Improving Signal Integrity in Circuit Boards by Incorporating Absorbing Materials

Weimin Shi*, Virendra Adsure, Yuzhe Chen**, and Harry Kroger
Department of Electrical Engineering,
Watson School, SUNY at Binghamton

Present addresses: * Intel Corp., Hillsboro, OR , ** Sigrity Inc., Santa Clara, CA

Abstract

Electrical signals that propagate through vias between layers of metal planes in circuit boards will generate radial waves that are guided by the planes. Multiple reflections of these parallel plate waves from the edges of the circuit board will cause resonances that greatly increase the effective impedance between the two planes at the resonant frequencies. Such resonances are highly undesirable for operation of high performance electronic packaging systems since they degrade signal qualities, increase crosstalk level and enhance simultaneous switching noise. In this paper we show that the magnitude of the resonances can be greatly reduced by incorporating an absorbing material between the metal planes at the perimeter of the circuit board. As a result the signal integrity of the system is improved. By using absorbing materials whose loss depends upon magnetic rather than electric effects, it is possible to choose materials whose resistivity is of the order of 10^{12} ohm-cm, making it possible to place the materials directly between power and ground planes without introducing any DC current leakage. These materials are available commercially in flexible and hard, dense forms and can be chosen to enhance losses at either the UHF band or various microwave frequency bands to accommodate different needs. Results of theoretical computation are compared with experiments performed on test boards characterized using a vector network analyzer between 50MHz and 6 GHz. Significant reduction in input impedance of the test structure at resonance frequencies is obtained, which shows the effectiveness of the proposed method and the accuracy of the calculation method. The paper also evaluates several ways of applying the lossy material.

Introduction

With microprocessor and ASIC clock frequencies increasing above 1GHz and power supply voltages headed to 2 volts and below, the power distribution to integrated circuits demands more careful design [1]. Signal integrity can be maintained only if the power distribution system has low impedance over the entire frequency range of the signals from DC to the highest switching speed [2,3]. Assuring low impedance over this entire range can be difficult because circuit board resonances typically occur over the frequency range from several tens of megahertz to several gigahertz (depending upon the size of the board or package). High impedances can occur if resonances in the circuit board have high Qs.

A related problem is simultaneous switching noise that can be mediated by parallel conducting planes of a printed circuit board [4, 5]. If the output of a driver spans the space between two conducting planes, a radially propagating wave will be emitted when current flows through the via. This wave will couple to all other vias between the planes [6]. Reflections from the edges of the circuit board provide another mechanism for interaction between vias and also a delayed reaction back onto the launching via itself.

Obviously it is desirable to reduce the resonances and mutual interaction between vias. There are several methods of dealing with these problems. Placement of decoupling capacitors is one approach [7, 8]. Another approach is to provide an array of shorting vias to move the resonant frequencies above any frequency of interest [9].

Both the journal and the patent literature contain several suggestions for the use of absorbing materials in circuit boards to reduce resonances and crosstalk. Apparently the first discussion was a patent by Brown, Radzik, Williams, and Pitts [10], which describes a laminate of a lossy material and a dielectric material placed between the voltage supply plane and the ground plane. This arrangement requires the lossy material to cover the entire area of the board, or at least a substantial part of it, to isolate layers above and below the lossy layer Kim, Lee, and Itoh described a similar approach [5].

The present paper deals with an alternative arrangement of lossy material in which the lossy material is placed primarily at the perimeter of the circuit board [11]. This reduces reflections from the edges of the board thus lowering Qs of resonances and reducing one channel of coupling between vias. Novak has also presented a paper on this approach [2]. Novak proposed the use of resistive material that requires a capacitance to be placed in series with the resistive material to permit placement between power and ground planes. The approach of this paper is to use lossy dielectric materials that are not electrically conductive placed at the perimeter of the circuit board. The absorbing property of the materials is mainly caused by magnetic rather than electric effects.

Use of Lossy Material to Reduce Reflections

Figure 1 presents the basic structure investigated in this paper. Figure 1 shows a multilayer board, but in this paper we report data from only a single layer board. Here the lossy material is placed only at the perimeter of the board, although reference 11 also envisions the possibility of judicious placement of the lossy material in the interior of the circuit board.

