为了维持电力供应电压的小幅度波动，必须确保低感应，或者更准确地说，必须确保电力分配系统的低阻抗。在较高的频率下，各平面的特性更为复杂。更确切地说，一对平面构成一个平行板传输系统。电力和地面噪音，或者相应的电磁场，通过并且根据这个平行板传输系统的规则传播。很明显各平面在低频率下作为电容器，而在高频率下成为两维传输线。通过使用退耦电容器，就可以在宽频率区域获得低阻抗电力输送系统。

Low-Impedance POWER DELIVERY over Broad Frequencies

Decoupling capacitors reduce impedances at low frequencies while removing resonances up to a few hundred MHz.

by JIAYUAN FANG and JIN ZHAO

As IC devices operate faster and power supply voltages drop, it is becoming increasingly more difficult to meet the noise margin permitted in power distribution systems[1]. To illustrate the significance of such a challenge, let's consider the cases of two circuits

a) A voltage supply of 5 V and a current rise time of 10 ns.
b) A voltage supply of 1 V and a current rise time 0.5 ns.

The change in current represents the switching of devices. The waveforms of the currents are shown in FIGURE 1.

In both cases, assume the change in current (ΔI) is of the same magnitude, 100 mA, and the power/ground loop inductance (L) is 3 nH. Using $\Delta V = L\ dI/dt$, the voltage fluctuations are plotted in FIGURE 2. In (a), the voltage ripple is under 30 mV, while the voltage fluctuation in (b) is over 550 mV.

The performance of the power distribution system can mean operational success or failure of the overall system. In order to maintain a low power supply voltage fluctuation, one must ensure low inductance, or more precisely, low impedance of the power distribution system. Power and ground planes can play a very important role.

Let us first look at the primary characteristics of planes for power distribution systems. Most think of a pair of metal planes as a parallel-plate capacitor. Thereby, the function of planes should be to provide the "plane capacitance" that helps maintain voltage stability. At low frequencies, where the wavelength is much larger than the plane dimension, the pair of planes does indeed behave as a capacitor.

However, as the frequency moves higher, the characteristics of planes become much more complex. More precisely, a pair of planes forms a parallel-plate transmission system. Power and ground noise, or its corresponding electromag-

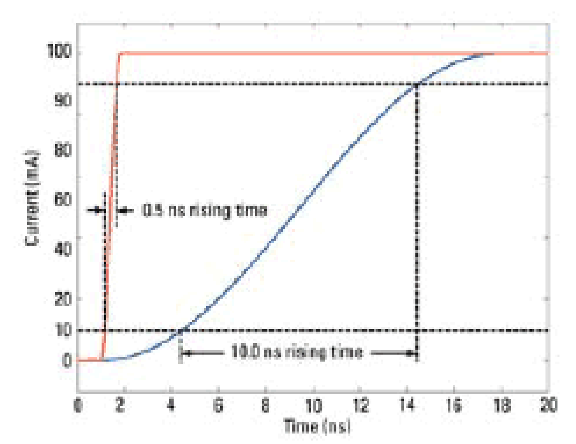

FIGURE 1. Current waveforms with rise times of 0.5 ns and 10 ns.

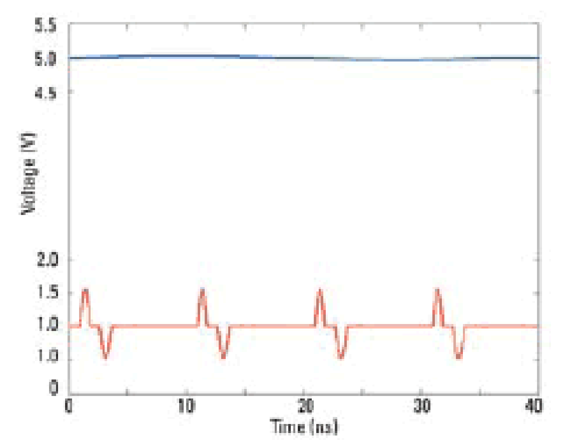

FIGURE 2. Voltage fluctuations for a 5 V voltage supply with 10 ns rise time of switching current and for 1V voltage supply with 0.5 ns rise time of switching current.

netic fields, propagates through and follows the rules of this parallel-plate transmission system.

