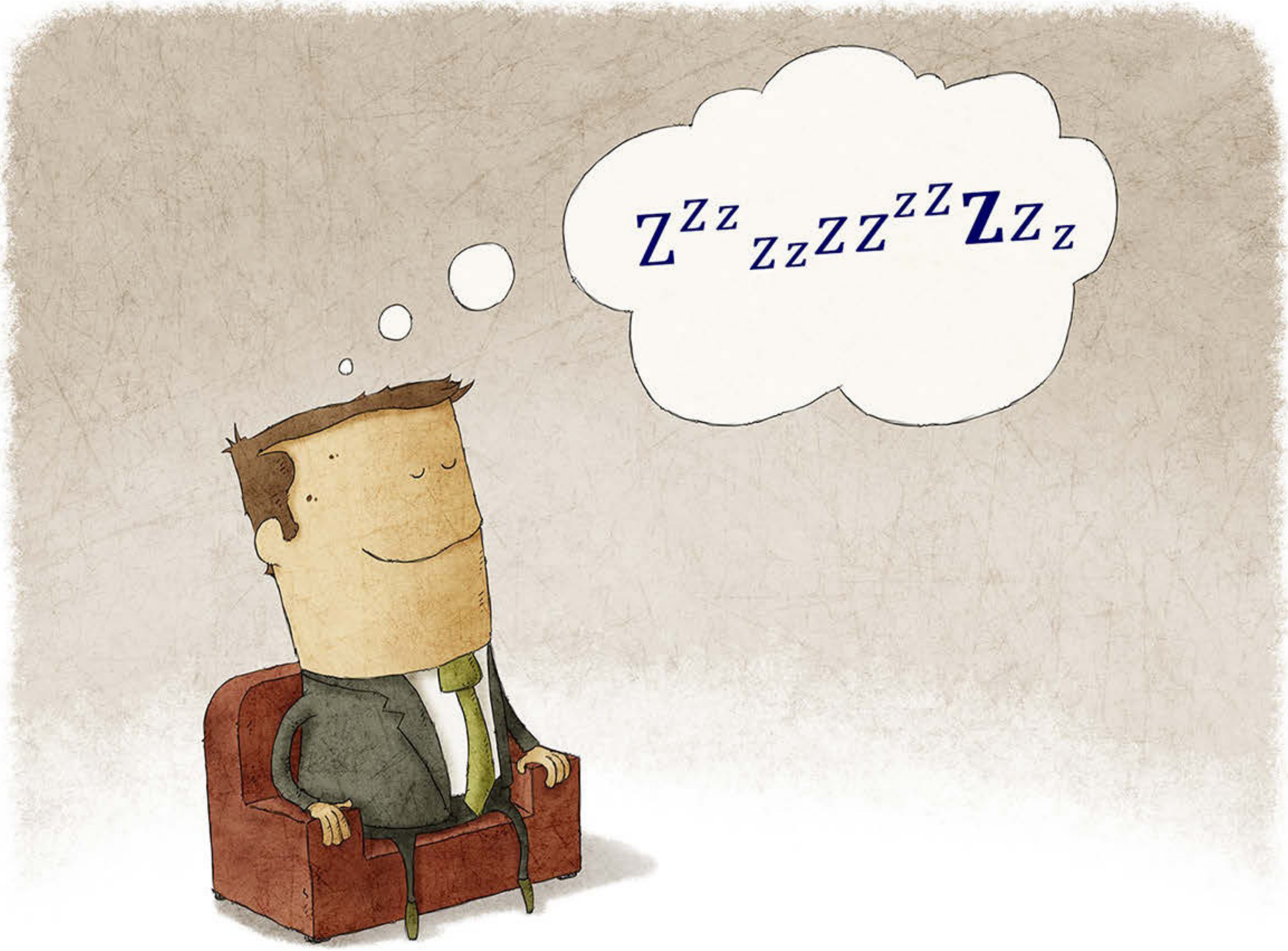
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The Proximity Effect

Beyond Design

by Barry Olney, IN-CIRCUIT DESIGN PTY LTD / AUSTRALIA

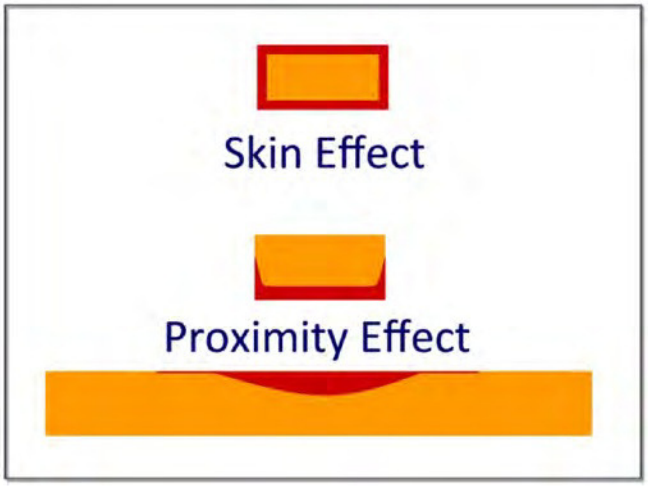

Figure 1: Skin vs. proximity effect.

