Numerical Prepackaging with PMC Lid − Efficient and Simple Design Procedure for Microstrip Circuits Including the Packaging

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Abstract ─ The paper presents an efficient method for the design of printed microstrip circuit with packaging in mind, referred to as numerical prepackaging with a perfectly magnetic conductive (PMC) lid. The method comprises making the design including the packaging from the start by using a PMC lid, rather than first designing the open-aired circuit; and thereafter, considering the packaging effect and the often required retuning of the circuits themselves. The advantage is that no parallel plate modes can propagate between the perfect electric conductor (PEC) ground plane and the PMC lid plate if the spacing is smaller than an effective quarter of wavelength. This provides a limited computational volume so that the computation time is significantly reduced in the case of the finite element method (FEM) or the finite difference time domain method (FDTD). By using numerical packaging with PMC lid, the ideal PMC lid has to be realized afterwards e.g. by using a lid of nails, which is a minor task as compared to existing approaches.

Index terms- Cavity resonance, FDTD, FEM, PMC, PEC, shielded microstrip line.

I. INTRODUCTION

In the design of printed microwave circuits using numerical methods such as the finite difference time domain method (FDTD) [1], finite element method (FEM) [2], finite integral method [3] or any volume type formulations, it is necessary to limit the computational space using virtual boundaries such as radiation boundaries [4] or perfect matching boundaries [5] in terms of different implementations as described in [6-8]. In order to use such boundaries some restriction should be enforced to make valid computations. For example, it is recommended that the distance between these boundaries and the actual circuits to be in order of a quarter wavelengths at the low frequency to have reliable results. Some of the perfect matching boundary conditions require several layers [1] that in some cases would be eight layers. Such requirement regarding the distance of the virtual boundaries increases the overhead of computational time and storage. After reaching a final circuit design in such a way, one will always need to package the circuit. In order to have a compact package circuit it is important that the package cavity be very close to the circuit. However, such packaging should not affect the circuit performance. Some engineers might use resistive loading inside the packaging cavity to suppress resonances of the cavity appearing within the operating frequency band. Such a technique increases the losses and reduces the circuit efficiency. It would be better if the packaging is not affecting the circuit efficiency and at the same time be compact and nearly lossless. However, as the packaging gets closer to the circuit, packaging might interact with the circuit and affect its performance and the designer might find that some tuning of his circuit is necessary to achieve the desired performance. Such a tuning may be quite tedious to perform and requires experience in designing circuits.

Here, we propose an efficient procedure to design printed circuits with packaging in mind.

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Packaging is needed for mechanical protection, but also to shield the circuits from outside strong fields and interference, and to prevent any possible radiation emissions from the circuit. In some cases resistive loading inside the package cavity can be used to suppress high order modes. Here, we propose, during the initial design to use perfect magnetic conductor (PMC) lid to shield the circuit and to consider it as an ideal packaging approach, which also will confine the computational domain volume. From the circuit point of view, one might consider the PMC as an open circuit surface dual to the perfect electric conductor (PEC) that is a short circuit surface. Note that a metal surface to a very good approximation can be considered a PEC in electromagnetic (EM) field analysis. PMC and PEC surfaces can be used as boundaries that limit the computational domain. Since PMC could be considered as an open circuit, its influence on the printed circuit is much smaller than a PEC (i.e. a metal surface). Possible parallel plate waveguide modes will be suppressed as far as the effective height of the parallel plates between the ground PEC and the PMC lid is less than an effective quarter wavelength [6]. As resonances are suppressed from the cavity the convergence of the FDTD method should improve as well. One might object on using PMC as it does not exist in nature, but nowadays we can artificially realize PMC or high impedance surfaces or what is referred to as an artificial magnetic conductor (AMC) using periodic surfaces. There are many ways to realize such surfaces, but it is important to realize it in a way that will not increase the losses of the system. Actually, the PMC lid packaging relates more to realizing a parallel-plate cut-off (or stopband) between PEC and AMC, and different ways of realizing this are studied numerically in [10]. The simplest realization is in terms of a lid of nails or pins, for which the practical demonstration of usefulness to packaging is described in [11].

