Algaba Brazález, A., Uz Zaman, A., Kildal, P-S. (2012) Improved microstrip filters using PMC packaging by lid of nails. *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 2, no. 7, pp. 1075-1084.

http://dx.doi.org/10.1109/TCPMT.2012.2190931

Improved Microstrip Filters Using PMC Packaging by Lid of Nails

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***Abstract*— The paper shows that microstrip filters perform like textbook examples when packaged with Perfect Magnetic Conductor (PMC). The PMC is realized as a pin surface or lid of nails, and this is employed to package a microstrip parallel coupled line bandpass filter. Measurements confirm that parallel plate and cavity modes, as well as radiation are suppressed. The paper also includes a study of the reasons for a frequency shift between the ideal PMC packaged case and the realized case.**

***Index Terms*— AMC, microstrip circuit, coupled line filter, packaging, gap waveguide, parallel plate mode.**

I. Introduction

It was previously experimentally demonstrated how local quasi-TEM modes could be confined in the air gap between a metal upper plate and a lower longitudinally corrugated hard surface [1]. This phenomenon was in [2] developed into a new gap waveguide by using metal pins rather than corrugations to create the stop band for parallel-plate modes. The gap waveguide originates from the concept of soft and hard surfaces [3], and comes in three different variants [4] depending on the choice of guiding structure between the pins: the ridge gap waveguide, the groove gap waveguide and the microstrip gap waveguide. The present paper relates to the microstrip gap waveguide. The stop band can also be generated by other means than pins [5]. Previous studies have also experimentally proven that the ridge gap waveguide has low loss [6]-[7] and that useful waveguide circuits can be realized [8].

The gap waveguide technology was also proposed as a useful way for packaging microstrip circuits [9]-[10]. The pin surface is then used as a lid (**lid of nails**) and works in such a way that it stops the propagation of parallel plate and cavity modes even when there is dielectric present between the plates. The removal of resonances was initially confirmed for the case of a single microstrip line with two 90° bends [9]. From this earlier research arises the interest to demonstrate that the lid of nails is also useful for packaging and improving the performance of critical microstrip passive devices such as filters. Thus, the current work focuses on applying the pin lid packaging solution for a typical microstrip bandpass filter. The achieved perfomance improvement is also compared with available or conventional packaging solutions.

The cavity resonance suppression has previously been studied in [11] where electromagnetic band gap structures were used as packaging for power delivery systems. The drawback of the EBG structures is the presence of dielectric, making it more lossy than metal pins. Other approaches, like Substrate Integrated Waveguide (SIW), have been applied in the design of microwave components [12]-[13]. One advantage of this technology is the inherent packaging capability of the structure, becoming a compact solution. However, the substrate material is always present in this technology, and then the dielectric losses cannot be avoided.

Improved packaging of high frequency circuits is needed, especially for microstrip technology, which is basically an open structure that should somehow be electrically shielded and physically protected. On the other hand, one important contribution to the losses in a microstrip circuit is the radiation from the device when it is not packaged. In order to reduce the radiation losses, the packaging is a critical aspect that should be taken into account during any circuit design.

The new gap waveguide packaging (or PMC packaging) is based on the presence of two parallel plates. One of them has a textured surface that should work as an Artificial Magnetic Conductor (AMC). The AMC establishes a high impedance condition behaving as an ideal PMC (Perfect Magnetic Conductor) but only within a specific frequency range. Still, the stop band of the parallel-plate modes can be very large. In this work, the textured surface is a periodic structure composed by pins. However, it could have other geometrical shapes depending on the frequency band of interest and as long as it provides a high impedance boundary condition (i.e. it is an AMC). The pin surface provides a cutoff of modes in metal cavities as long as the height between the two parallel plates is smaller than $\lambda/4$ and the stop band is larger the smaller the air gap height is. The modal propagation appears along any metal ridge, strip or groove placed between the plates.

The motivation for studying alternative methods of

Manuscript received June 20, 2011. revised October 5, 2011; accepted February 29, 2012.

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packaging is that as the frequency becomes higher (into upper microwave and millimeter bands), cavity resonances appear inside the metal shielded box destroying the performance of the device which is packaged [14]-[17]. This is what happens with the traditional packaging with smooth metal lid located above the circuit when at least two dimensions of the cavity are larger than $\lambda/2$. At lower frequencies these resonances can be avoided by fixing the dimensions of the box shorter than half wavelength or to use absorbing materials [14]-[16]. Nevertheless, at high frequencies these options are impractical since high-frequency circuits most often are many wavelengths in size, and the absorbers will introduce high losses while stopping the resonances. In addition, this last solution becomes expensive and difficult to integrate in the cavities (there are not available tools to determine the optimum location of the absorbers [15]). An example of design with cavities filled with absorbers that are used to damp the resonances is illustrated in reference [16]. The absorbing material is just fit into the different cavities without taking into account any placement criteria.

In the present study, the main objective is to demonstrate that the new gap waveguide packaging is particularly advantageous for shielding microstrip filters. For this purpose, two parallel coupled-line filters (3rd and 5th order) have been designed and analyzed when they are packaged with lid of nails and compared with other packaging conditions.

II. Filter Design procedure

Two microstrip coupled-line bandpass filters (3rd and 5th order) have been designed for 10% bandwidth. The center frequency of the passband was chosen to be f_o = 15 GHz in order to work at a frequency where we can use coaxial connectors and available vector network analyzer. The stop band, in which the pin lid forbids parallel plate modes, was realized to work between approximately 10 and 20 GHz. The main geometry parameter that affects this operating bandwidth is the height of the air gap, although the period of the pins and the size of each pin element also affect both the lower and upper ends of the stopband as shown in [5].

The two prototypes have been designed to produce a Chebyshev response with 0.5 dB ripple in the case of the 3rd order filter, and 0.1 dB ripple for the 5th order filter. The material employed as substrate for both filters is Rogers TMM 4 with relative permittivity ε_r = 4.5, loss tangent $\tan\delta$=0.002 and thickness h = 0.762 mm.

A coupled-line bandpass filter is composed of $n + 1$ parallel coupling sections, when n is the order of the filter. Each section is open-ended and has an electrical length of quarter wavelength at the center frequency f_o of the filter.

