A Novel Method for Suppression of Vertical Coupling in Multi-layered Substrates

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***Abstract*—This paper demonstrates the suppression of vertical coupling between multiple plane pairs in GHz range of frequencies with Electromagnetic Band-Gap structures (EBGs). For the first time, dispersion diagrams have been developed for the EBGs used in vertical isolation giving insight into the coupling suppression. Results from simulations, measurements and analytical methods are presented to demonstrate the proposed method.**

I. INTRODUCTION

With the current demands on electronic systems being miniaturization and diverse functionality, multilayer packaging of mixed signal systems is gaining predominance. In mixed signal systems, electromagnetic interference between the digital and RF/Analog sections critically affects the system performance. And when multiple power/ground planes are used in the system's power distribution network, noise voltages get transferred horizontally and vertically throughout the package. So far in literature various methods have been reported to counter the horizontal coupling within the same plane pair. One of the methods to effectively suppress this coupling is to use Electromagnetic Band-Gap structures (EBGs). Different types of EBGs have been reported in literature along with methods to evaluate their suitability to a particular application and performance [1], [2]. But there hasn't been much research on tackling the vertical noise coupling issue especially in the GHz range of frequencies where decoupling capacitors lose their effectiveness. This paper demonstrates a method to suppress vertical coupling in the GHz range of frequencies. The vertical coupling occurs when packages use multiple plane pairs with apertures as shown in Figs.1 and 2. In Fig.1 a die is embedded in a cavity in the substrate (embedded active) and apertures of such large sizes result in significant coupling from one plane pair cavity to another. The method demonstrated here is based on our previous research [3] and uses EBG structures to counter vertical coupling. In this paper, for the first time, computationally efficient analysis of the proposed technique by using dispersion diagrams is presented which was not explored in [3].

The paper is organized as follows: Section II discusses the vertical coupling phenomenon and the suppression method; Section III discusses the dispersion diagram analysis and the design of multilayer structures with EBGs; Section IV describes the test vehicle for vertical coupling suppression; and Section V summarizes the conclusions.

II. PROPOSED TECHNIQUE

Electromagnetic waves (EM waves) fringe through apertures/cutouts, present in the metal planes of multilayer packages, vertically and results in field coupling from one plane pair cavity to another. Fig.2 shows this with the help of wrap around currents. When plane pair cavity 2 is excited, there is flow of surface currents on the bottom side of Plane 2. When the aperture is encountered these currents wrap around and flow into the top cavity. This result in the flow of return currents on the bottom side of Plane 1 as well. Thus, even though the top plane pair cavity is not excited, field gets coupled into it from the bottom cavity due to these wrap around currents.