Skin effect and the proximity effect are manifestations of the same principle—magnetic lines of flux cannot penetrate a good conductor. The difference between them is that skin effect is a reaction to the magnetic fields generated by current flowing within a conductor (Figure 1), while proximity effect is generated by current flowing in other nearby traces or planes. The frequency at which both effects begin to occur is the same. In this month's column, I will focus on the proximity effect. Please see "Beyond Design: Effects of Surface Roughness on High-speed PCBs" for further information on skin effect.

The Proximity Effect

In multilayer PCBs, these effects start to take hold at rather low frequencies on the order of ~ 30 MHz. Below that frequency, due to changing currents in the traces, the magnetic forces are too small to influence the pattern of current flow. In a low-frequency or DC circuit, the return current takes the path of least resistance filling the entire cross-sectional area of the trace. As it returns to the source via the power/ground planes, this current tends to spread throughout the wide, flat sheet of copper. However, as the frequency increases, the magnetic forces surrounding a trace become significant and the return current takes the path of least inductance. This high-frequency distribution follows a tight path directly above and/or below the trace in the reference plane(s).

As represented in Figure 1, magnetic fields distribute current to a shallow depth around the perimeter of the trace (red), increasing the apparent resistance of the trace; this is the skin effect. The magnetic fields also distribute current around the perimeter of the trace in a non-uniform manner when referenced to a plane; this is the proximity effect. This draws current toward the side of the trace facing the reference plane and forms the return current into a narrow band directly above and/or below the trace. Figure 2 shows microstrip return current density. In an asymmetric stripline configuration (Figure 3), the proximity effect draws current in an uneven distribution towards the near and far reference planes.

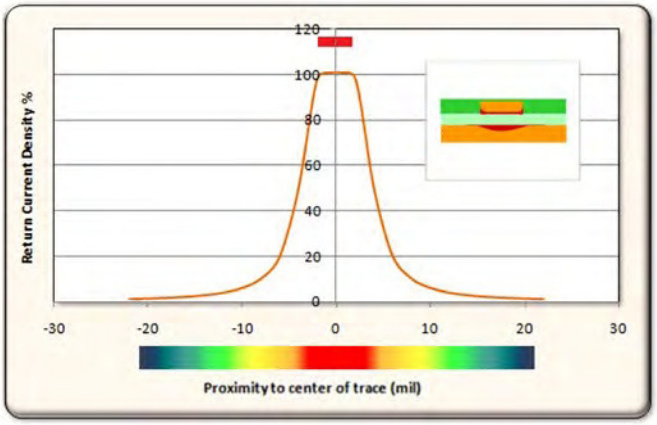

Figure 2: Microstrip return current density.

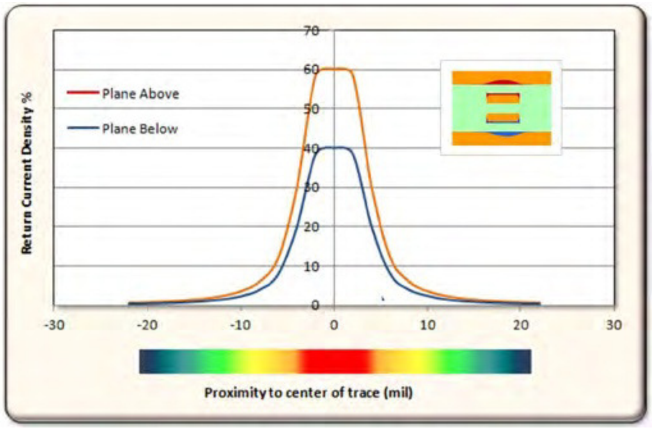

Figure 3: Return path current density for dual asymmetric stripline.

It is important to have a clearly defined return current path and to know exactly where the return current will flow. This is particularly critical with asymmetric stripline configurations where one or two signal layers are sandwiched non-uniformly between two planes. The question is not which plane does the return current flow on but rather how is the current distributed on each plane? Also, if a return path discontinuity (RPD) exists, then the current tends to divert increasing the loop area, inductance, and delay.

A via that provides the connection between signal traces referenced to planes of different DC potential creates RPDs. In other words, the return current has to jump between the planes to close the current loop, which increases the inductance and affects the signal quality. This return current can also excite the parallel plate resonance mode, causing significant electromagnetic radiation from the fringing fields.

