Improving Microstrip Filters with Gap Waveguide Packaging

Astrid Algaba Brazález[*], Ashraf Uz Zaman[*], Elena Pucci[*], Eva Rajo-Iglesias[+], Per-Simon Kildal[*] and Ahmed Kishk[#]

[*]*Department of signals and Systems, Chalmers University of Technology,*
41296 Gothenburg, Sweden
{astrid.algaba, zaman, elena.pucci, per-simon.kildal}@chalmers.se

[+]*Department of Signal Theory and Communication, University Carlos III of Madrid,*
Avda Universidad 30, 28911 Leganés (Madrid), Spain
eva@tsc.uc3m.es

[#]*Department of Electrical Engineering, University of Mississippi,*
University, MS38677, USA
ahmed@olemiss.edu

***Abstract*— A study is presented of the performance of microstrip filters packaged with Perfect Magnetic Conductor (PMC) and realization of the PMC using a lid of nails. A 3rd order parallel coupled-line bandpass filter is designed and packaged with a lid of nails at the Ku-band. The study shows the PMC packaging technique is very efficient in improving the filter characteristics including the insertion loss in the bandpass region.**

I. Introduction

Recently the suppression of parallel plate and cavity modes in metal packages, which contain a microstrip circuit using gap waveguide technology, has been presented [1]-[5]. This new type of waveguide is obtained via a generalization of the concept of soft and hard surface.

It was experimentally demonstrated how quasi-TEM modes can be confined in the gap between a hard surface and a metal plate [3]. In [1] and [2] the gap waveguide idea was theoretically introduced and proved by numerical simulations of a first gap waveguide structure. The experimental verification of this technology by means of **bed of nails** for parallel plate mode suppression has been validated already in [4]. Moreover, analytical solutions for the fundamental quasi-TEM mode including its characteristic impedance and dispersion equation for the first two modes of the ridge gap waveguide have been developed [6, 7]. The ridge gap waveguide can expectedly be used to realize low loss [8] and cost-effective millimeter and submillimeter circuits. Different microwave circuits have been developed in ridge-gap waveguide technology such as branch line and coupled-line directional couplers [9]. The gap waveguide is also promising for the design of filters at high frequency with low losses since there is no dielectric involved in the structure. There are previous studies about the implementation of waveguide low-pass filters with corrugations [10]. The ridge gap waveguide seems also likely to generate filter performance applying the same basis as in the Waffle-Iron filters. The present paper will instead show how microstrip filters can be improved by packaging with a **lid of nails**.

This new waveguide is composed of two parallel metal plates separated by a thin gap smaller than quarter of a wavelength, where one of the surfaces is generally smooth and can be the ground plane of a dielectric substrate, and the other contains a texture, e.g. in the form of a lid of nails. The nail-textured surface works ideally as a PMC (Perfect Magnetic Conductor) emulating a high impedance condition. The propagation of any modes is forbidden in all direction as long as the distance between the two plates is smaller than $\lambda/4$ with the exception of local waves that are allowed to propagate along metal strips or ridges between the plates. In [5] it was found that a lid of nails could be used to suppress cavity modes in a package containing a single microstrip line with two right-angle bends. The lid of nails imposes a cut-off of parallel plate and cavity modes even with the presence of the substrate between the two metal plates, and in addition it prevents the radiation leaking from the microstrip circuit. This makes the gap waveguide technology an advantageous and new method for packaging microstrip devices.

The microstrip transmission line is an open geometry which should be packaged suitably in order to provide electrical shielding and physical protection.

The main contributions for the losses in a microstrip circuit are: Ohmic losses α_c (due to the finite conductivity of the metal), dielectric losses α_d and radiation losses. The radiation losses in microstrip will be especially important when the prototype contains many discontinuities (right-angle bends or open-end circuits), as well as when the dielectric substrate is relatively thick with respect to the operating frequency band, and if it is not correctly packaged. For this reason, the packaging of microstrip circuits is critical in order to prevent efficiently the losses due to the radiation.

However, there is an important problem regarding the packaging at high frequencies. The traditional packaging using metal side walls and smooth metal lid located over the microstrip circuit has the disadvantage that as the frequency increases cavity resonances can be excited inside the metal box that degrade the performance of the device completely. Therefore, the gap waveguide technology has been proposed as a new kind of packaging since it can remove the cavity modes and stop the radiation from the circuit.

The objective of this work is to demonstrate the usefulness of the new gap waveguide for packaging of real passive microstrip devices. To this aim, a microstrip filter has been designed and packaged with the lid of nails and compared with three other packaging situations.

