Calculation of Optimal Ground Post Resistance for Reducing Emissions from Chassis-Mounted Printed Circuit Boards

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***Abstract*—When a printed circuit board (PCB) is mounted to a metal chassis, the cavity formed between the circuit board ground and the chassis can resonate at certain frequencies resulting in unintended radiated emissions. The cavity resonances can be effectively suppressed by using conductive mounting posts and adding a resistance in series with the connection between one or more of these mounting posts and the PCB ground plane. This paper derives a simple closed-form expression for determining an optimal series resistance for damping these cavity resonances over a wide range of frequencies. This analysis was done for rectangular boards mounted on four posts located near the corners. A similar analysis could be done to determine the optimal resistance values for other board shapes and mounting post locations. For the four-post configuration, shorting one or more of the posts does not affect the optimum resistance value for the remaining posts.**

***Index Terms*—Electromagnetic radiation, printed circuit board (PCB), resonance.**

I. INTRODUCTION

PRINTED circuit boards (PCBs) are often mounted in close proximity to a metal chassis using metal or plastic posts, as illustrated in Fig. 1. At high frequencies, the cavity formed between the PCB and the chassis can resonate resulting in elevated levels of radiated emissions [1]. Whether the posts are conductors or insulators, cavity resonances occur, though at different frequencies. At frequencies near these resonances, small amounts of energy coupled from the PCB to the cavity can result in significant unintended emissions.

To illustrate this effect, the radiated emissions from a 200 mm $\times$140 mm PCB with a 20-MHz clock circuit was measured in free space and mounted 10 mm above a copper chassis. The board was powered by a 3.3-V battery attached to one side,

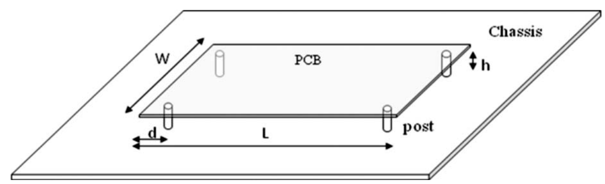

Fig. 1. Illustration of a PCB mounted over a chassis with four posts.

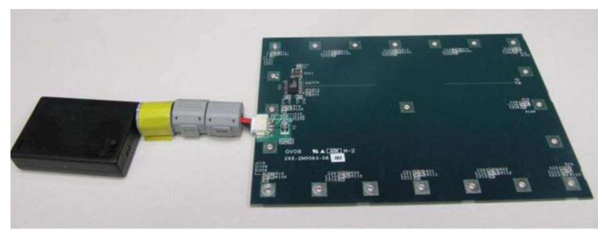

Fig. 2. PCB with an oscillator circuit driven using batteries.

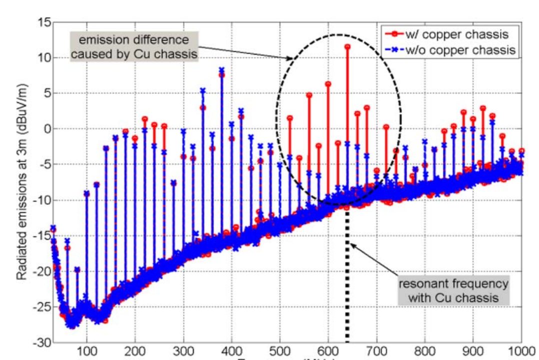

Fig. 3. Measured air cavity resonance effects with a chassis mounted below the PCB.

as shown in Fig. 2. When the board was mounted to the chassis with plastic posts, an air cavity was formed between the board's ground plane and the chassis with a TM_{10} resonance at around 640 MHz (accounting for edge effects). The plot of the radiated emissions in Fig. 3 shows that the presence of the cavity increases emissions by more than 12 dB at frequencies near the cavity resonance. Therefore, it is generally a good idea to ensure that cavity resonances are damped when a PCB is mounted over a conductive chassis.