The design is done by analyzing the even and odd mode impedances of the coupling sections starting with the study of their equivalent J circuits. The equations and method for calculating these values are available in [18]-[20]. Once we have calculated the odd and even mode impedances it is possible to get the layout parameters for both filters (width of each line section, spacing between the coupled lines and length) by means of some transmission line calculator (Linecalc provided by Agilent Design System, or Ansoft Designer).

Figure 1 presents the top view of the physical layout for both microstrip parallel coupled-line filters. Input and output lines are included in the design, the dimensions of which correspond to a 50 Ω microstrip line.

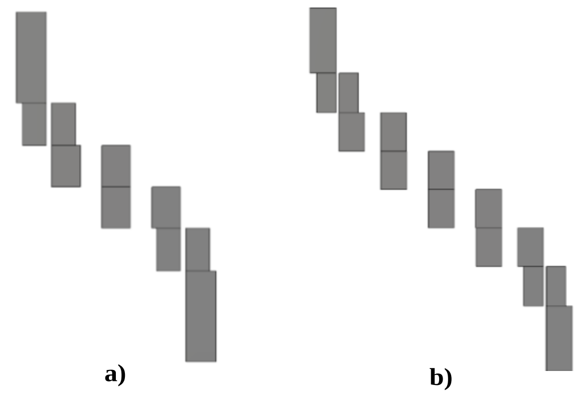


Fig. 1. Layout of a) 3rd order, and b) 5th order parallel coupled-line bandpass filters.

III. Packaging with lid of nails

The presence of discontinuities at each coupling section of the filter topology causes the excitation of cavity resonances when the device is packaged. The gap waveguide packaging suppresses the cavity resonances as well as eliminates in an efficient way the radiation loss due to the discontinuities. To demonstrate this, both filters designed in section II were simulated and compared for four types of packaging: unpackaged case, metal lid packaging, ideal PMC lid packaging, and lid of nails packaging.

The pin lid geometries proposed for packaging the 3rd and 5th order filters are described in figure 2. Realistic metal sidewalls are also taken into account in the simulations. The thickness of these metal walls is b = 3.175 mm in order to provide physical space for the screws and being able to fit the lid to the rest of the box.

After the first simulations using a preliminary packaging with lid of nails, a parametrical study was performed with CST Microwave Studio in order to determine the most suitable parameters for the main dimensions of the packaging structure (air gap, pin period and size of the pin).

We have chosen copper as conductor material for the whole box and the PCB. The dimensions of the proposed box are L_1 x L_2 x L_3 (L_1 is determined by the lengths of the different stages of the filter). The corresponding dimensions in mm for each filter are shown in Table I which is related to the information shown in figure II.

The lid of nails geometry has the same main dimensions for the packaging of both filters. The pin period is p = 6 mm, pin height is d = 5 mm, and pin size a = 1.5 mm. The air gap

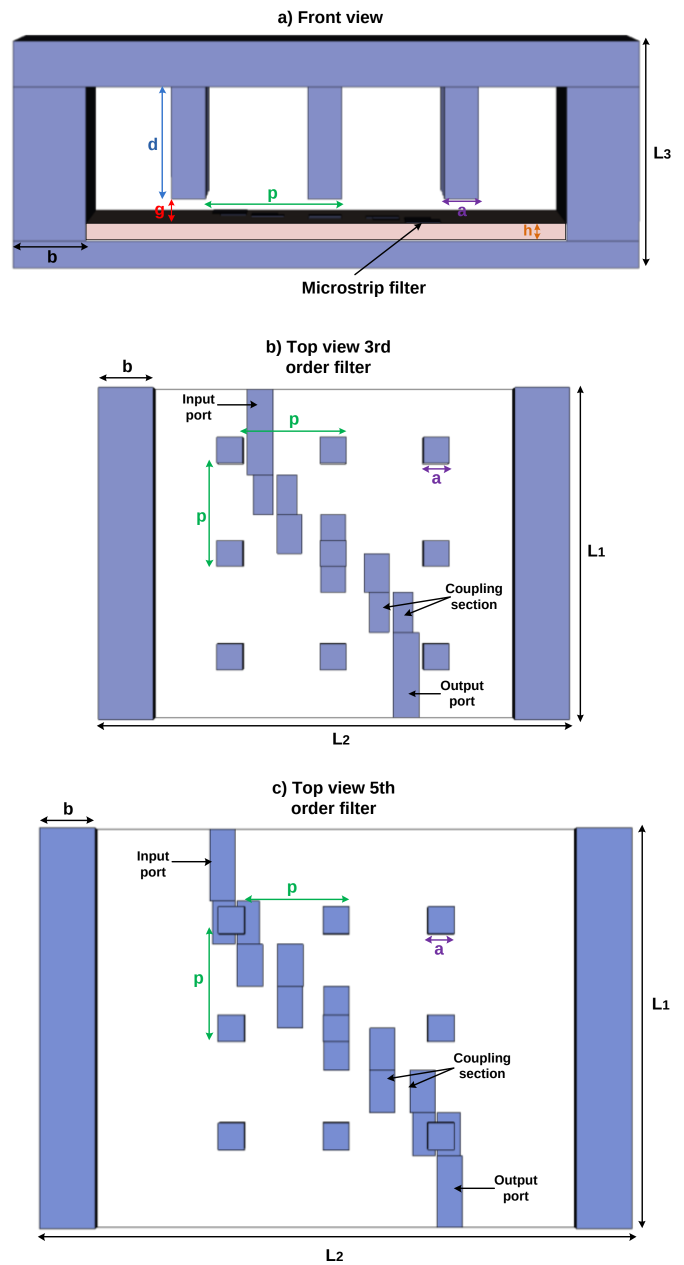


Fig.2. a) Front view of the lid of nails geometry for 3rd and 5th order filter, b) Top view of 3rd order filter packaged with lid of nails, c) Top view of 5th order filter packaged with lid of nails.

height is chosen to be g = 1 mm. In section VI we will explain how these values resulted from a parametrical study using CST Microwave Studio.

Basically, it is required to get a parallel-plate stop band between 10 and 20 GHz. In [9] the stop band was found to be between 8 and 21 GHz for the same dimensions, but with p = 7.5 mm. For the packaging of a microstrip filter we have also found that the return loss of the filters changes somewhat depending on the geometry of the lid of nails. Hence, a parametric analysis of the main parameters is needed in order to see which values are the most suitable for our prototype (see section VI).