If the reference planes are at the same DC potential, then they can be directly connected by stitching vias near the signal via transition to provide shorter paths for the return current. However, if the planes are at different DC potential, then decoupling capacitors must be connected across the planes at these points. Unfortunately, this can pass AC noise between power supplies. Two decoupling capacitors configured as the right example in Figure 4 is a much better solution because it eliminates the transfer of power supply noise from one supply to another. Although this does add a little loop area, it also provides additional decoupling to the planes, reducing power distribution network impedance. In addition, some of the return current flows through the interplane capacitance to close the loop.

Equations

The distribution of current for the three basic configurations depicted in Figure 5 is:

(a) The distribution of current $J(D)$ on a solid microstrip plane is given by:

$$J(D) = \frac{1}{1 + (d/h)\textasciicircum 2}$$

h = height of trace above/below the plane (mil)*
d = horizontal distance away from the center of trace (mil)*

* *um or mm can be substituted for mil providing the same units are used throughout*

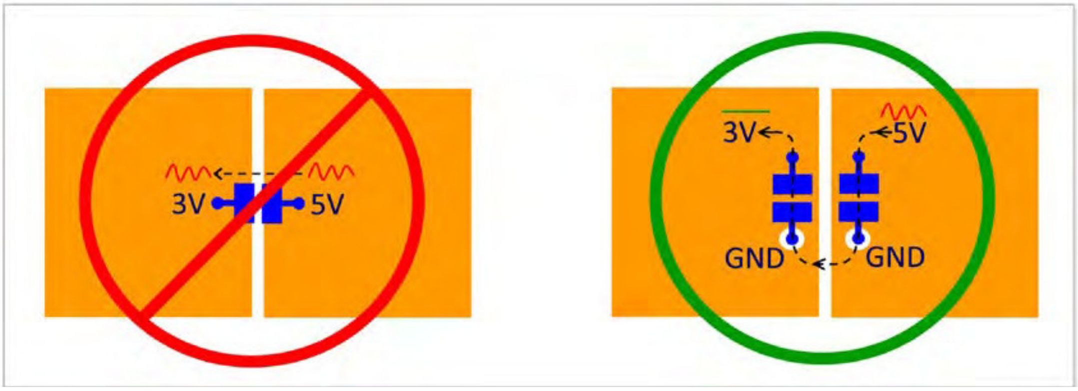

Figure 4: Eliminating the transfer of noise in the return path of split power planes (right).

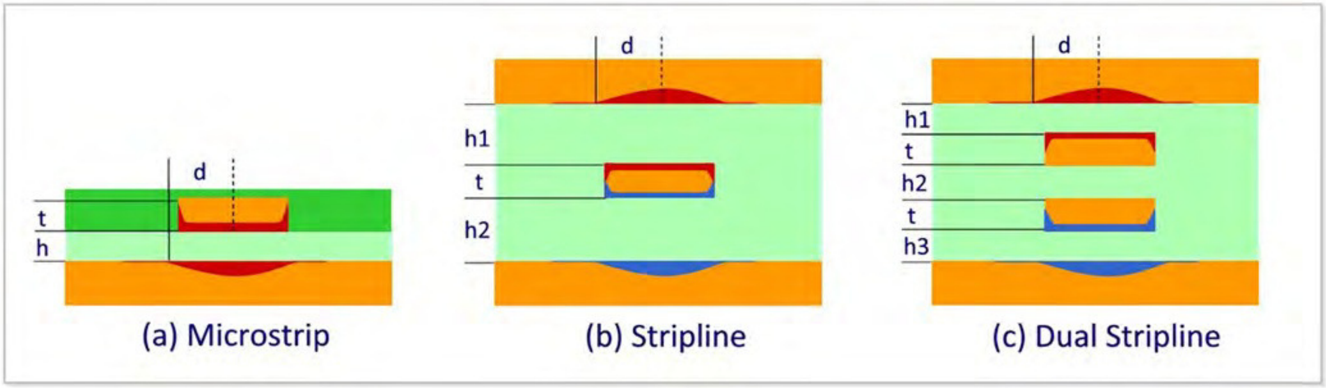

Figure 5: (a) Microstrip, (b) stripline, and (c) dual stripline configurations.

(b) However, for the stripline configuration, one needs to also take into account the ratio of *h1* (height of the plane above the trace) compared to *h2* (height of the plane below the trace). Then, h for the plane above becomes:

$$h = h1 \, . (1 - \frac{h1}{h1 + h2})$$

And for the plane below, *h* is:

$$h = h1 \, . (\frac{h1}{h1 + h2})$$

(c) You can easily extrapolate these equations to accommodate dual asymmetric stripline by adding the height of the appropriate dielectrics to each plane; *(h1 + h2)* becomes *(h1 + h2 + h3)* in the previous equations. This will result in a similar current distribution to that shown in Figure 3.