Some methods have been previously investigated to reduce PCB–chassis cavity resonant emissions. Using large numbers of grounded mounting posts can suppress the lower frequency

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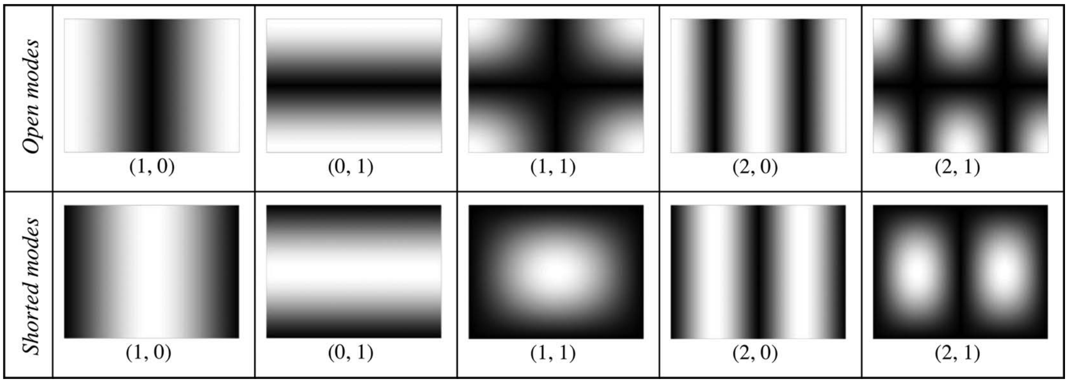

Fig. 4. Electric field distributions for several open and shorted modes in a 2-D cavity.

resonances [2]. However, this consumes more PCB area and adds cost. Connecting lossy components to the conducting posts is another method [3], but there is not an established formula to determine how much the post resistance should be in different situations. Also, arbitrarily adding loss to ground posts can result in higher radiated emissions by increasing the voltage drop between the chassis and objects connected to the board, such as cables and heatsinks.

In this paper, a closed-form expression is derived to calculate the optimum ground post resistance value for minimizing emissions from rectangular PCB–chassis cavities. The derived expression accounts for the PCB dimensions, the height of the cavity, and the post locations. It is shown that one resistance value can provide effective damping of cavity resonances over a wide frequency range. The expression for the optimum resistance is derived from equations for the quality factors of the "open modes" and the "shorted modes," which are proportional and inversely proportional to the post resistance, respectively. The expression is validated using full-wave simulations of PCB–chassis cavities.

II. Calculation of Optimum Series Resistance

When the spacing between the mounted PCB and the chassis is much shorter than a wavelength, the electric field inside the cavity can be considered constant along the vertical direction, and the cavity can be modeled as a 2-D TM cavity with two perfectly electrically conducting (PEC) surfaces corresponding to the ground of the PCB and the chassis. When the mounting posts do not connect the top and bottom surfaces of the cavity, the four open sides can be modeled with four perfectly magnetically conducting (PMC) walls [4], [5]. In this paper, the resonant modes in cavities, where the posts do not connect the top and bottom surfaces are referred to as *open modes*.

All of the open-mode resonances are squelched when metal mounting posts short the PCB ground to the chassis ground at the corners of the board. However, this configuration enables another set of resonant modes referred to here as *shorted modes*. The shorted modes are identical to the modes that exist in a rectangular cavity with six PEC walls, with the addition of TM_{x0} and TM_{0y} modes, which have non-zero electric fields on the walls but zero field at the corners. Shorting the top and bottom of the cavity everywhere along the walls eliminates the TM_{x0} and TM_{0y} modes, but shorting only at the corners does not.

When the posts are very near the corners, the resonant frequencies associated with the open modes are nearly the same as the resonant frequencies associated with the shorted modes. However, the field distributions within the cavity are very different, with the peaks and nulls of the electric field distribution interchanged.

Fig. 4 shows plots of the electric field distribution for several open and shorted modes in a rectangular 2-D cavity, as viewed from the top. The horizontal direction represents L and the vertical direction W (see Fig. 1). The gray scale indicates the normalized amplitude of the electric field, where brighter indicates higher values and darker corresponds to lower values.

When the posts connect the ground plane to the chassis through a resistance, both open and shorted modes can exist, but they will be damped to some extent. For any resonant mode, the quality factor associated with the resonance can be calculated as the ratio of the maximum stored energy to the energy dissipated per cycle.