Placing the lossy material on the perimeter will certainly reduce the Qs of resonances, but can have only a limited effect on interactions between vias. The absorbing material at the perimeter will not affect direct line-of-sight signals, but waves that reach other vias after reflection from the edges will be attenuated

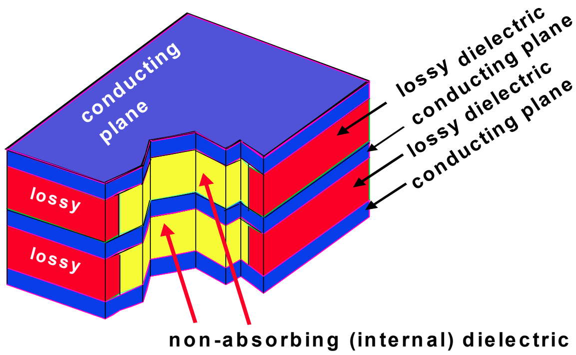

Figure 1. Basic structure of perimeter-absorber board.

Although we have experimented with conductive materials, we have concentrated on the use of lossy materials that are not electrically conductive. We report here experiments with Eccosorb®, a product of Emerson & Cuming Microwave Products [12], although we have experimented with non-conducting materials from another vendor, R and F Products [13]. Some of these materials rely mainly on magnetic properties, not on electrical conduction for absorption. These materials can have volume resistivities greater than 10^{11} Ω-cm. This class of materials is probably not familiar to most digital and packaging engineers, but it has a long history of providing absorbers in waveguides, reducing RF and microwave reflections in anechoic chambers, reducing radar cross sections, and reducing interactions between elements of phased array antennas.

The high resistivity of these materials is convenient for the present application, enabling their placement between power and ground planes. Furthermore, rough data available in 1995 suggested that real part of the dielectric constant of these materials was an approximate match to FR-4 materials, which implied a desirable low reflectance from an FR-4 - absorber interface. We have begun to measure the dielectric properties of these materials more accurately in a configuration relevant to our application.

The Eccosorb® materials have three forms: a flexible silicone rubber sheet, a castable epoxy-like material, and a rigid solid that can be machined. We experimented only with the first two types of materials. Eccosorb® materials also have properties specified generally as "narrow band" or "broad band" with indications over what frequency band they are most effective. We report measurements on the silicone elastomer materials Eccosorb® MFS – 117 and MFS – 124 and the castable material CR – 117.

Experimental Procedure

The purpose of the initial experiments described here was to confirm the practical utility of using absorbing material to reduce the Qs of board resonances. We conducted the experiments using the structures diagrammed in Figures 2 and 3. The board's dimensions were 152.4 mm by 228.6 mm. The position of the exciting via shown in Figure 2 was purposefully chosen to not have some obvious symmetrical relationship to the board. We hoped to excite many resonance modes of the board to permit a comprehensive comparison. It was located 96.5 mm from the short side of the board and 76.7 mm from the long side of the board.

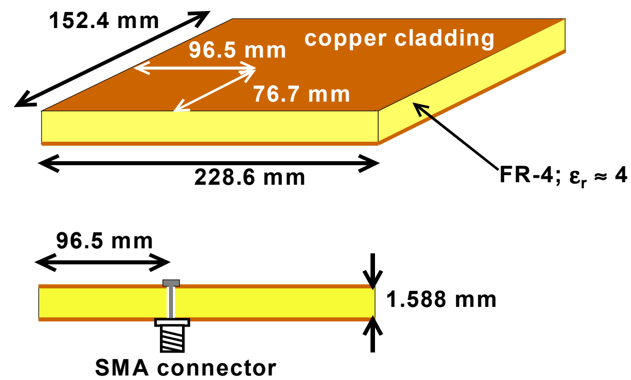

Figure 2. Experimental structure without absorber (not to scale).

