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Bed of Springs for packaging of microstrip circuits in the microwave frequency range

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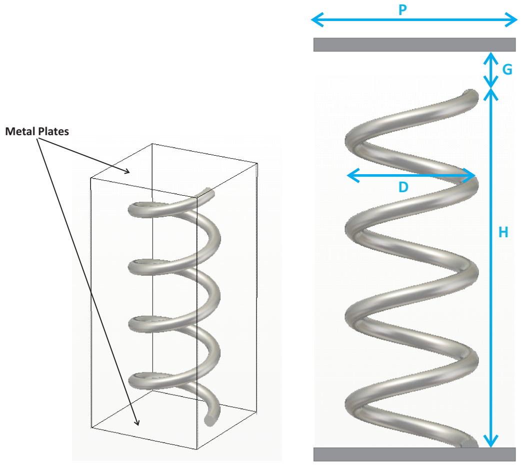
***Abstract*— After the use of the known as *bed of nails* for removing cavity modes in microstrip circuit packages, we propose herein a new version of this periodic structure, based on helices (springs) instead of nails. This new structure named *bed of springs* is much more compact and this allows its use at low frequencies where the bed of nails is not suitable as it is too bulky due to the required height of the nails (pins). The bandwidth of the proposed structure turns out to be similar to the case of the bed of nails. Parametric studies are presented as a design tool and a demonstrator has been manufactured and measured.**

***Index Terms*— AMC, gap waveguide, Parallel plate mode, packaging.**



(a) 3D view (b) Side view

Fig. 1. Description of the unit cell and all its parameters.

I. Introduction

Recently, the isotropic reactive surface known as bed of nails [1] has been proposed to design a new type of waveguide technology - the gap waveguide [2], [3], [4]- being particularly advantageous over 30 GHz and having potential for reaching the THz band. This technology is based of the use of a textured surface to create an Artificial Magnetic Conductor (AMC) in one of the plates of a conventional parallel plate waveguide to remove parallel plate modes, and thereby to generate a stopband. Then, any ridge or any groove included in that plate or metal strip between the plates will allow propagation of local quasi-TEM mode following the ridge, groove or strip without leaking into the rest of the parallel plate region. The parallel plate stopband provided by the AMC can similarly be used to remove cavity modes in metal boxes containing microstrip circuits, i.e. to enable packaging of high frequency components [5], [6].

Even though any type of AMC can be used as textured surface, an important advantage of the bed of nails structure is that it is made only with metal and no dielectric material is required. This makes the losses small at high frequencies, but the structure becomes too bulky at low frequencies (the pins length must be close to $\lambda_0/4$). A possible option at low frequencies is the use of AMC realized by printed technology (as for instance the classical mushroom-type EBG) [7]. However, in most cases the use of dielectric reduces the operating frequency bandwidth and increases the structure losses. Besides, AMC surfaces based on printed structures are typically making use of the 2D periodicity to achieve the AMC behavior rather than the dielectric thickness. This means that the periodicity becomes large i.e., comparable to $\lambda_g/2$ that can be a problem in small circuits. An example is the use of such structures to reduce mutual coupling between antennas where a narrow unit cell in the antenna plane will allow the use of more unit cells and thereby better performance. Another example is when it is desired to use low profile electric current antennas above a magnetic conductor surface because the antenna is not locally seeing magnetic conductor and always tricks are used to make it work. Therefore, compact unit cells not only in terms of height are also needed for many applications including packaging.

In this paper we propose a new structure that combines the advantages of both a compact unit cell and a reduced height (thickness). The replacement of nails with springs is inspired by two concepts. First, as a resonant structure that increases both the equivalent inductance as well as the capacitance of the cell therefore decreasing the resonant frequency. Second, the helix will have an equivalent depth that should be proportional with the helix wire length to provide low height structure. With some innovation this could be valid for many frequency bands, but definitely for low frequency applications this is a realistic structure. Some initial simulated results of this work were already presented in [8].

The purpose of this work is to present the bed of springs as an alternative to the bed of nails at low frequencies. The period of a periodic helical structure can be sub-wavelength and, due to the wire shape, the total height can also be small. This unit cell is represented in Fig. I.