Defining the origin ($x = 0$, $y = 0$) to be at the corner of the board when the posts are open, the electric field of the TM_{mn} mode at location (x, y) inside the cavity can be represented as follows [6]:

$$E_z = \frac{V_{\max\_\mathrm{open}}}{h} \cos\left(\frac{m\pi}{L}x\right) \cos\left(\frac{n\pi}{W}y\right) \tag{1}$$

where L, W, and h are the length, width, and height of the cavity (see Fig. 1), respectively, and $V_{\max\_\mathrm{open}}$ is the open-mode maximum voltage between the ground plane and the chassis. The stored energy within the cavity is then calculated as follows [6]:

$$\begin{aligned} W_s &= \frac{1}{2}\int_\Omega \varepsilon |E_z|^2 d\Omega = \frac{\varepsilon h}{2}\int_S |E_z|^2 dxdy \\ &= \frac{\varepsilon V_{\max\_\mathrm{open}}^2 LW}{2h} \chi_m \chi_n \end{aligned} \tag{2}$$

where ε is the permittivity of the medium filling the cavity, $\chi_i = 1$ when $i = 0$ and 1/2 otherwise, Ω denotes the volume of the cavity, and S is the area of the cavity's horizontal cross section.

Often, the posts are placed symmetrically at the four corners of the PCB at an equal distance d from the nearest edges. When a post is loaded with a resistance R, the average power dissipated at this post is

$$P_R = \frac{1}{2}\frac{V_{\text{post}}^2}{R} = \frac{V_{\max\_\text{open}}^2 \cos^2(((m\pi)/L)d)\cos^2(((n\pi)/W)d)}{2R}. \quad (3)$$

When with all four posts are loaded with resistance R, the quality factor is

$$Q_{\text{open}} = \omega\frac{W_s}{4P_R} = 2\pi f\frac{\varepsilon LW\chi_m\chi_n R}{4h\cos^2(((m\pi)/L)d)\cos^2(((n\pi)/W)d)} \quad (4).$$

When the posts are shorted, the electric field of the TM$_{mn}$ mode at location (x, y) inside the cavity can be represented using

$$E_z = \frac{V_{\max\_\text{shorted}}}{h}\sin\left(\frac{m\pi}{L-2d}x\right)\sin\left(\frac{n\pi}{W-2d}y\right), \quad mn \neq 0 \quad (5)$$

where $V_{\max\_\text{shorted}}$ is the shorted-mode maximum voltage between the ground plane and the chassis.

In this case, the origin ($x = 0$, $y = 0$) has been defined to be at the location of a corner post. For these modes, only the fields contained within the volume defined by the four posts are considered. As long as the posts are near the corners, the energy in the electric field outside this volume can be neglected. The stored energy, using the same integration method used in (2), is then

$$W_s = \frac{\varepsilon V_{\max\_\text{shorted}}^2(L-2d)(W-2d)}{8h}. \quad (6)$$

The calculation of the power dissipated in any post resistance is achieved by finding the current flowing through that post resistance. During each oscillation cycle, charge is exchanged between the top and bottom surfaces of the cavity. Fig. 5 shows the charge distribution of one particular shorted mode. Every half cycle, positive and negative charges trade positions. Away from the posts, charge flows horizontally back and forth. Near the posts, positive and negative charge on the top and bottom plates exchange positions causing current to flow vertically through the posts. The total amount of charge near each post that must move from one plate to another is

$$q = \int_s \varepsilon E dx dy = \frac{\varepsilon V_{\max\_\text{shorted}}}{h}\int_0^{\frac{L-2d}{2m}}\sin\left(\frac{m\pi}{L-2d}x\right)dx \times \int_0^{\frac{W-2d}{2n}}\sin\left(\frac{n\pi}{W-2d}y\right)dy = \frac{\varepsilon V_{\max\_\text{shorted}}(L-2d)(W-2d)}{h\pi^2 mn}. \quad (7)$$

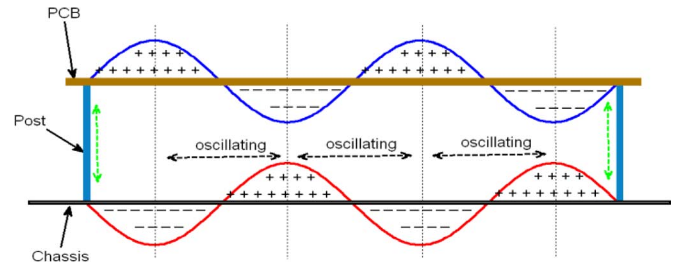

Fig. 5. Charge distribution and oscillating charge paths of one "shorted mode."