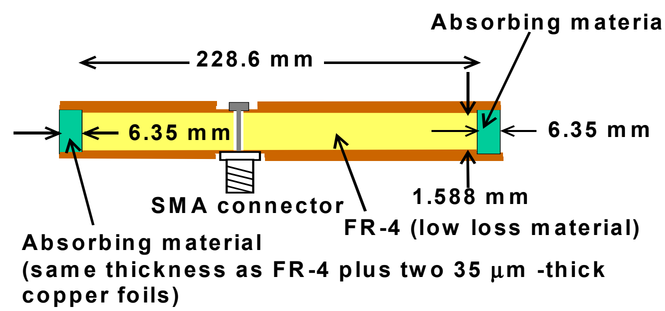

Figure 3. Cross section of board with absorber (not to scale)

The boards had an FR-4 dielectric with a nominal relative dielectric constant of 4 and a thickness of 1.59 mm. The copper cladding on both sides of the dielectric had a thickness of 35 µm.

Three different methods of attaching the absorbing material were used. In the original method, which enabled us to quickly gather data and to show that the concept was practical, we simply clamped thicker copper boards to the circuit board. These copper boards extended 6.35 mm beyond the edges of the FR-4 circuit board on all sides and also clamped the elastomer-versions of the lossy material. The lossy material did not extend beyond the clamping boards.

The second method was similar to the first in that we used larger (by 6.35 mm on each edge) copper boards clamped to the FR-4 board. But in this structure we used the castable epoxy version of the Eccosorb®. The overhanging copper boards acted as a mold for the uncured material.

The third method of attaching the absorbing material reverted to the elastomeric version, but instead of using copper plates to hold the absorbing material to the board, we used copper tape. The tape had adhesive on one side and readily stuck to the both the elastomer and the copper cladding of board.

We obtained the electrical measurements using an HP vector network analyzer. The absolute value of the impedance seen by the exciting via of Figure 3 is presented in this paper.

Theory

The impedance of a simple circuit board with a single dielectric constant material is easily calculated using, for example, the Sigrity SPEED2000 program [14]. Calculations beyond SPEED2000 are required when the circuit board contains frequency dependent dielectrics and different dielectric materials in the same layer. One method of obtaining this more complex result is based on the work of Shi [15], and this method is outlined here.

In electronics packages, such as printed circuit boards, conducting metal plates play very important roles. They are used to construct high-quality power delivery systems and also to provide well-controlled transmission line impedance for critical signal nets. Since the separation between these metal plates is a small fraction of the signal wavelength, the electromagnetic fields between each pair of plates can be expressed in the dominant parallel plate mode. This feature presents an opportunity for fast computation of the performance of electronics packages with power-ground planes.

The electrical field, $E = E_z$, of the dominant parallel plate mode in the region between two conducting planes, can be described by the Helmholtz equation and boundary conditions:

$$(\nabla_t^2 + k^2)E = 0 \quad \text{in } \Omega \qquad (1a)$$

$$E - g_1 = 0 \quad \text{on } \Gamma_1 \qquad (1b)$$

$$\frac{\partial E}{\partial n} - g_2 = 0 \quad \text{on } \Gamma_2 \qquad (1c)$$

$$\frac{\partial E}{\partial n} - g_3 E = 0 \quad \text{on } \Gamma_3 \qquad (1d)$$

$$\frac{\partial E}{\partial n} - g_4 E - g_5 = 0 \quad \text{on } \Gamma_4 \qquad (1e)$$

where $\Gamma = \Gamma_1 + \Gamma_2 + \Gamma_3 + \Gamma_4$ is the boundary of domain Ω; $\frac{\partial}{\partial n}$ denotes the normal derivative on the boundary, as shown in Figure 4. Γ_1 represents the boundary portion with constant electric field, Γ_2 represents the boundary portion with constant magnetic field, Γ_3 represents the portion with an impedance boundary condition (it can be used for non-perfect reflections from the edges of packages). A new type of boundary condition, the 4th kind of boundary, Γ_4, is proposed to represent the boundary with external excitation source such as on the vias. It can be seen that the 4th kind of boundary is evolved from the 3rd kind.

