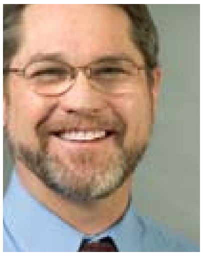

BY HOWARD JOHNSON, PhD

In-between spaces

I measured the inductance of four loops of wire. Each loop comprises the same length of insulated #10 AWG solid-copper wire (**Figure 1**). During testing, I probe the wires at their endpoints (bottom of **figure**), holding the wires vertically above the tester and well away from all other metal objects.

The leftmost loop, the round one, has a diameter of 10 in. It gives the largest inductance at 730 nH. Moving to the right, the inductance drops in each case until you reach the final loop, the twisted wire, at 190 nH.

I mention this simple experiment because I have all too often heard engineers say: "My via has an inductance of 1 nH," or "My bypass capacitor has an inductance of 500 pH." Those statements assume that you can ascribe discrete inductances to individual portions of a signal path.

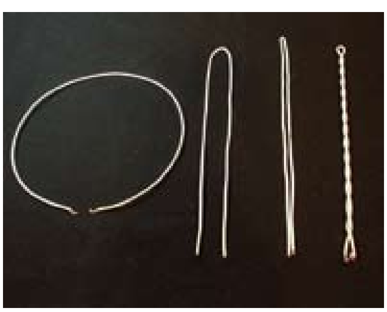

Figure 1 Each loop of wire is the same length, yet they each have inductances, from left to right, of 730, 530, 330, and 190 nH.

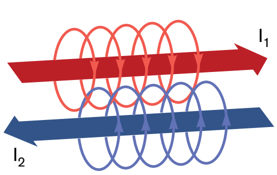

Figure 2 Magnetic fields from the outgoing current (red) nearly cancel the equal-but-opposite magnetic fields from the returning signal current.

That assumption is a good one when dealing with macroscopic components. According to Kirchhoff's laws for circuit analysis, the total inductance of two inductors in series should equal the sum of their independent inductances.

The correctness of Kirchhoff's analysis hinges upon a crucial precondition, namely that no significant electromagnetic fields inhabit the spaces between conductors. High-speed digital currents infuse the spaces between conductors with massive, fast-changing electromagnetic fields. These digital circuits do not meet Kirchhoff's precondition; therefore, Kirchhoff's laws are invalid in the high-speed domain.

In high-speed electronics, you must supplement Kirchhoff's laws with parasitic capacitance, due to electric fields, and parasitic inductance, due to magnetic fields.

Figure 2 illustrates the pattern of magnetic fields surrounding two wires. The wires carry equal and opposite currents, much like the hairpin structures in **Figure 1**. Imagine current I_1 going out on one wire, changing direction at a hairpin turn, and returning as I_2 on the other wire.

If you observe from a remote distance, the magnetic fields that I_1 generates nearly cancel the equal-but-opposite magnetic fields that I_2 generates. The closer you bring the wires, the better the cancellation, and the smaller the overall magnetic-field energy.

Inductance L represents nothing more and nothing less than the total magnetic-field energy, E, surrounding a current-carrying circuit. The precise relation between inductance and field energy is:

$$E=\frac{1}{2}LI^2.$$

If the spacing between wires affects the stored magnetic energy, then the spacing affects the circuit inductance, as well.

This interaction between magnetic fields explains why you cannot ascribe inductance to one part of a distributed circuit without also specifying the shape and location of the complete signal-current path. It might increase or decrease the inductance. All parts of the path influence the inductance.

For example, the inductance of a via depends on the location of nearby interplane connections. The inductance of a bypass capacitor depends on its proximity to the reference planes.

Inductance is not a property of an individual component. In distributed circuits, inductance is a property of the spaces between conductors. EDN

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