The current formed by this charge flow is

$$I_{\text{post}} = \omega q = \omega\frac{\varepsilon V_{\max\_\text{shorted}}(L-2d)(W-2d)}{h\pi^2 mn} = 2f\frac{\varepsilon V_{\max\_\text{shorted}}(L-2d)(W-2d)}{h\pi mn}. \quad (8)$$

Thus, the power dissipated in each post resistance is

$$P_R = \frac{1}{2}|I_{\text{post}}|^2 R = \frac{1}{2}\left[2f\frac{\varepsilon V_{\max\_\text{shorted}}(L-2d)(W-2d)}{h\pi mn}\right]^2 R = 2\left[\frac{f\varepsilon V_{\max\_\text{shorted}}(L-2d)(W-2d)}{h\pi mn}\right]^2 R. \quad (9)$$

The quality factor of the cavity with four resistive posts is, therefore,

$$Q_{\text{short}} = \omega\frac{W_s}{4P_R} = \omega\frac{(\varepsilon V_{\max\_\text{shorted}}^2(L-2d)(W-2d))/(8h)}{4\frac{1}{2}\left[2f(\varepsilon V_{\max\_\text{shorted}}(L-2d)(W-2d))/(h\pi mn)\right]^2 R} = \frac{\pi^3 hm^2 n^2}{32 f\varepsilon(L-2d)(W-2d)R}. \quad (10)$$

It is found from the derivations that the quality factors of the "open modes" are proportional to R, and those of the "shorted modes" are inversely proportional to R, as illustrated in Fig. 6. In order to have both types of modes optimally suppressed, both quality factors should be minimized simultaneously. This implies that the quality factors should be equal. Thus, from (4) and (10), the optimum R is calculated as follows:

$$R_{mn} = \frac{h}{\omega\varepsilon}\frac{m\pi}{\sqrt{L(L-2d)}}\frac{n\pi}{\sqrt{W(W-2d)}} \times \cos\left(\frac{m\pi}{L}d\right)\cos\left(\frac{n\pi}{W}d\right) = \eta h\frac{(m\pi/(\sqrt{L(L-2d)}))(n\pi/(\sqrt{W(W-2d)})}{\sqrt{((m\pi)/L)^2+((n\pi)/W)^2}} \times \cos\left(\frac{m\pi}{L}d\right)\cos\left(\frac{n\pi}{W}d\right) \quad (11)$$

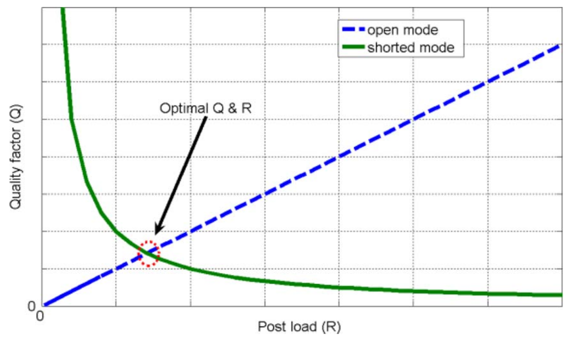

Fig. 6. Relation between quality factor and post resistance for both types of modes.

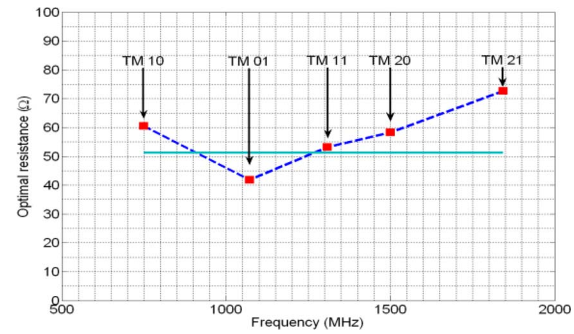

Fig. 7. Optimum *R* for each possible mode in the first configuration.

where η is the intrinsic impedance of the medium filling the cavity.

In the electric field distribution formula (5), *m* and *n* must be nonzero; otherwise a null field is derived. However, since the posts only short the field at the corners and not along the entire side of the cavity, TM_{m0} and TM_{0n} modes are also possible. For TM_{m0} modes, the electric field at location (*x*, *y*) inside the cavity can be represented as follows:

$$E_z = \frac{V_{\max\_\text{shorted}}}{h} \sin\left(\frac{m\pi}{L-2d}x\right), \qquad m \neq 0 \tag{12}$$

and the stored energy is

$$W_s = \frac{\varepsilon V^2_{\max\_\text{shorted}}(L-2d)(W-2d)}{4h}. \tag{13}$$