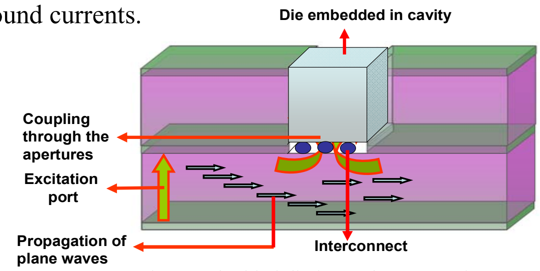


Fig.1.Embedded die in a substrate cavity

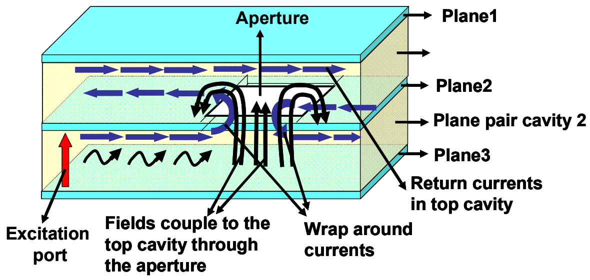


Fig.2. Vertical Coupling through apertures

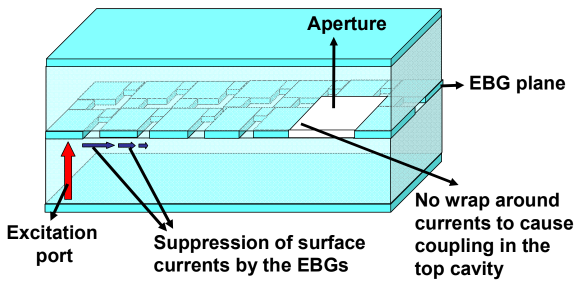


Fig.3. Vertical Coupling suppression by EBGs

To suppress the vertical coupling that is shown in Fig.2, the middle plane which has an aperture in the three-metal layer structure is patterned to form EBG structures as shown in Fig.3. The EBGs used throughout this paper are planar Alternating Impedance EBGs (AIEBGs) [1]. The AIEBG structure consists of alternating metal patches and branches. The entire EBG structure is periodic as the patches and branches are repeated throughout the structure. These patches and branches cause impedance perturbation and suppress the propagation of EM waves within a selected frequency range. The propagation of surface currents is suppressed by the presence of EBGs and thus the wrap around currents at the apertures are also suppressed providing considerable isolation between the top and the bottom plane pair cavities. It is important to connect the planes on either side of the EBG plane by vias to ensure the EBG band-gap property is not lost [4]. This concept of using EBGs to suppress vertical coupling can also be extended to non-adjacent plane pair cavities. Since the EBGs suppress the flow of surface currents on both sides of the patterned plane, return currents on the planes adjacent to the EBG plane are also suppressed. In case of Fig.4, the currents on plane 2 are suppressed, thus avoiding coupling of noise from plane pair cavity 2 to 3. Thus it is possible to suppress vertical coupling across two layers of plane pair cavities on either side of the patterned plane by the method demonstrated.

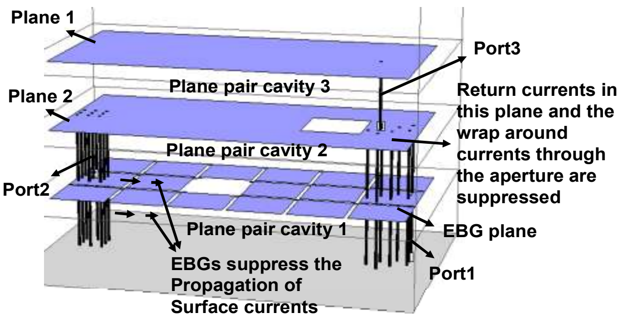


Fig. 4.Four metal layer structure with EBGs

III. Dispersion Diagrams

This section discusses the dispersion diagrams for predicting vertical coupling in multiple plane pairs and consists of 2 parts. Part 1 explains the basics of the analysis while part 2 deals with the development of unit cells for EBGs with multiple plane pairs and the prediction of stop bands using the dispersion diagram analysis.

A. Analysis

Conventionally EBGs have been analysed by performing an eigenmode analysis using a full wave EM solver or by developing equivalent transmission line circuit models representing the EBG structures. Recently dispersion diagram analysis using a single unit cell of the EBG structure (exploiting the periodic property of EBGs) has been reported to predict the stop-bands [5]. The analytical methods to characterize the EBGs make use of Bloch's and Floquet's theorems which describe the nature of wave propagation in periodic structures/crystals. According to Bloch's theorem, in an infinite periodic structure of periodicity 'd', the fields in adjacent unit cells, E(x) and E(x+d), differ by a constant attenuation and phase shift

$$E(x+d) = E(x) * e(\pm \gamma d) \qquad (1)$$

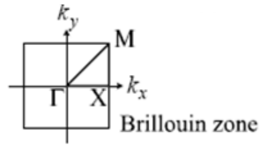
Considering 2-dimensional wave propagation in the EBG structure, in X and Y directions, the propagation constant in the X direction is γ_x and in the Y direction is γ_y. The general solution for a wave propagating in the +X direction in a medium is $e^{-\gamma x}$, where the propagation constant, $\gamma = \alpha + j\beta$. α is the attenuation constant and β, the phase constant. Assuming material losses to be zero (α = 0), we have $e^{-j\beta x}$. Considering a periodic interval of 'd' for the EBG cells in X and Y directions, the fields in the adjacent unit cells differ by a factor of $e^{-j\beta xd}$ and $e^{-j\beta yd}$ in the X and Y directions respectively. A single unit cell of the 2-dimensional EBG structure is represented by a 4 port network for the derivation of Eigen value equation, which is solved for different frequencies and the stop bands and pass bands are predicted based on the solutions obtained. Voltages and currents at the 4 port locations form the input and output variables and are related through Z parameters. The derivation of the Eigen value equation in terms of the transmission (ABCD) parameters is explained in detail in [5]. The Eigen-value equation for the 2D case is

$$\left\{ \begin{pmatrix} \overline{\overline{F}}_{11} & \overline{\overline{F}}_{12} \\ \overline{\overline{F}}_{21} & \overline{\overline{F}}_{22} \end{pmatrix} - \begin{pmatrix} e^{\gamma x d}\overline{\overline{I}} & 0 \\ 0 & e^{\gamma y d}\overline{\overline{I}} \end{pmatrix} \right\} \begin{pmatrix} \overline{X0} \\ \overline{Y0} \end{pmatrix} = \mathbf{0} \qquad (2)$$

where, F matrix represents the 4 port transmission parameters, I is a 2X2 unit matrix and X0, Y0 are output vectors containing voltage and current elements