The PMC prepackaging is a result of research on soft and hard surfaces originating from a generalization of the corrugated surfaces used in corrugated horn antennas. This surface concept was first defined in 1988, and improved in 1990 [12]. The hard surface was already in 1996 applied to realize what today is known as cloaking [13]. The original soft surface is a transverse PEC/PMC strip grid acting as an anisotropic electromagnetic bandgap (EBG) surface, as explained in [14] and [16]. Other marvels of EBG surfaces are described in [15]. The ideal PEC surface, PMC and PEC/PMC strip grids are in [16] referred to as canonical surfaces. The use of simplified canonical representations of advanced periodic surfaces with many details is very important in conceptual and numerical work; in conceptual work they improve physical understanding and creativity, and in numerical work they are fast and convenient to use in initial studies. The canonical surface concept has e.g. resulted in the present PMC prepackaging approach. Note that canonical representation of the EBG surface is proposed in [17], although not yet being so generally applicable as the PEC, PMC, and PEC/PMC strip grid. The EBG surface can also be used to create parallel-plate cut-off [10]. The concepts of soft and hard surfaces and canonical surfaces are also the background of the gap waveguide technology, as introduced in [6], verified by measurements in [11-18], and studied by plane wave spectral domain solutions in [19] and by classical subdomain plane wave expansions in [20]. The latter theoretical work is extended to more analytic expressions in [20]. There exists three types of gap waveguides; ridge gap waveguide, groove gap waveguide, and microstrip gap waveguide [22]. The PMC packaged microstrip line of the present paper is a kind of microstrip gap waveguide.

In this paper, we perform a parametric study of microstrip transmission lines in the presence of PMC cover. We look at what is the proper separation distance between the microstrip lines and the PMC that does not affect the original characteristic of the microstrip lines as ideal transmission line. We also study the effect of the PMC shielding on microstrip lines that violates the radiation condition as provided in [23-24]. The study shows how the PMC shielding removes such radiation condition constraints. Also, we look at some discontinuities that cause radiation losses from the circuit and how the PMC shielding also suppress such radiation losses. After that we introduce a periodic structure that is designed to realize the PMC surface and compare the ideal PMC shielding with the realized artificial magnetic conductor. We believe that such a procedure will eliminate or at least reduce the needs for any tuning for the printed circuit after packaging. In addition, the design can be performed in one combined process, which certainly will be much faster than what is currently performed (as the circuit is designed in one process and the packaging in a second process). For the proposed design to be implemented, the software has to have the ability to model and include PMC surfaces. There are several commercial software codes that have such capabilities. Here, we considered a commercial software CST microwave studio [25], which is based on the volume integral equation in frequency and time domain.

II. COMPARISON OF RESONANCE FREQUENCIES OF CAVITIES WITH PEC OR PMC LIDS

Usually, printed circuits are packaged in a conducting cavity, i.e. the circuit is located in a metal box so that it is surrounded by six conducting walls (ground plane, four conducting sidewalls, and a conducting lid). This creates an inhomogeneous cavity as shown in Fig. 1, i.e. being filled with a dielectric substrate layer located on the ground plane wall and with metal traces on the other side of it. The height h of the cavity is suggested to be higher than the substrate surface by 5 or 4 times substrate thickness in order not to affect the characteristic impedances of the microstrip lines, and not to interact with the circuit, and in turn not to affect the designed circuit performance. Since the total height is usually small, a transverse magnetic TM_z mode with mainly z-directed electric field is supported. This makes the first resonance of the cavity determined by the dimensions of the ground-plane of the cavity. If the cavity modes are within the operating frequency band of the circuit, the cavity will interact strongly with the circuit and distort its characteristics. The effect is in particular severe when packaging active components such as mixers, oscillators, and amplifiers. The cavity may be loaded with resistive sheets or absorbers in order to suppress the resonances.