Microstrip filters are widely applied for RF/Microwave applications. They are especially important in wireless communication systems where it is necessary to suppress undesired signals induced by typical non- linear components like mixers or amplifiers. The introduction of filters is crucial in both transmitter and receiver stages in order to separate frequency components or suppressing signals that are considered noise for the system.

II. Microstrip Filter Design

A 3rd order microstrip parallel coupled-line bandpass filter has been chosen to work at a center frequency of f_o = 15 GHz. This center frequency guarantees that the filter will work within the cut-off bandwidth of those pin and gap dimensions that have been used in previous. The filter is specified to produce Chebyshev response with 0.5 dB ripple. The fractional bandwidth of the filter is established to be 10%. The substrate employed is Rogers TMM 4. Its relative dielectric constant is $\varepsilon_r = 4.5$ thickness t = 0.8 mm and loss tangent $\tan\delta = 0.002$.

A parallel coupled-line filter is composed of several coupling sections depending on the order of the filter. Since our filter is 3rd order, we will have four resonator stages. The length of each one is quarter wavelength at the center frequency f_o, and it is finished by an open-end circuit. This topology was chosen because many discontinuities are present, so that we can expect cavity modes to be easily excited. We want to demonstrate that the lid of nails suppresses these resonances, and removes the associated radiation losses for the open non-packaged case.

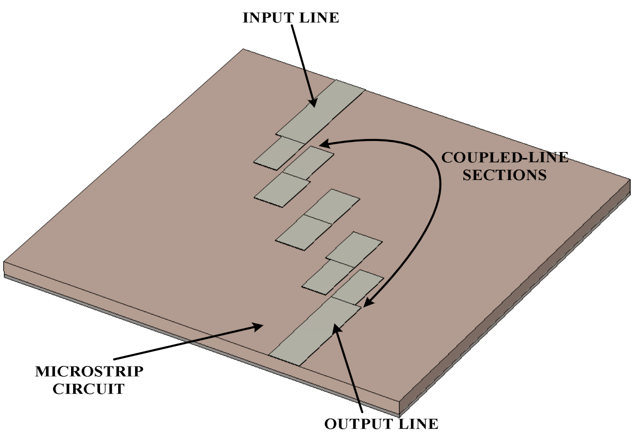

Fig. 1: Unpackaged 3rd order parallel coupled-line microstrip filter

Figure 1 shows the microstrip filter with the different coupled-line sections. Input and output 50 Ω lines are also included to provide feeding to the circuit.

The microstrip filter is firstly analysed by following the equations available in [7-9] in order to calculate the even and odd impedances of each coupled-line stage. Taking these impedance values and using any kind of software with available transmission line calculator tool (Agilent Design System or Ansoft Designer) it is easy to get the physical dimensions of each line section of the filter (width, separation between coupled-lines and length).

III. Packaging a Microstrip Filter

The microstrip filter explained in the previous section has been analysed for four cases concerning the packaging of the filter: unpackaged or open case, packaged with smooth metal cover, packaged with an ideal PMC lid, and packaged with lid of nails.

The unpackaged situation is represented by the microstrip filter without any kind of metal lid cover.

The packaging with smooth metal cover and metal sidewalls is the traditional packaging employed to shield microstrip devices. The lid is usually located several times the substrate thickness above the dielectric. In this case we have simulated it with the lid located 5 times the thickness of the substrate above the circuit.

The PMC lid represents the ideal case in which a high impedance boundary surface covers the microstrip circuit creating cut-off of parallel plate modes. This PMC cover is located 1 mm above the filter.

Figure 2 shows the smooth metal lid packaging and the PMC packaging, both including metal sidewalls.