Parallel-plate or radial transmission lines of simple geometries have been well documented in university textbooks[2]. Some analytical studies of PCB power and ground planes of rectangular shapes can be found in public literature[3]. The analysis of arbitrarily shaped power and ground planes, made up of two or more metal layers connected by vias, often requires software tools.

To illustrate the power and ground plane characteristics, consider a pair of copper metal planes (FIGURE 3). The dimensions of the planes are 30 x 20 cm with 18 µm metal thickness. The dielectric medium between the planes is 0.004″ in thickness with a 4.0 dielectric constant (Dk) and 0.015 loss tangent. Vias connected to the planes have a radius of 0.005″. A pair of vias connected to the pair of planes is located at point A as shown in Figure 3.

Consider a current source linked to the pair of vias at point A with a current source waveform of 0.5 ns rise time as shown in Figure 1. Snapshots of voltage distributions between the two planes are shown for t = 0.69 ns and t = 1.13 ns in FIGURE 4a and FIGURE 4b respectively. Figure 4 illustrates what physically happens between power and ground planes in the event of a transient switching current. As Figure 4 shows, the power and ground noise originates from vias carrying the switching currents, then propagates away from vias in a radial direction. Reflections occur as the noise reaches the edges of the metal planes. Multiple reflections from the edges of planes cause resonance.

Another way to assess the power and ground system performance is through its impedance vs. frequency curves[1,5]. Looking into the pair of planes at the vias at location A, the impedance of the power and ground planes is plotted in FIGURE 5. Also plotted in Figure 5 is the impedance of a 20.9 nF capacitor representing the capacitance value of the pair of planes. The planes here behave as a capacitor up to tens of MHz. Above 100 MHz, the impedance of the planes is mostly inductive and has a number of peaks corresponding to the resonant behavior of the fields between planes.

Often, the planes are connected to a voltage regulator module (VRM). Assume the VRM is modeled by a 3 nH inductor in series with a 1 mΩ resistor, located at point B shown in Figure 3. The impedance of the planes looking at point A is plotted also in Figure 5. A significant impedance peak occurring at about 20 MHz is caused by the resonance of the VRM inductor and plane capacitor. The effect of the VRM becomes invisible above 100 MHz.

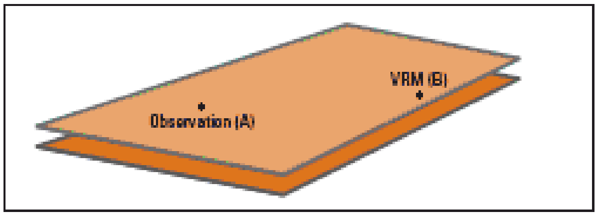

FIGURE 3. Physical configurations of a pair of planes.

Clearly, planes behave as a capacitor at low frequencies, while at higher frequencies they are two-dimensional transmission lines. Planes can potentially provide low impedances for power distribution systems, although one has to carefully deal with the resonance caused by plane capacitance and external inductance and the resonance inherent to the planes themselves.

Factors Affecting Performance

Let us examine important factors that may affect the performance of planes: a) Separation between power and ground planes; b) Horizontal size of power and ground planes; c) Dk of materials between power and ground planes; d) The number of power and ground planes.

Correspondingly, we will observe the following cases

Case A: Plane separation = 0.002″, 0.004″, 0.010″ and 0.020″
Plane size = 30 x 20 cm
Dk = 4 (loss tangent 0.015)
Number of plane layers = 2

Case B: Plane separation = 0.004″
Plane size = 30 x 20 cm, 15 x 10 cm and 7.5 by 5 cm
Dk = 4 (loss tangent 0.015)
Number of plane layers = 2

Case C: Plane separation = 0.004″
Plane size = 30 x 20 cm
Dk = 4 (loss tangent 0.015), 10 (0.0) and 100 (0.0)
Number of plane layers = 2

Case D: Plane separation = 0.004″
Plane size = 30 x 20 cm
Dk = 4 (loss tangent 0.015)
Number of plane layers = 4

