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Decoupling Strategies for Printed Circuit Boards Without Power Planes

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Abstract

Traditional decoupling capacitors connected between V_{CC} and GND traces can be relatively ineffective at frequencies above their self-resonant frequency. This paper evaluates decoupling capacitor mounting strategies on boards without power planes. Techniques for minimizing mutual inductance and improving decoupling at frequencies above resonance are investigated.

INTRODUCTION

Decoupling capacitors are generally supposed to serve two functions. First, they provide a local source of charge to meet the transient current needs of active devices. Second, they serve as low-pass filters to attenuate noise on the power bus.

Decoupling strategies for boards with power and ground planes have been widely studied and there are many established design rules for these boards. Though multi-layered boards are widely used today, many electronic products are still built with single- or double-sided boards due to their relatively low manufacturing cost. However, designers are given very little guidance for power bus decoupling of single/double sided boards other than to minimize the inductance of the connection.

In this paper, techniques to improve the behavior of decoupling capacitors on single/double sided boards are described. Since the mutual inductance of a capacitor connection plays an important role in its ability to filter high-frequency noise [1], several different connection methods designed to minimize mutual inductance were evaluated. Test boards with simple layouts were built and measured. Measured results were compared to simulation results to explore ways to maximize the effectiveness of decoupling capacitors on boards without power and ground planes.

It is known that two capacitors in parallel can improve the decoupling by at least 6 dB (compared to a single capacitor) at frequencies above the self-resonant frequency [2]. This is because two capacitors in parallel have approximately half the inductance (or mutual inductance) of a single capacitor. To reduce the mutual inductance even further, a distributed capacitor is considered here. The results show that a distributed capacitor (even with a very low capacitance) can significantly improve high-frequency attenuation.

CIRCUIT MODEL

A typical circuit representing a decoupling capacitor and its parasitics is shown in Figure 1. Generally, the performance of the capacitor as a filter is improved by keeping its transfer coefficient, S_{21} as low as possible. The first series resonant frequency fz and maximum value at frequencies above resonance, $S_{21,HF}$, are written as [1],

$$f_z = \frac{1}{2\pi\sqrt{C_d(L_{PWR\ trace} + ESL)}} \tag{1}$$

$$S_{21,HIGH} = \frac{M}{L+M} \tag{2}$$

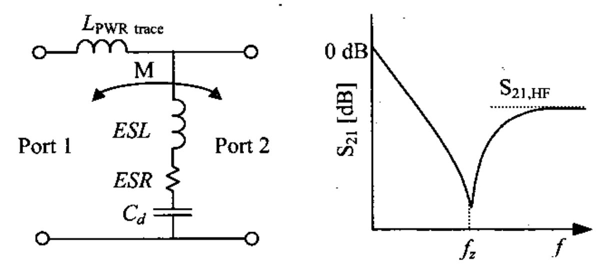

Figure 1. Equivalent circuit for a decoupling circuit and its transfer coefficient, S_{21}

Since a single- or double-sided board does not have solid plane, the inductance associated with power trace is usually much larger than ESL (Equivalent Series Inductance) of the capacitor alone. Equation (1) requires the inductance associated with the power traces to be minimized to keep the first resonant frequency f_z higher. A real printed circuit board has pads, traces, and vias (for double sided board) to mount necessary components. These structures inherently contribute tens of nanohenries to the total connection inductance. Therefore, the first resonant frequency f_z typically occurs below 10 MHz in most single- or double-sided boards. This means that a designer is counting on a decoupling capacitor to perform adequately at frequencies well above the self-resonant frequency.

The maximum level of $S_{21,HF}$ is determined by the mutual inductance between the loops, as indicated in Equation (2) [1]. Two different methods were suggested to minimize the mutual inductance between the loops. First, the magnetic

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flux created by the capacitor was cancelled by carefully arranging a pair of capacitors so that the magnetic flux coupling one would tend to cancel the magnetic flux coupling the other. Second, a distributed capacitor made with copper tape was considered.

FLUX CANCELLATION BY A PAIR OF LUMPED CAPACITORS

Test Boards

Figure 2 shows the layout of the test boards used for this study. The thickness of the boards was 30 mils and the relative permittivity of the dielectric material was 3.85. The width of the traces was 2 mm. Additional dimensions are provided in Figure 2. A pair of capacitors was connected at one of three different locations on the test board.

At Location 1, both capacitors are connected to the same return path. There are two possible current return paths (the plane on either side of the trace), but only one of them is connected to the decoupling capacitors. A significant portion of the return current is forced to return on one side of the trace at frequencies where the decoupling capacitors are working.