The current flowing through each post is

$$\begin{aligned} I_{\text{post}} &= \omega q \\ &= \omega \frac{\varepsilon V_{\max\_\text{shorted}}}{h} \frac{W-2d}{2} \int_0^{\frac{L-2d}{2m}} \sin\left(\frac{m\pi}{L-2d}x\right) dx \\ &= f \frac{\varepsilon V_{\max\_\text{shorted}}(L-2d)(W-2d)}{hm}. \end{aligned} \tag{14}$$

The quality factor of a TM_{m0} mode is then

$$\begin{aligned} Q_{m0} &= \omega \frac{W_s}{4P_R} \\ &= \omega \frac{(\varepsilon V^2_{\max\_\text{shorted}}(L-2d)(W-2d))/(4h)}{4(1/2)\left[f(\varepsilon V_{\max\_\text{shorted}}(L-2d)(W-2d))/(hm)\right]^2 R} \\ &= \frac{\pi h m^2}{4f\varepsilon(L-2d)(W-2d)R}. \end{aligned} \tag{15}$$

By forcing the quality factor equal to that of the "open mode", the optimum *R* is

$$R_{m0} = \frac{2hL\eta}{\sqrt{L(L-2d)W(W-2d)}} \cos\left(\frac{m\pi}{L}d\right). \tag{16}$$

Similarly, the optimum *R* for TM_{0n} modes is

$$R_{0n} = \frac{2hW\eta}{\sqrt{L(L-2d)W(W-2d)}} \cos\left(\frac{n\pi}{W}d\right). \tag{17}$$

Note that for the TM_{m0} and TM_{0n} modes, the optimum resistance values for any mode number *m* or *n* are nearly the same when all posts are near the corners. An optimum series resistance for all possible modes can be calculated by combining (11), (16), and (17).

Generally, for a 2-D TM_z rectangular cavity, the modes that radiate the most are the TM_{m0} and the TM_{0n} modes [8], [9]. An optimum *R* that effectively suppresses these modes should also work reasonably well for the other modes. A simple formula for calculating the optimum resistance based on the average of the optimum values for the TM_{m0} and TM_{0n} modes is

$$\begin{aligned} R_{\text{opt}} &= \frac{R_{m0}+R_{0n}}{2} \\ &= \frac{\eta h\left[L\cos(((m\pi)/L)d) + W\cos(((n\pi)/W)d)\right]}{\sqrt{L(L-2d)W(W-2d)}}. \end{aligned} \tag{18}$$

When the posts are mounted close to the corners (i.e., $d \ll L, W$), this formula can be further simplified to

$$R_{\text{opt}} = \frac{\eta h(L+W)}{LW} = \left(\frac{h}{L} + \frac{h}{W}\right)\eta. \tag{19}$$

III. Application Examples

To validate the model, two PCB–chassis configurations were evaluated using full-wave simulation software [7]. In the full-wave simulations, various values of series resistance *R* were connected to the four posts, and the maximum electric field was obtained as a function of frequency from 10 MHz to 2 GHz. The value of *R* that resulted in the lowest radiated emissions over the entire frequency range was compared to the optimum resistance calculated using (19).

The first PCB–chassis configuration was 200 mm × 140 mm with a height $h = 10$ mm. The posts were symmetrically located at the four corners and were 10 mm away from each of the corner's two edges. The cavity was excited by an ideal 1-A current source at one of two possible locations: the board center or the middle of the cavity's shorter edge.

Fig. 7 shows the optimum *R* for each mode below 2 GHz calculated using (11), (16), and (17). The optimum overall resistance calculated using (19) is about 50 Ω for this configuration, which is denoted by the solid horizontal line.

Figs. 8 and 9 show the maximum radiated electric field of the cavity as determined by full-wave simulations. For each source configuration, at each frequency, seven simulations were run with various post resistances ranging from infinite resistance

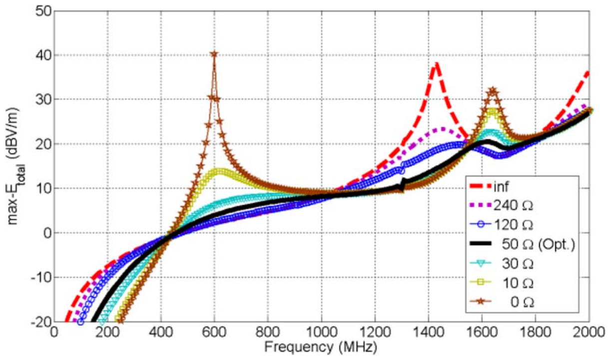

Fig. 8. Maximum *E*-field 3 m from the first configuration with various post resistance values and a 1-A current source located at the center of the cavity.

