

# Signal Integrity Applications of an EBG Surface

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**Abstract**—Electromagnetic band-gap (EBG) surfaces have found applications in mitigation of parallel-plate noise that occurs in high speed circuits. A 2D periodic structure previously introduced by the same authors is dimensioned here for adjusting EBG parameters in view of meeting applications requirements by decreasing the phase velocity of the propagating waves. This adjustment corresponds to decreasing the lower bound of the EBG spectra. The positions of the EBGs' in frequency are determined through full-wave simulation, by solving the corresponding eigenmode equation and by imposing the appropriate boundary conditions on all faces of the unit cell. The operation of a device relying on a finite surface is also demonstrated. Obtained results show that the proposed structure fits for the signal integrity related applications as verified also by comparing the transmission along a finite structure of an ideal signal line and one with an induced discontinuity.

**Index Terms**—circuit noise, electromagnetic propagation, microwave integrated circuits.

## I. INTRODUCTION

Parallel-plate noise occurs in multi-layered high speed digital-, mixed signal integrated circuits and printed-circuit boards (PCB's) [1-3]. Its origin stems from radiation of fast switching surface current density mainly flowing through vias, which is conducted in the parallel-plate waveguide formed by the power planes of the circuit [4]. This radiation is captured by the different circuit components and adds as noise to the signal, leading to malfunctioning of the circuits and/or devices. The noise power spectral density is of low-pass type and extends up to several GHz.

2D periodic structures that present electromagnetic band-gaps (EBG's) have found applications in solving this signal integrity issue [1-13]. Namely, a plane containing metal patches arranged in a periodic pattern and connected to the ground plane through one or several vias per unit cell can be inserted in between the power planes; noise is prevented from propagating within the frequency range of the EBG.

Interest in periodic surfaces that present EBG's has been triggered following publication of [14]. Quite low cost periodic structures can be obtained by impressing a periodic metal pattern on one face of a microstrip board. Such an electromagnetic object carries surface Bloch waves in some frequency ranges and prevents propagation in other frequency ranges, namely the EBG's. The EBG's depend on the dimensions and geometry of the surfaces, the dielectric material the separates the patterned surface from the ground plane and on the number, dimensions and positions of the vias that connect the metal patch within each unit cell with the ground plane [4], [7], [12-13].

The EBG's can be calculated by solving an eigenmode

equation for the electromagnetic field associated to an infinite extension of the periodic surface in order to calculate the dispersion diagram (DD) [15]. In real applications, only finite regions of the EBG surface can be inserted into the circuit. Therefore, in order to have a large number of unit cells within the circuit, the spatial periods of the EBG surface must be as small as possible. Small dimensions of the unit cell lead to the positioning of the EBG in the high frequency range. However, in order to be effective in filtering wide-band noise in circuits, the EBG must be as large as possible and the stop-band it exhibits should be placed in the lower range of the frequency spectrum, where the different types of noise spectra (white, 1/f etc.) are mostly localized.

In this paper, we consider an EBG planar structure that we have capacitively loaded in view of decreasing the phase velocity of waves. We demonstrate by full-wave simulation that an effect of decreasing phase velocity is shifting the lower end of the EBG towards lower frequencies. While the idea of capacitive loading of periodic structures and the corresponding slowing down of waves is not new [16], we demonstrate its effectiveness in the 2D case for all directions of propagation and we outline its applications to the noise mitigation problem.

In the next section, we introduce the structure on which the technique of reducing the phase velocity of waves is demonstrated. In Section III, we discuss the influence of various geometrical and material parameters on the position of the EBG in the frequency domain. The behavior of a real device, containing a finite surface is assessed in Section IV. Conclusions are drawn in the last section.

All real structures contain finite surfaces and therefore frequency related performances are dependent on the dimensions of the surface. Previous works [1] have shown that EBG's revealed by the DD's associated to infinite surfaces can be used as a good estimate of the stop band featured by a finite surface provided the number of unit cells is sufficiently large. Therefore, we assess the considered structures by calculating the DD's with a commercial full-wave solver [17]. The DD's are obtained by solving the eigenmode equation associated to the unit cell geometry considering appropriate periodic boundary conditions in both Cartesian directions. These conditions assure that the analysis corresponds to an infinite surface. Results concerning finite structures presented below have been obtained by full-wave simulation relying on the transient solver provided by [17].