The equation above can be illustrated with the help of dispersion diagrams which plot frequency (Hz or rad/s) versus phase constant. The frequency regions in which no solution exists for the Eigen value equation are the stop bands, the regions where the equation converges and the phase constant can be determined are the pass bands. The boundaries of ± (π/d) define the irreducible Brillouin zone which contains the principal (non-redundant) values of the phase constant.

The brillouin triangle is given below. The limiting sides of the triangle are Γ - X, X – M and M - Γ. The co-ordinates of the high symmetry points are, Γ (0, 0), X (π/d, 0) and M (π/d, π/d). When calculating the dispersion diagram, the phase constant is evaluated along Γ-X, X-M, and M-Γ for different frequencies.



B. Design

To the best knowledge of the authors, all the methods reported so far in literature are based on analysing EBGs formed in a single plane pair and predict the band-gaps for horizontal coupling suppression. In the case of vertical isolation prediction, multiple plane pairs are involved and the periodicity is lost due to the presence of apertures/cutouts and ports at different plane pairs. To effectively predict the isolation in vertical direction, we develop an analysis based on the 2D Dispersion diagram method. Importantly the unit cell used for this analysis is a multilayer unit cell. The coupling patterns vary significantly with every different set of port locations in multilayer structures. This unit cell though does not signify periodicity, can predict the regions where potential coupling can take place.

It is important to properly characterize the vertical coupling through the aperture to predict the stop bands offered by the EBGs. Once the coupling occurring through the aperture in the presence of the EBGs is characterized, the propagation of waves in the non-aperture regions consisting of the EBG plane can be deduced from Bloch's theorem. Analytical methods to compute the vertical coupling through cutouts/apertures are non-trivial and it is hard to adapt them for apertures of different sizes since the field coupling in the vertical direction is very much dependent on the aperture size. So, to avoid these complexities we use an EM solver to model the proposed multilayer unit cell (Fig 5 and Fig. 6). In section II, EBGs were demonstrated to suppress vertical coupling in a 3 - metal layer and a 4 - metal layer structures. For the case in which the patterned EBG plane houses the aperture, the unit cell is shown in Fig.5 and for the case in which the plane adjacent to the EBG plane houses the aperture, the unit cell is shown in Fig.6. To demonstrate this vertical isolation approach, EBGs were patterned on 3-metal layer and 4-metal layer packages. The sizes of the metal patches used are 8 X 8 mm and that of the metal branches are 0.5 X 0.5 mm.

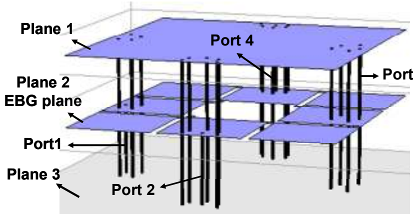


Fig.5. 3-metal layer structure - Unit cell

The dispersion diagram analysis described in the previous section is applied to these structures. Figs. 7 and 8 show a 3 metal and 4 metal layer structure for which simulation and analytically predicted stop-band results are shown in Figs. 9 and 13 and in Figs.14 and 15 respectively. The multiple graphs shown in Figs. 9 and 14 are for different variations of the structures in Figs. 7 and 8 in terms of aperture and port locations. The graph shown in Fig.15 indicates that when the phase constant in evaluated along Γ - X and X – M, the results show pass bands at lower frequencies near the origin (circled in the graph). In the actual case the EBG used is a 2D structure and Figs. 10 and 11 show the difference between a 1D and a strictly 2D EBG. The graphs in Fig.12 show the differences in evaluating the EBGs as 1D and 2D structures.

When evaluating the phase constant along Γ - X and X – M, atleast one of the co-ordinates, either X or Y becomes zero, and this reduces to a 1D EBG case and hence we see pass bands around the origin. But considering the phase constant determination along M - Γ, both the propagation constants along X and Y directions exist and we see a stop band at the origin. Based on the simulation results presented in Fig.14 and also measurement results reported in [3], the results given by M - Γ branch are more accurate than the others and the stop bands predicted are based on this. As seen from Figs. 9 and 14, the EBGs provide good vertical isolation in select frequency bands and also the analytical method proposed with dispersion diagram correlates well with frequency domain simulations.

