本文说明选择用于高频印刷电路板设计的材料时要考虑的介电基板以及有关特性。随着无线通讯和宽带应用的发展，频率提高到1GHz以上，而且现在必须考虑无源电路元件。随着频率的提高，基板中的信号损耗更为显著。因此，选择基板材料对于设计的成功变得更为重要。检查材料种类时，聚合物和基板分别对层压材料的电气特性有主要影响。对于3-6 GHz范围内的印刷电路板设计，要考虑的主要问题包括趋肤效应、表面粗糙度、临近效应、电磁兼容性和介电基板。

Best Materials for 3-6 GHz DESIGN

Fighting signal loss at higher frequencies can be an uphill battle. But the right substrate can tilt the odds back into your favor. **by DOUG LEYS**

Wireless communication and broadband applications are moving digital circuitry into the analog world. High-speed circuit designs emphasize the usefulness of passive circuit elements. When designing below 1 GHz, passive elements such as the dielectric substrate can generally be ignored and standard FR-4 materials usually work very well. But as frequencies increase beyond 1 GHz, the passive circuit elements must be taken into account. Primary considerations for circuit design in the 3-6 GHz arena include skin effect, surface roughness, proximity effect, EMC and dielectric substrate. This article will cover dielectric substrates and the related properties to consider when choosing materials for your high-frequency design.

As frequencies increase, the amount of signal loss into the substrate becomes more significant. As a result, the choice of substrate material becomes more important to the success of the design. When examining material types, the polymer and the substrate each has a major influence on the electrical characteristics of the laminate materials. Most electrical laminates are made with e-glass. **TABLE 1** compares a range of polymers available on e-glass.

The two properties that primarily affect high-speed circuit design are dielectric constant and dissipation factor. Dielectric constant (Dk) or permittivity is the measurement of relative capacitance of insulating material to that of air or a vacuum. It is important to a high-speed circuit design because it directly affects the speed at which the signal travels. To calculate propagation delay due to the material's dielectric constant for a microstrip circuit we can use the following formula:

$$t_{pd} = 1.017\sqrt{\varepsilon eff}$$

Where:
t_{pd} = Propagation delay in nsec/foot
εeff = Effective relative dielectric constant of material

If we plug this equation into a spreadsheet and calculate the propagation delay over the frequency range of 1-10 GHz, we can quantify the effect of permittivity on propagation delay.

Three secondary properties affect the primary properties of permittivity and loss tangent, and these should be considered when deciding which laminate is best for high-frequency

TABLE 1. A Comparison of Polymers Available on e-glass

MATERIAL	MATERIAL TYPE	PERMITTIVITY (1 – 10 GHz)	LOSS FACTOR (1 – 10 GHz)
N4000-6FC	Standard FR-4	4.3 – 3.9	0.02 – 0.025
N4000-13	CE Modified FR-4	3.9 – 3.6	0.007 – 0.009
N8000	Cyanate Ester	3.65 – 3.5	.009 – .010
NY9000	Reinforced PTFE	2.2	0.001

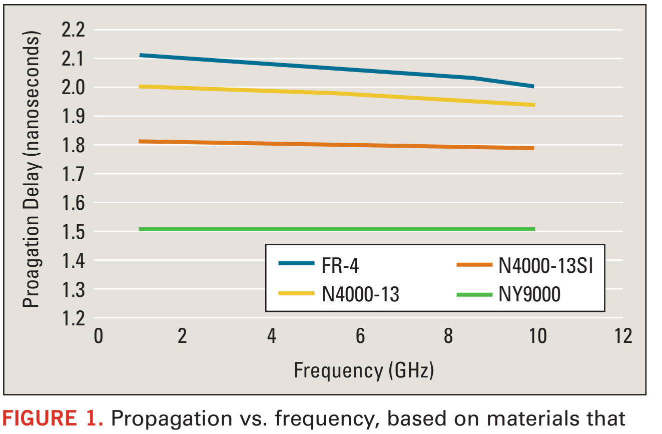

FIGURE 1. Propagation vs. frequency, based on materials that are 50% polymer, 50% e-glass.

