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TECHNICALTIDBITS

MATERION PERFORMANCE ALLOYS

A signal of high integrity. – How high frequency electrical signals are affected by the dielectric properties of surrounding materials.

- Permittivity (ε)
- Dielectric Constant (Dk or *k*) / Relative Permittivity (ε_r)
- Magnetic Permeability (μ)
- Relative Magnetic Permeability (μ_r)
- Drift Speed
- Impedance (Z)
- Capacitance
- Inductance
- Resonance
- Free Space Impedance (Z_0)
- Low k Dielectric

The next issue of Technical Tidbits will discuss the skin effect and skin depth.

DIELECTRIC PROPERTY EFFECTS ON HIGH FREQUENCY SIGNALS

The speed of an electromagnetic wave is a function only of the **permittivity (ε) and magnetic permeability (μ)** of the medium it travels through. In a vacuum, these are the free space permittivity ($\varepsilon_0 = 8.854 \times 10^{-12}$ F/m) and free space permeability ($\mu_0 = 4\pi \times 10^{-7}$ H/m). So, the speed of light in a vacuum is as follows: $c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$ (If you are curious, a Farad is an A•s/V, and a Henry is a V•s/A, so the units do work out to m/s). Air has approximately the same permeability and permittivity as vacuum, so the speed of light in air is approximately the same as in a vacuum.

If you have an electrical signal propagating in a circuit, or an electromagnetic wave travelling through a medium other than vacuum or air, its speed is:

$$v = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{1}{\sqrt{\mu_0\mu_r\varepsilon_0\varepsilon_r}} = \frac{1}{\sqrt{\mu_0\varepsilon_0}} \bullet \frac{1}{\sqrt{\mu_r\varepsilon_r}} = \frac{c}{\sqrt{\mu_r\varepsilon_r}}$$

The relative magnetic permeability and the relative permittivity of the medium and the surrounding media effectively slow the signal down from the speed of light, since **relative magnetic permeability (μ_r)** and **relative permittivity (ε_r)** [also known as **dielectric constant (Dk or *k*)**] are almost always equal to or greater than 1. Astute readers will note that some diamagnetic materials (more on this in a future issue) have a relative magnetic permeability slightly less than 1, but they will have a relative permittivity greater than 1, thus ensuring that the universal speed limit is safe.

Interestingly, while the signal travels near the speed of light, the speed of the electrons moving through a conductor (known as the electron **drift speed**) is much, much lower. Namely, $v_d = \frac{I}{q \bullet n \bullet A}$, where I is the current in Amps (Coulombs per second), q is the charge of each electron in Coulumbs, n is the charge carrier density (number of carriers per cubic meter), and A is the cross sectional area of the conductor in square meters. For constant current, the drift speed decreases as the cross sectional area increases. For 1 amp of current, this would be about 81 millimeters per second in 56 gauge copper wire and 172 nanometers per second in 0 copper gauge wire, assuming 2 available conduction electrons per copper atom.

Impedance (Z) is the ratio of voltage to current in a circuit element (*Z=V/I*). In an ideal resistor, this is exactly equal to the resistance by Ohm's law (*V=IR*). The units of impedance are always in ohms. Real circuits and circuit elements also have **capacitance** (energy stored in electric fields) and inductance (energy stored in magnetic fields.) **Inductance** is determined by the geometry of the circuit (specifically, the area enclosed by the circuit loop), as well as the change in current over time through the particular circuit element in question. Capacitance is affected by dielectric constant, geometry and distance between circuit elements, and the change in voltage over time through the element.

The impedance of a circuit element is as follows, where f is the frequency of the signal passing through the element in Hz: $Z = \sqrt{[R^2 + (wL - 1/wC)^2]}$, where $w = 2\pi f$. Impedance of a circuit therefore increases with frequency if it is mainly inductive ($wL > 1/wC$), and decreases with frequency for if it is mainly capacitive ($wL < 1/wC$). If ($wL = 1/wC$), then the circuit is said to be in **resonance**. In resonance, the impedance is minimized, which means that the current reaches its maximum for a given voltage. Electromagnetic waves traveling through vacuum or air also experience impedance. This is called the **free-space impedance (Z_0)**. It is calculated as follows: $Z_0 = \sqrt{(\mu_0 / \varepsilon_0)}$, which is equal to 377 ohms.