TABLE I
DIMENSIONS FOR BOTH FILTERS INCLUDING LID OF NAILS

	L_1	L_2	L_3
3rd order filter	19.258 mm	27.35 mm	9.962 mm
5th order filter	22.24 mm	33.85 mm	9.962 mm

For the unpackaged case, the filter is analyzed with open boundary condition. The metal lid packaging is the case in which the PCB is covered and surrounded by smooth metal walls. The smooth metal lid is located 3.9 mm above the dielectric (more than 5 times the thickness of the employed substrate) for both filters. Figure 3 illustrates the 3rd order filter when this is packaged with metal walls.

We also computed the ideal PMC packaging case for which the microstrip coupled line filter is covered by a PMC lid placed 1 mm above the dielectric (the same as the air gap between the peak of the pins and the substrate). The PMC cover establishes a high impedance condition and it is considered the ideal situation in which the cavity modes are totally suppressed for all frequencies below the frequency at which the gap is effectively $\lambda/4$. The lid of nails emulates this PMC packaging case providing a high impedance condition within a certain limited frequency band.

The microstrip filters which are shown in figure 2 represent the final versions. First, preliminary versions of both the 3rd and 5th order filters were realized using the method explained in Section II. Afterwards, both circuits were packaged for the four situations mentioned above and simulated. Results for PMC and pin lids were satisfactory, but they could be improved by carrying out a full optimization of the dimensions for the different coupling sections (width and gap between the strips for each section). In this step, it was found that running a full optimization using open or smooth metal lid took much longer time than optimizing the filter using PMC lid in order to approach the same convergence. After having finished the optimization procedure with PMC lid the resulting filter was packaged with the pin lid, and the final performance was better

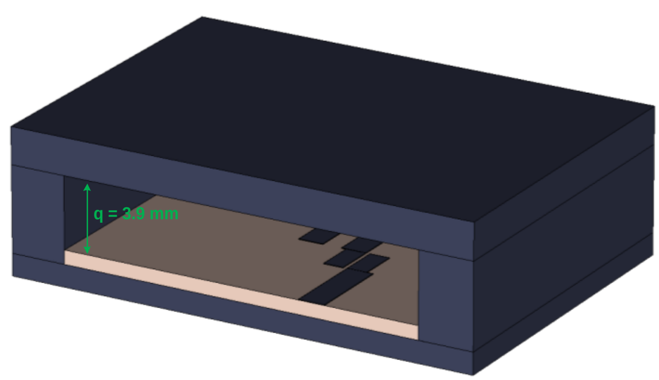


Fig.3. 3rd order filter packaged with smooth metal lid (traditional packaging).

than both the unpackaged and metal lid cases. In the next section the simulation results for both the two final optimized filters are presented and compared for all the cases under study.

IV. Simulation of S Parameters

The microstrip filters were simulated when packaged under the four conditions explained in section III. In addition, the 5th order filter was simulated when a thin plate of absorbing material is attached to the inner side of the smooth metal lid. The material was ECCOSORB MCS with thickness equal to 1 mm, and therefore the distance between the absorber and the dielectric is 2.9 mm. The S parameters were extracted and compared.

Figure 4 presents S_{21} and S_{11} parameters for the 3rd order coupled line filter and figure 5 the same for the 5th order filter.

The unpackaged and smooth metal lid cases do not show good filter performance due to radiation losses and presence of cavity modes. The return losses are high, and the bandpass shape is not flat as it should be. When the packaging includes absorbing material the resonances are suppressed and the filter performance is close to the unpackaged case, but with higher

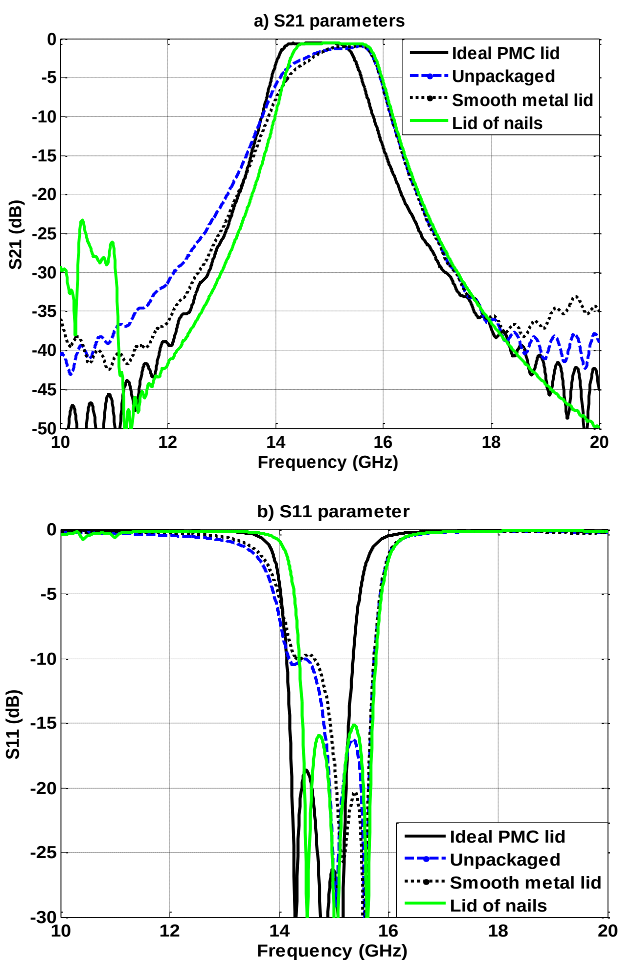


Fig.4. Comparison of filter responses between four types of packaging, a) S_{21} parameter for 3rd order filter, b) S_{11} parameter for 3rd order filter.