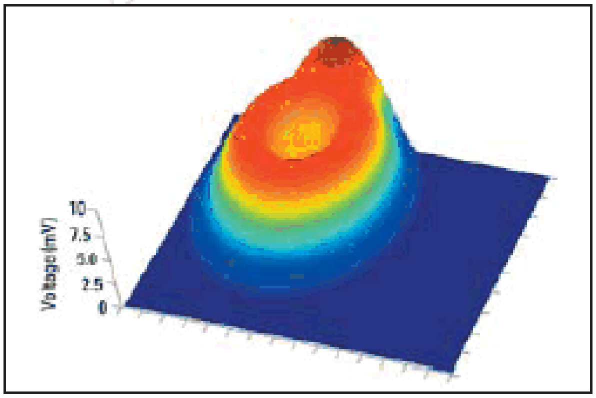

FIGURE 4a. Snapshot of spatial voltage distribution at t = 0.69 ns.

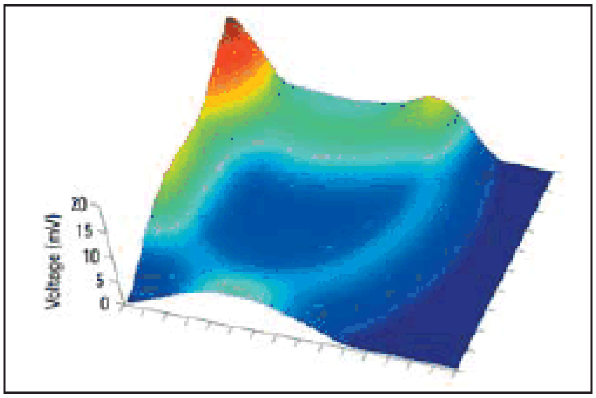

FIGURE 4b. Snapshot of spatial voltage distribution at t = 1.13 ns.

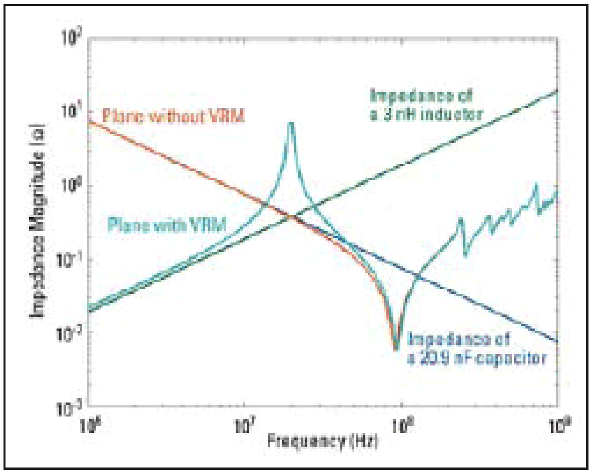

FIGURE 5. Impedance of planes with and without VRM.

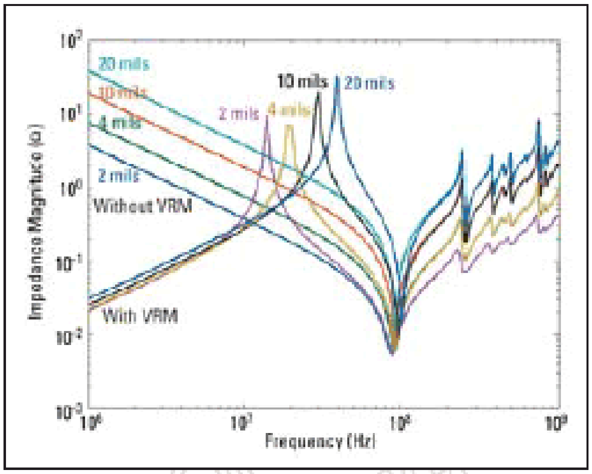

FIGURE 6. Impedance of planes of different plane separations.

Effects of different separations of power and ground planes (from case A) are illustrated in **FIGURE 6**. This shows that the smaller the separation between the planes, the larger the plane capacitance and the smaller the impedance. The separation between planes has virtually no effect on the inherent resonant frequencies of planes, but the larger the separation, the more significant the inherent resonances. Different plane separations yield different plane capacitance, and therefore different resonant frequencies for the resonance caused by plane capacitance and VRM inductance. At the resonant frequencies, the decrease in plane separation leads to the decrease in the peak impedance values.

