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Estimation of Printed Circuit Board Power Bus Noise at Resonance Using a Simple Transmission Line Model

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Abstract: The maximum coupling between printed circuit board components connected to the same power-ground plane pair often occurs at or near power bus resonances. Theoretically, the transfer coefficient, S_{21} , between two locations on the power bus can be as high as 0dB (i.e. perfect coupling) near resonant frequencies. However, in practice the coupling is usually much less due to losses in the power bus structure. Determining exactly what the maximum coupling will be in a lossy power bus structure requires a numerical model or measurement. However, an estimation of the maximum coupling can be obtained by drawing an analogy between two-dimensional printed circuit board power buses and one-dimensional transmission lines. In this paper, a one-dimensional lossy transmission-line model is employed to simulate power-ground plane pairs and calculate S_{21} between a noise source and a load. A simple formula for estimating the maximum coupling is derived from the transmission line model. This formula illustrates the effect that plane spacing, dielectric loss and board dimensions have on the maximum coupling between components attached to the same power bus structure.

INTRODUCTION

Power and ground-plane noise in a printed circuit board (PCB) or multichip module (MCM), commonly known as delta-I noise, results from pulses of current that flow between the planes during the high-to-low or low-to-high transitions of logic gates on digital integrated circuits [1]. This switching noise is a potential source for radiated EMI and should be effectively mitigated in high-speed digital circuit designs. On boards with low-impedance power-ground plane pairs, power bus noise is directly proportional to the transfer impedance, Z_{21} , between the location of the noise source and the location of the noise measurement. At resonant frequencies of the power bus, the transfer impedance may exhibit large peaks [2]. For low-impedance power buses, the transfer coefficient, S_{21} , measured between two locations is directly proportional to Z_{21} . Therefore, S_{21} measurements can be used to indicate the amount of electrical isolation provided by a power-ground plane pair. For a lossless power-ground pair, the power at a source can be completely coupled to a load at resonant frequencies, in which case the peak value of $|S_{21}|$ reaches 0dB.

In practice however, the amount of power coupled is much lower due to losses in the circuit board.

In order to quantitatively examine the peak values of S_{21} in power-ground plane structures, an accurate and efficient simulation of the two-dimensional power bus is needed. However, a great deal of insight can be obtained from a simple one-dimensional transmission line model [3]. In this paper, we use a transmission line model to explore the impact that dielectric loss and other parameters have on the maximum coupling in printed circuit boards with power and ground planes.

TRANSMISSION LINE MODEL FOR SIMULATION

Figure 1 shows a transmission line model for a parallel plate power bus. A noise source of magnitude V_s with internal impedance Z_s is connected to a power bus of characteristic impedance Z_c and length L . The line is terminated with a load impedance, Z_L .

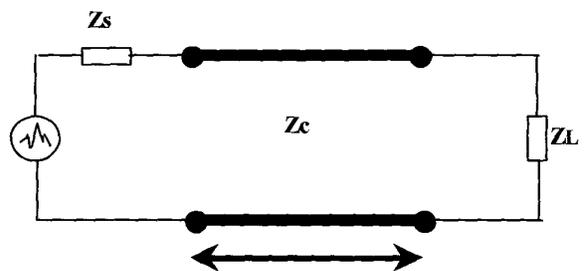


Figure 1. Transmission line model for parallel plate power bus section [3].

From transmission line theory, we can derive the following expression for the value of S_{21} between the source end of the line and the load end,

$$S_{21} = \frac{2}{e^{\gamma L} + e^{-\gamma L} + \frac{e^{\gamma L} - e^{-\gamma L}}{2} \left(\frac{Z_c}{Z_0} + \frac{Z_0}{Z_c} \right)}, \quad (1)$$

where the parameter Z_c represents the characteristic impedance of the transmission line, and Z_0 represents the characteristic impedance of the system (50 ohms in this paper), and

$$\gamma = \alpha + j\beta, \quad (2)$$

where the quantity β is the propagation constant,

$$\beta = 2\pi / \lambda, \quad (3)$$

and λ is the wavelength in the dielectric. The term α represents the line losses

$$\alpha = \alpha_c + \alpha_d, \quad (4)$$

$$\alpha_c = \frac{R_s}{wZ_c}, \quad (5)$$

$$\alpha_d = \frac{\omega \sqrt{\epsilon_r} \tan \delta}{2 \times c}, \quad (6)$$

α_c represents conductor losses (Np/m) where R_s is the surface resistance of a conductor of width w and characteristic impedance Z_c . α_d represents dielectric losses (Np/m) in terms of the loss tangent, $\tan \delta$, and the relative permittivity of the dielectric material, ϵ_r . The term L represents the power plane length.

Using this approach, S_{21} between the noise source and the load may be calculated. S_{21} calculated for a transmission line which has characteristic impedance $Z_0=0.004$ ohms, loss tangent $\tan \delta=0.001$ and length $L=0.25$ m is shown in Figure 2.

