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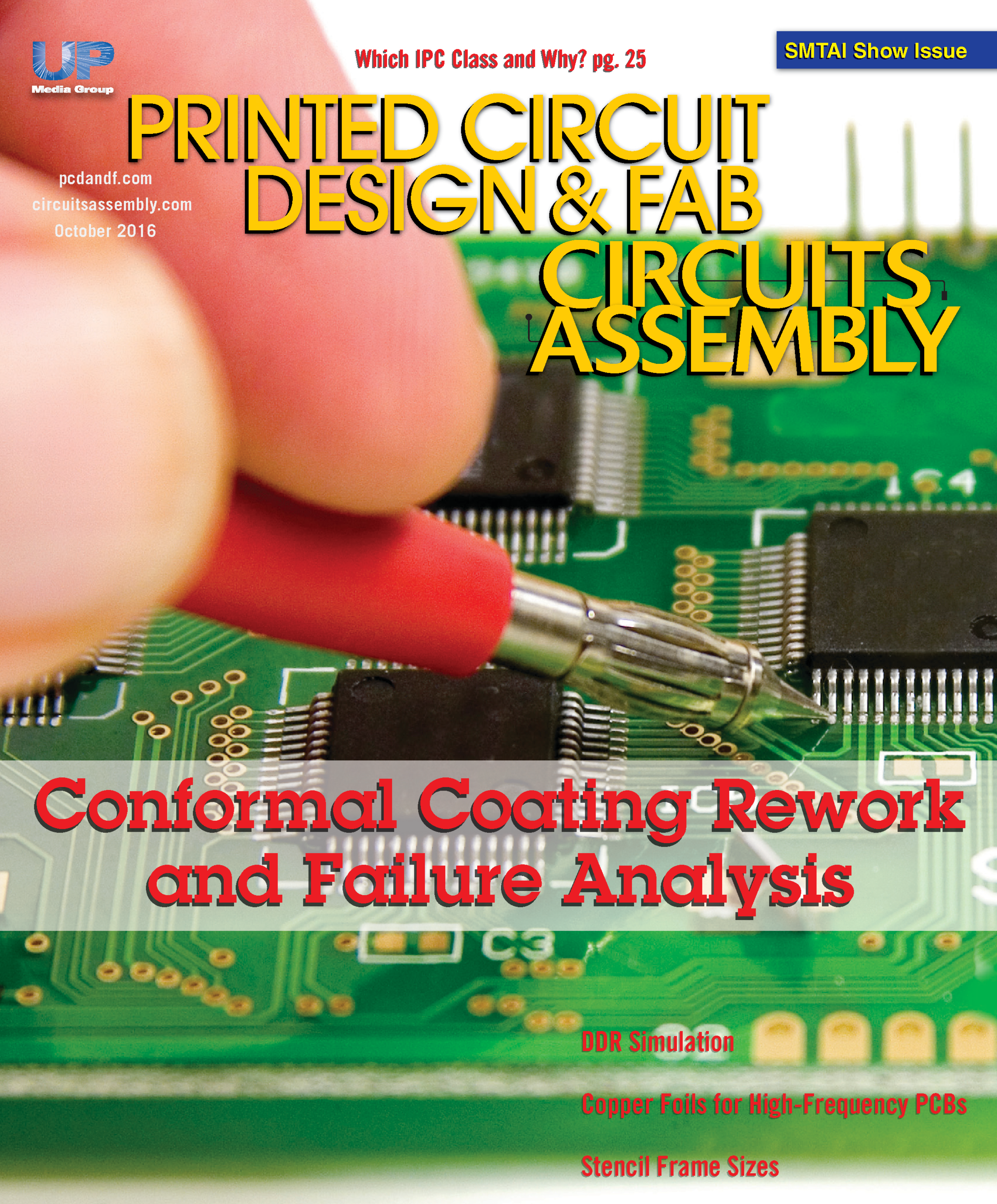

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CHOOSING COPPER FOILS for High-Frequency PCBs

Thinner materials for microwave boards benefit from smooth surfaces to decrease insertion loss. **by JOHN COONROD**

The contributions of copper foil to the performance of high-frequency printed circuit boards (PCB) would seem simple: how different can the types of copper be? As signal frequencies increase into the microwave and millimeter-wave regions, however, the effects of a PCB's copper foil also increase, requiring careful consideration of the different copper types at these higher frequencies.

Two main types of copper are used in PCBs: electrodeposited (ED) copper and rolled wrought copper. Each type, in turn, has many possible variations, with the most choices available for ED copper. To add to the complexity of choosing copper for a high-frequency circuit laminate, many copper treatments are available for the two foil types. The same type of ED copper processed with two different treatments can yield two different levels of circuit performance.