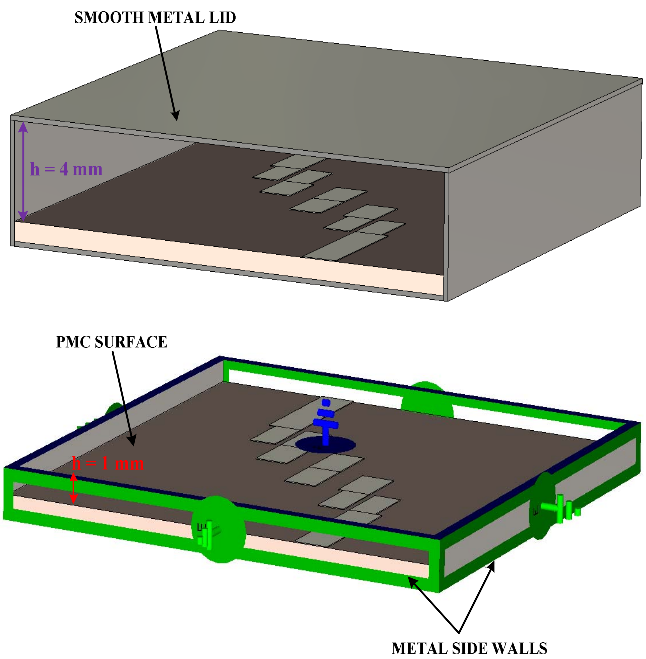

Fig. 2: Smooth metal lid packaging and PMC lid packaging

The lid of nails should emulate a high impedance boundary and behave as close as possible to the PMC case, but only over a certain operating bandwidth. The proposed geometry for the lid of nails above the microstrip filter is illustrated in figure 3. The dimensions of the packaging box are 20x19.26x7.2 mm^3. The period of the pins in the lid is p = 6 mm, the width of each pin unit is a = 1.5 mm and its height is d = 5 mm (corresponding to $\lambda/4$ at 15 GHz). The air gap is h = 1 mm. We choose this value in order to have the same conditions for the PMC packaging and the pin lid packaging.

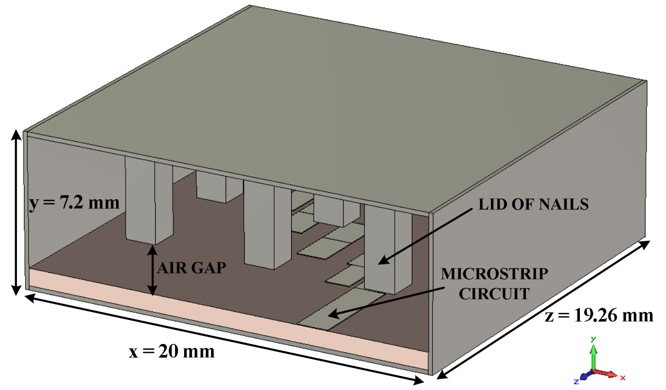

Fig. 3: Packaging with gap waveguide technology

The front view of the pin geometry with all dimensions is represented in figure 4.

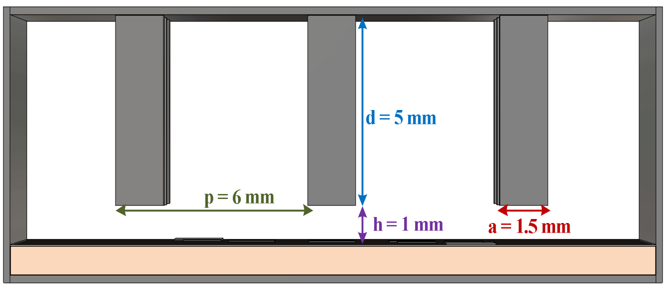

Fig. 4: Front cross-sectional view of the lid of nails

IV. SIMULATION RESULTS

In this section the simulations in terms of S parameters of the coupled-line filter are presented. These results are computed for the four different conditions of packaging explained in section III. Figure 5 shows a comparison of the S_{21} parameters among the four cases.

As we can appreciate in figure 5, when the filter is not packaged the radiation losses are so high that the passband is not clearly defined. If the filter is packaged with a smooth metal cover, a slightly sharper response is obtained compared with the open case, but the passband is not flat and suffer from larger losses. However, when the microstrip circuit is covered with the PMC surface the passband is much more clearly defined as expected with less losses than the other two cases. This response is the closest to the theoretical one since the PMC packaging is the ideal situation. When the filter is packaged with the lid of nails the performance of the filter is in good agreement with the PMC case (and therefore the theoretical result), obtaining a sharper response than with the metal lid and open case, but there is a frequency shift of about 270 MHz.