## II. DESIGN OF THE UNIT CELL AND CALCULATED DD'S

We consider a 2D planar EBG structure, periodic on a quadratic grid of period  $d=10$  mm, bounded by the two

metallic power planes, Fig. 1 (a). The unit cell contains a circular metal patch of radius  $r=4.5$  mm, connected to the ground plane by four vias with metal walls, of radii  $r_v=0.4$  mm, placed at  $x_v=\pm r/3$ ,  $y_v=\pm r/3$  with respect to the coordinate system of Fig. 1 (a). The distance from the lower metal plane (ground) to the patch plane is  $t_1=6.4$  mm and the distance from the patch plane to the upper metal plane (power plane) is  $t_2=t_1/2$  (the upper metal plane has been removed in Fig. 1 (a) in order to reveal the interior of the unit cell). The space in between the ground plane and the patch plane is filled with a material having a dielectric constant  $\epsilon_{r1}=3.5$ . In most situations, the space in between the patch plane and the upper power plane is filled with a material having a dielectric constant  $\epsilon_{r2}=\epsilon_{r1}$ , but this value has been changed in some simulations in order to reveal its impact on the behavior of the proposed device. This structure has been introduced in [18] and results of a parametric study are reported in [19]. Various applications of some special instances for the shape of the unit cell have been considered, e.g. [13], [20-21]. For the present - signal integrity - application, a large extension of the EBG in the frequency range is desirable. Therefore, by relying on [18-19], the geometrical dimensions of the patches and the number of vias have been optimized for the width of the EBG, which for the values considered above is comprised in the interval 3.1233 GHz ... 5.9202 GHz. The characterized (first) EBG is considered to spread between the highest frequency of mode 1 and the lowest frequency in mode 2, since, by definition, the cut-off of the lowest mode 1 is equal to zero, due to the presence of the two power lines.

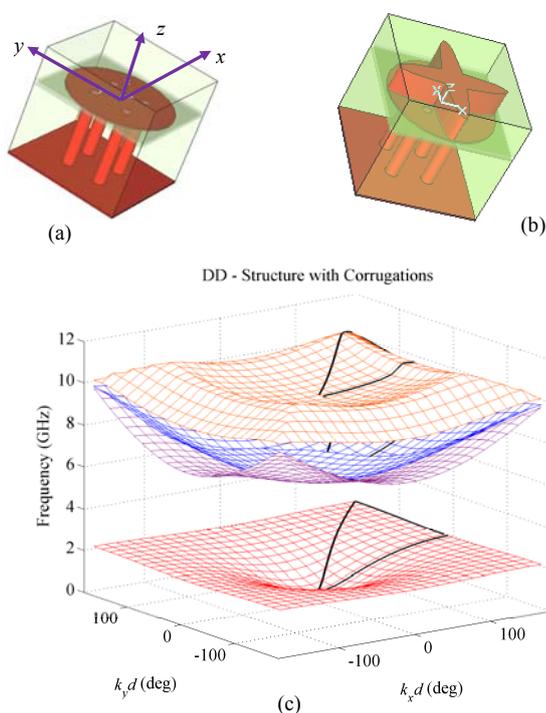


Figure 1. (a) Unit cell without capacitive loading (upper metal plane removed); (b) Unit cell with capacitive loading; (c) Dispersion diagram for the first four modes for the structure with capacitive loading: frequency versus normalized wavenumbers

Several known solutions for increasing the EBG width exist, such as increasing the dielectric constant  $\epsilon_{r2}$  (e.g. by using high  $k$  materials [22]) or decreasing the width of the upper layer. However, these solutions are not always feasible in the case of PCB's and integrated circuits. Another

solution is to add corrugations on the top of the patches in order to capacitively load the parallel-plate waveguide, since the field of the first mode is concentrated mainly in that region for such "mushroom" structures [14] (see also Fig. 3 below). The corrugations we have selected consist of elliptical cylinders, of half-axes  $r/5$  and  $r$  and an initial value of the height  $h=3/4t_2$ , Fig. 1 (b). The height has also been varied for exploring various feasibility alternatives. The computed 2D DD for this periodic structure, featuring the first four modes, is represented in Fig. 1 (c). The presence of the EBG revealed by Fig. 1 (c) makes this structure suitable for noise suppression in high-speed circuits.

Fig. 2 (a) displays the DDs corresponding to the first mode of the structure without corrugations (upper surface) and with corrugations (lower surface). The shift to lower frequencies as a consequence of adding corrugations is obvious. This shift can be explained by considering the phase velocities, Fig. 2 (b). It is known that a capacitive loading of a transmission line has the effect of decreasing phase velocity of waves propagating on that line [16]. In our case, the upper surface corresponds to the first mode of the structure without corrugations and the lower surface corresponds to the structure with corrugations (a part of the upper surface has been suppressed in order to render visible the lower one, but it can be reconstructed by symmetry). Here we can also mention that the insertion of a load which does not break down the symmetry of either direction of the unit cell alters in a very weak manner the symmetry of the spectral response. Since the phase velocity relates to the slope of the line connecting the origin with a given point of the DD surface and the DD of the first mode contains the origin of the  $(k_x, k_y)$  plane as explained above, slowing down the wave has the effect of bending downward the surface corresponding to the first mode, like in Fig. 2 (a) and consequently translating the lower bound of the EBG towards smaller frequencies. This behavior has been hypothesized also in [23] and verified for axial propagation. Here we have demonstrated the validity for all directions of propagations.