For high-frequency circuits, a number of copper foil characteristics are important. Many PCBs used for high-frequency circuit assemblies are actually hybrids composed of different types of PCB materials, for example, with different material layers for power, digital control and high-frequency signals. **FIGURE 1** shows a simple cross-sectional view of a hybrid multilayer circuit structure, where copper layers 1 (top) and layer 2 are the critical layers for high-frequency performance.

The top copper layers form a simple circuit with high-frequency microstrip transmission lines, where layer 1 is the signal conductor, and layer 2 is the ground plane. Most of the electric fields for the high-frequency waves propagating on this medium are between the bottom of layer 1 and top of layer 2; however, there is a higher concentration of the electric fields at the edges of the signal conductor. **FIGURE 2** provides a simple illustration of the electric fields and current density for a microstrip transmission line on a PCB.

Skin depth is the amount of the conductor used by the RF current for a high-frequency signal. In general, skin depth is frequency-dependent; at lower frequencies, the RF current will use more of the cross-sectional area of a conductor than at higher frequencies. The opposite is true at higher frequencies, where the RF current uses very little of the cross-sectional area of a conductor.

Treatments are applied to copper foils typically for a few reasons. For one thing, a treatment can help enhance the bond between the copper foil and the substrate material. For another, a treatment can improve the thermal robustness of the copper-substrate interface, permitting the bond to survive higher temperatures or wider temperature ranges. A third reason is because a treatment can be an antioxidant that prevents the surface of the copper foil from oxidizing prior to its attachment to the substrate material. A treatment for copper is typically itself not copper and will not have the high conductivity of copper.

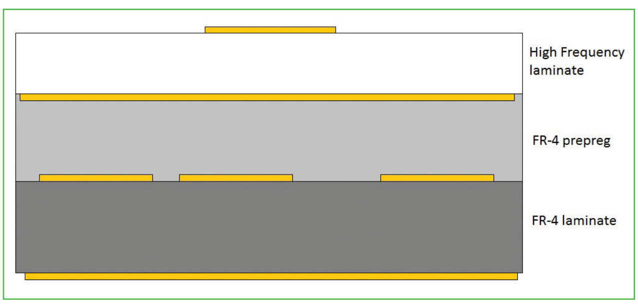


FIGURE 1. Hybrid multilayer high-frequency PCB.

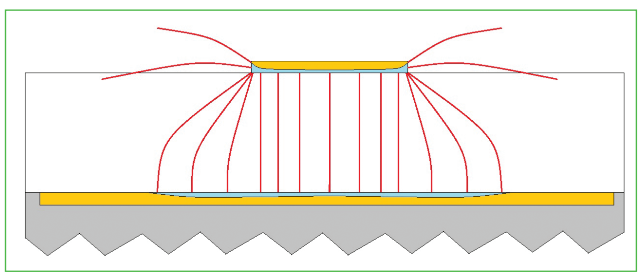
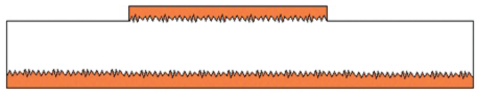


FIGURE 2. Simple illustration of the electric fields (red lines) and current density (blue shading) for a microstrip transmission line circuit.



Freq. (GHz)	Skin Depth (mils)	Skin Depth (microns)
0.01	0.822	20.87
0.5	0.116	2.95
1	0.082	2.09
5	0.037	0.93
10	0.026	0.66
30	0.015	0.38
50	0.012	0.30
80	0.009	0.23

Copper Type	Typical Roughness RMS or Rq (microns)
Rolled annealed copper	0.3
Reverse treat VLP ED copper	0.6
Reverse treat LP ED copper	1.0
Standard ED copper	1.6
High profile ED copper	2.2

FIGURE 3. Cross-sectional view of a microstrip circuit showing an exaggerated image of copper surface roughness, with data tables for typical RMS copper surface roughness values and skin depths at different frequencies.

Most metals and alloys used in PCBs are less conductive than copper, which is true for most of the treatments used on copper foils. At high frequencies, the reduced conductivity that results from a copper treatment can increase insertion loss.