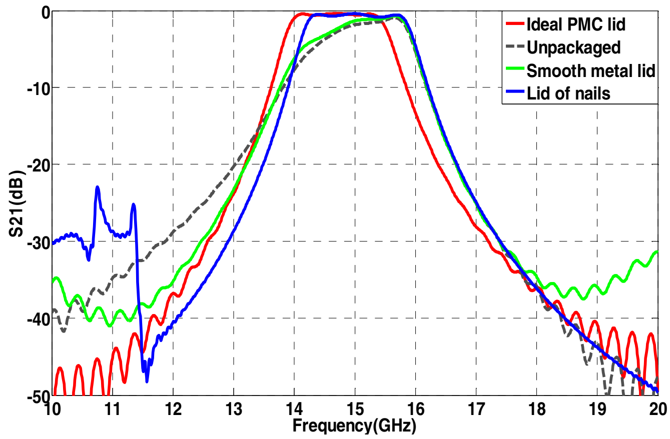

Fig. 5: Computed S21 parameters

The filter response for the lid of nails case shows some resonance peaks around 11 GHz which level is lower than -23 dB. This is due to the lower frequency limit of the parallel-plate stop band caused by the lid of nails. The lid of nails works from 11 GHz to 20 GHz approximately for the parameters that have been chosen for this work. In [11] it was found that by varying the main parameters of the pin lid it is possible to increase or decrease its operating bandwidth.

If the bandpass response is zoomed from 0 to -5dB (see figure 6), it is easy to check the ripple characteristic of the Chebyshev prototypes present when the filter is packaged either with PMC or gap waveguide technology. The insertion losses for the PMC packaging are less than -0.61dB, and with the gap waveguide packaging are less than -0.87 dB.

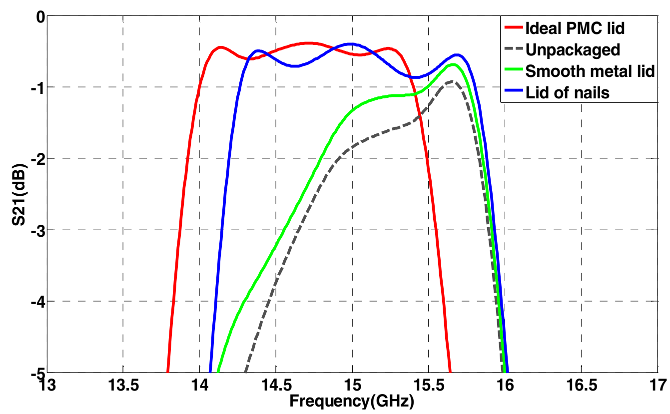

Fig. 6: Bandpass response zoomed

Next plot shows the comparison of the S_{11} parameters for the four packaging situations. The performance of the unpackaged and smooth metal lid cases show high return losses and no clear identification of poles corresponding to a 3rd order filter. Nevertheless, for the PMC lid and pin lid cases the filter poles can be clearly observed and the return losses are lower. The value of return loss for the PMC case is smaller than -13.5 dB, and for the lid of nails it is smaller than -10.2 dB.

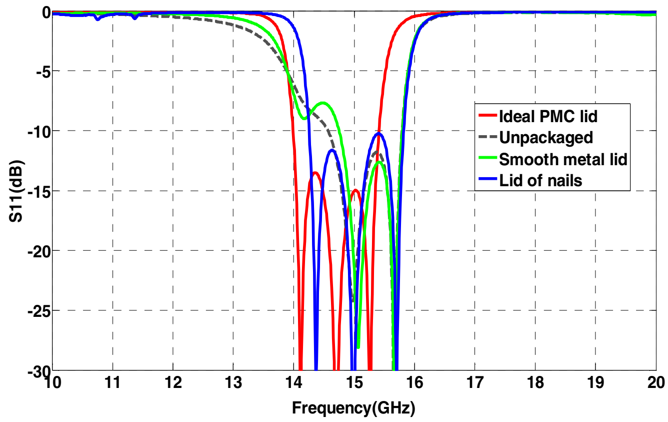

Fig.7: Computed S11 parameters

Unfortunately, there is a frequency shift between the otherwise similar S-parameters of the PMC and pin lid cases. The reason has not been found yet.

These simulation results are preliminary since the different packaging techniques were applied to a first version of the microstrip filter without any optimization of its dimensions. It is possible to get better filter performance by optimizing the width and separation between the coupled lines present at each section of the filter. It was found that it is faster to optimize the design initializing the procedure from the PMC case using CST (since it starts already with almost theoretical filter behaviour) instead of starting from the unpackaged or smooth metal walls packaging cases.

V. Conclusions

In this paper, it has been demonstrated the removal of parallel plate and cavity modes, as well as the efficient suppression of the radiation losses, when microstrip filters are packaged with lid of nails working within the Ku-band. A numerical study in terms of S parameters of a microstrip coupled-line bandpass filter was carried out employing different packaging techniques. It was found that there is a significant improvement in the filter performance when it is packaged with lid of nails and an ideal PMC surface compared to the unpackaged and smooth metal lid packaging cases. Similar filter response was obtained for the pin lid (i.e. gap waveguide) packaging approach and the PMC lid. Both of these resemble the theoretical behaviour of a Chebyshev coupled-line filter. Thereby, the gap waveguide technology has been shown to be a very good way of packaging microstrip filters at high frequency.