In the same way as the bed of nails was successfully used to remove cavity modes when packaging microstrip circuits [5] the proposed bed of springs could be used for the same aim at low frequencies. For this reason this study will be focused on the stopband behavior of the periodic helical spring structure when it is connected to a ground plane and topped by another metal plate at a given distance. This stopband will also prevent cavity modes when the two plates are connected by surrounding walls for packaging. Besides, the bed of springs may also find application as a normal EBG surface in a free space or open situation as it may have advantages compared to alternative solutions [9], [10] in particular at low frequencies.

II. Parametric study via dispersion diagrams

For the analysis of the structure we initially consider only one unit cell as shown in Fig. I and we use periodic boundary conditions in both sides and PEC in bottom and top (allowing a gap with size g). Then the dispersion diagram of the structure is computed by using the Eigenmode Solver of CST Microwave Studio [11]. The main parameters of the structure to be taken into account are described in Fig. I. We consider the following dimensions: G=2 mm, H=30 mm, D=10 mm, and P=15 mm as our initial or reference case. Besides N is the number of turns of the helix, which is N=3 and the radius of the wire itself was selected as 0.75 mm in Fig. I.

With these dimensions we obtain the dispersion diagram in Fig. 2. A wide stop band is created in the parallel plate mode from 0.55 GHz to 1.41 GHz. At the cutoff frequency the height of the helix H is $0.0686\lambda_0$ i.e., the structure is electrically very thin. The considered period is also very sub-wavelength ($0.0343\lambda_0$). The total electric length of the wire is approximately $0.36\lambda_0$ at 0.55 GHz.

In this structure we can expect (and use for its design) that the theoretical bandwidth go from the frequency where the total length of the wire is close to $\lambda/4$ to the one where the total length is $\lambda/2$ or when the distance in between upper and lower plates (H+G) is $\lambda/2$, but typically the limit from the wire length comes before. Obviously it is expected that the different parameters of the structure have some secondary effects which make these initial limits more flexible. Nevertheless what it is clear when compared with the bed of nails is that for the spring case we do not get a strong capacitive effect from top of springs to upper plate and this makes the gap not so key aspect for design as it is in the case of bed of nails or mushroom type surface.

The parameters of the unit cell are now varied and the effect on the stop band investigated. We start from the total number of turns, N keeping all the other parameters constant (including the height H). The results are summarized in Fig. 3 for values between 2 and 8 turns. In the figure, we plot the value of the lower cutoff of the stop band and the value of the upper limit. This means that the structure will stop

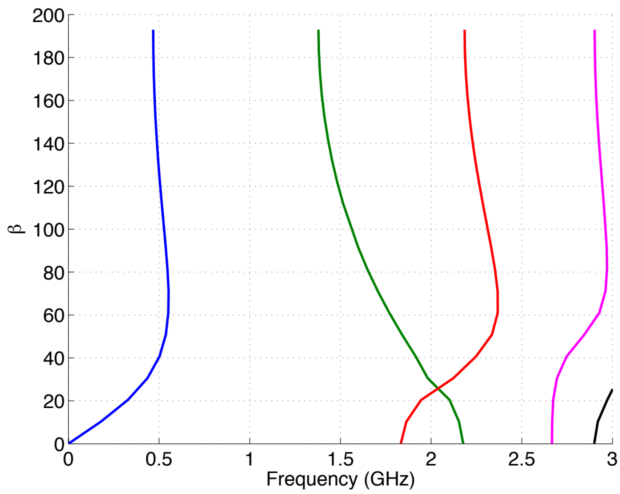


Fig. 2. Dispersion diagram of the reference structure. G=2 mm, H=30 mm, D=10 mm, and P=15 mm. N=3.

propagation of waves and cavity modes in the frequency range in between the two solid lines represented in the figure. As expected, increasing the number of turns or in other words the electrical length of the wire, we move all the modes to lower frequencies as seen in the graph. This means that the structure can be even more compact if required by increasing N decreasing the structure height H and keeping the unit cell size. In the same figure the relative bandwidth f_{end}/f_{start} of the stopband is as well represented with a dashed line, where f_{end} means the upper limit of the stopband and f_{start} the lower one. We can see how the relative bandwidth is larger than 2 to 1 in all cases and is larger for small values of N. The reason why the ratio is not constant is probably caused by the fact that when we increase the number of turns and keeping the same height H, the turns are then closer and closer and more coupling effects appear that are not included in the simple calculation of total length.