However, if the cavity has a PMC lid, the TM_z mode will be in cut-off, as well as TE_z modes, as long as the cavity height is smaller than a quarter of the wavelength, effectively. Therefore, the first resonance will appear at a much higher frequency than for the PEC lid case. The PMC concept is rather new, so it is not possible to find fundamental results like resonance frequencies of conducting cavities with PMC lids. Therefore, we will here present the formulas together with those of a conducting cavity with PEC lid. To that end, we consider an ideal rectangular cavity with PEC floor and sidewalls, and either a PEC or PMC lid at a height h above the floor, and the cavity has a dielectric layer of thickness t at the floor, as shown in Fig. 1. The cavity planar dimensions are *a* x *b*, and ε_1 is the relative permittivity of the dielectric substrate.

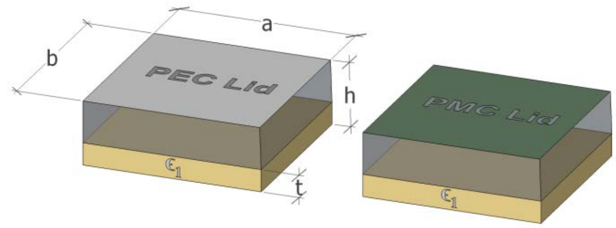

Fig. 1. Partially filled cavity with PEC base and sidewalls, and (a) PEC lid and (b) PMC lid. The sidewalls are not shown.

The resonance frequencies can for the PEC lid case be obtained by solving the transcendental dispersion equations, in [26] for k_z, i.e.

for TM_x mode:

$$\frac{k_{z1}}{\varepsilon_1}\tan k_{z1}t = -\frac{k_{z2}}{\varepsilon_2}\tan k_{z2}(h-t) \qquad (1.a)$$

for TE_x mode:

$$k_{z1}\cot k_{z1}t = -k_{z2}\cot k_{x2}(h-t) \qquad (1.b)$$

Similar equations can be derived for the PMC lid case, taking the form:

for TM_x modes:

$$\frac{k_{z1}}{\varepsilon_1}\tan k_{z1}t = \frac{k_{z2}}{\varepsilon_2}\cot k_{z2}(h-t) \qquad (2.a)$$

for TE_x modes:

$$k_{z1}\cot k_{z1}t = k_{z2}\tan k_{z2}(h-t) \qquad (2.b)$$

where in both cases

$$k_{z1} = \left[\omega^2 \varepsilon_1 \mu - \left(\frac{n\pi}{a} \right)^2 + \left(\frac{m\pi}{b} \right)^2 \right]^{1/2} \qquad (3.a)$$

$$k_{z2} = \left[\omega^2 \varepsilon_2 \mu - \left(\frac{n\pi}{a} \right)^2 + \left(\frac{m\pi}{b} \right)^2 \right]^{1/2} \qquad (3.b)$$

and where n and m are integer numbers.

For a homogeneous cavity there exists closed form expressions for the resonant frequencies, which for the TM_z case is given as:

$$f(GHz)^{PEC}_{mnl} = \sqrt{\left[\left(\frac{l\pi}{d} \right)^2 + \left(\frac{n\pi}{a} \right)^2 + \left(\frac{m\pi}{b} \right)^2 \right]}, l = 0, 1, 2 \cdots, m = 1, 2 \cdots, n = 1, 2 \cdots \qquad (4.a)$$

$$f(GHz)^{PMC}_{mnl} = \sqrt{\left[\left(\frac{(l+1)\pi}{2d} \right)^2 + \left(\frac{n\pi}{a} \right)^2 + \left(\frac{m\pi}{b} \right)^2 \right]}, l = 0, 1, 2 \cdots, m = 1, 2 \cdots, n = 1, 2 \cdots \qquad (4.b)$$

Table 1 shows the first resonance in a cavity with different dimensions and different dielectric materials, computed from the above formulas. For a homogenized cavity, the base dimensions of the cavity determine the first resonant frequency when the cover is PEC, but the height determines the first resonance frequency when the cover is PMC. In both cases, the height must be much smaller than the cavity base dimensions and smaller than a quarter of a wave length. It is in our interest to show results when the cavity is partially filled with dielectric substrate and the separation between the dielectric surface and the top is small. The results are shown in Table 1 for different separation distances ranging from 2*t* (i.e. *h* = 3 mm) to 4*t* (i.e. *h* = 5 mm). We see that the size of the cavity base and the dielectric loading determines the first resonance for the PEC case, and again the cavity height and the permittivity determine the first resonance for the PMC case. It can also be seen that the resonance frequency decrease when the permittivity increases and when the separation between the substrate and the lid increases. The resonances for the PMC lid case are 3 to 5 times higher than those of the PEC case.