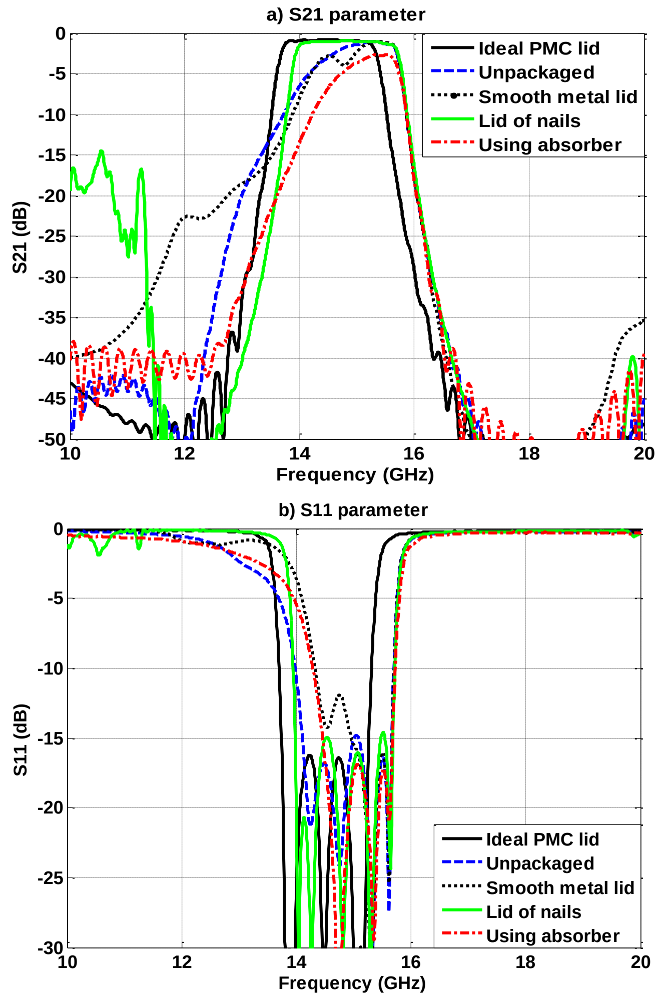


Fig.5. Comparison of filter responses between five types of packaging, a) S_{21} parameter for 5th order filter, b) S_{11} parameter for 5th order filter.

insertion loss due to the presence of the absorber.

However, for the PMC lid and the lid of nails the obtained filter responses are close to those of theoretical Chebyshev filters. Table II presents a comparison between the return loss and insertion loss for these two cases for both filters.

When the filter is packaged with ideal PMC surface, the cavity resonances are suppressed at all frequencies below 20

TABLE II

Comparison of Return Loss (Return Loss is Considered to be the Worst Value over the Filter Bandwidth) and Insertion Loss (Insertion Loss is Taken at the Center Frequency of the Passband) Between PMC Packaging and Lid of Nails Packaging for Both Filters

	PMC packaging		**Lid of nails packaging**	
	3rd order	**5th order**	**3rd order**	**5th order**
Return loss (dB)	-18.6	-16.3	-15.2	-14.6
Insertion loss (dB)	-0.55	-0.83	-0.56	-0.94

GHz, and the radiation losses are removed. The lid of nails realization of the PMC also shows very good filter performance with similar values of insertion loss, which means that the lid of nails works as expected. We see the existence of some transmission peaks below 11.5 GHz. This means that the total suppression of parallel plate and cavity modes is ensured within the frequency bandwidth from 11.5 to 20 GHz. The dispersion diagram which corresponds to the dimensions of the pin lid presented in figure 2 has been computed with CST Eigenmode solver and it is illustrated in figure 6. The stopband obtained in the simulations covers a frequency range from 10.6 to 21 GHz. Therefore, a response free of spurious of the packaged filter is expected over the mentioned stopband.These peaks at lower frequencies in the S cannot be completely avoided but they can be moved further away from the desired band. Studies have shown that wider stopbands can be achieved with different geometrical shapes of the pin such as mushroom type or inverted pyramidal type [21].

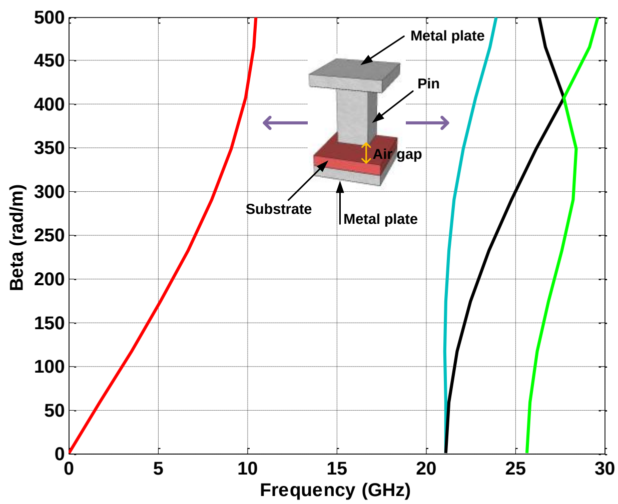


Fig.6. Dispersion diagram of the infinite lid of nails with presence of substrate above the ground plane.

It is important to point out that the lid of nails emulates the behavior of the PMC within a certain frequency band, but in all the simulations there was an unfortunate frequency shift between the filter response for the ideal PMC case and the realized lid of nails case. This displacement is analyzed in the next section.

V. PMC FREQUENCY SHIFT

The simulations in section IV shows that there exists a frequency shift of around 290 MHz between the filter response when the circuit is packaged with PMC, and when it is packaged using lid of nails for both the 3rd and 5th order filters. When the microstrip filters are packaged with PMC lid, the resulting performance is closer to the theoretical behavior of a Chebyshev bandpass filter, but the shift in frequency is a discrepancy that needs to be explained.

Each coupling section in the filter circuit, and the input/output ports were designed in order to get approximately 50 Ω of characteristic impedance. However, when the filter is covered with different lids, the value of the characteristic impedance will change. Table III shows the characteristic impedance obtained for the four cases for the 5th order filter. The values are obtained from CST that provides the characteristic impedance after having carried out the calculation of the port modes.

TABLE III
CHARACTERISTIC IMPEDANCE OBTAINED IN THE INPUT WHEN 5TH ORDER FILTER IS PACKAGED WITH DIFFERENT LIDS

	PMC	Lid of nails	Smooth metal lid	Unpackaged
Z_o	50.53 Ω	47.75 Ω	47.73 Ω	47.81 Ω

Since there is a variation in the characteristic impedance and this depends on the effective permittivity, it is obvious to think that the resonance frequencies of the coupled microstrip resonators are not the same with a PMC lid as with other lids. If the value of the guide wavelength for each case is different, the $\lambda_g/4$ sections composing the individual resonators will have different electrical length, and therefore the frequency band of the filter will shift. In order to see the effect of this we performed a parametric sweep of ε_r when we computed the response of the 5th order filter packaged with PMC lid using CST Microwave Studio. Figure 7 represents the resulting filter response for three values of ε_r.

