Benefits of Mixed Dielectrics When Used for High-Frequency PCB Applications

By John Coonrod, Rogers Corporation, Advanced Circuit Materials Division

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Multilayer printed-circuit boards (PCBs) can provide many advantages to RF/microwave circuit designers in terms of achieving high functional density in a small size, while also improving reliability and cutting cost. As some designers have found, the multiple layers need not be the same dielectric materials: a growing number of RF/microwave circuit designs are being implemented with hybrid multilayer PCBs, in which different materials are used among the layers. This allows the choice of materials to be tailored to the various functions on the different layers of the PCB. Of course, there are some areas of concern when adopting such a design approach, and this article will provide a simple overview of these hybrid multilayer PCBs in terms of fabrication, electrical performance, and the types of circuit materials that are suitable for hybrid multilayer PCBs.

One circuit material that is used quite often in high-frequency hybrid multilayer PCBs is FR-4, although it may not be the most ideal choice for some circuits. Low-cost FR-4 circuit materials have been in use for a wide range of circuits for decades. FR-4 is glass-reinforced epoxy laminate material. Its performance is predictable and reliable, and it can be processed with basic fabrication methods. However, FR-4 exhibits a very high dissipation factor, which translates into high dielectric losses for circuits at microwave frequencies. Because of its loss characteristics, FR-4 is typically not used for pure RF/microwave circuits, but has been used in some high-frequency hybrid multilayer PCBs for various reasons.

FR-4 is available in standard grade and with high glass transition temperature (Tg), which is the temperature at which the modulus of the material will change dramatically. Such temperature changes can impact the reliability of plated through holes (PTHs) through the laminate, as used to interconnect different circuit layers in a multilayer PCB. Some high-Tg FR-4 materials provide good stability with the processing temperatures required for many circuit fabrication techniques, with relatively low coefficient of thermal expansion (CTE) in the z-axis for good PTH reliability.

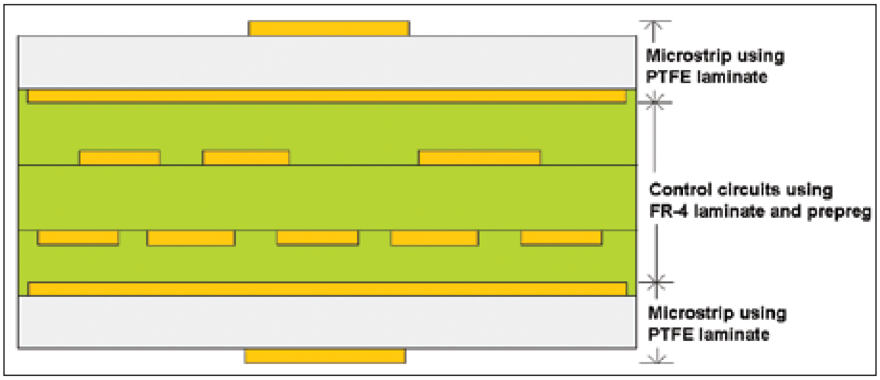

Figure 1 • This hybrid multilayer PCB combines FR-4 and PTFE circuit materials.

In contrast, some high-frequency circuit materials which are based on polytetrafluoroethylene (PTFE) have high CTE values and can suffer from excessive material expansion when subjected to the elevated temperatures of some circuit fabrication processes. Combinations of low-CTE FR-4 and high-CTE PTFE circuit materials are sometimes used to fabricate composite circuits, with the different circuit materials handling different circuit functions. The composite circuit with the two materials yields an acceptable CTE for handling the temperatures of many fabrication processes as well as some end-use applications. Figure 1 shows an example of such a multifunction, multilayer circuit, where high-frequency microstrip-based circuits are separated by FR-4 control circuitry.

PTFE laminates are commonly used for RF/microwave circuits due to their excellent electrical performance at higher frequencies. PTFE circuit materials typically exhibit a dissipation factor of around 0.002, signifying very low dielectric loss, whereas FR-4 materials typically have a dissipation factor of around 0.020 for much higher dielectric losses. The CTE values of the two materials are also much different, but the relatively low CTE of FR-4 can be an advantage in a multilayer circuit construction. The CTE for PTFE material is about 200 ppm/°C, compared to about 50 ppm/°C for some high-Tg FR-4 materials. But when the two circuit materials are combined, as in the multilayer circuit of Fig. 1, the CTE of the FR-4 layers helps to lower the overall CTE of the multilayer circuit.