At Location 2, each capacitor is connected to a different return path. Because of the symmetry of the board, the current should equally divide between the two return paths. The mutual inductance between the two capacitors is expected to be low, since only a small portion of the magnetic flux couples both capacitors.

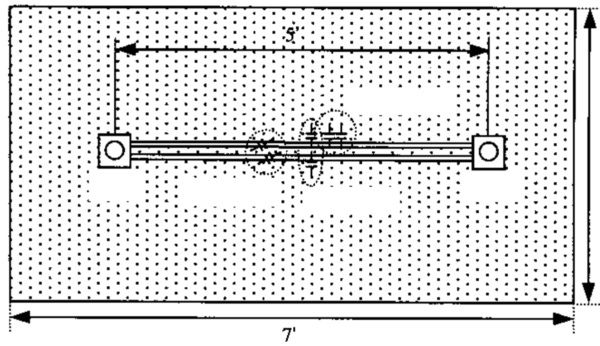
At Location 3, the two capacitors are placed side by side in a position that maximizes their mutual inductance. The current distribution will be similar to that with the capacitors at Location 2, but this configuration provides more inductive coupling between the two capacitors. The directions of magnetic flux are opposite. This magnetic flux cancellation is expected to reduce the mutual inductance between the input and the output of this capacitor/filter. The direction of current flow through each capacitor and the corresponding magnetic flux are shown in Figure 3. The most flux cancellation is expected at Location 3.

The test board shown in Figure 2(a) has a return path on both sides of the trace. But most single- and double-sided boards have only one preferred current return path. To investigate this geometry, an additional test board with one return path was built. This is shown in Figure 2(b).

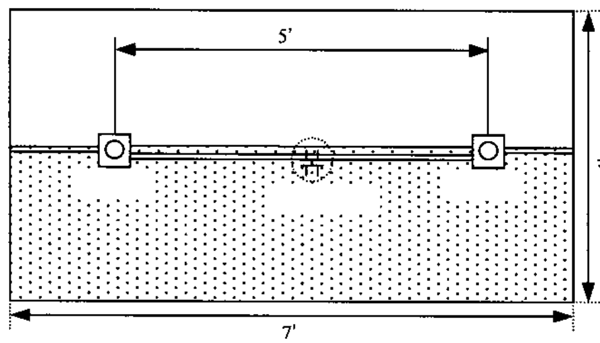
Measured S_{21} of the Test Boards

Figure 4 (a) shows the measured voltage transfer coefficient for the board with two return paths. The transfer coefficient with capacitors at Location 1 is higher than at Location 2 indicating that the decoupling is more effective when the capacitors are connected to both return paths.

The transfer coefficient for Location 3 shows the effect of flux cancellation. The configurations corresponding to Locations 2 and 3 are electrically the same except that the direction of the current flowing through each capacitor is reversed. The difference in S_{21} between Locations 2 and 3 is only about 2 dB up to 1 GHz. Therefore, flux cancellation obtained by placing the pair of capacitors side by side had only a minor effect on the overall behavior of the decoupling capacitors.



(a) Test board with two return paths



(b) Test board with one return path

Figure 2. Test boards with different return paths

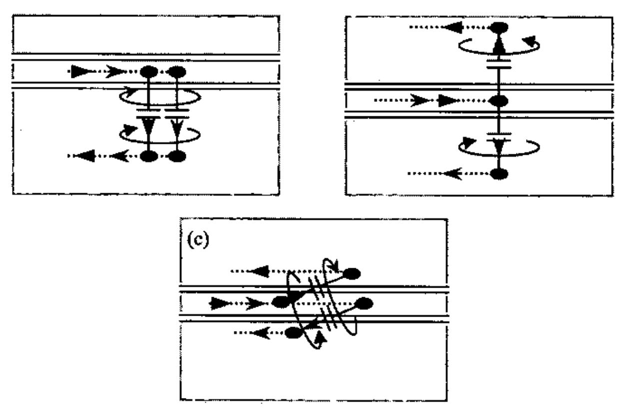
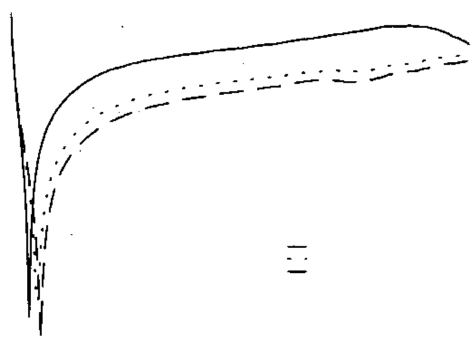