As seen in Figure 2, the current density is high at the copper-substrate interface, which is the surface of the copper foil on which a treatment has been applied. Because signal wavelengths shrink in size with increasing frequencies, the current density at higher frequencies will be concentrated closer to the surface of a PCB and to the area of this interface, a phenomenon known as skin depth. As a result, at higher frequencies, any copper treatment that affects the conductivity of the copper will also play a part in insertion loss performance. Any copper treatment that is significantly less conductive than copper will increase conductor loss, which is one of the loss components of the total RF loss at higher frequencies known as insertion loss.

Another item related to high-frequency conductors and conductor loss, with an impact on insertion loss, is the roughness of the copper surface.[1] Specifically, the roughness of the copper surface at the copper-substrate interface is a matter for concern. In general, a rough copper surface at this interface will cause an increase in insertion loss, especially at higher frequencies.

The effects of copper roughness on insertion loss are frequency-dependent due to skin depth. Electromagnetic (EM) waves will use more of a conductor at lower frequencies, with deeper skin depth, so the copper surface roughness will have less of an impact on insertion loss at lower frequencies. At higher frequencies, with shrinking skin depths and where less of the conductor is used, when the skin depth is about the same value or less than the value of the copper surface roughness, the copper surface roughness will have an increased effect on conductor loss and, ultimately, insertion loss.

FIGURE 3 shows a simple depiction of a microstrip circuit with exaggerated copper surface roughness at the copper-substrate interface. It can be seen in the table of information that at lower frequencies, such as 10MHz (0.01GHz), the copper surface roughness should have minimal or no impact on insertion loss. However, if a circuit employs high-profile ED copper, which is not uncommon, the copper roughness can affect insertion loss starting around 1GHz and will have substantial impact at 10GHz.

However, if a microstrip circuit is fabricated on circuit material with rolled copper, with a typical surface roughness of only 0.3µm root mean square (RMS), Figure 3 shows copper roughness will have negligible impact on insertion loss at 10MHz, 1GHz or 10GHz. Not until 50GHz or higher will this smoother copper surface have a noticeable effect on the insertion loss of a microstrip circuit.

The impact of copper surface roughness on insertion loss also depends on the thickness of the substrate material. The effects of copper surface roughness on insertion loss will be greater for thinner circuits

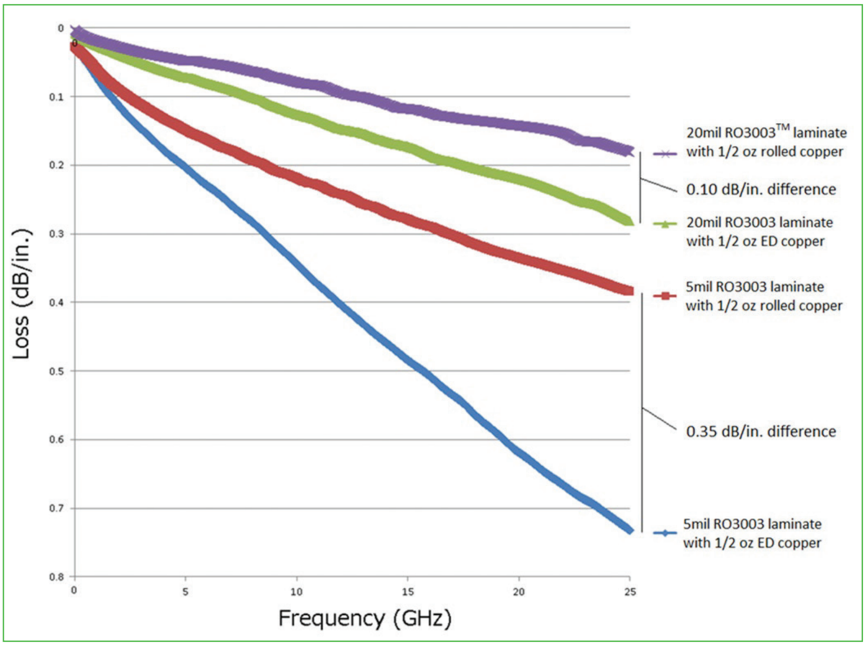


FIGURE 4. The insertion loss responses versus frequency are shown for the same PCB material with different thicknesses and different types of copper foil.