In order to gain some insight on the impact of the corrugations on the fields, we have represented in Fig. 3 the electric fields for mode 1 in the two structures, for propagation along the  $x$  axis, at a frequency of 1.15 GHz, a  $60^\circ$  phase shift along the unit cell and at a moment of maximum amplitude. A comparison of the field images in Figs. 3 (a) and 3 (b) clearly reveals the capacitive effect of corrugations by the concentration of the electric field in the space in-between the upper surface of the corrugations and the upper metal layer (top of the structure). This effect is not present in the field images for mode 2 (not shown here). In general, simple models like capacitive loading cannot be applied to higher order modes. This explains the quite high impact of capacitive loading on the lower bound of the EBG and the mild impact on the upper bound. Indeed, the EBG obtained following the introduction of corrugations is in the interval 2.2238 GHz ... 6.0899 GHz. The lower bound of the EBG has decreased by 28.8% with respect to the EBG corresponding to the structure without corrugations, while the upper bound has not been significantly affected (an increase of 2.87% has been obtained, which is however favorable for this situation). The 1.45 octaves large EBG

makes this structure suitable for signal integrity applications.

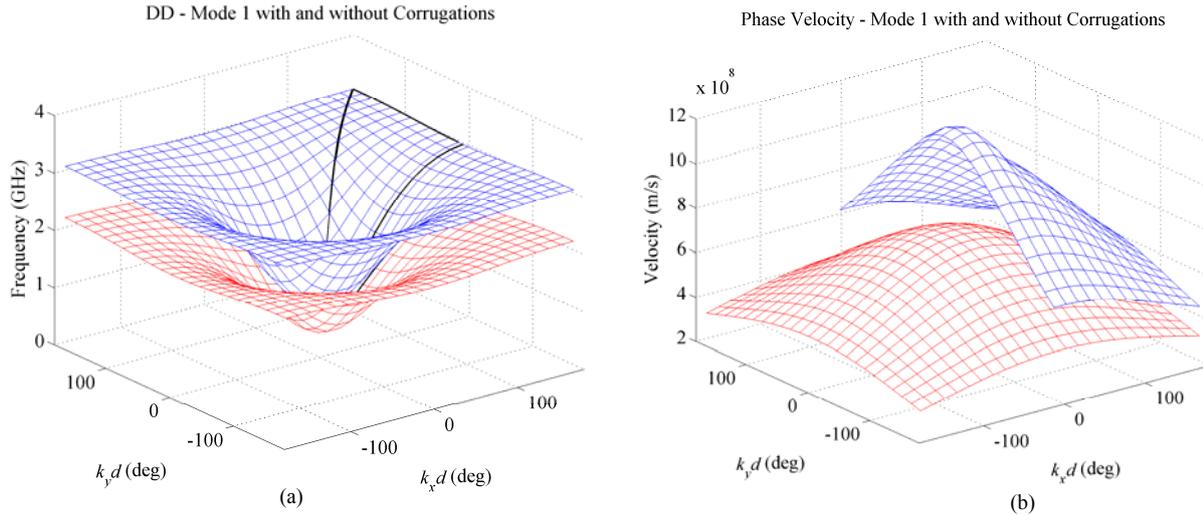


Figure 2. (a) DDs for mode 1 of the structure without capacitive loading (upper surface) and with capacitive loading (lower surface); curves on surfaces correspond to bounds of the first Brillouin zone. (b) Phase velocity versus normalized wavenumbers, mode 1 without capacitive loading (upper surface) and with capacitive loading (lower surface).