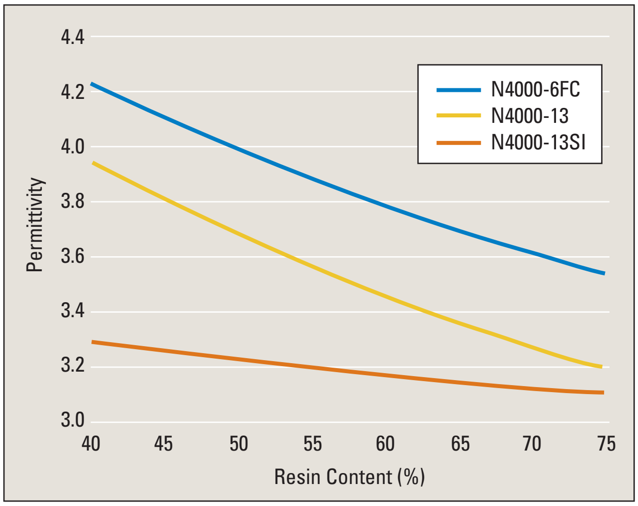

FIGURE 2. Permitivity vs. percent resin content.

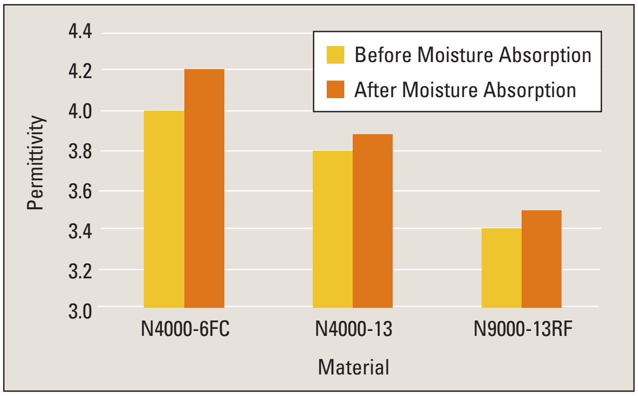

FIGURE 3. Three materials' permitivity, before and after moisture absorption.

design. They are resin percentage, moisture absorption and temperature. **FIGURE 1** is based on a material that is 50% polymer and 50% e-glass. If the resin content is changed, there is a corresponding change in permittivity and propaga-

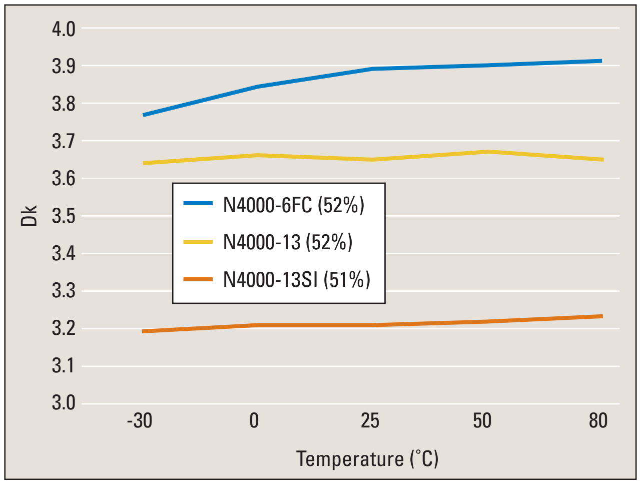

FIGURE 4. Dk vs. temperature at 10 GHz.

tion delay. **FIGURE 2** illustrates the magnitude of the effect of resin content within the range of typical prepreg and laminate.

Remember that different polymers absorb moisture at different rates. Since H20 has a very high permittivity (≈80), even a small amount of water can have a detrimental effect on a laminate material's performance. The numbers in **FIGURE 3** were generated by placing a material in a pressure cooker for one hour and retesting Dk and Df using a split post cavity at 2 GHz and 10 GHz. Figure 3 illustrates a 2-5% change in permittivity from moisture absorption.

Temperature is not a major factor in the range of ambient conditions, but if the temperature range is extreme it should be taken into account. Different materials are more or less stable when comparing permittivity over temperature. As **FIGURE 4** illustrates, a material such as N4000-13 not only starts out lower than standard FR-4 in permittivity but is also more stable over extreme temperatures.