III. PMC PACKAGING EXAMPLES FOR MICROSTRIP CIRCUITS

First, we consider a simple 50 Ω microstrip line as a two port device, and we use waveguide ports in CST in order to have perfect match to the microstrip line ports. We need this perfect match in order to get good accuracy in determining the reflection coefficient and associated transmission losses. The computational domain is bounded by the radiation box as suggested by the software developer. Thereafter, the PMC is added with different separations between the substrate surface and the PMC. Notice that the upper bound of the computational domain now is bounded by the PMC, and there is no need for any upper radiation boundary. However, the side walls of the computational domains are still bounded by what is suggested by the software developer. The computational domain is now limited between the ground plane and the PMC. This reduces the computational domain a lot. To make simple design guide, the separation distance will be related to the physical substrate thickness and transmission line width, but we have to keep in mind that this distance must be smaller than the quarter of a wavelength of the upper frequency to

Table 1: First resonance frequency in GHz of a cavity with PEC lid and PMC lid, with a substrate thickness *t* =1mm

cavity base *a* x *b* (mm)	ε_1	h = 5 mm		h = 4 mm		h = 3 mm	
		PEC lid	PMC lid	PEC lid	PMC lid	PEC lid	PMC lid
50 x 50	1.0	4.243	15.588	4.243	19.224	4.243	25.357
	2.3	3.994	15.329	3.930	18.781	3.820	24.281
	10.2	3.832	14.274	3.724	16.525	3.538	18.982
50 x 60	1.0	3.905	15.588	3.905	19.224	3.905	25.357
	2.3	3.677	15.260	3.618	18.729	3.517	24.246
	10.2	3.528	14.224	3.429	16.497	3.258	18.970
60 x 60	1.0	3.536	15.588	3.536	19.224	3.536	25.357
	2.3	3.329	12.277	3.275	18.677	3.184	24.211
	10.2	3.195	14.182	3.106	16.469	2.951	18.956

make sure that the high order modes of the cavity will not be excited. Several parameters are considered such as the permittivity and thickness of the substrate.

a) Insertion losses: Here, we consider an example of a 20 mm long 50 Ω microstrip line with a substrate thickness t = 0.635 mm and two different relative permittivities of 10.2 and 6.15 and loss tangent 0.0027. The conductor is considered to be copper. The transmission coefficient S_{21} is shown versus frequency in Fig. 2 for three cases; open, with PEC at 4t from the substrate, and PMC. It can be seen that packaging eliminates the radiation losses which is large for the open case above 18 GHz. However, the PMC packaging provides smaller insertion losses than both the open and PEC cases. It can also be seen that higher permittivity cause larger insertion loss. It should be mentioned that based on [6], the microstrip line will have radiation losses if:

$$f\,\{GHz\} \times t\,\{mm\} > \;\; 2.14\sqrt{\varepsilon_r} \qquad (5)$$

which corresponds to 10.8 GHz when the relative permittivity is 10.2 and 8.4 GHz when it is 6.15.

