

## 6.17 High-Permeability Materials

There is an important term affecting skin depth that applies to only a few special materials. This term is the *permeability of the conductor*. Permeability refers to how the conductor interacts with magnetic-field line rings. Most metals have a permeability of 1 and they do not interact with magnetic-field line rings.

However, when the permeability is greater than 1, the number of field line rings in the metal is amplified over what would be there if the permeability were 1. There are only three metals that have a permeability other than 1. These are the ferromagnetic metals: iron, nickel, and cobalt. Most alloys that contain any combination of these metals have a permeability much greater than 1. We are most familiar with ferrites, which usually contain iron and cobalt and can have permeabilities of over 1,000. Two important interconnect metals are ferromagnetic: Alloy 42 and Kovar. The permeability of these metals can be 100–500. This high permeability can have a significant impact on the frequency dependence of the resistance and inductance of an interconnect made from these materials.

For a ferromagnetic wire, at DC frequency, the self-inductance of the wire will be related to the internal and external self-inductance. All the field line rings that contribute to the external self-inductance see only air, which has a permeability of 1. The external self-inductance of a ferromagnetic wire will be exactly the same as if the wire were made of copper. After all, for the same current in the wire, there would be the same external-field line rings per amp of current.

However, the internal-field line rings in the ferromagnetic wire will see a high permeability, and these magnetic-field line rings will be amplified. At low frequency, the inductance of a ferromagnetic wire is very high, but above about 1 MHz, all the field line rings are external and the loop self-inductance is comparable to a copper loop of the same dimension.

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**TIP** The loop inductance that high-speed signals would encounter in a ferromagnetic conductor is comparable to the loop inductance if the conductor were made from copper, since above the skin-depth limit the loop inductance is composed almost solely of external-field line rings.

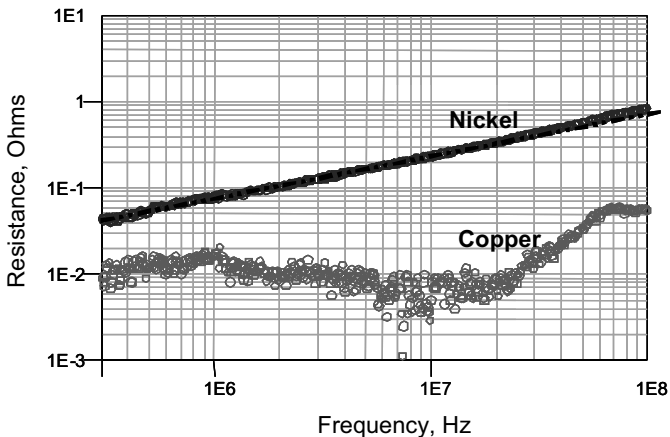
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The skin depth for a ferromagnetic conductor can be much smaller than for a copper conductor, due to its high permeability. For example, nickel, having a bulk conductivity of about  $1.4 \times 10^7$  Siemens/m and permeability of about 100, has a skin depth of roughly:

$$\delta = 13 \text{ microns} \sqrt{\frac{1}{f}} \quad (6-32)$$

At the same frequency, the cross section for current in a nickel conductor will be much thinner than for an equivalent-geometry copper conductor. In addition, the bulk resistivity is higher. This means the series resistance will be much higher. Figure 6-27 shows the measured series resistance of 1-inch-diameter rings of copper wire and nickel wire of roughly comparable cross section. The resistance of the nickel wire is more than 10 times higher than that of the copper wire and is clearly increasing with the square root of frequency, which is characteristic of a skin-depth-limited current distribution. This is why the high-frequency resistance of Kovar or Alloy 42 leads can be very high compared to nonferromagnetic leads.

Surface microstrip traces on circuit boards are often plated on their top surface with a nickel/gold layer to facilitate solder-attach of components. This nickel layer has virtually no impact on the electrical properties of the trace because it is on the other side of the trace from the return path. The current will travel the path of lowest impedance, which is not through the nickel layer. If the conductor were solid nickel, the resistance and inductance would be strongly frequency dependent. With the thick copper on one side, all the current can flow through the lower-impedance path in the copper.



**Figure 6-27** Measured resistance of a 1-inch-diameter loop of copper wire and nickel wire, of roughly the same cross section, showing much higher resistance of the nickel conductor, due to skin-depth effects. The resistance increases with the square root of frequency, shown by the superimposed line. The noise floor of the measurement was about 10 milli-Ohms.

This is why a plating of silver is sometimes applied to Alloy 42 leads to limit their resistance at high frequency. It provides a nonferromagnetic conductor on the outer surface for high-frequency currents to travel. The highest frequency components will experience a larger skin-depth and the higher conductivity material.

The precise resistance of a conductor will depend on the frequency-dependent current distribution, which, for arbitrary shapes, may be difficult to calculate. This is one of the values of a good 2D field solver that allows the calculation of frequency-dependent current distributions and the resulting inductance and resistance.

## 6.18 Eddy Currents

As mentioned previously, if there are two conductors and the current in one changes, there will be a voltage created across the second, due to the changing mutual magnetic-field line rings around it. This voltage induced in the second conductor can drive currents in the second conductor. In other words, changing the current in one conductor can induce current in the second conductor. We call the induced currents in the second conductor *eddy currents*.

There is an important geometry where eddy currents can significantly affect the partial self-inductance of a conductor and the loop self-inductance of a current loop. This geometry occurs when a loop is near a large conducting surface, such as a plane in a circuit board or the sides of a metal enclosure.

As the simplest example, consider a round wire above a metal plane. It is important to keep in mind that this metal plane can be any conductor and can float at any voltage. It does not matter what its voltage is, or what else it is connected to. All that is important is that it is conductive and that it is continuous.

When there is current in the wire, some of the field line rings will pass through the conducting plane. There will be some mutual inductance between the wire and the plane. When current in the wire changes, some of the magnetic-field line rings going through the plane will change and voltages will be induced in the plane. These voltages will drive eddy currents in the plane. These eddy currents will, in turn, produce their own magnetic fields.

By solving Maxwell's Equations, it can be shown that the pattern of the magnetic-field line rings generated by the eddy currents looks exactly like the magnetic-field lines from another current that would be located below the surface of the plane (i.e., a distance below equal to the height above the plane of the real current). This is illustrated in Figure 6-28. This fictitious current is called an *image current*. The direction of the image current is opposite the direction of the