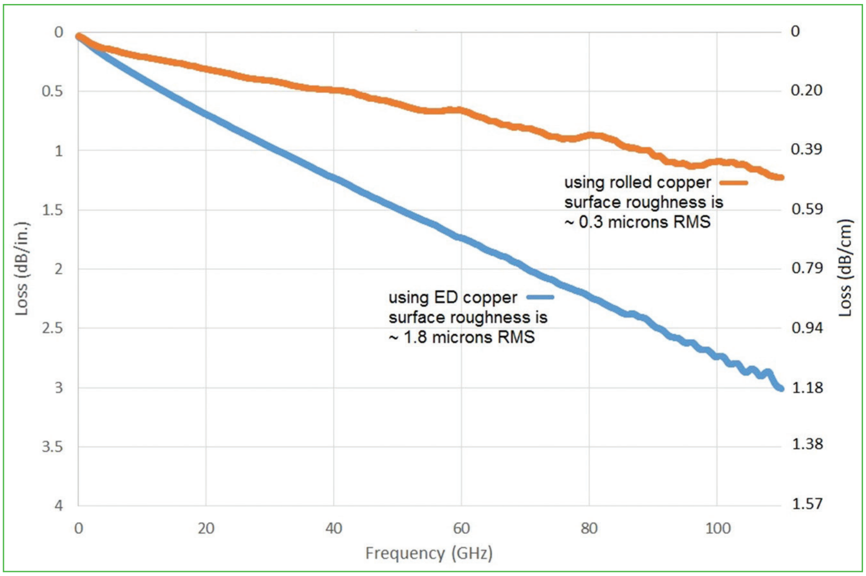


FIGURE 5. Microstrip insertion loss for the same 5-mils-thick PCB material is plotted vs. frequency for two different copper types.

than for thicker ones. Basically, when the copper planes of a microstrip circuit are closer together, such as with thinner substrates, the copper roughness will have a more significant effect on insertion loss. **FIGURE 4** plots the effects of substrate thickness and copper surface roughness on the insertion loss of microstrip circuits at microwave frequencies.

Figure 4 shows insertion loss test results for 50Ω microstrip transmission line circuits when using the same circuit substrate material, but with different thicknesses and different copper types. The main difference between the copper types is the amount of copper surface roughness. Rolled copper is smooth, with a surface roughness of about 0.3µm RMS, while ED copper has greater surface roughness, approximately 1.8µm RMS.

The purple curve at the top of the graph indicates the least amount of insertion loss, for circuits with the thicker (20 mil) substrate and smooth rolled copper. When using the same substrate and thickness but with ED copper and its rougher surface, there is an increase in insertion loss, as shown by the green curve in Figure 4. The difference in insertion loss between copper with smooth and rough surfaces for the 20-mil substrate is about 0.10dB/in. at 25GHz.

The next two curves in Figure 4 are based on thinner, 5-mil substrates with smooth and rough copper. The difference in insertion loss between copper with smooth and rough surfaces for the 5-mil substrate is about 0.35dB/in. at 25GHz. As these plots clearly show, the impact of copper surface roughness on insertion loss is very much a function of substrate thickness.

At millimeter-wave frequencies, roughly 30GHz to 300GHz, thinner circuit materials are typically needed to avoid unwanted wave propagation and minimize radiated energy. But, as **FIGURE 5** shows, thinner circuit materials will also show increasingly significant effects of copper surface roughness on insertion loss at millimeter-wave frequencies.

Copper surface roughness can impact the performance of high-frequency circuits in ways other than just insertion loss performance. For example, it has been found that copper surface roughness also impacts the propagation properties of electromagnetic waves resident on the circuit. The copper surface roughness can alter the phase constant of an EM wave,[2] changing the phase response of the circuit. One way to think of the phase response is to imagine a sine wave traveling along the circuit and noting the angle of the sine wave that occurs at the end of the circuit. A circuit comparison with only differences in smooth and rough copper surfaces will show each circuit to have a different angle of the sine wave at the end of the circuit.

Copper surface roughness can also affect the way that high-frequency EM waves travel through a PCB, by altering the dielectric constant (Dk) of the PCB material as it affects high-frequency transmission lines. As **FIGURE 6** shows through millimeter-wave