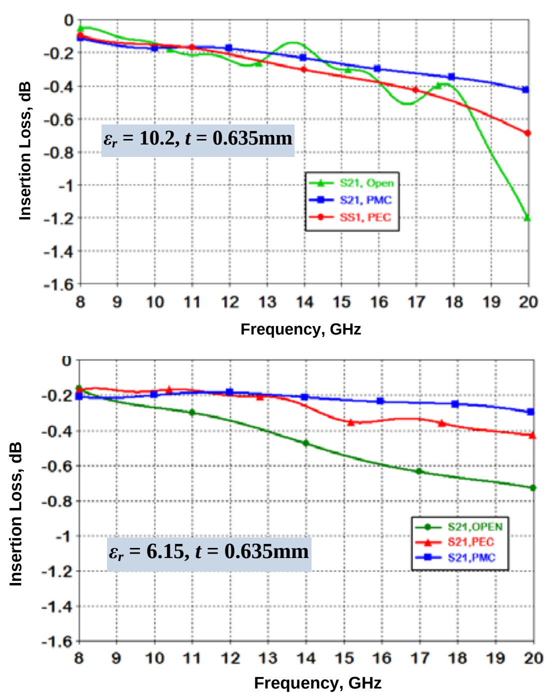

Fig. 2. Insertion losses of a straight microstrip line for different packaging cases, and for two different relative permittivities.

b) Characteristic Impedance: Figure 3 shows the variation of the characteristic impedance with frequency for the PMC lid located at different heights above the substrate. As expected, the characteristic impedance increases as the PMC lid gets closer to the line, because then the electric fields becomes more confined to the line so that its effective width is reduced. As such, the characteristic impedance increases since the characteristic impedance value is inversely proportional to the effective width of the microstrip line. The results indicate that a *3t to 4t* air gap is sufficient to keep the characteristic impedance the same as the open case (no lid).

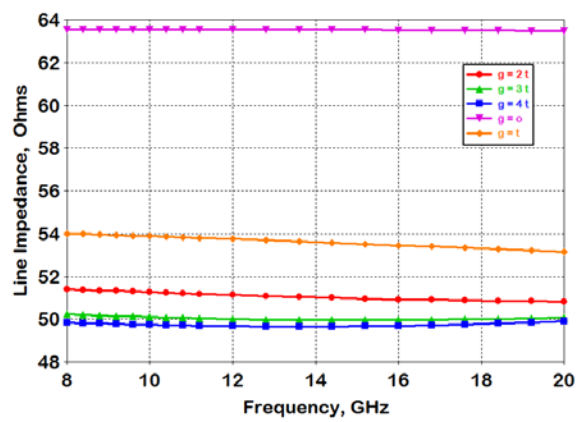

Fig. 3. Effect of the PMC lid on the characteristicimpedance of the microstrip line, *g = h-t*.

c) Bended microstrip line: A microstrip line of 20 mm length and having a right angle bend is shown in Fig. 4a. The bend is mitered at the corner to reduce the effect of the discontinuity at the bend. It should be mentioned that physical microstrip line discontinuities can be designed for minimum reflections, but radiation losses are always inevitable. Here, two cases are considered. One with a thin substrate (t = .25 mm; ε_r = 2.2, w = .8mm) and the other with a thicker substrate (t = 0.815 mm; ε_r = 3.38, w = 1.85 mm). Fig. 4b shows the comparison between the thin substrate case and the thick substrate case under open condtion and also the thick substrate covered with PMC at 3h. It can be seen that the PMC cover removed any kind of radiation loss and provides an overall better insertion loss, even for the open thin case.

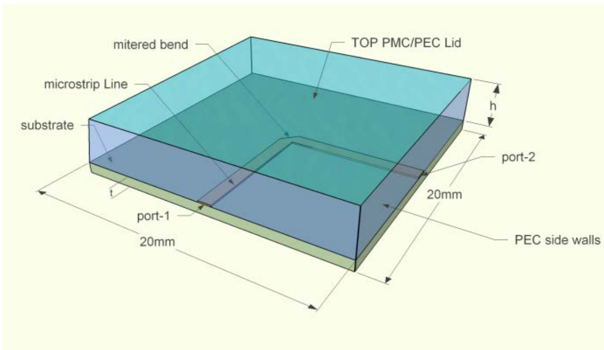

Fig.4(a). Bended microstrip line.