If the value of ε_r decreases, ε_{eff} decreases as well, and Z_o increases. In table III we can see that with PMC lid the value of Z_o is higher than for the other lids, so we can expect that this should correspond to a change in ε_{eff}. Figure 7 shows that if ε_r decreases, the filter response will be shifted to higher frequencies. When ε_r = 4.3, the center frequency of the filter packaged with PMC is the same as with the lid of nails, which was designed initially at 15 GHz using ε_r = 4.5. Therefore, we

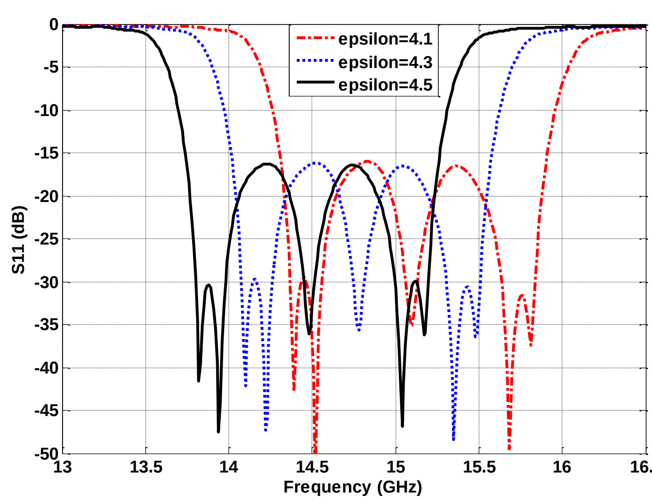


Fig.7. Changes of bandpass characteristics for three values ε_r when the 5th order filter is packaged with PMC lid.

can extract these conclusions from this parametric study:

$$\left.\begin{array}{l} \varepsilon_{r1} = 4.5 \rightarrow \left. f_o \right|_{PMC} < \left. f_o \right|_{PINS} \rightarrow \lambda_{g1} = \dfrac{\lambda_o}{\sqrt{\varepsilon_{eff\,1}}} \\ \varepsilon_{r2} = 4.3 \rightarrow \left. f_o \right|_{PMC} = \left. f_o \right|_{PINS} \rightarrow \lambda_{g2} = \dfrac{\lambda_o}{\sqrt{\varepsilon_{eff\,2}}} \end{array}\right\}$$

$$\rightarrow \varepsilon_{eff\,1} > \varepsilon_{eff\,2} \rightarrow \lambda_{g1} < \lambda_{g2}$$

For the PMC packaging case, the sections of the circuit resonate for an electrical length λ_{g1} smaller than λ_{g2} (which is the one that makes the filter resonate at 15 GHz).

Since we keep the same physical layout of the filter and ε_r = 4.5 for studying all cases of packaging, the response will shift to a lower center frequency when it is packaged with PMC. The filter sections are slightly longer than the actual value of $\lambda_g/4$ which corresponds to the PMC packaging case.

Nevertheless, once we know the reason of the frequency shift, we can predict in advance the amount of the shift and use this during the design and optimization for the case of the PMC lid. Then, the optimized dimensions should work also for the lid of nails for which there is no frequency shift.

Even with the existence of this frequency shift, it has been seen that it is much more efficient to optimize the filter parameters when packaged with PMC lid and afterwards apply a realized AMC in the form of a lid of nails in which case the computation time is much larger.

VI. Parametric Study

In section III the main parameters for designing the lid of nails were fixed in order to have a stop band from 10 to 20 GHz, since the microstrip filter under study works within this frequency range. A complete parametric study of the cut-off bandwidth between textured parallel plates is presented in [5] showing how the main parameters affect the stop band. It has been observed during the study of the packaging of microstrip filters, that the change of the dimensions of the lid of nails not only changes the cut-off bandwidth but also modifies the performance of the bandpass filter. Hence, it is needed to find a trade-off between operating bandwidth and filter performance in the process of designing the lid for gap waveguide PMC packaging.

A parametric study in terms of S parameters by sweeping the period, the width of the pin and the air gap was performed in order to see which dimensions show the best filter performance as well as an acceptable cut-off bandwidth. Figure 8 a, b, c and d show the filter performances for four values of width of pins, respectively, and within each graph a sweep of the pin period over 5 values. For all cases there were three rows of three pins. For smaller pin width, the spurious or low frequency peaks are moving closer to the passband of the filter but with lower level. For smaller value of period, the filter response shows worse return losses and the low frequency peaks move closer with higher levels. In figure 9 it is presented a parametric sweep of the air gap and as we know