Dissipation factor (Df) or loss tangent is the amount of energy dissipated (electrical loss) into an insulating material when voltage is applied to the circuit. It directly affects the

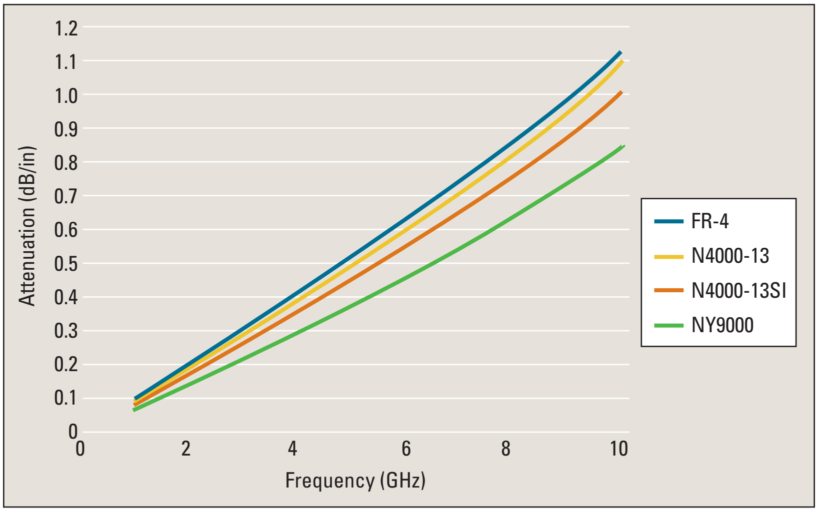

FIGURE 5. Attenuation vs. frequency at 5 GHz.

amount of signal loss or attenuation. The amount of attenuation can be estimated with the following formula:

$$\alpha = 2.3 \cdot f \cdot \tan(\delta) \cdot \sqrt{\varepsilon eff}$$

Where
α = Attenuation in dB/in
f = Frequency component in GHz
tan (δ) = Material dissipation factor
εeff = Effective relative dielectric constant of the material

If we plug this equation into a spreadsheet and calculate the attenuation from 1-10 GHz we can see that at higher frequencies the material's influence becomes more important. At 5 GHz and 20 inches of circuit length we will see an attenuation of -10.3 dB when using a standard FR-4. By using a low Dk/low loss product like N4000-13SI, the attenuation from materials drops 13% to -8.9dB. See **FIGURE 5**.

As with permittivity, loss tangent also suffers from moisture absorption, as shown in **FIGURE 6**. Here, too, the effect of moisture is greater on the standard FR-4 product. Less moisture yields the benefit of a lower loss tangent, as well as less variation.

But temperature also affects loss tangent. **FIGURE 7** illustrates how an increase in temperature causes a large corresponding increase in loss tangent for standard FR-4 products such as N4000-6FC, but has much less of an effect on a modified FR-4 such as N4000-13.

Composite permittivity is a function of the volume fraction. Since substrate can make up as much as 60% of the composite, the substrate used in the manufacture of prepreg and laminates can have a dramatic influence on the properties affecting high-speed design.

TABLE 2. Loss Tangent and Permittivity of e-glass and Two Alternatives, SI glass and an LCP Random Fiber Substrate, All Tested Between 3 and 5 GHz

SUBSTRATE MATERIAL	ε	TAN (δ)
e-glass	6.5	.006
SI glass	4.5	.004
LCP	2.9	.002

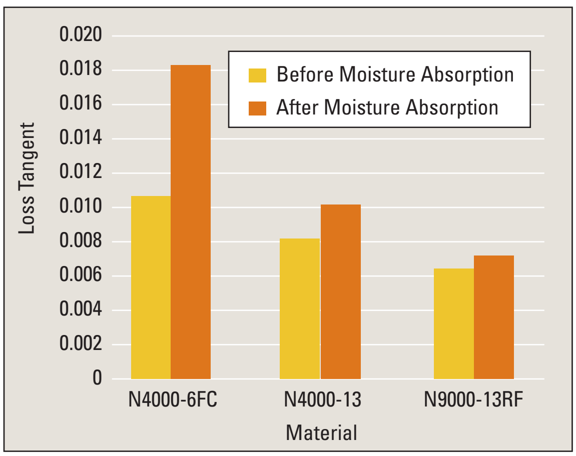

FIGURE 6. After moisture absorption, the N4000-6FC standard FR-4 has the biggest change in loss tangent.