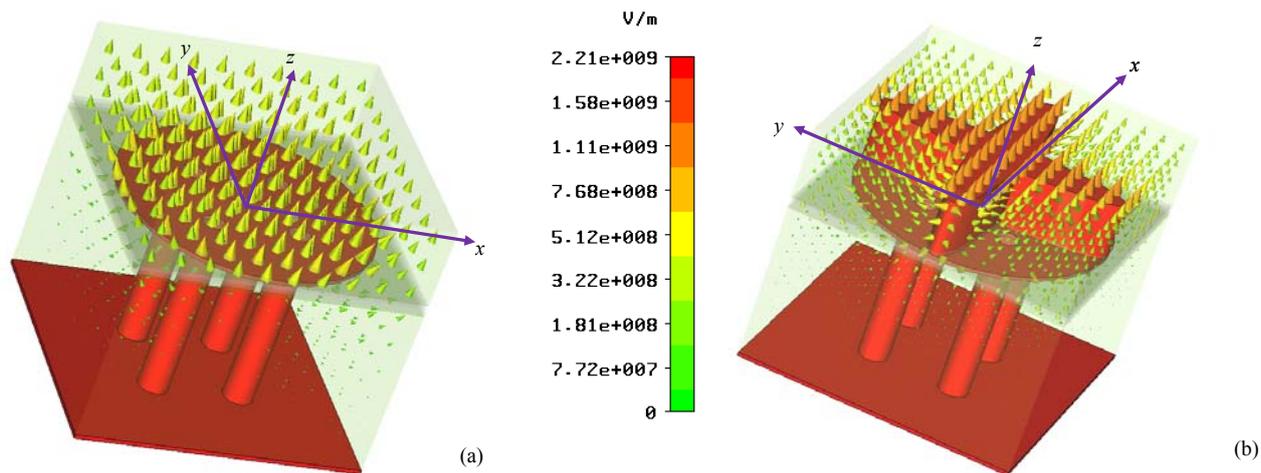


Figure 3. (a) Electric field pattern of mode 1 in the structure without corrugations for propagation in the x direction, at a frequency of 1.15 GHz and a phase shift of  $60^\circ$  across the unit cell (b) Electric field pattern of mode 1 in the structure with corrugations, calculated in the same conditions as in (a).

In the following we present the effect of the variation of some geometrical and material parameters on the EBG characteristics. These results complement those reported in [23].

### III. PARAMETRIC STUDY AND DISCUSSION

As already mentioned, it is known that increasing the dielectric constant of the upper layer, decreasing the height  $t_2$  of that same layer or increasing the capacitive loading result in modification of the limits of the EBG. This aspect is important in choosing appropriate parameters fitting various application dependent requirements. We have performed several simulations in order to illustrate this point and to provide data that can be used in conjunction with those reported in [23] for the design of this kind of EBG surfaces.

The obtained results are reported in Tables 1 and 2. As compared to [23], we have insisted on a higher value of the

height  $t_2$  of the upper dielectric layer, in order to facilitate insertion of circuits and devices in that layer, as demonstrated in the next Section. A small height of the upper dielectric layer is appropriate for situations targeting suppression of the parallel-plate noise. By choosing larger values for this parameter, we have opened the way for a different kind of application, demonstrating the flexibility of the proposed surface.

The data presented in Table 1 show that the introduction of corrugations and the increase of their height  $h$  enlarge the EBG and translate the lower bound to lower frequencies. Moreover, the results in Table 2 demonstrate that increasing the dielectric constant leads to a further shift towards low frequencies. However, in all cases the EBGs' width diminishes since the upper bound is also affected.

TABLE I. EFFECT OF THE VARIATION OF THE CORRUGATION HEIGHT ON THE WIDTH OF THE EBG

Corrugations	$h$	$\epsilon_r$	EBG Range (GHz)	EBG Width (GHz)
Absent	0	3.5	3.1233 ... 5.9202	2.7969
Present	$0.15t_2$	3.5	2.9762 ... 5.8438	2.8676
Present	$(1/4)t_2$	3.5	2.7817 ... 5.8093	3.0276
Present	$(1/2)t_2$	3.5	2.4828 ... 5.7881	3.3053

TABLE II. EFFECT OF THE VARIATION OF THE DIELECTRIC CONSTANT OF THE UPPER LAYER ON THE WIDTH OF THE EBG

Corrugations	$h$	$\epsilon_r$	EBG Range (GHz)	EBG Width (GHz)
Absent	0	3.5	3.1233 ... 5.9202	2.7969
Present	$(3/4)t_2$	3.5	2.2238 ... 6.0899	3.8661
Present	$(3/4)t_2$	7	1.7933 ... 5.5160	3.7227
Present	$(3/4)t_2$	12	1.4583 ... 4.7366	3.3270

IV. THE FINITE CASE

A small value of the height of the upper dielectric layer has the result of a large value of the EBG width (2.56 octaves and more have been reported in the cited paper [23]).