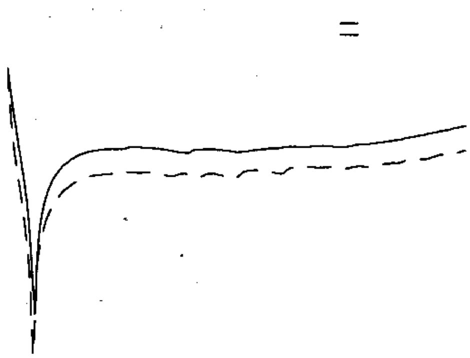
Figure 3. The current flow through each capacitor and the corresponding magnetic flux at (a) Location 1, (b) Location 2, and (c) Location 3

Figure 4 (b) shows the measured S_{21} of the test board with only one return path. In this case, the measured S_{21} is almost constant up to 1 GHz. It is also important to compare the difference between S_{21} with one capacitor and two. The measurement shows that the difference is about 4~6 dB over the frequency range of the measurement. This is to be expected, since the parallel connection of two capacitors reduces the overall inductance to about half of the inductance of original capacitor [2].

It is also useful to compare the results for the two different test boards. By comparing results in Figure 4 (a) and (b), the S_{21} of the test board with one return path is observed to be lower and flatter than the S_{21} of the board with two return paths. S_{21} with the capacitor at Location 1 shows the worst results (the highest S_{21}) of all the cases. There are two return paths when decoupling capacitors are connected to the Location 1. But only one return path is decoupled. This suggests that multiple paths for return current may not be a good choice for power bus decoupling, unless decoupling is provided for all paths.



(a) Measured S_{21} of the test board with two return paths



(b) Measured S_{21} of the board with one return path

Figure 4. Measured S_{21} of the test boards

MULTIPLE CAPACITORS

Assuming we can ignore the mutual inductance between capacitor connections, the behavior of multiple capacitors can be described using the simple circuit shown in Figure 5. S_{21} with the dotted and dashed lines corresponds to the expected result when only one capacitor is considered. The solid line illustrates the response when both capacitors are present. At the lower frequencies, only the capacitor with the larger capacitance is effective. At frequencies above self-resonance, the response is determined by the parallel combination of the inductances.

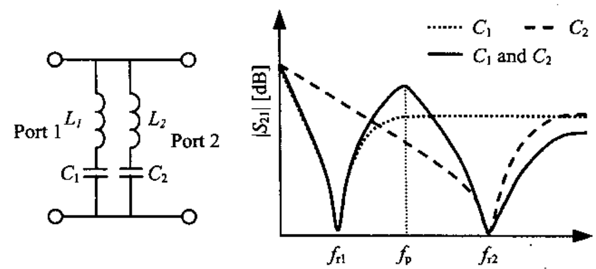


Figure 5. Equivalent circuit model and S_{21} of multiple capacitor decoupling

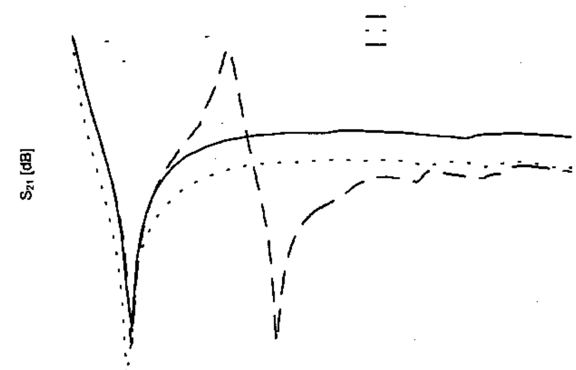


Figure 6. S_{21} with multiple capacitors

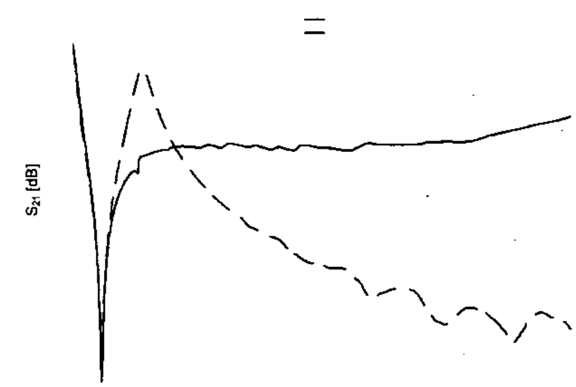


Figure 7. The effect of a distributed capacitor

Two different pairs of capacitors were used for this study. First, a pair of two identical capacitors was used. The value of each capacitance was 1 nF. Second, two different capacitors were connected. One of the capacitor was 1 nF and the other was 82 pF.