Another important parameter to be checked is the gap G to the upper plate. Fig. 4 contains the summary of results of the simulations of dispersion diagrams for gap sizes from 1mm up to 16mm. The upper limit of the stop band is almost unaffected by this parameter, whilst the lower limit increases a bit with the increasing of the gap. In any case, this parameter is not moving the stop band in a meaningful way. This gives quite a lot of flexibility to the design when compared to pins or even mushroom-type EBG geometries as in those geometries the effect of the gap size was critical. That was caused by the fact that the flat surface of the top of both mentioned unit cells in parallel with the upper metal plate creates a capacity with strong effect on the stop band whilst in the spring geometry such capacity is not existing. The insensitivity to the distance to the upper plate allows a large range of gap heights to the printed circuits when we use it for packaging, thus allowing the presence of rather large discrete components like capacitors, transistors and ICs on the circuit board.

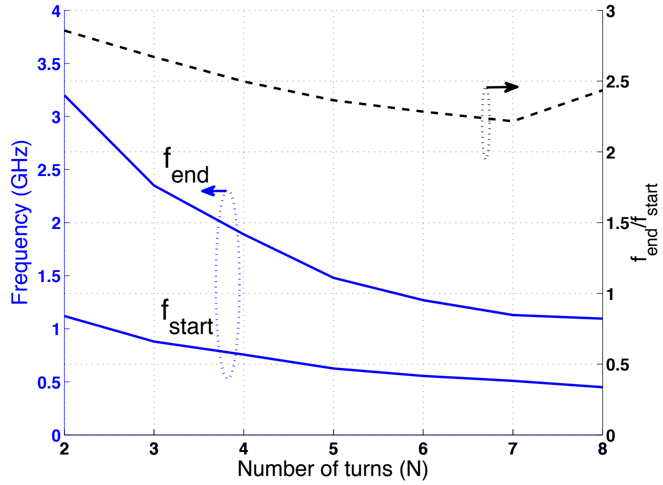


Fig. 3. Stop band as a function of number of turns N. The other parameters are the following: G=2 mm, H=30 mm, D=10 mm and P=15 mm. Right axis represents the relative bandwidth where f_{end} means the upper limit of the stopband and f_{start} the lower one.

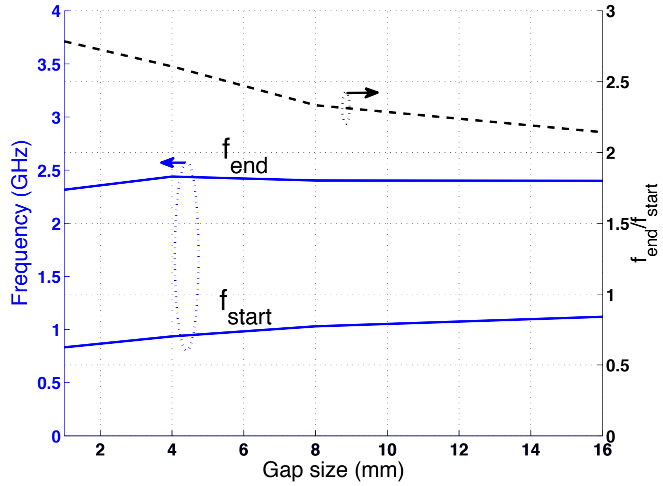


Fig. 4. Stop band as a function of gap size G. The other parameters are H=30 mm, D=10 mm and P=15 mm. N=3. Right axis represents the relative bandwidth where f_{end} means the upper limit of the stopband and f_{start} the lower one.