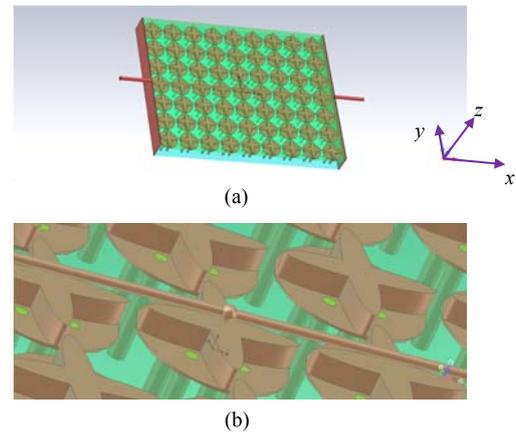


Figure 4. (a) Metal shielding box with EBG surface and coaxial feeding lines. Metal walls are removed for revealing the interior of the box. (b) Metal sphere on the cylindrical conductor.

While this value makes the surface a good candidate for noise suppression applications, insertion of circuit elements in such a thin layer is technologically difficult. Therefore, here we have considered a larger value for  $t_2$  in view of the application described below. Let us consider a strip-line based circuit shielded in a metal box. Discontinuities and

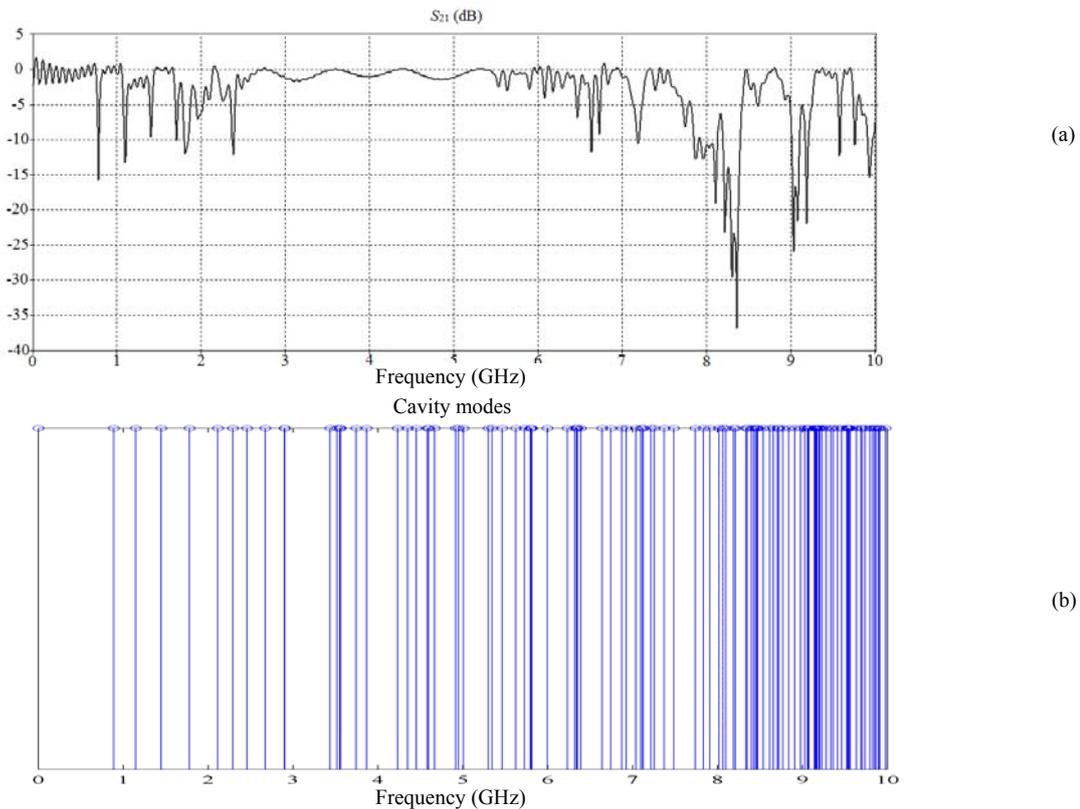


Figure 5. (a) Computed transmission S parameter (dB) versus frequency of the structure in Fig. 4 (a) (b) Frequency distribution (spectrum) of cavity modes.

radiation of circuit elements trigger cavity modes in the box that can lead to malfunctioning. A solution to this problem relies on the above introduced surface. This solution is inspired from the air-gap waveguide [24-26] that has been introduced for microstrip applications. A finite version of the surface embedded in a metal box is presented in Fig. 4

(a). The box is filled with a material having a dielectric constant of 3.5. The upper and lower walls of the box play the role of the metal planes that confine the infinite structure. The dimensions of the box are 90x70x9.6 mm, resulted from the number of unit cells in the horizontal plane (9 and 7 in the  $x$  and  $y$  directions, respectively) and the

height  $t_1+t_2$  in the vertical direction.