The impedances of a pair of planes of different sizes in case B are plotted in **FIGURE 7**. The size of planes directly affects all the resonant frequencies. The smaller the plane size, the higher the resonant frequencies; therefore, the size of planes will affect the types and the number of decoupling capacitors needed on the board.

The effects of high Dk materials between power and ground planes in case C are displayed in **FIGURE 8**. At the lower frequency range, the larger the Dk, the larger the plane capacitance. At the higher frequency range, when the plane impedance becomes inductive, the resonant frequencies of the inherent resonance inside the planes – as well as the peak impedance values at each resonance – differ substantially. But the overall variations of impedances vs. frequencies do not differ very much for different Dks.

In case D, there are a total of two power planes and two ground planes with all planes of the same size. The power and ground planes alternate in order. Compared to the results of two planes, four planes provide more plane capacitance, which leads to lower resonant frequency for the resonance caused by the plane capacitance and VRM inductance, as shown in **FIGURE 9**. For inherent resonance inside planes, the four-plane structure has the same resonant frequencies as those of the two-plane structure, while the resonant peaks for the four-plane structure appear to be lower.

Planes vs. Decoupling Capacitors

Decoupling capacitors can often be modeled as a series connec-

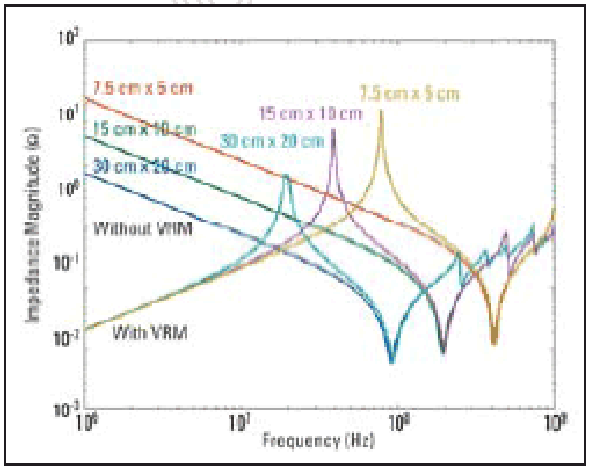

FIGURE 7. Impedance of planes of different plane sizes.

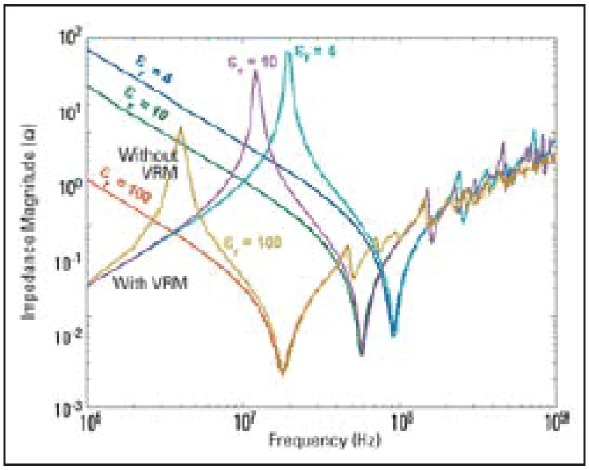

FIGURE 8. Impedance of planes of different Dk materials.

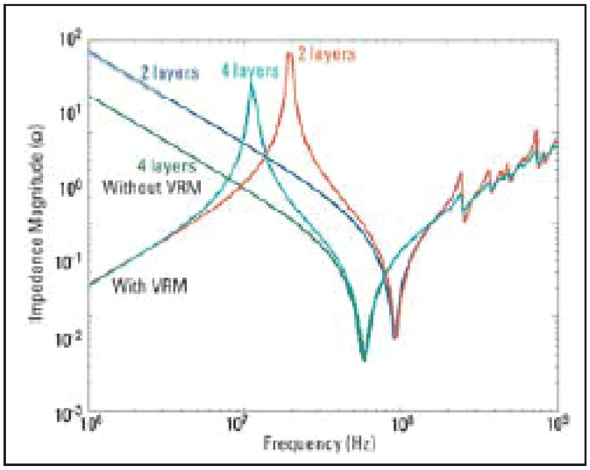

FIGURE 9. Impedance of planes of different layers.