The period of the unit cell is also an important parameter as it determines the number of required unit cells for a given application. A summary of simulation results is presented in Fig. 5 for this parameter changing between 13 and 25 mm. Within this range the stopband is not very modified by this parameter. We have to stress that we are using periods that are very small in terms of wavelength. We have observed that when the period is significantly increased without increasing simultaneously the diameter D, the stop band is strongly reduced, especially the upper limit as some modes can propagate in the space between wires. The lower limit is still determined mainly by the total length of the wire and is not affected by the period. When the period size is comparable to the one of the diameter, there is coupling between neighbouring cells.

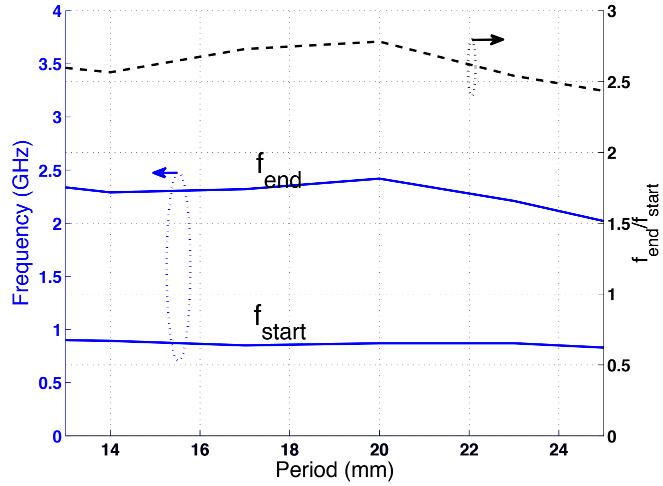


Fig. 5. Stop band as a function period of the unit cell P. The other parameters are the following: G=2 mm, H=30 mm and D=10 mm. N=3. Right axis represents the relative bandwidth where f_{end} means the upper limit of the stopband and f_{start} the lower one.

The diameter of each turn D (keeping same period) is now considered. The achieved results for the stop band are represented in Fig. 6. The effect of this parameter as in the case of the number of turns is clear, a larger diameter shifts down all the modes in frequency as the total wire length is increasing, but the relative size of the stop band is not much affected as seen in the figure where the diameter has been varied from 2 to 7 mm.

Some of the parameters have also been tested in a parallel plate waveguide of finite width which is more similar to the prototype that will be later manufactured and measured. To this aim, the S_{21} parameter for the parallel plate waveguide is computed, having springs on one of the walls.These results have already been presented in [8] and are not repeated in this paper as the conclusions are identical to the ones obtained from the dispersion diagram analysis.

III. Experimental Results

A. Design of the prototype

In order to demonstrate the presented results, a prototype has been designed. The methodology to demonstrate its performance will be the same as the one employed in [5] i.e., a microstrip transmission line with two 90° bends is designed and packaged with the bed of springs as shown in one of the pictures of Fig. 10. Then, it is also packaged with a smooth metal lid and both results are compared. The substrate employed for the line is Duroid with ϵ_r = 4.4 and thickness t =0.5 mm. The dimensions of the box inside which the circuit is mounted, are 55 mm x 100 mm. Springs were designed to cover a frequency range of 3 to 6 GHz. This frequency range is

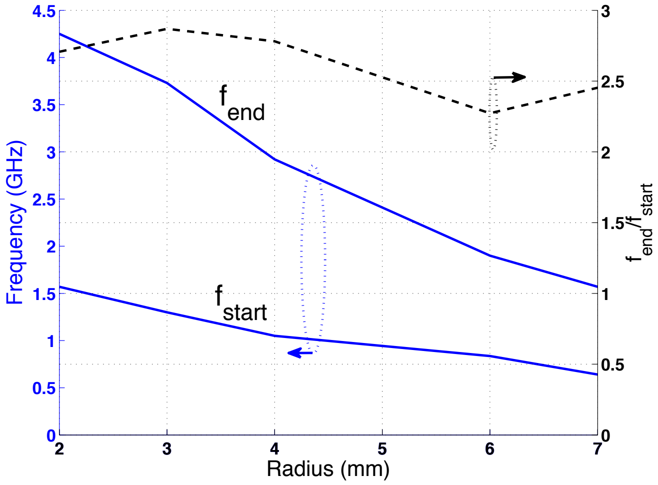


Fig. 6. Stop band as a function of the diameter D. The other parameters are the following: G=2 mm, H=30 mm and and P=15 mm. N=3. Right axis represents the relative bandwidth where f_{end} means the upper limit of the stopband and f_{start} the lower one.