Figure 6 shows the measured S_{21} between the two ports. The results show that the transfer coefficient with identical capacitors is decreased by 6 dB above the resonant frequency. S_{21} with different capacitors is reduced by 6 dB at frequencies above 400 MHz. But, there is a peak between the two series resonant frequencies.

S_{21} with multiple capacitors can be higher than with one capacitor at frequencies where the parallel resonance between the capacitors occurs. This problem can generally be avoided by using two identical capacitors. This is also shown in Figure 6. Since inductance of a capacitor connection is not only a function of the structure of capacitor itself but also a function of pad and traces, which are used for soldering. This requires that the pads and traces for the capacitors should be identical as well.

A distributed capacitor provides an excellent means of reducing the mutual inductance between the input and output of a capacitor/filter. A simple distributed capacitor was made with copper tape. One side of the copper tape was connected to the power trace, while the other side extended over the return path but was isolated by a layer of electrical tape. Figure 7 illustrates the effectiveness of the distributed capacitor connected in parallel with a regular SMT capacitor. The results show that the distributed capacitor even with a very low capacitance, significantly improved the high-frequency attenuation.

Of course, building a distributed capacitance into a printed circuit board may not be cost effective. Another option is to use multiple discrete capacitors with a certain amount of space between them. In this way, the inductance of the trace between capacitors contributes to the filtering of the signal at high frequencies. An example of this is illustrated in Figure 8. A trace over a ground plane is filtered with either one capacitor (A) or two capacitors (B) with a given distance between them. The trace characteristic impedance is 100 ohms.

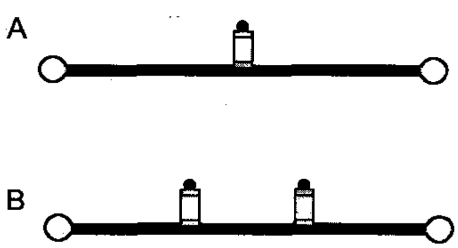


Figure 8. One- and two-capacitor configurations

Figure 9 shows the measured transfer coefficient corresponding to this filter for different capacitor spacings. In each case, the total capacitance is approximately 10 nF. Note that when the capacitors are 2 mm apart, the high-frequency performance is improved by 6 dB compared to the single-capacitor configuration. However, when the spacing is increased to 10 mm, the improvement is greater than 12 dB at high frequencies. There is a small parallel resonance at approximately 50 MHz that gets stronger as the separation is increased. However this example illustrates that it is possible to get better filtering/decoupling from multiple capacitors if they have a little space between them.

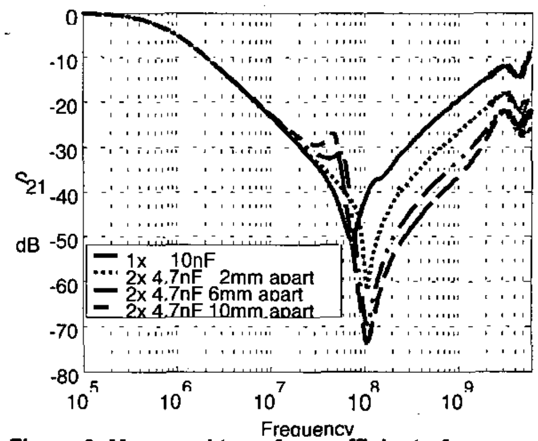


Figure 9. Measured transfer coefficient of one- and two-capacitor configurations

CONCLUSIONS

To investigate the behavior of decoupling capacitors on single-sided boards, several test configurations were built. Various connection methods were suggested and tested in an attempt to minimize mutual coupling. The results indicate that the number of possible return paths plays an important role in decoupling. When there is more than one return path, a decoupling capacitor should be provided for each path.

The results also demonstrate the importance of minimizing the mutual inductance associated with a decoupling capacitor connection. Attempts to minimize the mutual inductance associated with the flux wrapping the capacitor by mounting capacitors so that their currents were in opposing directions were relatively ineffective (~2 dB improvement). On the other hand minimizing the mutual inductance by using a distributed capacitance was very effective at reducing the high-frequency coupling. It was also shown that multiple identical capacitors with appropriate spacing can be used to reduce coupling at frequencies above self-resonance.

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[2] C. R. Paul, "Effectiveness of multiple decoupling capacitors." *IEEE Trans. on Electromagnetic Compatibility*, vol. 34, no. 2, pp.130-133, May 1992.