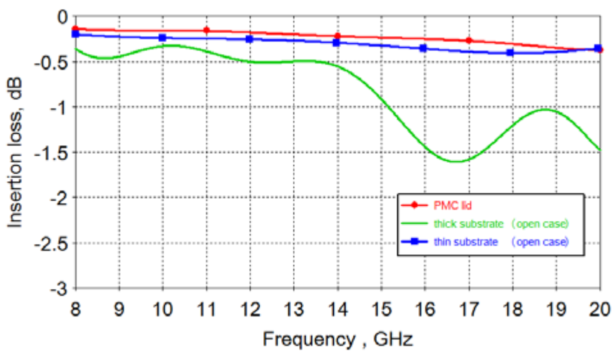

Fig. 4(b). Comparison between bended microstrip line on thin or thick substrates, open and with PMC lid 3t above substrate.

III. Realization of PMC Packaging

PMC is not a natural material so it has to be realized artificially. One method to realize the PMC lid is using a lid of periodic conducting nails [27] as shown in Fig. 5a. The artificially realized AMC surfaces have limited bandwidth, unlike the PEC that is a good approximation of conducting metal surfaces at all microwave frequencies. The lid of nails consists of nails connected to a solid ground plane which then is turned up-side-down. The magnetic surface appears at the open end of the nails, due to a transformation of the waves from the shorted end of the nails to the open end. The waves will in the nail layer propagate mainly along the nails, independent of the angle of arrival on the nails surface.

The pin structure is periodic, and therefore one cell can be analyzed by using the eigenmode solver of CST. The dispersion diagram of such an infinite periodic nail surface over a smooth metal surface is shown in Fig. 5b. We see that the structure is providing a stop band of parallel-plate modes (i.e. it is acting as an AMC surface) over a frequency band of 1:2. The S_{21} computed for a right angle bended microstrip line covered by the lid of nails is shown in Fig. 5c. We see that the bandwidth is similar to the bandwidth obtained from the dispersion diagram. We, also, see that the losses are very close to the ideal PMC case. A parameter study of the stopband can be found in [7].

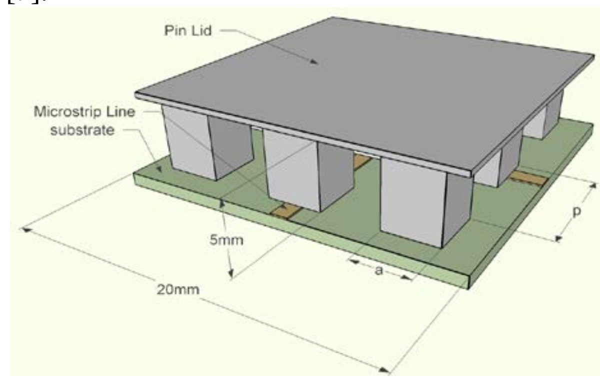

Fig. 5 (a). Geometry of the bended microstrip line in a cavity with metallic sidewalls and lid of nails.

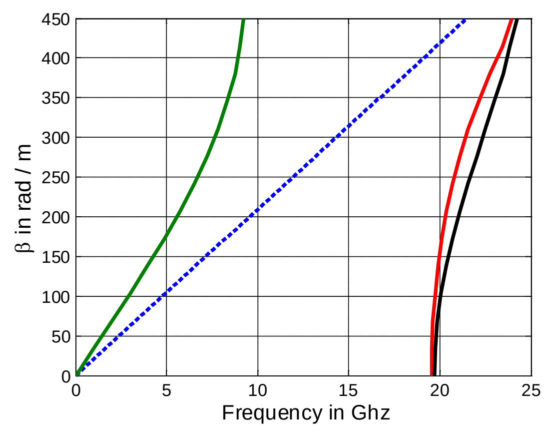

Fig. 5 (b). Dispersion diagram obtained for unit cell of periodic pin with a = 3mm and p = 6.75mm.

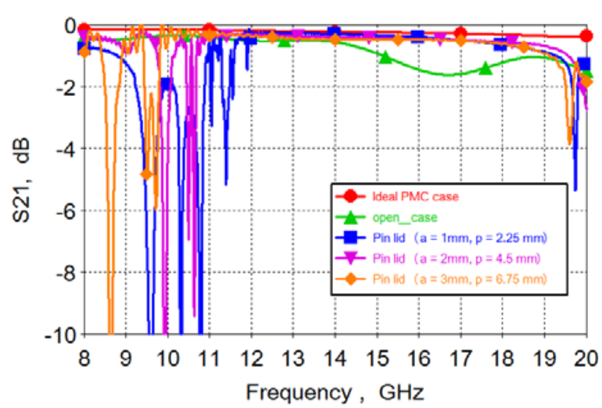

Fig. 5 (c). Simulated S_{21} of the right angle microstrip line with different *a* and the same *a*/*p*.