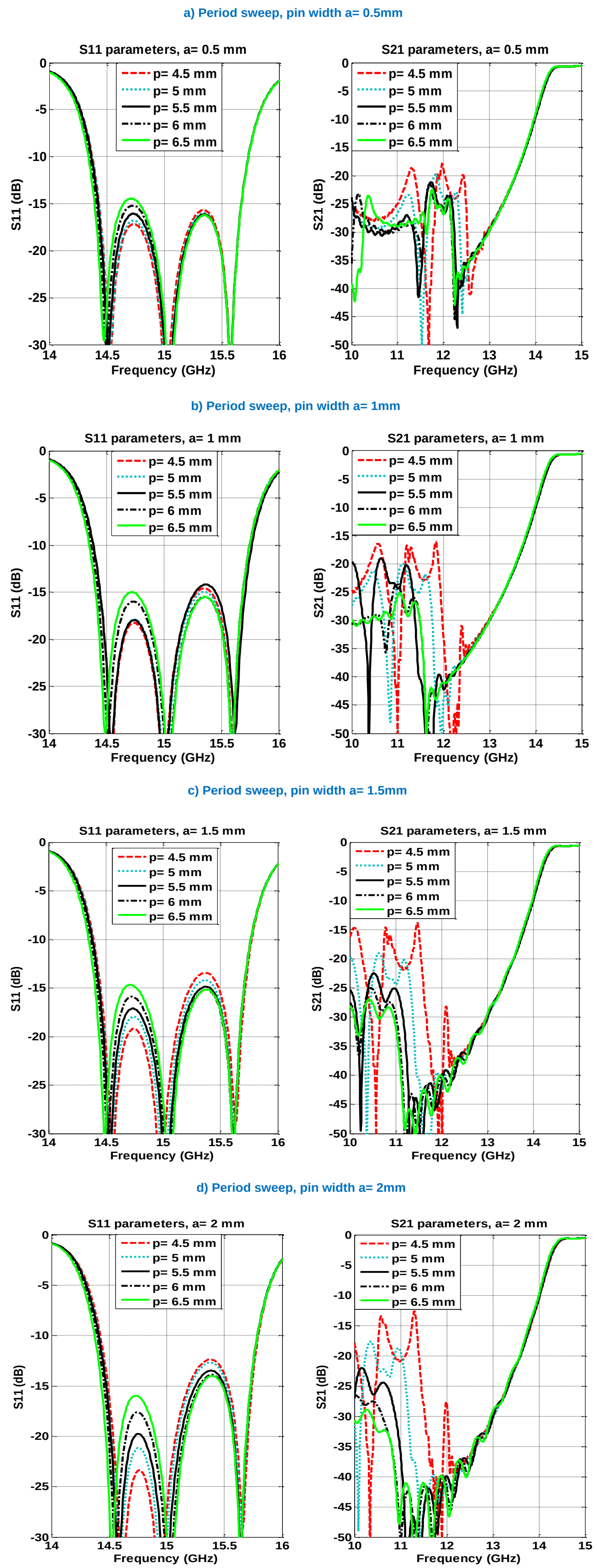


Fig.8. Parammetric study for four values of pin width sweeping the period (values of the period in mm) for each one, a) a= 0.5mm, b) a= 1mm, c) a= 1.5mm, d) a= 2mm.

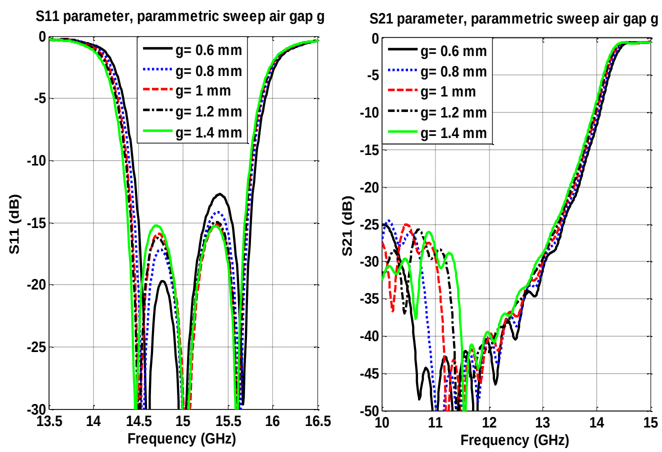


Fig.9. Parammetric study of the air gap for the microstrip filter packaged with lid of nails.

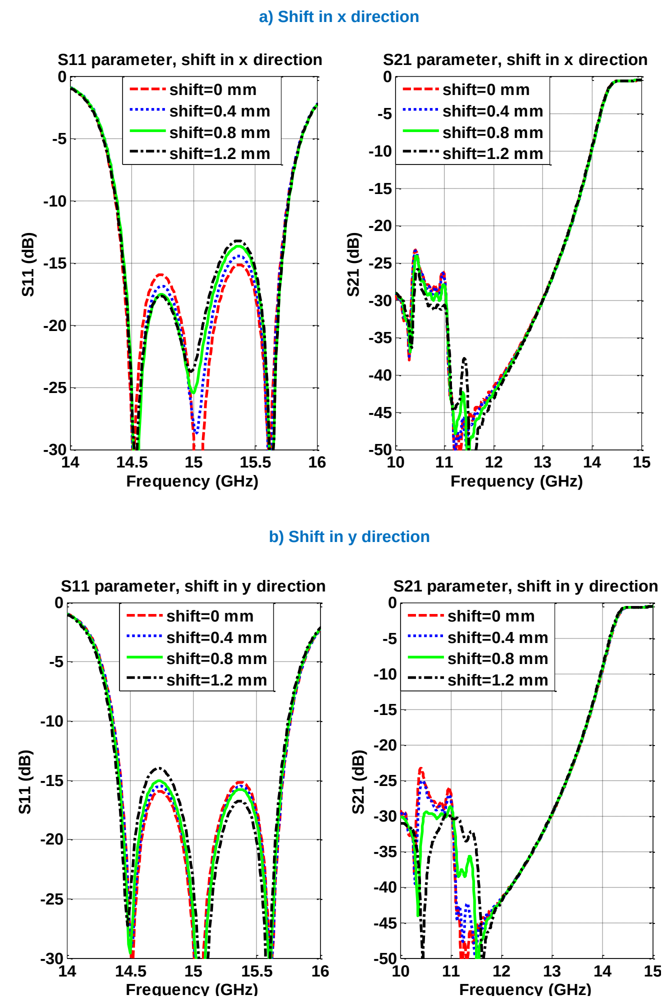


Fig.10. Study of the relative position of the pin lid respect to the coupling sections of the filter, a) Shift in x direction, b**)** Shift in y direction.

from [5], when the air gap is decreased the stop band increases, but in the present case with the additional drawback of a worse filter performance. As a conclusion of this parametric study we found that choosing the pin width a=1.5 mm, period p=6 mm, and air gap g= 1 mm gave good filter response between 11.5 and 20 GHz.

Other parameter that can be relevant for the gap waveguide packaging is the pin height d. This value must be close to $\lambda/4$ in order to make the lid of pins to provide a high impedance boundary condition. In this way, the pin surface can emulate the behavior of the PMC in a certain frequency band. A parametric sweep of the pin height was carried out and it was seen that when the value d is smaller than 5 mm ($\lambda_o/4$ at 15 GHz) the filter performance is degraded and the spurious get closer to the passband. If d is bigger than 5 mm the spurious get further from the passband but it also affects to the return losses. The degradation of S11 is more dramatic when the value of d is less than 5 mm. The influence of the main parameters of the pin lid to the stop band is further studied in [5].

Moreover, a dependence of the relative location of the pins with respect to the strips which compose the filter was found. Therefore, this effect was studied by displacing the pins in the x direction and in the y direction with respect to the center strip section of the filter. It was found that the more symmetric the pins are with respect to the center strip section (shift= 0), the better is the filter performance. On the other hand, the shift of the pin lid did not have any significant effect on the stop band. The dependence of the relative position of the pins in the circuit should be studied more in future works.

Figure 10 shows the effect on the filter performance when there is a shift of the pin lid in x and y direction.