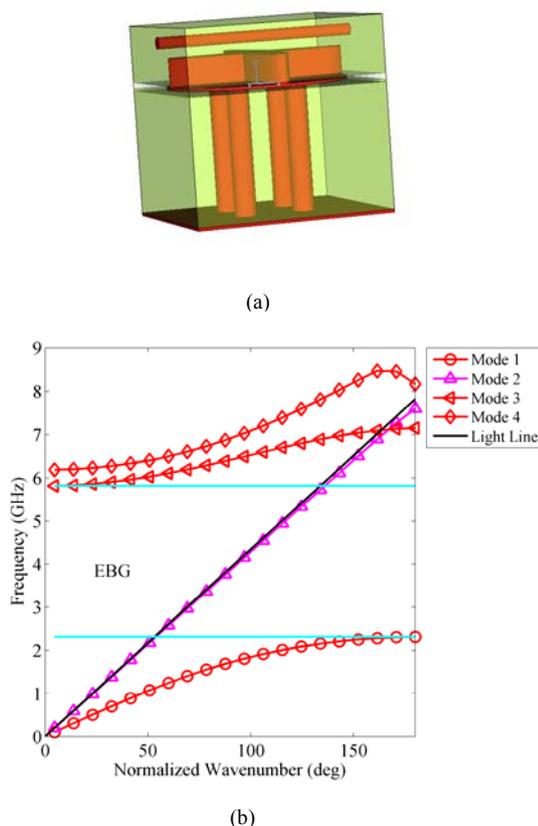


Figure 6. (a) Unit cell with additional metal, cylindrical rod parallel to the  $x$  axis. (b) DD corresponding to the 2D infinite repetition of the unit cell in (a).

The height of the corrugations is  $t_2/2$ . The box is accessed from opposite sides through two coaxial lines, of interior radii of 0.3 mm, exterior radii of 0.75 mm and filled with the same dielectric like the box ( $\epsilon_r=3.5$ ). The input and output lines are connected by a cylindrical conductor with the same radius as the inner conductor, which is contained in the interior of the box. A metal sphere of radius 0.5 mm is placed on the conductor, at midway between input and output (Fig. 4 (b)). The role of the sphere is to create a discontinuity that is likely to trigger cavity modes in the shielding box. Although this example involves coaxial lines for simplicity, the results presented below are also relevant for other technologies, like strip-line or microstrip.

A time-domain simulation [17] has been carried over on the structure in the band from 0 to 10 GHz that covers the EBG of the surface (data line 4 in Table 1). The computed  $S_{21}$  is reported in Fig. 5 (a). The frequencies of the cavity modes of the metal box filled with a dielectric with  $\epsilon_r=3.5$  are represented in Fig. 5 (b).

Fig. 5 clearly reveals that the functioning of the device is affected by the cavity modes outside the EBG, while these modes do not occur inside the EBG, demonstrating in this way the effectiveness of the solution. Inside the EBG, the device presents the periodic behavior in function of frequency that is characteristic to this kind of structures. The coincidence of the EBG bounds calculated in two different ways, namely through solving the eigenmode equation and

through time-domain solver demonstrates the reliability of the obtained results. It also demonstrates that the EBGs calculated for the infinite structures are good estimates for those obtained in real situations, with finite structures, provided that the number of unit cells is large enough in that particular case.

A further argument that supports the results concerning the behavior of the finite structure can be obtained by calculating the DD associated to its infinite version in the case when propagation of TEM waves is also possible [12]. Let us consider a through metallic cylindrical rod, of radius 0.3 mm that is placed in each unit cell, parallel to the  $x$  axis, like in Fig. 6 (a). The 2D infinite repetition of the unit cell contains then a lattice of parallel rods that enables propagation of TEM waves in the direction parallel to the rods. That this is indeed the case is demonstrated by the DD represented in Fig. 6 (b). Mode 2 in Fig. 6 (b) closely follows the light line (the solid, black line) within the EBG determined by the bounds of the modes denoted there by 1 and 3. The lattice of rods carries waves in the  $x$  direction, similarly to the conductor contained in the screened, finite structure and represented in Fig. 4. The DD in Fig. 6 (b) does not feature a true EBG due to the presence of the TEM mode. However, apart from this mode, the frequency range between the upper bound of mode 1 and lower bound of mode 3 is almost coincident with the one that allows transmission through the box that is not affected by cavity modes, as displayed in Fig. 5 (a).

## V. CONCLUSIONS

We have presented and assessed a method of enlarging the EBG revealed by the DD of periodic structures intended for mitigation of parallel-plate noise in high-speed digital and mixed-signal integrated circuits and printed circuit boards mainly by decreasing the lower frequency bound.