It was also found that it is much easier to start the design and optimization of the filter with a PMC lid rather than with an open microstrip circuit that can radiate. After this has been optimized, the PMC lid can be replaced by a pin lid. There is frequency shift of around 1.8% relative to the center frequency of the PMC and pin lid results. This represents an annoying limitation with the simple fast initial design using PMC lid. The reason for this remains to be understood.

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.

References

[1] P.-S. Kildal, E. Alfonso, A. Valero-Nogueira, E. Rajo-Iglesias, "Local metamaterial-based waveguides in gaps between parallel metal plates" *IEEE Antennas and Wireless Propagation Letters*, vol. 8, pp.84-87, 2009.

[2] P.-S. Kildal, "Three metamaterial-based gap waveguides between parallel metal plates for mm/submm waves", *3rd European Conference on Antennas and Propagation EUCAP 2009*, Berlin, Germany, 23-27 March 2009.

[3] A. Valero-Nogueira, E. Alfonso, J. I. Herranz, P.-S. Kildal, "Experimental demonstration of local quasi-TEM gap modes in single-hard-wall waveguides", IEEE Microwave and Wireless Components Letters, Vol. 19, No. 9, pp. 536-538, Sept. 2009.

[4] P.-S. Kildal, A. Uz Zaman, E. Rajo-Iglesias, E. Alfonso, A. Valero-Nogueira, "Design and experimental verification of ridge gap waveguides in bed of nails for parallel plate mode suppression", accepted for publication in IET Microw Antennas Propag.,, Sept. 2010.

[5] E. Rajo-Iglesias, A. Uz Zaman, P.-S. Kildal, "Parallel plate cavity mode suppression in microstrip circuit packages using a lid of nails", *IEEE Microwave and wireless Components Letters*, Vol. 20, No. 1,pp. 31-33, Dec. 2009.

[6] A. Polemi, S. Maci, P.-S. Kildal, "Dispersion characteristics of metamaterial-based parallel-plate ridge gap waveguide realized by bed of nails", accepted for publication in IEEE Transactions on Antennas and Propagation, July 2010

[7] A. Polemi, S. Maci, "Closed form expressions for the modal dispersion equations and for the characteristic impedance of a metamaterial based gap waveguide". Special Issue on Microwave Metamaterials: Application to Devices, Circuits and Antennas in IET Microw Antennas Propag, Vol. 4, Iss. 8, pp. 1073–1080, August 2010.

[8] E. Pucci, A. Uz Zaman, E. Rajo-Iglesias, P.-S. Kildal, A. Kishk, "Losses in ridge gap waveguide compared with rectangular waveguide and microstrip transmission lines", *4th European Conference on Antennas and Propagation EUCAP 2010*, Barcelona, Spain, 12-16 April 2010.

[9] E. Alfonso, M. Baquero, P.-S. Kildal, A. Valero-Nogueira, E. Rajo-Iglesias, J.I. Herranz, "Design of Microwave circuits in ridge-gap waveguide technology", *2010 IEEE MTT-S Microwave symp. digest,* pp. 1544-1547, 2010.

[10] E. D. Sharp: "A high-power wide-band waffle-iron filter", IEEE Trans. MTT, Vol. 11, No. 2, pp. 111-116, March 1963

[11] E. Rajo-Iglesias, P.-S. Kildal, "Numerical studies of bandwidth of parallel plate cut-off realized by bed of nails, corrugations and mushroom-type EBG for use in gap waveguides", accepted for publication to IET Microwaves, Antennas & Propagation, July 2010.

[12] K. Kuang, F. Kim, S.S. Cahill, RF and Microwave Microelectronics Packaging, Springer, 2010.
[13] D. Pozar, Microwave Engineering, 3rd edition, Wiley, 2005.
[14] J-S. Hong, M.J Lancaster, Microstrip Filters for RF/Microwave Applications, Wiley-Interscience Publication. 2001.
[15] G. Matthaei, L. Young, E.M.T. Jones, Microwave Filters, Impedance-Matching Networks, and Coupling Structures, Artech House, 1980.
[16] CST Microwave Studio 2009, www.cst.com