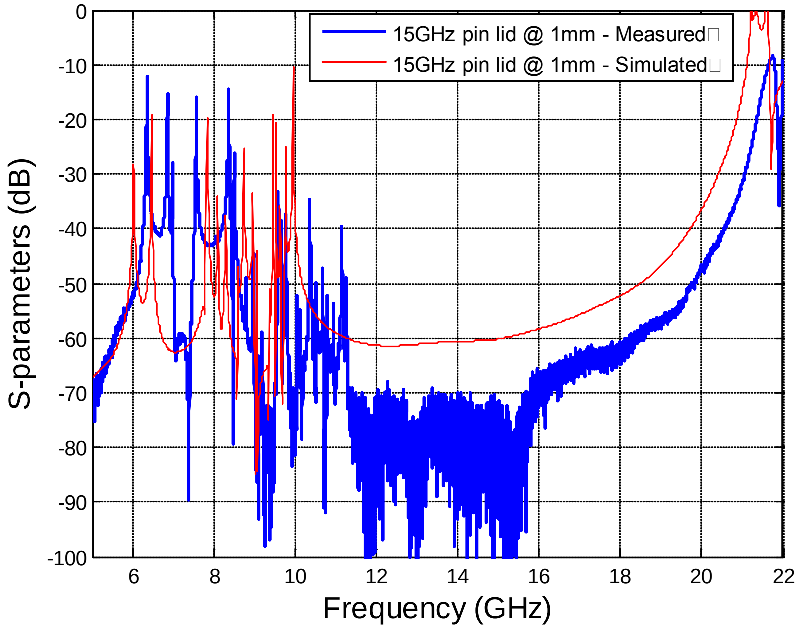


Fig. 41 Measured and simulated plot of 15GHz pins at 1mm

6.5 15 GHz Pin Lid @ 3mm

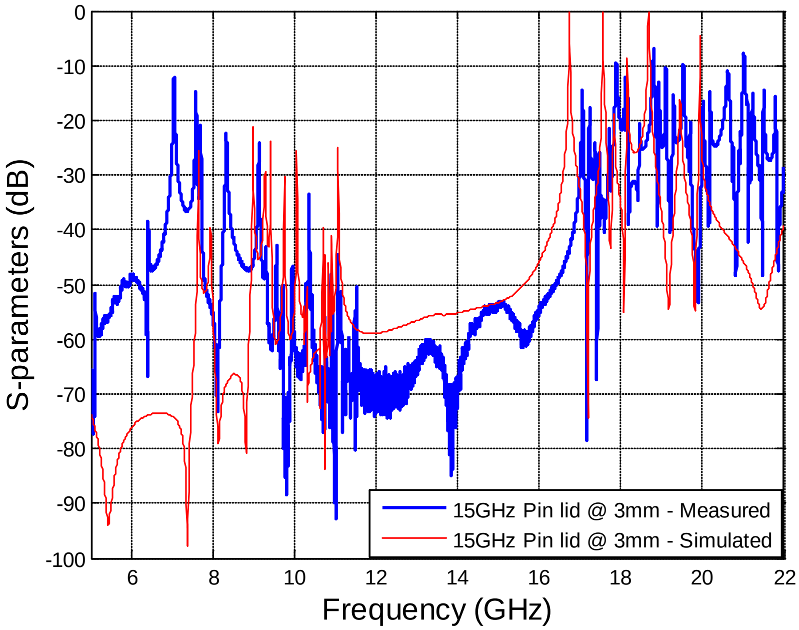


Fig. 42 Measured and simulated plot of 15GHz pins at 3mm

6.6 8GHz Pin Lid @ 3mm

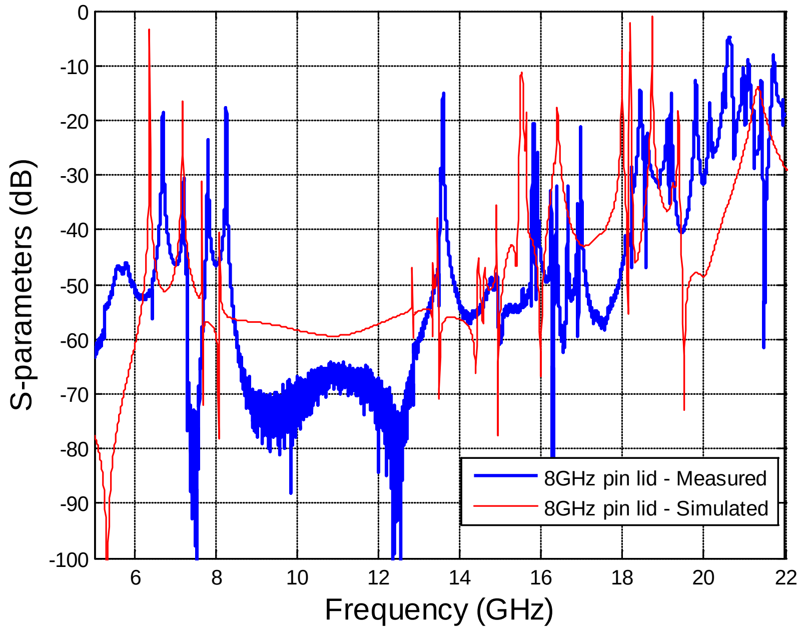


Fig. 43 Measured and simulated plot of 8GHz pins at 3mm

The plots above show a pretty good agreement between simulated and measured results. The little discrepancies noticed are mainly due to numerical errors in the simulation software and also from mechanical tolerance incorporated with the manufactured lids.

CONCLUSION

This report has demonstrated the use of gap waveguide to provide packaging of a microwave circuit. The gap waveguide concept has been used as a better way to shield the circuit components previously shielded by metal walls and via holes. It has been demonstrated that, with gap waveguide shielding, more room can be created between circuit components by removing the previously used metal walls and via holes. The available room can be reused to place more circuit components or even shrink the size of the cavity to make it less combusome.

The results show that all the pins well with in a specific bandwidth and the measurement results are in good agreement with the simulated results. The shielding solution associated with metal wall and vias are usually more broadband. On the other hand the gapwaveguide solution is more suitable over a specific bandwidth and does not depend on the cavity size. The cavity can be of any dimension, still the pin lids will work well over the specific frequency band where the pins work as PMC.

There are also some drawbacks with the gap waveguide solution. For shielding, we need different pins heights for different areas of the circuit. For example, the PA and LO might need different pin heights which makes the shielding cost grow for increasing types of covers. Also since the room below the pin or the airgap is limited to $\lambda/4$, the application of the PCB is limited to around 10GHz +/-5GHz, if too high, there is no space left for components, if too low, the pin height dramatically increases the module size. With the pins being conductive and hard, there is risk that they might put pressure on the components or even cause short circuits, as compared to when absorbers are used.

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