Using the second Green's identity, for a trial solution E and a weighting function W, we have [16]

$$\int_\Omega \left(W\nabla^2 E - E\nabla^2 W\right) d\Omega = \oint_\Gamma \left(W\frac{\partial E}{\partial n} - E\frac{\partial W}{\partial n}\right) d\Gamma \qquad (2)$$

Substituting the wave equation and boundary conditions in (1) into (2) gives an integral equation as follows

$$\int_\Omega E(\nabla^2 + k^2)W d\Omega + \int_{\Gamma_1}\left(W\frac{\partial E}{\partial n} - g_1\frac{\partial W}{\partial n}\right)d\Gamma + \int_{\Gamma_2}\left(Wg_2 - E\frac{\partial W}{\partial n}\right)d\Gamma \qquad (3)$$
$$+ \int_{\Gamma_3}\left(Wg_3 - \frac{\partial W}{\partial n}\right)E d\Gamma + \int_{\Gamma_4}\left(Wg_4 - \frac{\partial W}{\partial n}\right)E d\Gamma + \int_{\Gamma_4} g_5 W d\Gamma = 0$$

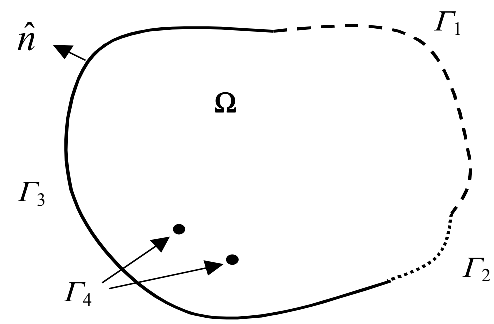

Figure 4. EM wave problem with boundaries.

Because of the two-dimensional nature of the fields, the Green's function of the problem is

$$G(\rho \mid \rho') = \frac{-j}{4} H_0^{[2]}(k \mid \rho - \rho' \mid) \qquad (4)$$

where, $H_0^{[2]}(\cdot)$ stands for the zero order Hankel function of the second kind. By choosing the Green's function as the weighting function, that is $W = G(\rho \mid \rho')$, the integral equation (3) can be solved by employing boundary integral equation approach.

For parallel plate structures with more than one region filled with uniform medium, additional sets of equations similar to equation (3) can be established and field continuity conditions at their common boundary can be derived. All the integral equations can be solved jointly together with all their boundary conditions to obtain the field distribution in all the regions between a pair of parallel plates.

Experimental Results

Figure 5 presents the observed impedance of the circuit board as a function of frequency for two different experimental arrangements: an open edge, and with MFS - 117 and MFS–124 Eccosorb® absorbing materials clamped to the edges of the board. The absorbers greatly reduced the magnitude of the resonances of the board. Figure 6 presents the impedance of a function of frequency for two different absorbing materials, MFS-117 and MFS- 124. It is obvious that different absorbing materials result in different impedances as a function of frequency, but that both offer a substantial improvement of the open edge board.

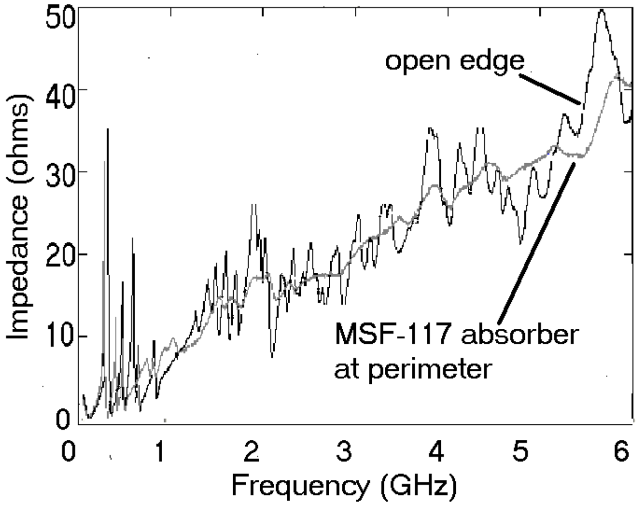

Figure 5. Input impedance as a function of frequency for an open edge circuit board a circuit board with an MFS-117 absorber on its perimeter