The enlargement has been achieved by capacitive loading of a periodic surface embedded in a dielectric layer, bounded by the metal power planes and containing circular patches connected to the ground plane by vias. The presented discussion relied on 2D DD's computed by full-wave simulation. Results of a parametric study have also been reported. The proposed structure has been successfully tested in an application requiring suppression of cavity modes in a metal shielding box. EBG's calculated by solving the eigenmode equation and by running a time-domain simulation showed a remarkable coincidence, demonstrating that the considered number of spatial periods in the enclosure has been enough to make it exhibiting the same spectral behavior as its counterpart of infinite extension.

## REFERENCES

- [1] R. Abhari, G.V. Eleftheriades, "Metallo-dielectric electromagnetic band-gap structures for suppression and isolation of the parallel-plate noise in high-speed circuits", *IEEE Trans. Microwave Theory Tech.*, vol. 51, no. 6, pp. 1629-1639, June 2003. [Online]. Available: <http://dx.doi.org/10.1109/TMTT.2003.812555>
- [2] S. Shahparnia, O.M. Ramahi, "Electromagnetic interference reduction from printed circuit boards using electromagnetic bandgap structures", *IEEE Trans. Electromagn. Compat.*, vol. 46, no. 4, pp. 580-585, Nov. 2004. [Online]. Available: <http://dx.doi.org/10.1109/TEMC.2004.837671>
- [3] T. Kamgaing, O.M. Ramahi, "Design and modeling of high-impedance surfaces for switching noise suppression in power planes,"