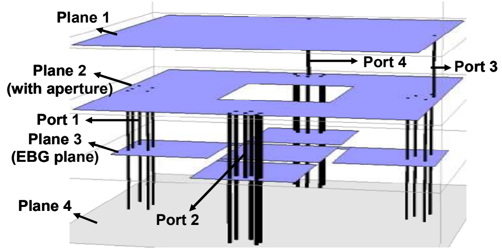


Fig.6. 4-metal layer structure - Unit cell

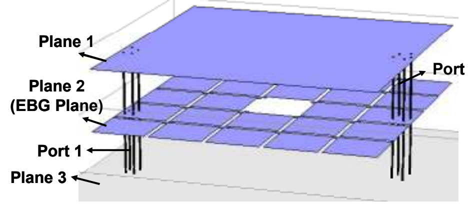


Fig.7. 3-metal layer structure (bandgap predicted from unit cell)

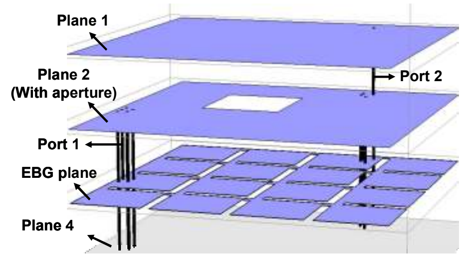


Fig.8. Four metal layer structure (bandgap predicted from unit cell)

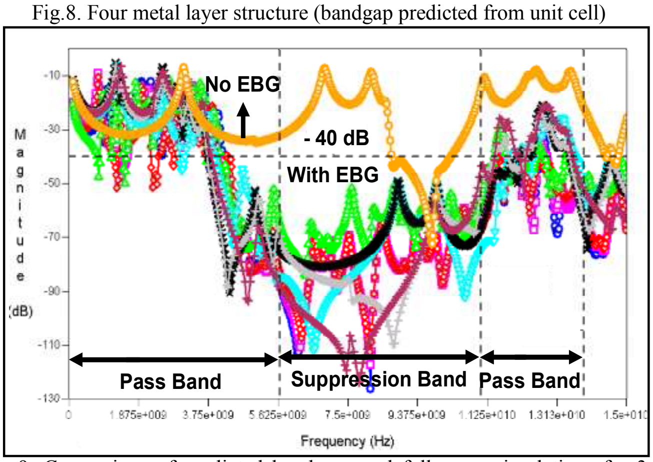


Fig.9. Comparison of predicted bandgaps and full wave simulations for 3-metal layer structure

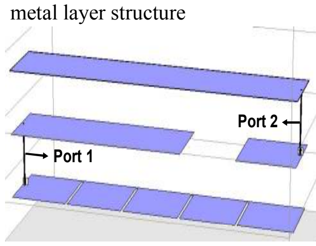


Fig.10. 1D EBG structure

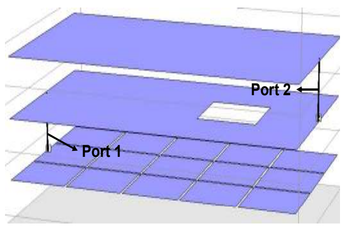


Fig.11. 2D EBG structure

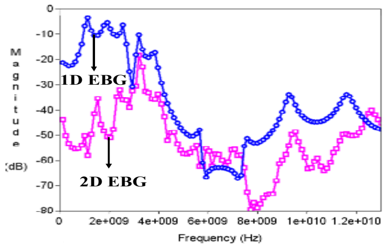


Fig.12. Comparison of S21 (dB) for Figs 10 and 11

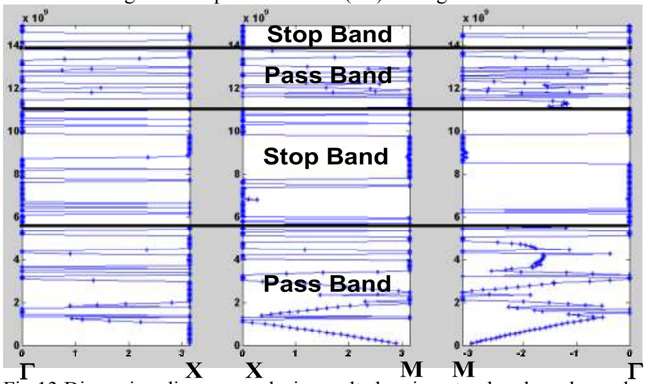


Fig.13.Dispersion diagram analysis result showing stop bands and pass bands for a 3 metal layer structure unitcell