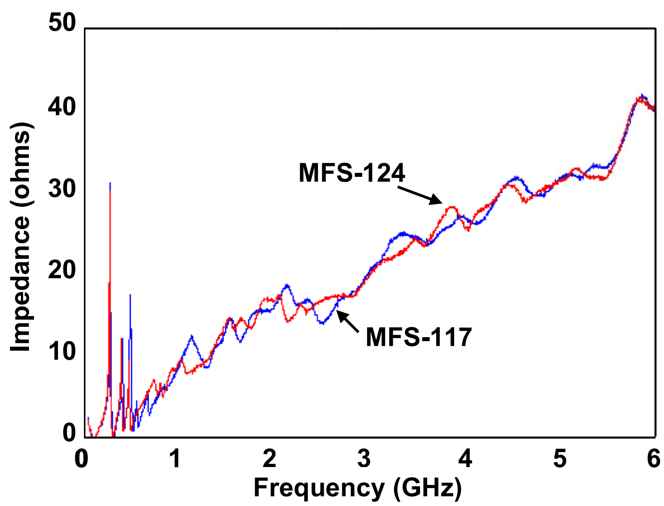

Figure 6. Input impedance as a function of frequency for two circuits with MFS-117 and MS-124 absorbers on their perimeter.

Figure 7 presents the theoretically expected results calculated using the method previously described. There is reasonable agreement when comparing these results to the experimental results shown in Figures 5 and 6.. The greatest differences occur at low frequencies. We suspect that the major source of discrepancy lies in the assumptions of what the real and imaginary parts of the dielectric constant of the absorbing materials are and how they may vary with frequency.

Several different geometric arrangements can be used to add the absorbing material to the perimeter [11]. Two are illustrated in Figure 8. The structure with the absorber contained within an extension of the metal cladding of the circuit board will result in lower reflections from the perimeter, because there is a less abrupt impedance transition to the absorbing material (configuration A). This is borne out experimentally in the magnitude of the resonances observed in Figure 9. Setting the absorbing material "outside" the metal (configuration B) results in only a minor change in impedance as a function of frequency compared to an open edge structure as shown in Figure 10.

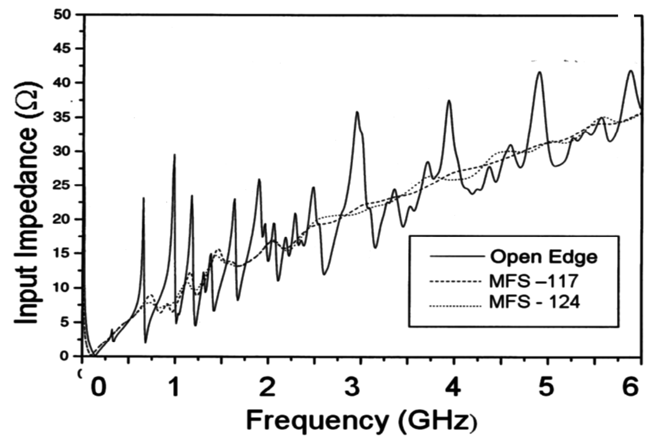

Figure 7. Theoretically calculated input impedance as function of frequency for the three configurations whose measurements are displayed in Figures 5 and 6.

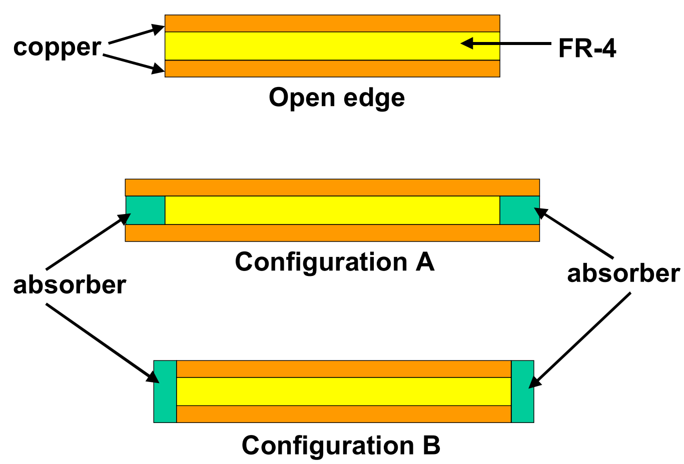

Figure 8. Cross section (not to scale) of open edge board and two methods of mounting the absorbing material.