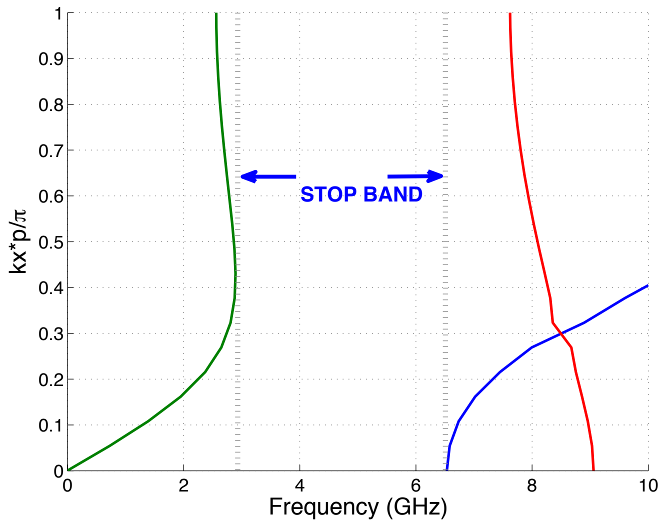


Fig. 7. Dispersion diagram of the designed unit cell creating a stopband from 3 to 6 GHz. N=2; H=5 mm, G=1 mm, P=6.13 mm and diameter D= 5.12 mm

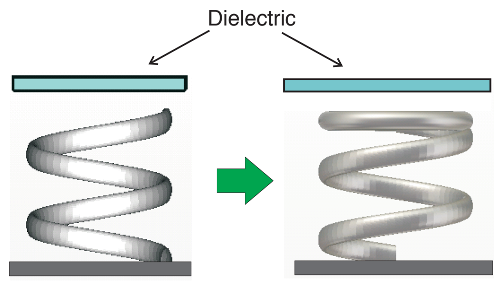


Fig. 8. Modified designed unit cell

not too low and consequently the springs will be quite small (in all dimensions). Initially the spring dimensions were chosen as follows N=2; H=5 mm, G=1 mm, P=6.13 mm and diameter D=5.12 mm including the wire radius which was forced to be 0.4mm by the manufacturer. As the geometry is very compact the number of springs for this case will be high. In the design, the dielectric layer where the microstrip line is printed was taken into account as indicated in Fig. 8. The ideal dispersion diagram is shown in Fig. 7 where we can clearly see how the desired bandwidth is perfectly covered.

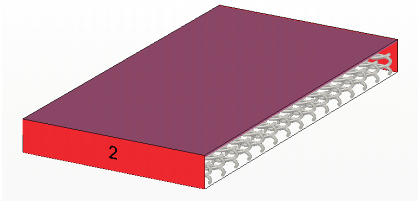
Before manufacturing the prototype a small modification was made to the spring related to its top as suggested by the manufacturer. The intention is to provide the design with more robustness and to have a more precise control of the distance from top of the springs to the circuit (even if in this design that distance is not too critical). With this purpose, a flat top closed ring was added to the springs and the structure was redesigned as presented in Fig. 8 . The dispersion diagram was almost unaffected, the lower limit of the stop band was moved a bit down in frequency but still the whole desired stopband was covered.

As mentioned in the previous Section, another way of doing veryfication of the stop band is with the transmission coefficient S_{21} by using a finite structure and two waveguide ports (as defined in CST software) as it can be seen in Fig. 9.a and proposed in [8]. This simulation corresponds to the box of springs (with the the modified unit cell) closed on top by a grounded substrate layer at a distance G from the top of the springs. Then the S_{21} coefficient is calculated considering the complete narrow sides of the structure as waveguide ports as shown in Fig. 9.a. We have considered a total of 8 by 15 springs as there will be in the manufactured prototype. From this simulation (shown in Fig. 9.b) it is very clear where is the stop band of the structure as below and above there is the propagation of a TEM mode in between the upper and lower metal plates.