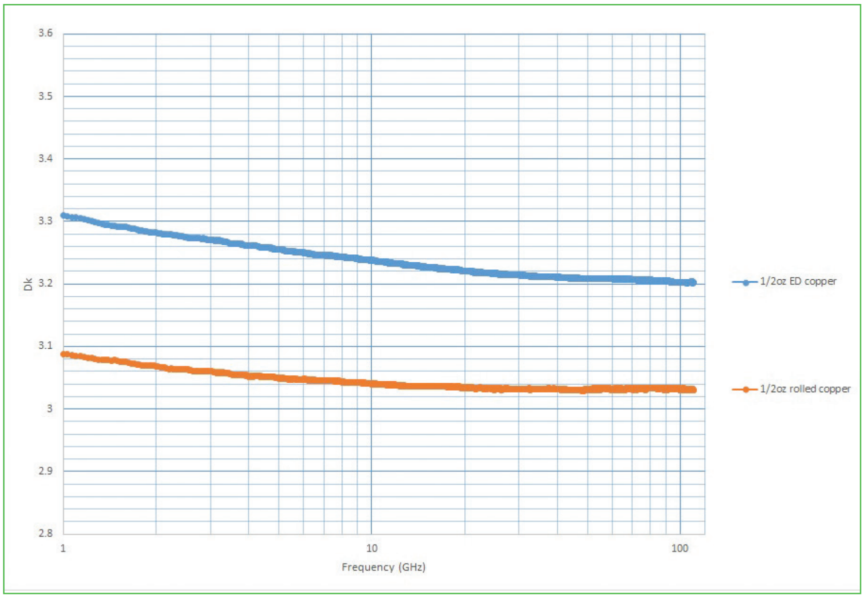


FIGURE 6. Dielectric constant vs. frequency curve for microstrip transmission line circuits on the same PCB material with different copper surface roughness.]

frequencies, for two circuit laminates based on the same substrate material and differing only by copper surface roughness, the same microstrip circuits see different values of Dk, which will result in differences in impedance for those microstrip transmission lines.

Figure 6 plots the Dk or dielectric constant (ε_r) for the same 5-mil circuit materials with two different copper types. The circuit material with smooth rolled copper exhibits a Dk approaching 3.0 at higher frequencies. The circuit material with ED copper and its rougher surface exhibits a Dk of about 3.2 or higher across the wide range of frequencies measured. In general, rougher copper will cause the Dk of a circuit material seen by a high-frequency microstrip circuit to be higher than the Dk of the same circuit material with smoother copper. It is worth noting the intrinsic Dk value for this 5-mil-thick circuit material is 3.0; when rolled copper is used, it has minimal impact on the Dk, even at millimeter-wave frequencies.

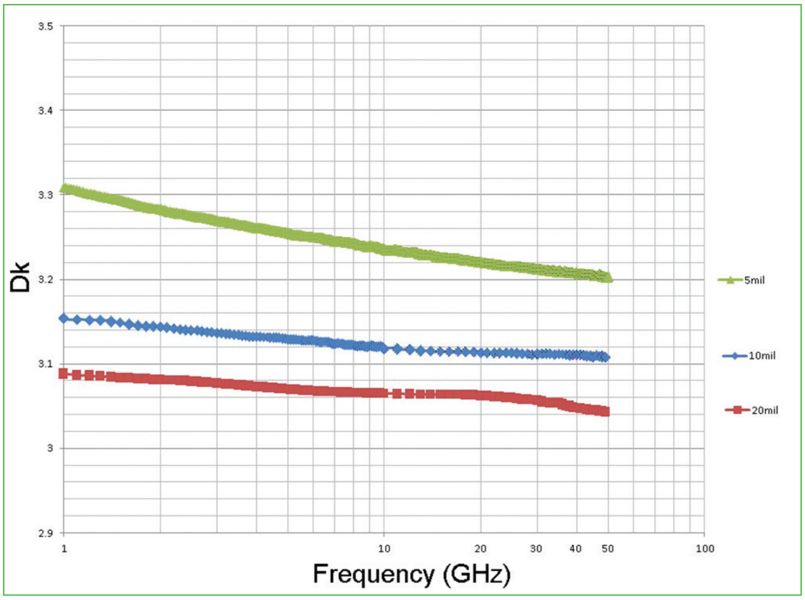


FIGURE 7. Dk vs. frequency curves for microstrip transmission line circuits, using the same circuit material and copper type (0.5 oz. ED) but differences in substrate thickness.

The influence of copper roughness on circuit perceived Dk is also dependent on the thickness of the circuit material. The Dk of a thinner circuit will be influenced more by copper surface roughness than the Dk of a thicker circuit.

FIGURE 7 shows Dk vs. frequency curves for microstrip circuits based on substrates with the same material and copper type, but having different thicknesses of 5, 10 and 20 mils. An ED copper with surface roughness of about 1.8µm RMS was used with a substrate having intrinsic Dk of 3.0. The apparent trend is that Dk decreases with increasing thickness of substrate, approaching the intrinsic Dk value of the material as the substrate thickness increases. With thicker circuit materials, the circuit's copper conductors are further apart, and the copper surface roughness has less impact on the circuit's phase response. As a result, there is less difference in Dk versus frequency for thicker circuit materials compared to an ideal circuit material with Dk of 3.0. For this particular circuit material and copper type, the Dk curve will approach a value of 3.0 for circuits of 50 mils or thicker.

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