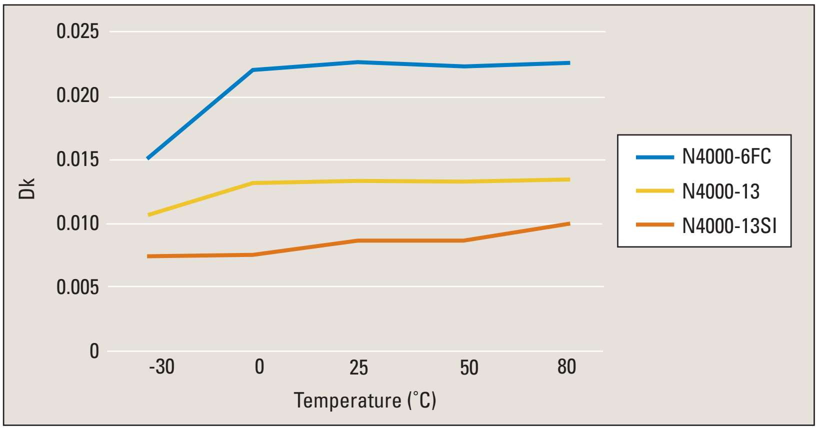

FIGURE 7. An increase in temperature also causes an increased loss tangent for the N4000-6FC standard FR-4.

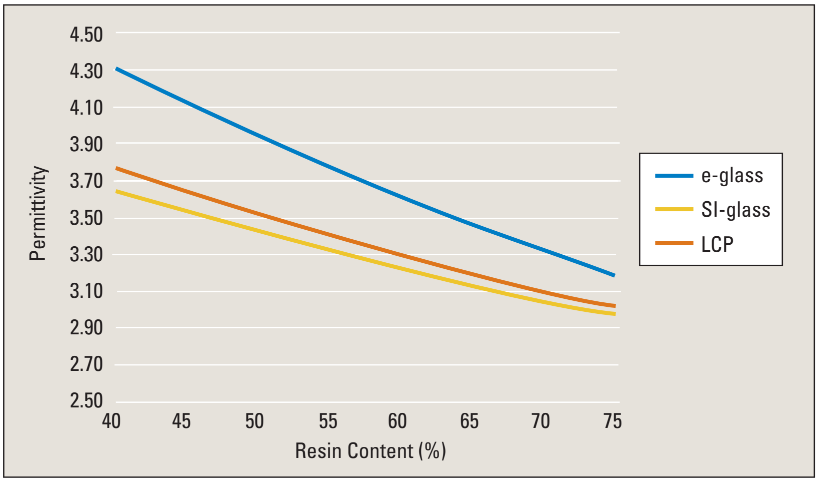

FIGURE 8. Resin content changes have have the biggest effect on the permitivity of substrates made with e-glass.

Several alternatives to e-glass are available. The Park Nelco e-glass alternative SI has both a lower permittivity and a lower loss tangent. The permittivity of this fiberglass is 4.5 as compared to 6.5 for typical e-glass. **TABLE 2** shows the permittivity and loss tangent for e-glass, SI glass and an LCP random fiber substrate. All were tested between 3 and 5 GHz.

Figure 2 illustrates a good example of what happens when a dielectric substrate's permittivity is more closely matched to the polymer. The resin content changes have less effect on the composite permittivity of N4000-13SI than they have on N4000-13. If we make a prediction of the permittivity of N4000-13 manufactured with e-glass, SI glass and LCP we see the dramatic effect that a substrate can have on permittivity. See **FIGURE 8**.

There are many more resin systems and other substrates available for applications in the 3-6 Ghz range. However, the properties to evaluate will be the same. Of course, there are other factors to consider as well, with ease of processing and cost being at the top of the list. **PCD&M**

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