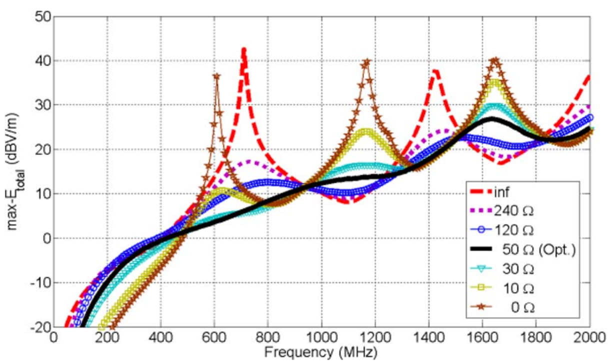

Fig. 9. Maximum *E*-field 3 m from the first configuration with various post resistance values and a 1-A current source located at the middle of the shorter edge of the cavity.

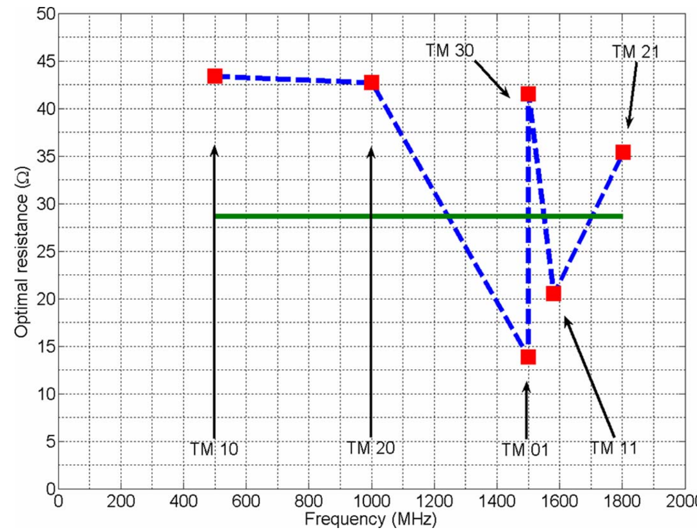

Fig. 10. Optimum *R* for each possible mode in the second configuration.

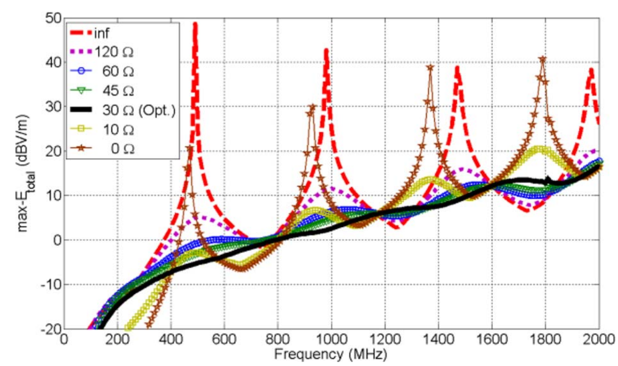

Fig. 11. Maximum *E*-field 3 m from the second configuration with various post resistance values.

(open) to zero resistance (shorted) including the optimum resistance calculated using (19). The maximum radiated electric field was selected from all directions for any frequency. The seven results are shown in the same figure to demonstrate the effectiveness of the radiated emissions suppression for each value of post resistance.

For either the open or shorted case, sharp peaks are seen at the structure resonances. With a finite resistance in series with the posts, these peaks are suppressed. On an average, over the frequency range evaluated, the resistance calculated using (19) optimally suppresses the resonances. Notice in Fig. 9 that the peaks of the shorted modes ($R = 0$) can be observed at lower frequencies than the corresponding open modes. This is due to the fact that there is a small amount inductance associated with the shorting posts and the voltage is not exactly zero at the post locations.

A second, narrower PCB–chassis structure was also evaluated. This cavity was 300 mm × 100 mm with a height $h = 5$ mm. The posts were symmetrically located at the four corners 10 mm away from each of the corner's two edges. An ideal current source of 1 A was located at the middle of the cavity's shorter edge.