- IEEE Trans. Electromagn. Compat., vol. 47, no. 3, pp. 479-489, Aug. 2005. [Online]. Available: <http://dx.doi.org/10.1109/TEMC.2005.850692>
- [4] S.D. Rogers, "Electromagnetic bandgap layers for broad-band suppression of TEM modes in power planes", IEEE Trans. Microwave Theory Tech., vol. 53, no. 8, pp. 2495-2504, Aug. 2005. [Online]. Available: <http://dx.doi.org/10.1109/TMTT.2005.852776>
- [5] B. Mohajer-Iravani, S. Shahparnia, "Coupling reduction in enclosures and cavities using electromagnetic bandgap structures", IEEE Trans. Electromagn. Compat., vol. 48, no. 2, pp. 292-303, May 2006. [Online]. Available: <http://dx.doi.org/10.1109/TEMC.2006.874666>
- [6] A. Tavallee, and R. Abhari, "2-D characterization of electromagnetic bandgap structures employed in power distribution networks," IET Microwave. Antennas Propag., vol. 1, no. 1, pp. 204-211, 2007. [Online]. Available: <http://dx.doi.org/10.1049/iet-map:20050336>
- [7] M.-S. Zhang, Y.-S. Li, C. Jia, L.-P. Li, "A power plane with wideband SSN suppression using a multi-via electromagnetic bandgap structure," IEEE Microwave Wireless Comp. Letters, vol. 17, no. 4, pp. 307-309, April, 2007. [Online]. Available: <http://dx.doi.org/10.1109/LMWC.2007.892992>
- [8] J. Qin, O.M. Ramahi, V. Granatstein, "Novel planar electromagnetic bandgap structures for mitigation of switching noise and emi reduction in high-speed circuits", IEEE Trans. Electromagn. Compat., vol. 49, no. 3, pp. 661-669, Aug. 2007. [Online]. Available: <http://dx.doi.org/10.1109/TEMC.2007.902193>
- [9] A. Ciccomancini Scogna, A. Orlandi, V. Ricchiuti, "Signal integrity analysis of single-ended and differential signaling in PCBs with EBG structures", IEEE International Symp on Electromagnetic Compatibility, EMC 2008, 18-22 Aug, pp. 1-6, 2008. [Online]. Available: <http://dx.doi.org/10.1109/ISEMC.2008.4652005>
- [10] T.-L. Wu, H.H. Chuang, T.-K. Wang, "Overview of power integrity solutions on package and PCB: decoupling and EBG isolation", IEEE Trans. Electromagn. Compat., vol. 52, no. 2, pp. 345-354, May 2010. [Online]. Available: <http://dx.doi.org/10.1109/TEMC.2009.2039575>
- [11] P.H. Rao, M. Swaminathan, "A novel compact electromagnetic bandgap structure in power plane for wideband noise suppression and low radiation", IEEE Trans. Electromagn. Compat., vol. 53, no. 4, pp. 905-1004, Nov. 2011. [Online]. Available: <http://dx.doi.org/10.1109/TEMC.2011.2156408>
- [12] S.L. Huh, M. Swaminathan, "A design technique for embedded electromagnetic bandgap structure in load board applications", IEEE Trans. Electromagn. Compat., vol. 54, no. 2, pp. 443-456, Apr. 2012. [Online]. Available: <http://dx.doi.org/10.1109/TEMC.2011.2162337>
- [13] A. De Sabata, L. Matekovits, "Electromagnetic bandgap solution for mitigation of parallel-plate noise in power distribution networks," Microwave and Optical Technology Lett., vol. 54, no.7, pp. 1689-1692, 2012. [Online]. Available: <http://dx.doi.org/10.1002/mop.26918>
- [14] D. Sievenpiper, L. Zhang, F. J. Boas, N. G. Alexopoulos, E. Yablonovitch, "High-impedance electromagnetic surfaces with a forbidden frequency band," IEEE Trans. MTT, vol. 47, no. 11, pp. 2059-2074, Nov. 1999. [Online]. Available: <http://dx.doi.org/10.1109/22.798001>
- [15] L. Brillouin, Wave Propagation in Periodic Structures, New York, Dover, 1953.
- [16] R.E. Collin, *Foundations for Microwave Engineering*, Second Edition, New York: Wiley-IEEE, (2001), Ch. 8.
- [17] Computer Simulation Technology, Microwave Studio 2014.
- [18] L. Matekovits, A. De Sabata, M. Orefice "Parametric study of a unit cell with elliptical patch for periodic structures with variable number of grounding vias," *Proc. of the Fourth European Conf. on Antennas and Propagation, EUCAP*, Barcelona, April 12-16, pp. 1-3, 2007. [Online]. Available: [http://ieeexplore.ieee.org/xpls/abs\\_all.jsp?arnumber=5505362](http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5505362)
- [19] A. De Sabata, L. Matekovits, "Design charts for grounded, elliptically shaped microstrip periodic structures featuring electromagnetic band-gap", 8th International Conference on Communications (COMM), București, Romania, June 10-12, pp. 239-242, 2010. [Online]. Available: <http://dx.doi.org/10.1109/ICCOMM.2010.5509010>
- [20] A. De Sabata, L. Matekovits, "Reduced complexity biasing solution for switched parallel-plate waveguide with embedded active metamaterial layer", Journal of Electromagnetic Waves and Applications (JEMWA), vol. 26, no. 14/15, pp. 1828-1836, 2012. [Online]. Available: <http://dx.doi.org/10.1080/09205071.2012.716148>
- [21] L. Matekovits, A. De Sabata, K. P. Esselle, "Effects of a coplanar waveguide biasing network built into the ground plane on the dispersion characteristics of a tunable unit cell with an elliptical patch and multiple vias", IEEE Antennas and Wireless Propagation Letters, vol. 10, pp. 1088-1091, 2011. [Online]. Available: <http://dx.doi.org/10.1109/LAWP.2011.2170653>
- [22] W. H. She, Z. N. Wing, J. W. Halloran, W. J. Chappell, "Variable dielectric constants by structured porosity for passive ceramic components," *Digest of 2005 IEEE MTT-S International Microwave Symposium*, pp. 865-869, 12-17 June 2005. [Online]. Available: <http://dx.doi.org/10.1109/MWSYM.2005.1516755>
- [23] L. Matekovits, A. De Sabata, "Patterned Surface with Added Corrugations in View of Displacing EBGs to Lower Frequencies," IEEE International Symposium on Antennas and Propagation and USNC-URSI national Radio Science Meeting, Orlando, FL, pp. 81-82, July 7-13, 2013. [Online]. Available: <http://dx.doi.org/10.1109/APS.2013.6710701>
- [24] E. Rajo-Iglesias, A.U. Zaman, P.-S. Kildal, "Parallel-plate cavity mode suppression in microstrip circuit packages using lid of nails", IEEE Microw. Wireless Compon. Lett., vol. 20, no.1, pp. 31-33, Jan. 2010. [Online]. Available: <http://dx.doi.org/10.1109/LMWC.2009.2035960>
- [25] E. Rajo-Iglesias, E. Pucci, A. A. Kishk P.-S. Kildal "Suppression of parallel plate modes in low frequency microstrip circuit packages using lid of printed zigzag wires," IEEE Microwave Wireless Comp. Lett., vol. 23, no. 7, pp. 359-361, 2013. [Online]. Available: <http://dx.doi.org/10.1109/LMWC.2013.2265257>
- [26] P.-S. Kildal, E. Alfonso, A. Valero-Nogueira E. Rajo-Iglesias "Local metamaterial-based waveguides in gaps between parallel metal plates," IEEE Antennas Wireless Propag. Lett., vol.8, pp. 84-87, 2009. [Online]. Available: <http://dx.doi.org/10.1109/LAWP.2008.201114>