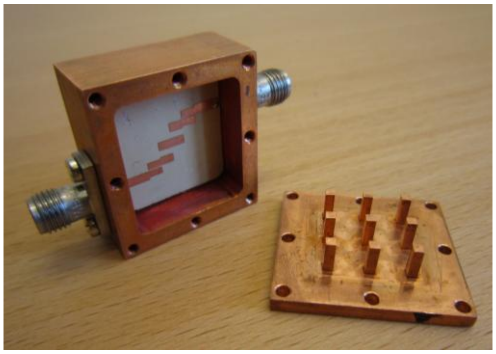
VII. Measurements of Filter Prototypes

With the purpose to validate the study of the packaging of microstrip filters with gap waveguide packaging, the 3rd order and 5th order filters designed in section II were manufactured and the resulting performances compared when they are unpackaged, packaged with smooth metal lid and packaged with lid of nails. An additional case was taken into account for packaging the 5th order filter using an absorbing material attached into the metal lid. Due to mechanical problems with the manufacturing of the prototypes of lid of nails, the measurements were taken with an air gap of 0.9 mm instead of 1 mm. Simulations with gap equal to 0.9 mm were carried out and results were quit similar to the ones shown in section IV, therefore new prototypes were not manufactured and measurements are taken with air gap g= 0.9 mm.

The microstrip filters were fitted into a copper box and the lids were manufactured separately in copper as well. Afterwards, the lids can be screwed to the box and the complete device is measured with a vector network analyzer. Both filters and the lid of nails are illustrated in figure 11.

Figure 12 shows the performance of the 3rd order filter and figure 13 the 5th order filter. For packaging the 5th order filter, two lids of nails were manufactured, one with 3 rows of 3 pins (period p = 6 mm) and the other one with 3 rows of 5 pins (period p = 5.5 mm). The reason to manufacture these two lids of nails was to compare the performance of the same microstrip filter packaged with different pin lids in terms of

a) 3rd order filter and lid of nails



b) 5th order filter and lids of nails

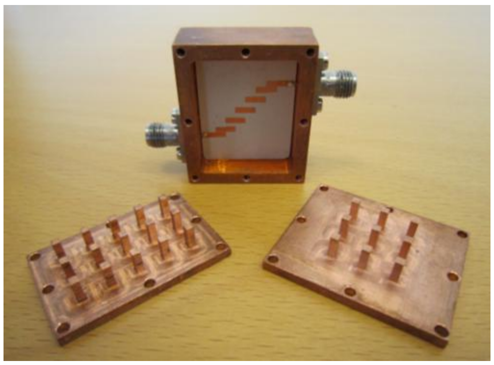
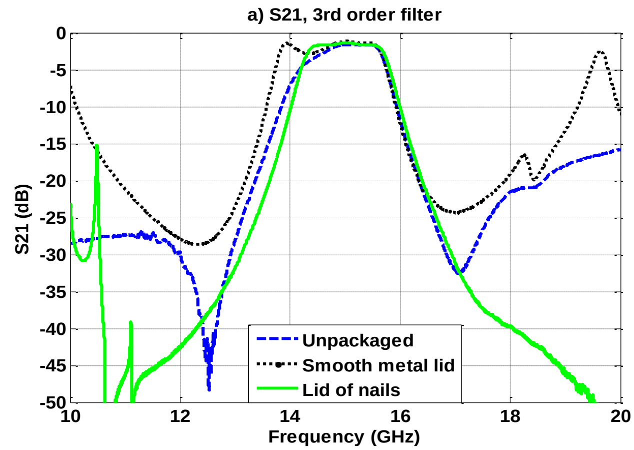


Fig.11. Manufactured filters with their respective gap waveguide packagings. a) 3rd order filter and lid of nails with 3 rows of 3 pins, b) 5th order filter and two lids of nails, one with 3 rows of 5 pins, and another one with 3 rows of 3 pins.



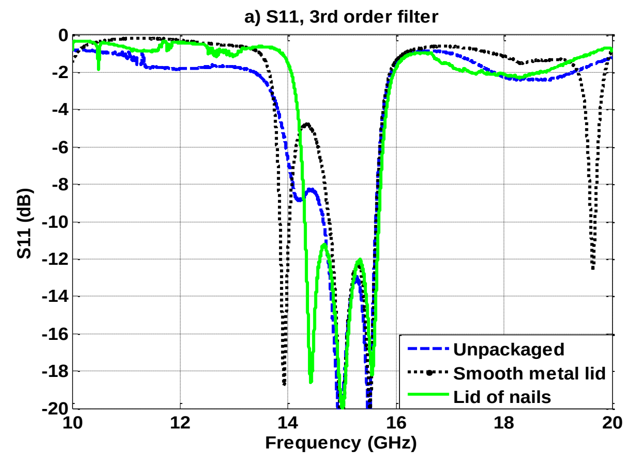


Fig.12. Measurements 3rd order filter comparing with three types of packaging, a) S_{21} parameter, b) S_{11} parameter

low frequency peaks and losses. Another argument was to see if the displacement of the pins affects the behavior of the filter in the same way for both lids of nails, or if it is less sensitive to this displacement when there are more pins in the lid.

For both filters the unpackaged situation shows a performance in which the radiation losses are high and, therefore, the response is not sharp and flat at all. For the smooth metal lid packaging the measurements presents slightly flatter response in the passband but still not sharp. The return losses are not satisfactory and it is very important to point out the presence of resonances even in the passband of the filter (see figure 14).

When the 3rd and 5th order filters are packaged with the lid of nails the measurements show an improved performance than with the other lids. This improvement is illustrated in the obtained sharper, flatter and neater response, as well as good filter performance in terms of return losses. Moreover, the specific resonances that were present for the smooth metal lid have disappeared. Table IV presents a comparison of the measured values of insertion loss (taken at the center frequency of the passband) and return loss (taken over the filter response bandwidth) between smooth metal lid and lid of nails.

If the 5th order filter is packaged using the lid of nails with 3 rows of 5 pins (p= 5.5 mm), some low frequency peaks appear at 11.74 GHz, being closer to the passband of the filter than if we use the lid with 3 rows of 3 pins (p= 6 mm) in which case these peaks appear at around 11.1 GHz. By the simulations shown in section IV we already know that the lower limit of the stop band will be higher if the period of the pin geometry is smaller. This is exactly what is illustrated in the plot of the S_{21} parameter on figure 13 where two lids with pins disposed with different periods are packaging the 5th order microstrip filter. Besides, if the filter is packaged with the lid with more pins, it has been seen that the passband performance is also dependent on the location of the pins relative to the microstrip circuit. Due to manufacturing tolerances the pin lid can be slightly shifted relative to its centered position resulting in a different filter behavior. Therefore, it is necessary to study in future works the way to homogenize the pin lid structure in order to mitigate the effect of the location of the pins with respect to the strips in the circuit response.