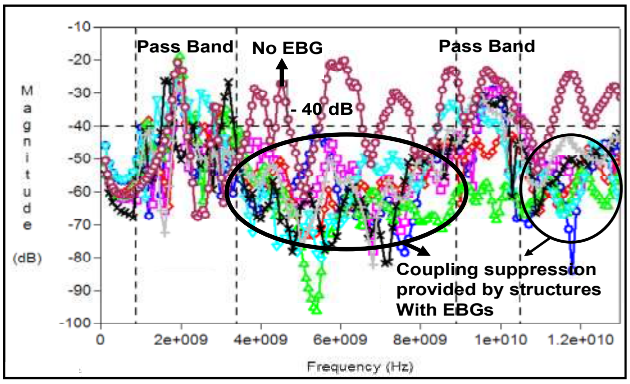


Fig.14. Comparison of predicted bandgaps and full wave simulations for 4-metal layer structure

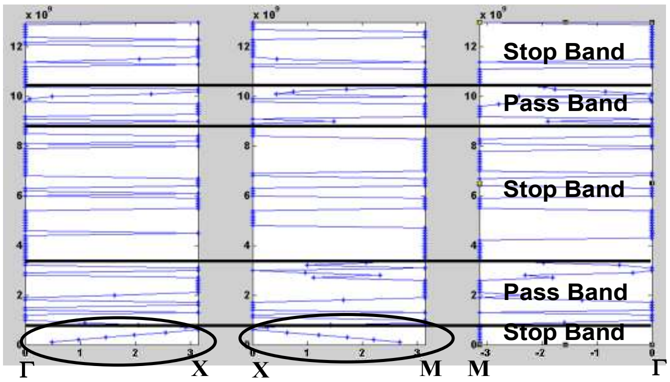


Fig.15.Dispersion diagram analysis result showing stop bands and pass bands for a 4 metal layer structure unitcell

IV. Proof of Concept

As a proof of concept, a 3 metal layer test vehicle similar to Fig.3 was designed using FR4 material. Fig.16 shows the fabricated structure. The comparison between simulation, measurement and dispersion diagram based band-gap prediction for this structure are shown in Fig. 17.

To demonstrate the proposed vertical isolation technique, EBGs were patterned on Plane 2 (center plane with aperture) of the structure in Fig.3. The size of each metal patch is 8mm X 8mm and each metal branch is 1mm X 1mm and ports 1 and 2 are placed in bottom and top plane pair cavities. It can be inferred from Fig. 17 that the proposed technique suppresses vertical coupling into the GHz range indicated by the negative slope in the graphs with EBGs and these multilayer EBG structures can be analyzed satisfactorily using the proposed dispersion diagram analysis.

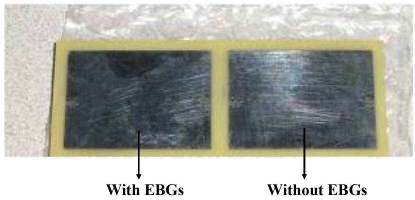


Fig.16. Fabricated Test vehicle

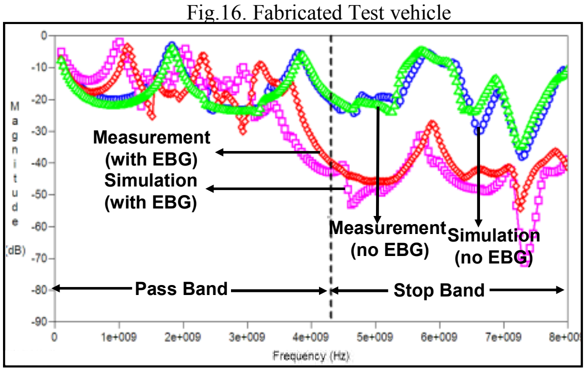


Fig.17. Comparison of Simulation and Measurement results for structures with and without EBGs – S21 (dB) plots

V. Conclusion

In this paper, a novel approach is demonstrated for the suppression of vertical coupling in GHz range and a fast efficient analysis of the vertical coupling suppression method using Dispersion diagrams is proposed. Simulations and measurements have been presented to validate the vertical coupling suppression method and its Dispersion diagram analysis.

VI. References

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