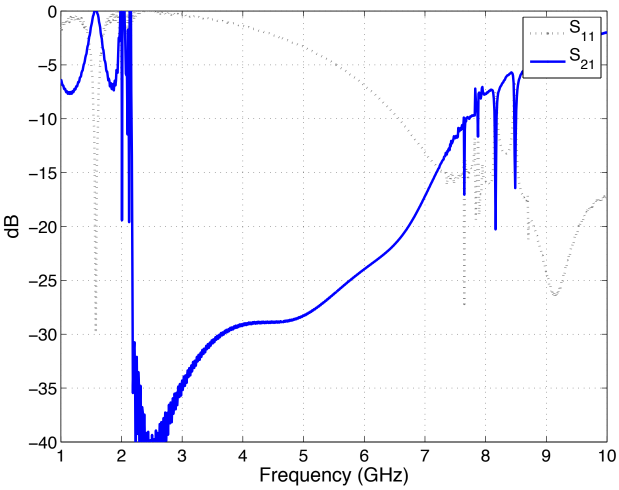
B. Measurements

In the measured prototype we expect to observe how the cavity modes are not excited due to the effect of the springs. For this reason it is convenient to know at which frequencies these resonances should be located. The cavity modes of such a cavity including the dielectric have been numerically computed both with CST Microwave Studio and with HFSS simulators getting similar results and are included in Table I.

The manufactured prototypes can be seen in Fig. 10. The total size of the cavity is 55 mm x 100mm. The corresponding measurements are presented in Fig. 11. In the figure we have included the measurements of the microstrip line without any packaging (open case), the line packaged with the bed of springs and the line packaged with an ordinary smooth metal lid (situated 2 mm apart from the line). We can see how the packaging with the bed of springs removes the cavity modes within the frequency range of operation and its very similar



(a) Simulation setup

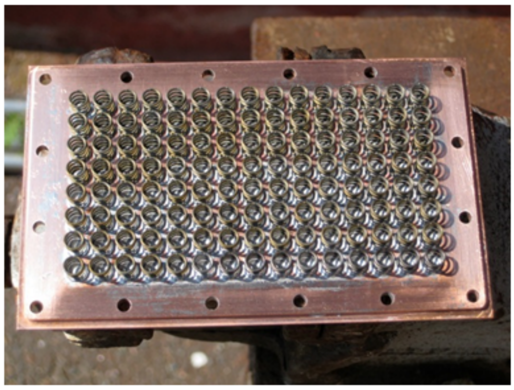


(b)

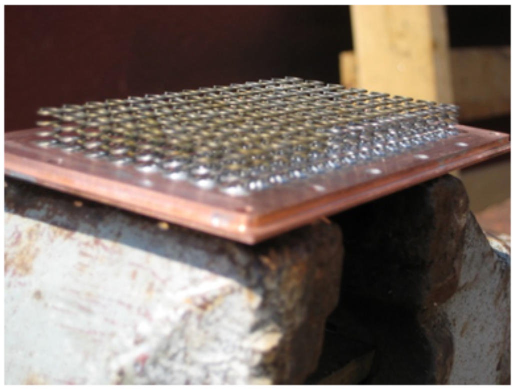
Fig. 9. Simulated S_{21} parameter.

2.67	3.48	4.52	4.86	5.35	5.66	6.07	6.85

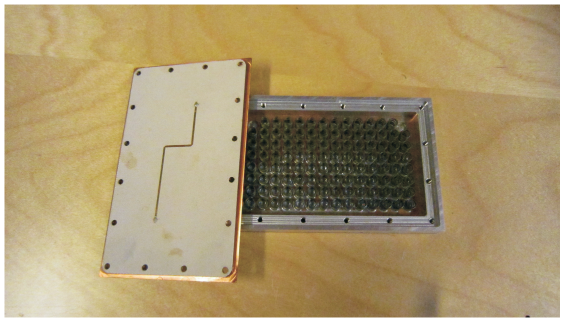
TABLE I
FREQUENCIES OF THE FIRST 8 CAVITY MODES (IN GHZ) IN THE PARTIALLY FILLED CAVITY COMPUTED WITH HFSS



(a) Top view.