We now consider an example with an inhomogeneous nonrectangular cavity with the same right angle bended microstrip line, as shown in Fig. 6a. However, here the microstrip line is printed on a GaAs substrate with permittivity 12.9 and loss tangent 0.006 at 10 GHz, and thickness t = 50 µm. The 50 Ω microstrip line has a width of 30 µm. The dispersion diagram from one cell is shown in Fig. 6b. S_{21} versus frequency is shown in Fig. 6c. Figure 6c shows the performance of the three different cases; open, PEC lid, and PMC lid. We see that the PMC lid gives the smallest insertion loss, and the PEC lid curve shows some resonances within the frequency band.

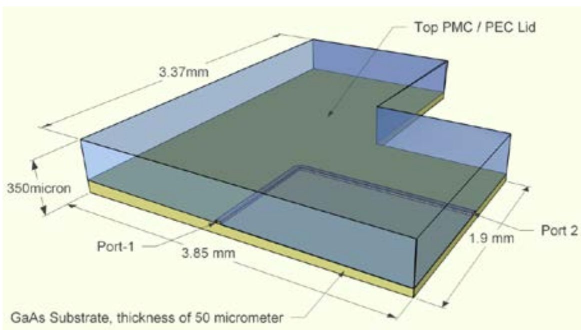

Fig. 6 (a). Geometry of the bended microstrip line in an inhomogenously filled nonrectangular cavity with metal.

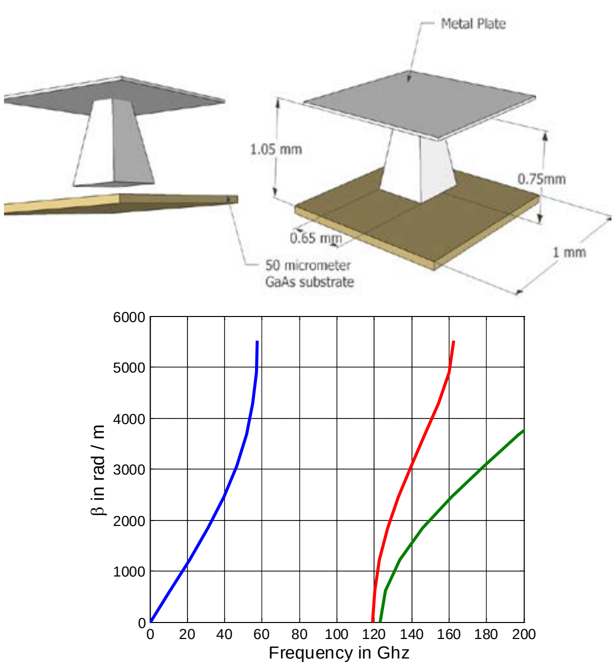

Fig. 6(b). Dispersion diagram obtained from the for one cell with inverted pyramidal-shaped pins that provide the wider bandwidth than the rectangular pins.

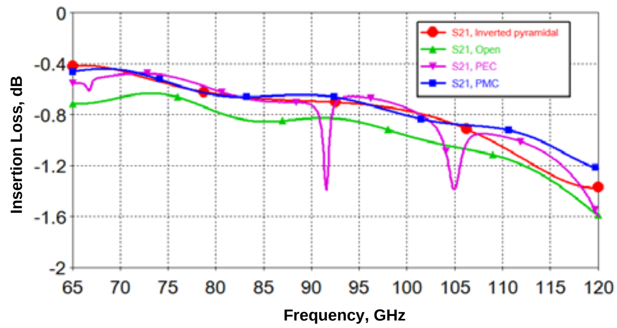

Fig. 6(c). S_{21} of the right angle microstrip line for the open case, PEC lid, PMC lid, and inverted pyramidal-shaped pin lid.