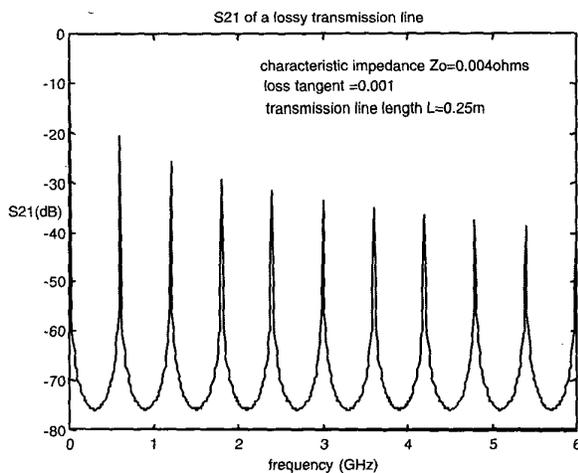


Figure 2. Calculated S_{21} of a lossy transmission line

ESTIMATION AND ANALYSIS OF THE PEAK VALUES OF S_{21}

As we can see from Figure 2, the maximum values of S_{21} occur at resonance frequencies and are well below 0dB. Since the maximum values of S_{21} appear at $\beta L = n\pi$ (n is odd), we can obtain an approximate expression for the maximum value of S_{21} by performing a Taylor series expansion at these points and eliminating the higher order terms. The resulting expression is,

$$S_{21} = \frac{2}{2 + \left(\frac{Z_0}{Z_c}\right) \alpha l} \quad (7)$$

This simplified expression is plotted in Figure 3.

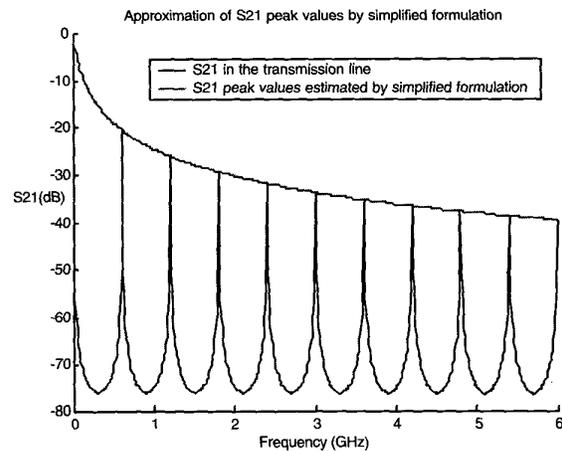


Figure 3. Calculated S_{21} of a lossy transmission line

We can see that the simplified formula provides a good estimation for the S_{21} peak values. Note that with only a small loss tangent ($\tan \delta=0.001$), the maximum value of the resonant peaks in this case is no higher than -20 dB.

From Equation (7) we can easily see that the amount of attenuation depends on three factors: the characteristic impedance of the board, the loss in the circuit board and the board size. Attenuation of the peak values increases with increasing loss and/or decreasing characteristic impedance. Figures 4 and 5 compare values of S_{21} for boards with different characteristic impedances and loss tangents. The loss tangent for the simulation in Figure 4 was 0.001. The characteristic impedance for the simulation in Figure 5 was 0.004 ohms.

It is clear that relatively small amounts of loss result in significant amounts of attenuation when the characteristic impedance of the line is small. It is also apparent that a given amount of loss reduces the amount of coupling more when the characteristic impedance is lower.

Of course, two-dimensional printed circuit boards do not have a single well-defined characteristic impedance. The ratio of voltage to current in the planes is a function of position and the modes that are excited. However, for the TM_{x0} and TM_{0x} modes, it is possible to define an approximate characteristic impedance as,

$$Z_c \approx \eta \frac{h}{w}, \quad (8)$$

where η is the intrinsic impedance of the dielectric, h is the plane spacing and w is the width of the plane.

CONCLUSIONS

A simple transmission line model has been used to illustrate the relative effect that board loss, board impedance, and board size have on the maximum coupling between two locations on a printed circuit board with power and ground planes. Based on this model, we observed that the attenuation of peak values of S_{21} increases with increasing loss or decreasing space between the two planes. The formula derived for estimating the maximum coupling is relatively simple and shows the interactions and trade-offs between different board parameters.

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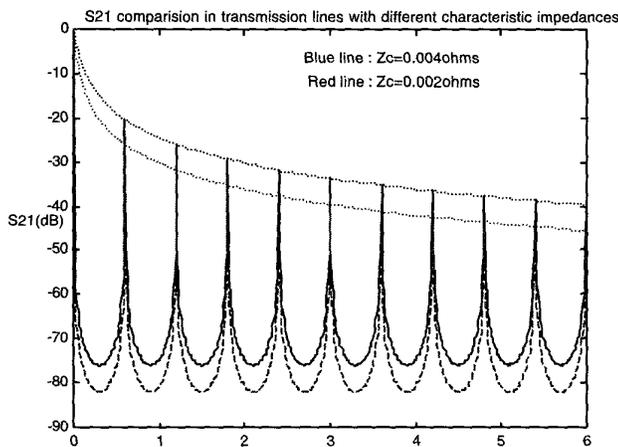


Figure 4. S_{21} comparison of transmission lines with different characteristic impedances

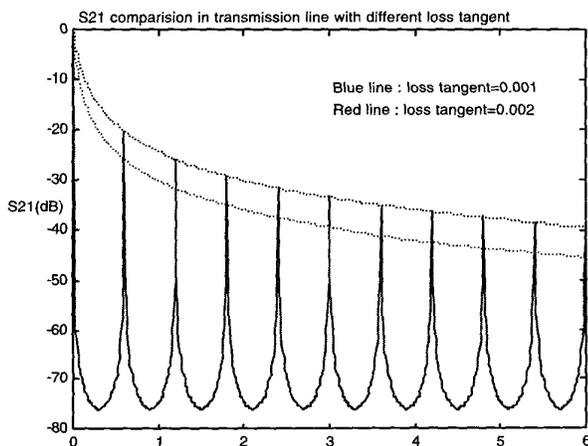


Figure 5. S_{21} comparison of transmission lines with different loss tangents