(b) Side view.



(c) Circuit to be packaged.

Fig. 10. Manufactured prototype

to the open case. On the contrary, when the microstrip line is packaged with an ordinary smooth metal lid, the cavity resonances are clearly observed.

There is an additional advantage which must be pointed out, in the case of lid of springs, there is no need for a very good electrical contact in the walls the box as the leakage is totally nonexistent as the parallel plate modes are all stopped.

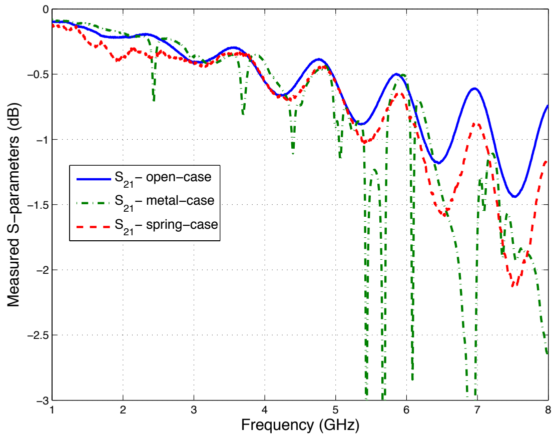
Compared to the case in [5] we are now in front of much lower frequencies and consequently the field in the microstrip line is more confined and the radiation from the edges of the bended line are negligible even in free space. Even more, the 0.5 mm thickness substrate is really thin at these frequencies and do not generate radiations. As observed in the measurements, the cavity modes are excited when the structure is packaged with a smooth metal lid. The frequencies at which these perturbations appear in the S parameters are very similar to the theoretical ones presented in Table I.

IV. Conclusion

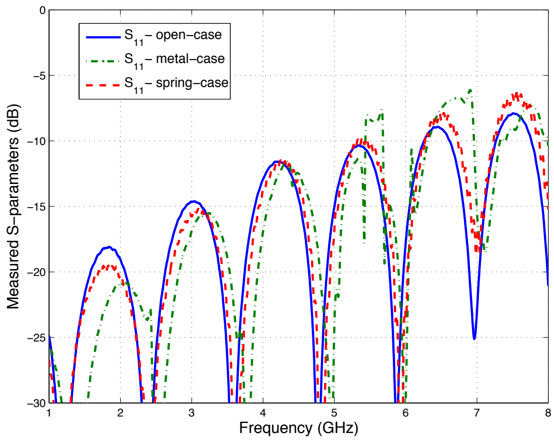
We have proposed the use of a new type of structure, the lid of springs to be used for removing cavity resonances in metal packages containing microstrip circuits. The structure works in the same way as the bed of nails but the bed of springs is advantageous at low frequencies because of its reduced size.

To this aim, we have presented parametric studies of the structure in terms of the frequency range in which all modes are stopped. The structure is electrically compact and the achieved bandwidths are equally large as those achieved using the bed of nails and it is not so sensitive to gap size. Thus, more than octave bandwidths can easily be obtained.

A demonstrator has been manufactured and measured to verify the proposed design. To this aim, the removing of cavity resonances when packaging a microstrip line with the bed of spring was experimentally demonstrated. Besides



(a) S_{21}



(b) S_{11}

Fig. 11. S parameters measurements of the prototype in Fig. 10 and comparison with a smooth lid packaging.

the shown example with a simple bent line, we want to point out how this technique can be extremely useful when dealing with active components producing undesired radiation at unexpected frequencies.

When comparing the proposed technique with the use of an absorber on the top lid, the main difference is that here the radiations from the discontinuities are not absorbed but avoided and therefore the advantage comes in terms of efficiency as the losses in the circuit are suppressed.

ACKNOWLEDGEMENT

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