Rule of Thumb #4: Skin depth of copper

Eric Bogatin - January 03, 2014

This rule of thumb estimates the effective current distribution in a conductor at high frequency**:**

Skin depth = 2 microns at 1 GHz and scales with sqrt(f)

Remember: before you start using rules of thumb, be sure to read the Rule of Thumb #0: Use rules of thumb wisely. Previous Rule of Thumb: RoT #3, Signal speed on an interconnect.

At DC, current flows uniformly throughout a conductor. However, this is not the case when AC current flows. The redistribution of current in the signal and return path is usually referred to as the skin depth effect and associated proximity effect. These are really one and the same effect.

The figure below shows a simulation of the current density in the signal and return paths of a microstrip transmission line illustrating the two behaviors: current moves to the outer surface in each conductor, and signal and return currents move closer together.

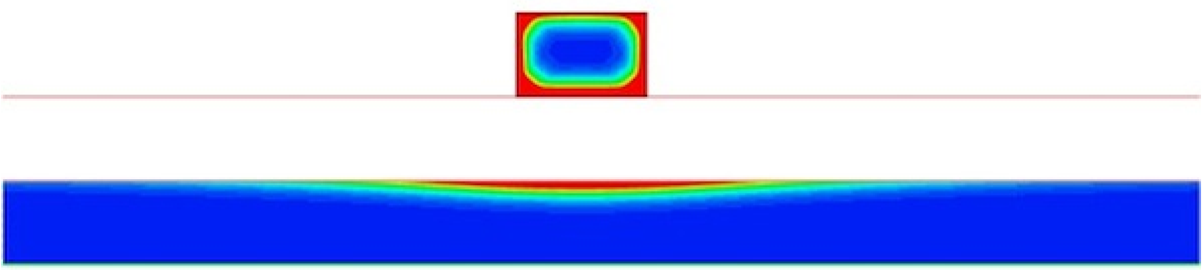

Figure 1. Current density in a microstrip at 100 MHz. Blue means no current, red means a lot of current. Simulated with ANSYS SI2D.

Sometimes, the words “skin depth” refer to the current re-distribution toward the outer surface of a conductor and the “proximity effect” refers to the re-distribution of signal and return currents closer to each other. It’s the combination of these two effects that give rise to the specific current distribution. These effects have the same origin and should not be considered two separate effects.

The origin of this current re-distribution can be thought of in two ways. In the fields view of the world, the changing AC current in the wire produces a changing magnetic field which induces a changing electric field which suppresses some of the currents in the center of each conductor, and in the other conductor. In the circuits approximation of the world, the current re-distributes to reduce the loop inductance. This translates to having the current spread out as much as possible in each conductor to reduce the self inductance and having the signal and return currents move as close together as possible to increase their mutual inductance.

Other than in infinitely wide or coaxial or cylindrical shaped conductors, it is really difficult to calculate the current distribution in conductors with pencil and paper.

Planar geometries like stripline or microstrip require a 2D field solver to calculate their current distribution at a specific frequency. But, it can be roughly approximated. In general, the current density will drop off exponentially into the surface of the conductor. The depth at which the current density has dropped by 1/e is called the skin depth.

If the geometrical thickness of the conductor is large compared to the skin depth, the conductor resistance is equivalent to having all the current uniformly distributed in a thickness equal to the skin depth. This makes the skin depth a useful figure of merit to describe the effective thickness of the current distribution.

For the case of wide and thick conductors, the skin depth can be analytically calculated as

$$\delta = \sqrt{\frac{1}{\sigma \pi \mu_0 \mu f}}$$

Where
σ = the conductor conductivity
μ_0 = permeability of free space
μ = relative permeability for the conductor
f = the sine wave frequency

For the special case of Copper, the skin depth is

$$\delta = \sqrt{\frac{1}{\sigma \pi \mu_0 \mu f}} \sim 2\mu \sqrt{\frac{1}{f[\mathrm{GHz}]}}$$

This is a very powerful rule of thumb. The skin depth for copper is about 2 microns at 1 GHz and scales inversely with the sqrt(f).

For example, if the skin depth is thinner than the rms roughness of the copper, most of the current will be traveling in the rough part of the copper, so the series resistance, and conductor loss, will increase more rapidly than the sqrt(f). A typical rms thickness is about 2 microns. Surface roughness will increase the series resistance of copper traces above 1 GHz.

Try these two simple examples:

1. At what frequency is the skin depth about the geometrical thickness of ½ oz copper, 17 microns? Above this frequency, the resistance of a trace will be frequency dependent.

2. At 100 Hz, close to the line frequency, what is the skin depth of copper?

Next rule of thumb: RoT #5: The capacitance per length of all 50 Ohm transmission lines

Also See:

- RoT #3, Signal speed on an interconnect
- RoT#2 Signal bandwidth from clock frequency
- PCB Design Basics
- Profiles in Design: Eric Bogatin