Figure 11 presents the impedance of the circuit board using the same absorbing material, but with different methods of attachment. Using adhesive copper foil always reduces the magnitude of the resonances compared to clamping the absorber in place with thick plates. Presumably this is because of more uniform contact of the copper to the absorbing material. We also found that using the castable version of Eccosorb® reduced the magnitude of the resonances compared to clamping the elastomers in place, an expected result given the improvement brought about by the adhesive foil.

Summary and conclusions

The results described in this paper indicate that the use of perimeter absorbers can beneficially reduce the reflections from the edges of circuit boards. Furthermore the absorbing materials need not be electrically conductive.

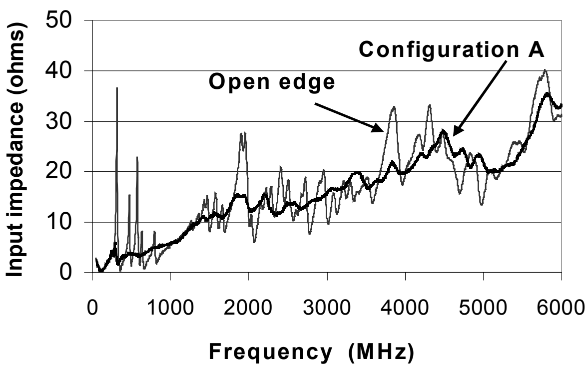

Figure 9. Comparison of input impedance as a function of frequency for open edge board with absorber mounted as shown as "configuration A" as defined in Figure 8.

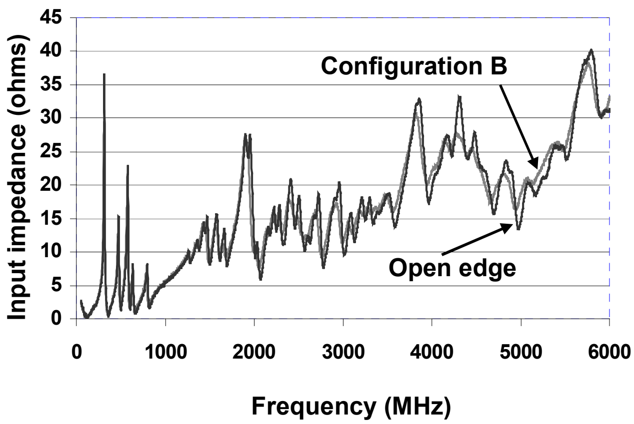

Figure 10. Comparison of input impedance of open edge board with that of board with absorber mounted as in "configuration B" as defined in figure 8. There are only small differences in impedance between these cases.

These results are preliminary but indicate that further investigation is warranted. The effect of changing (perhaps optimizing) the properties of the absorbing material should be investigated. Experimental and theoretical work on the effect of varying the absorber's dimensions has yet to be studied. Finally, one may wish to investigate if the absorbing material can be laminated together with the low loss dielectric as part of the fabrication process in manufacturing the circuit boards.

The use of absorbing material does not preclude the use of other methods of reducing impedance and adjusting resonances in circuit boards. Shorting vias and decoupling capacitors can be used in conjunction with the absorbers. Placing an absorber at the junction perimeter will also reduce radiation from the board.

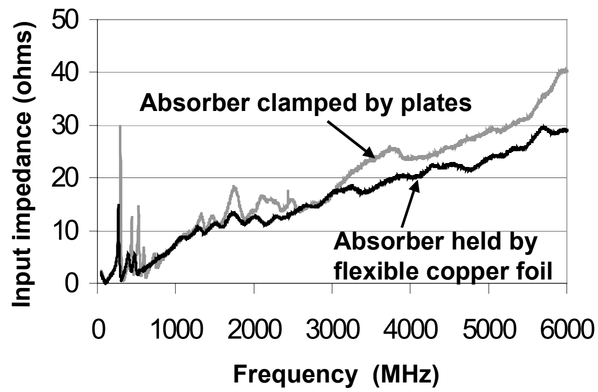

Figure 11. Comparison of input impedance as a function of frequency for absorber clamped between copper plates and absorber held by flexible copper tape.

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