Also, to be more accurate, in the stripline configurations, the trace thickness *(t)* sinks into the prepreg material, bringing the trace closer to the plane and reducing the trace impedance. So, accounting for this resin flow adds a little more complexity to the equation. However, given that you know which dielectric material is core and which is prepreg, the height of the prepreg can be reduced by *(t)*.

The fundamental distribution of the current equation is also the basis for simple crosstalk estimates. Crosstalk changes very rapidly with distance and plummets roughly quadratically with increased separation *(d)* or decreased dielectric height *(h)*. For microstrip:

$$Xtalk = \frac{k}{1 + (d/h)^{\wedge}2}$$

Crosstalk is expressed as a ratio of noise voltage to the driving signal amplitude. The constant *(k)* depends on the circuit rise time and the length of the interfering trace segments. This is always less than one.

Surprisingly, these equations are based on Newton's 300-year-old inverse-square law: the force acting between two objects is inversely proportional to the square of the separation distance. It always amazes me how math, physics, electromagnetics, and other disciplines all align with the exception of subatomic quantum theory, which does not seem to comply with any established law of nature.

Conclusion

When modeling a trace above a solid plane, you will find that the current density is greater on the reference plane side of the trace than on the other. The same principle applies for two traces placed in close proximity in parallel segments—the current tends to concentrate on the two facing edge surfaces. The proximity effect is a simple manifestation of the general rule that high-speed current tends to concentrate near its return path.

Key Points:

- In a low-frequency or DC circuit, the return current takes the path of least resistance filling the cross-sectional area of the trace
- As the frequency increases, the magnetic forces surrounding a trace become significant and the return current takes the path of least inductance
- High-frequency return current distribution follows a tight path directly above and/or below the trace in the reference plane(s)
- The skin effect is the tendency for magnetic fields to distribute current to a shallow depth around the perimeter of the trace
- The proximity effect is the tendency for magnetic fields to distribute current around the perimeter of the trace in a non-uniform manner when referenced to a plane
- It is important to have a clearly defined return current path and to know exactly where the return current will flow
- Return path discontinuities tend to divert current increasing the loop area, inductance, and delay
- If the reference planes are at the same DC potential, they can then be directly connected by stitching vias near the signal via transition to provide shorter paths for the return currents
- If the reference planes are at different DC potential, then decoupling capacitors must be connected across the planes at these points to provide a return path
- Two decoupling capacitors spanning split power planes is a better solution as this eliminates the transfer of power supply noise from one supply to another
- The distribution of the current equation provides insight into where the return path current flows
- The fundamental distribution of the current equation is also the basis for simple crosstalk estimates

Further Reading

- Olney, B. "Beyond Design: The Dark Side–Return of the Signal," *The PCB Design Magazine,* May 2017.
- Olney, B. "Beyond Design: Effects of Surface Roughness on High-speed PCBs," *The PCB Design Magazine,* February 2015.
- Olney, B. "Beyond Design: Mythbusting–There Are No One-way Trips!" *The PCB Design Magazine,* April 2014.
- Olney, B. "Beyond Design: Plane Crazy, Part 1," *The PCB Design Magazine,* December 2015.
- Olney, B. "Beyond Design: Controlling the Beast," *The PCB Magazine,* December 2011.
- Olney, B. "Beyond Design: Return Path Discontinuities," *The PCB Design Magazine,* April 2017.
- Johnson, H., & Graham, M. *High-speed Signal Propagation: Advanced Black Magic,* Prentice Hall, 2003.

Barry Olney is managing director of In-Circuit Design Pty Ltd (iCD), Australia, a PCB design service bureau that specializes in board-level simulation. The company developed the iCD Design Integrity software incorporating the iCD Stackup, PDN, and CPW Planner. The software can be downloaded from www.icd.com.au. To read past columns or contact Olney, click here.

Tiny Silicon Nanoparticles Cement New Era for Ultra-high Capacity Batteries

Scientists believe that silicon could be the answer to your battery woes with the potential for a charge capacity 10 times larger than current lithium-ion batteries. Now, University of Alberta chemists have published research that studies the effect of nanostructuring the silicon within lithium-ion batteries to understand the importance of size.

In their research, the researchers examined silicon nanoparticles of four different sizes within highly conductive graphene aerogels. The results show that the smaller the particle, the less likely it is to crack or fracture upon lithiation

The next steps are to develop technology for creating silicon nanoparticles in a faster and less expensive way, making these tools more accessible for industry and technology developers.

The paper was published in *Chemistry of Materials.*

(Source: University of Alberta)