IV. Computation Summary

All the computations mentioned so far were done with CST Microwave Studio. Table 2 shows the number of mesh cells used for the different cases. For the PEC lid, PMC lid, and open case, we made a comparison based on the required number of cells. However, the open case needs matching layers, and the number of cells in this layer is not included in the number. CST does not provide the cell numbers in the matching layers that is actually five layers in the present case. Still, from the CPU time shown in Table 3, we see that the open case needs almost twice the CPU time of the PMC lid case when the PMC is at a height of 2t.

Table 2: Comparison of mesh cell numbers for different simulation cases

Simulation case (Bended microstrip line)	Total Mesh cells
Open case (without matching layers)	258763
PMC lid (at a distance of t)	251550
PMC lid (at a distance of 2 × t)	301860
PEC lid (at a distance of 3 × t)	473616
Pin lid case (a = 3mm, p = 6.75 mm)	773616

Table 3: Comparison of CPU time for different simulation cases

Simulation case (bended micosrtrip line)	Simulation time
PMC lid (at a distance of 2t)	2 min 42 sec
PEC lid (at a distance of 3t)	3 min 10 sec
Open (with 5 matching layers)	4 min 48 sec
Pin Lid (a = 3 mm, p = 6.75 mm)	7min 12 sec

V. PACKAGING OF PRACTICAL MICROSTRIP FILTER

As a proof of previously mentioned PMC and pin lid packaging concept, a 3rd order microstrip coupled line bandpass filter is manufactured as shown in Fig. 7a. Three cases are considered: open unpackaged case, smooth metal package case, and pin lid packaging case. Figure 7b shows the measurement results compared with the simulated ideal PMC case.

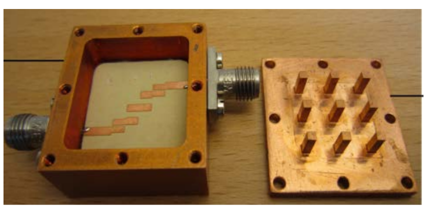

Fig. 7(a). Photo of the microstrip coupled line filter with the pin lid cover on the side.

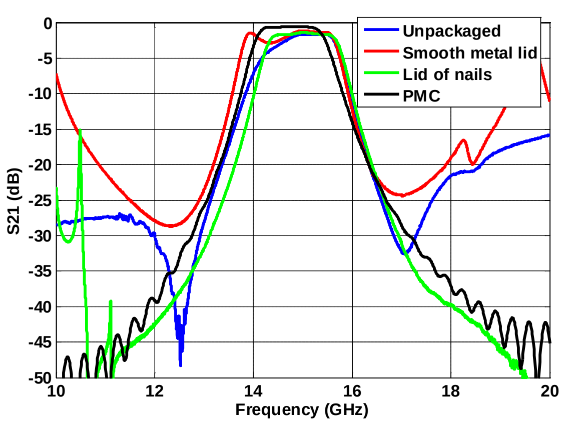

Fig. 7(b). The microstrip filter measurement response in three cases compared with the simulated PMC packaging case.

As seen from the measurement results of Fig. 7, ideal PMC and the pin lid packaging provide a good filter response in the pass band and the rejection bands. On the other hand, for the open case and smooth metal lid case, the response of the filter is distorted within the pass band, which of course is not desired. The details of this work can be found in [24].

VI. CONCLUSION

An efficient method for the design of printed microstrip circuit with packaging in mind was presented. The results showed that the presented PMC prepackaging concept is more appropriate than PEC packaging regardless of the computational efficiency because of the wider bandwidth that can be provided by the PMC, and in particularly for packaging of large printed circuit boards. Engineers can use shorter time during the design process and optimize the circuit already from the start with the packaging in mind. After having designed with ideal PMC, the PMC can be realized by e.g. the bed of nails. This can be designed for a large stopband using simple design rules or the design curves in [10] to operate within the frequency band of interest. Larger stopband-widths can be achieved by using inverted pyramidal-shaped pins, or mushrooms (patches with via holes).

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