Fig. 10 shows the optimum values of *R* for all possible modes below 2 GHz calculated using (11), (16), and (17). The optimum resistance calculated using (19) is approximately 30 Ω, which is denoted by the solid horizontal line.

Radiated emissions from the cavity were calculated with seven possible post resistance values. The results in Fig. 11 show that the 30-Ω post resistance was the most effective over the whole frequency range.

IV. Discussion

The previous sections demonstrated that (19) works well for calculating the optimum damping resistance when all four posts are loaded. However, there are many situations, where it is important to short one or more of the chassis mounting posts to the PCB ground plane. A specific example of this is when objects connected to the PCB (such as cables) must be referenced to the chassis ground. Since the derivation of $R_{\rm opt}$ for each post was independent of the other post resistances, shorting one or more posts does not affect the optimum resistance of the remaining posts. To illustrate this, Figs. 12–14 show the maximum radiated emissions from the first configuration with 1, 2, and 3 posts shorted, respectively.

In each case, the optimum resistance is still 50 Ω. It should be noted, however, that the overall emissions are higher when fewer resistive posts are used. This result is expected because fewer resistive posts mean that less power is dissipated relative

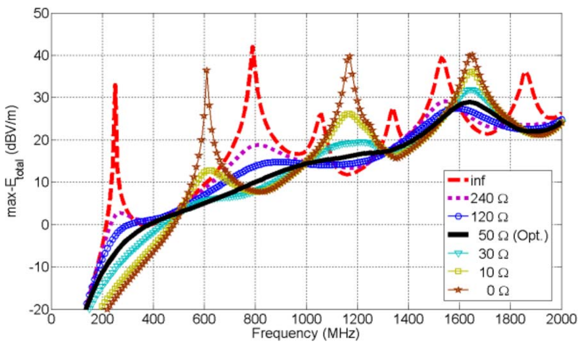

Fig. 12. Maximum *E*-field 3 m from the first configuration with one post shorted and various resistance values in the other three.

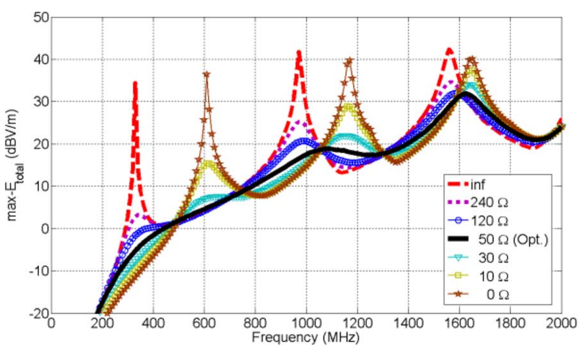

Fig. 13. Maximum *E*-field 3 m from the first configuration with two posts shorted and various resistance values in the other two.

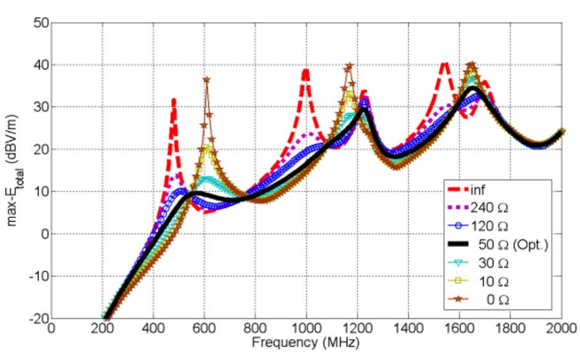

Fig. 14. Maximum *E*-field 3 m from the first configuration with three posts shorted and various resistance values in the remaining one.

to the stored energy for each resonant mode, resulting in a higher quality factor.

V. Conclusion

When a PCB is mounted to a metal chassis, the cavity formed between the circuit board ground and the chassis can resonate at certain frequencies resulting in unintended radiated emissions. The cavity resonances can be effectively suppressed by using conductive mounting posts and adding a resistance in series with the connection between one or more of these mounting posts and the PCB ground plane.

This paper derives a simple closed-form expression for determining an optimal series resistance for damping these cavity resonances over a wide range of frequencies. This analysis was done for rectangular boards mounted on four posts located near the corners. A similar analysis could be done to determine the optimal resistance values for other board shapes and mounting post locations. For the four-post configuration, shorting one or more of the posts does not affect the optimum resistance value for the remaining posts.

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