As discussed last month, the capacitance of two charged conductors can be increased by putting a dielectric medium between them. This effect occurs not just in capacitors, but also in circuits. So, the dielectric materials used in circuit construction will have an effect on the impedance of these circuits as well. Note that the dielectric constant of a composite material like a circuit board will depend on the resin and the filler materials (how much filler, what type, what orientation, what density, etc), so it can easily vary from lot to lot, while ceramic materials have much less variation.

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DIELECTRIC PROPERTY EFFECTS ON HIGH FREQUENCY SIGNALS (CONTINUED)

An electrical circuit only works when it is a closed loop. Signals move through the circuit when a voltage source produces a change in voltage, which moves through the circuit at the speed of light in that circuit as discussed above. Theoretically, the signal moves out along the signal line, through the load at the end, and then back through the return line. However, what actually happens is when the voltage source produces this signal, a positive charge propagates out of one terminal and negative charge comes out of the other.

As the signal moves down the line, the signal line and the return line have opposite charges. So we have two conductors in close proximity with equal and opposite charge, and they effectively form a capacitor. Therefore, the capacitance of the circuit will be influenced by the dielectric constant of the medium between the signal and return paths. Of course, they will also be capacitance between this circuit and ground, this circuit and other circuits, etc. But if this circuit is well shielded, or uses a controlled impedance line like coaxial cable, microstrip, or stripline, then the characteristic impedance of the line will be dominated by the relative permittivity of the dielectric medium between the signal and return paths.

When the dielectric constant of the medium is large, more energy is stored in the electric field between the signal and return line, more energy is dissipated by the dielectric, and the signal speed is reduced as discussed earlier. This is why you will hear talk about **low k dielectrics**, which means dielectrics with lower relative permittivity. (Here, the English letter "k" is substituted for the Greek letter "κ").

On a final note, many circuit simulation programs require dielectric constant as a material property. This is appropriate for circuit boards, insulators, and dielectric materials such as those in circular and military connectors used to keep the electrical contacts electrically separated. The dielectric constant has no physical meaning for conductors such as the copper traces on circuit boards or for electrical contacts, and cannot be measured or specified.

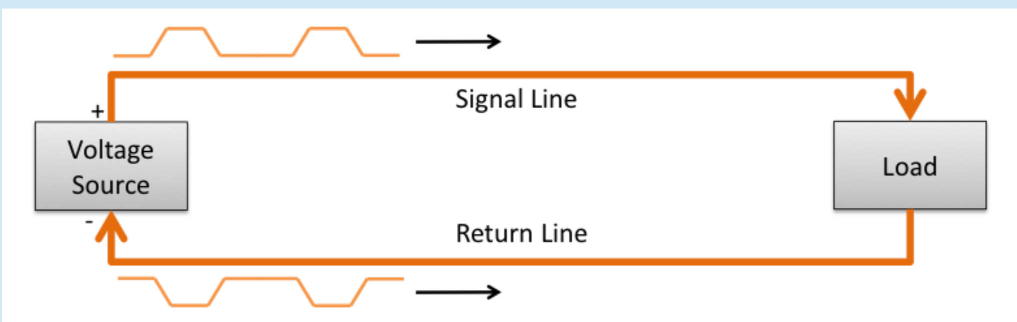

Figure 1 – Signal Propagating Along a Circuit Path.
Equal and opposite voltage changes leave the source and propagate toward the load at the speed of light in the circuit.

Written by Mike Gedeon of Materion Performance Alloys Marketing Department. Mr. Gedeon's primary focus is on electronic strip for the automotive, telecom, and computer markets with emphasis on application development.

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Materion Performance Alloys
6070 Parkland Blvd.
Mayfield Heights, OH 44124

MATERION

Sales
+1.216.383.6800
800.321.2076
BrushAlloys@Materion.com

Technical Service
+1.216.692.3108
800.375.4205
BrushAlloys-Info@Materion.com

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