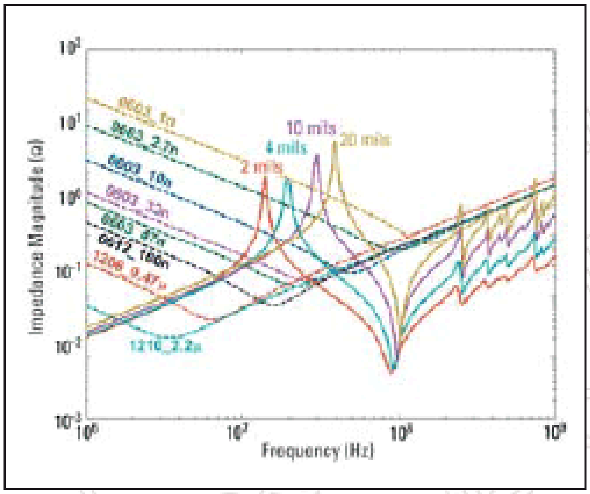

FIGURE 10. Impedances of different types of decoupling capacitors (broken lines) and impedances of planes of different plane separations (solid lines).

tion of a capacitor (C), an effective series inductor (ESL) and an effective series resistor (ESR). Impedances of a number of decoupling capacitors with their models obtained from the AVX Web site (avx.com) are plotted in **FIGURE 10**, together with impedances of a pair of planes of different separations. An additional 0.2nH – 0.3nH inductance, regarded as mounting inductance, is added to the ESL values of the original capacitor models.

As seen in Figure 10, when the plane separation is very small, say 0.002", the impedance of planes at high frequencies is much lower than the impedances of any conventional capacitors, such that decoupling capacitors are hardly needed there. When the plane separation is large, say 0.020", and at high frequencies, the inherent resonance inside planes can be significant. Since the impedance of planes becomes comparable to those of decoupling capacitors, the placement of decoupling capacitors can help remove certain inherent resonances. In the lower frequency range, the smaller separation between metal planes should also lead to less demand for decoupling capacitors.

In the board configuration shown in Figure 3, the following capacitors were placed on the board:

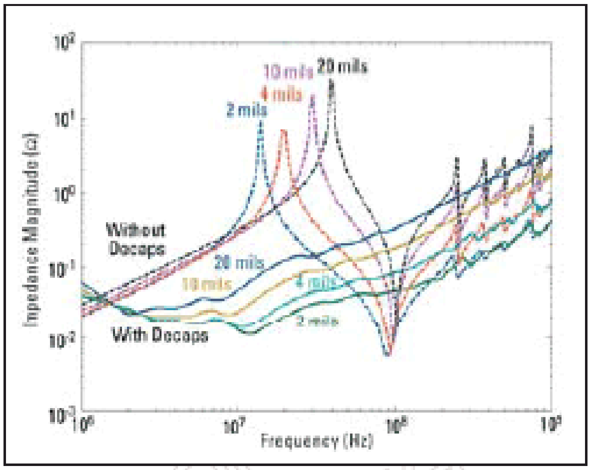

FIGURE 11. Impedances of planes of different planes separations without decoupling capacitors (broken lines) and with decoupling capacitors (solid lines).

1210 2.2 μF	x 1
1206 0.47 μF	x 2
0612 100 nF	x 8
0603 47 nF	x 2
0603 33 nF	x 4
0603 10 nF	x 8
0603 2.7 nF	x 16
0603 1 nF	x 24

The impedances of the board with and without these decoupling capacitors are plotted in **FIGURE 11**. It can be seen that decoupling capacitors reduce the impedances at low frequencies while removing resonances up to a few hundred MHz.

The location, types and the number of decoupling capacitors are by no means optimal in this analysis. However, the preceding examples clearly illustrate that with the proper design of power and ground planes and by using decoupling capacitors, one can obtain a low-impedance power delivery system over a broad frequency range. **PCD&M**

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