As brief comparison, we can expect that the SIW approach might be more loss than gap waveguide solution due to possible leakage of fields from the vias into the substrate. This leakage cannot happen with gap waveguide approach since there is cutoff of all unwanted waves within the operating band. A wideband SIW filter designed at around 11.5 GHz and

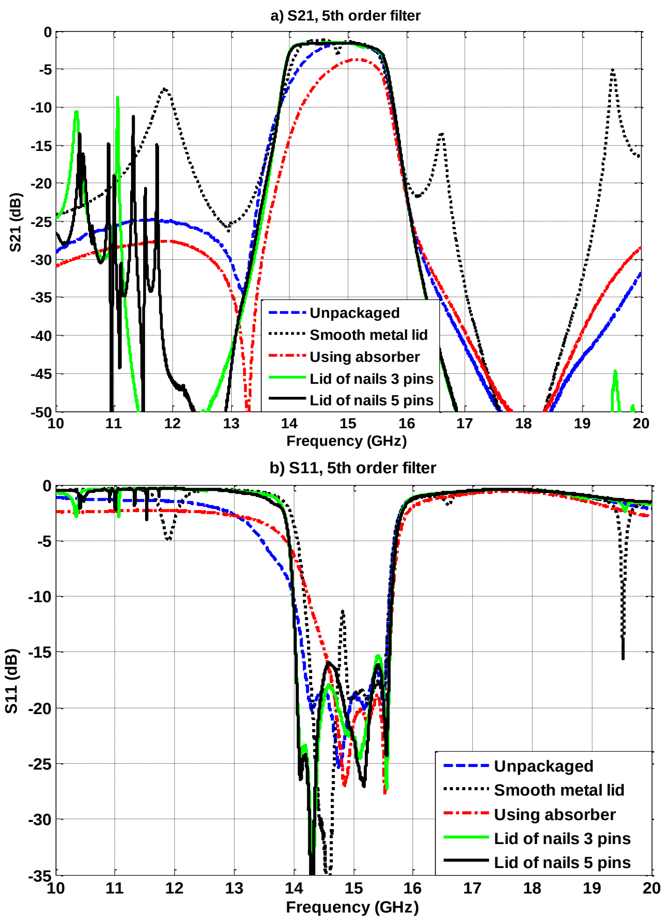


Fig.13. Measurements 5th order filter comparing with five types of packaging, a) S_{21} parameter, b) S_{11} parameter.

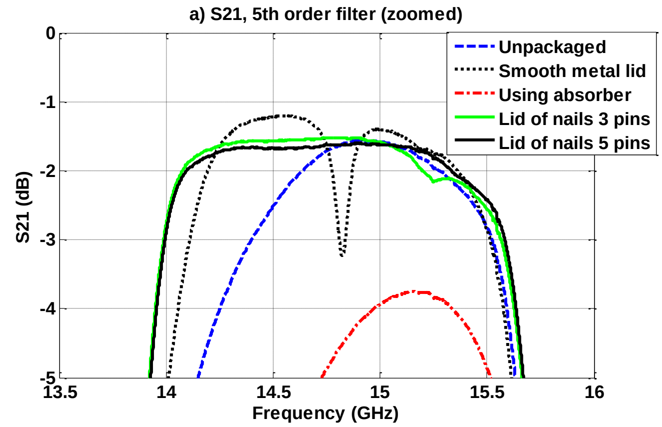


Fig.14. Measurement of S_{21} parameter for the 5th order filter zooming from -5 to 0 dB.

an UWB filter working at center frequency equal to 7.25 GHz are studied in [12] and [13] respectively. The first filter presents an insertion loss better than -2.3 dB, and the second less than -1 dB after removing the contribution from the connectors and transitions. These filter solutions will have worse insertion loss at 15 GHz, frequency in which the microstrip filter packaged with lid of nails has shown insertion loss better than -1.5 dB without removing the contribution from the connectors.

TABLE IV

COMPARISON OF MEASURED VALUES OF RETURN LOSSES (RETURN LOSS IS CONSIDERED TO BE THE WORST VALUE OVER THE FILTER BANDWIDTH) AND INSERTION LOSSES (INSERTION LOSS IS MEASURED AT THE CENTER FREQUENCY OF THE PASSBAND) BETWEEN SMOOTH METAL LID PACKAGING AND LID OF NAILS PACKAGING FOR BOTH FILTERS

	Smooth metal lid packaging		**Lid of nails packaging**		
	3rd order	**5th order**	**3rd order**	**5th order (3 pins)**	**5th order (5 pins)**
Return loss (dB)	-4.8	-11.4	-11.2	-15.3	-16
Insertion loss (dB)	-1.8	-3.2	-1.4	-1.5	-1.6

VIII. CONCLUSION

The PMC packaging solution realized via the gap waveguide technology has been studied in order to demonstrate the improvement in the performance of microstrip filters. Two conventional coupled-line bandpass filter were designed and shielded in four ways. The lid of nails is an advantageous way to suppress cavity modes and unwanted radiation from the discontinuities within a certain stop band. The reason for a frequency shift between the ideal PMC lid and the lid of nails has been numerically analyzed. Simulations and measurements show good electrical performance for both 3rd order and 5th order filters when they are packaged with PMC lid (only simulations) and lid of nails. Moreover, the optimization of the initial filter topology to achieve the desired response, turned out to be much faster when the microstrip circuit is packaged with PMC lid instead of unpackaged, smooth metal lid or absorbing material case. The initial ideal PMC packaging makes the design procedure much simpler and more efficient.

ACKNOWLEDGMENT

This work has been supported mainly by the Swedish Research Council VR, but also partly by Swedish Strategic Research Foundation (SSF) within the Chalmers Microwave Antenna Systems Research Center CHARMANT, and by the Swedish research council VINNOVA via a project within the VINN Excellence center Chase. The authors would also like to thank Prof. Ahmed A. Kishk from University of Mississippi for his advices and help to this project during his stage at the Department of Signals and Systems of Chalmers University of Technology from July 2009 to July 2010; and Dr. Miroslav Pantaleev of Onsala Space Observatory, Sweden, for its contribution to this study with the assembling of the microstrip filters into the packaging.

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