The dimensional stability of FR-4 circuit materials can also benefit hybrid multilayer constructions also using PTFE. Those PTFE circuit laminates which are not reinforced with woven glass in the manner of FR-4 are less stable dimensionally than PTFE laminates with such reinforcement. But in a hybrid multilayer circuit with PTFE, the added FR-4 layers are typically reinforced by woven glass, improving the overall dimensional stability of the multilayer construction.

DuPont™ Teflon® fluoropolymer resins and other PTFE materials have a reputation for being “non-stick” in nature, where organic materials will not adhere to the PTFE. With such a reputation, it is easy to understand why many would believe that it would be difficult to bond FR-4 materials to PTFE, but this is not necessarily the case. Most FR-4 prepreg materials will bond quite well to a PTFE laminate, provided that the surface of the PTFE is properly prepared. A large part of this preparation involves ensuring that the surface of the PTFE laminate is clean and undisturbed after the cop-

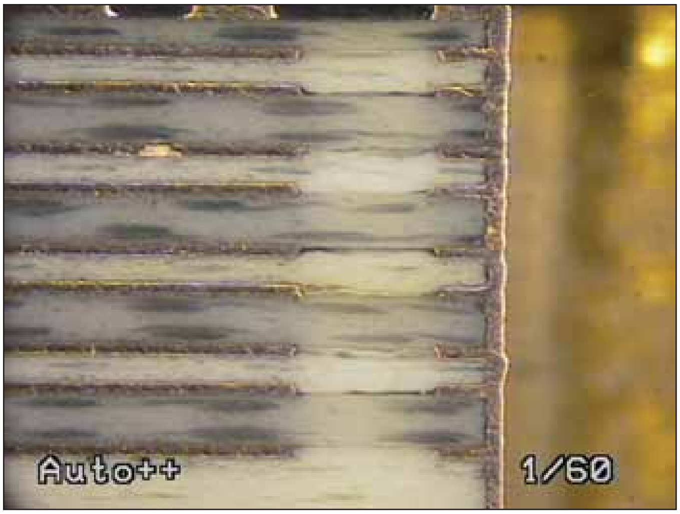

Figure 2 • The low-pressure areas formed in some PCB constructions can lead to resin separation (space between conductors which are stacked on top of each other) when using a low-flow prepreg material.

per has been etched to form the circuit traces. Following the etching of the copper to form the circuit patterns on the PTFE laminate, it should go through standard chemical cleaning processes, but without any scrubbing of the substrate. The PTFE substrate surface will hold a mirror image of the copper that was etched away, and that rough surface will promote bonding between the PTFE and FR-4 prepreg. But if the PTFE surface is scrubbed, that surface roughness will be lost, replaced by a smooth, polished surface with less capability of forming a strong bond with the FR-4.

Proper grounding is essential to the performance of hybrid multilayer PCBs such as the PTFE/FR-4 example mentioned in the previous paragraph. It is necessary to ensure that the buried microstrip ground planes are properly grounded, by means of a sound electrical ground connection from the outside of the circuit to the inner microstrip ground planes. If the ground viaholes are not optimally and sufficiently located with the hybrid multilayer PCB, then buried ground planes for the microstrip circuits can suffer added parasitic inductance. This will cause instability in the microstrip circuit impedance over frequency, resulting in higher losses than expected.

Hybrid multilayer PCBs often make use of circuit materials with very different values of dielectric constant (Dk). For example, some multilayer antenna circuits may consist of a low-Dk circuit material as the outside layer for radiating elements, a moderate-Dk circuit material internally for a stripline antenna feed line, and a high-Dk material for an internal layer for filter circuitry. The different Dk materials are often based on different resin systems. The outer, low-Dk layer may be PTFE material while the inner, moderate-Dk circuit layer is formed on a ceramic-filled hydrocarbon-based laminate. The bonding materials could be based on either type of material, although hydrocarbon-based bonding materials are more often used for their ease of circuit fabrication.

Most ceramic-filled hydrocarbon bonding materials or prepreg materials are considered to have low-flow behavior. This refers to the resin flow characteristics during the lamination process used to bond the different circuit materials to form a multilayer PCB. Low-flow materials will not flow excessively when heat is applied, so low-flow prepreg materials tend to require a slower temperature ramp rate and higher applied pressure as part of their lamination process. Such low-flow prepreg materials can be affected by any low-pressure areas within a multilayer circuit construction, if proper pressure is not applied in those areas. Because of the way that circuits are routed on the different conductor layers of a multilayer PCB, the thickness can vary as the different circuits align, forming thicker areas or “pillars” that support the majority of the pressure applied during the lamination process. Areas between the pillars will receive less pressure, which can result in resin separa-

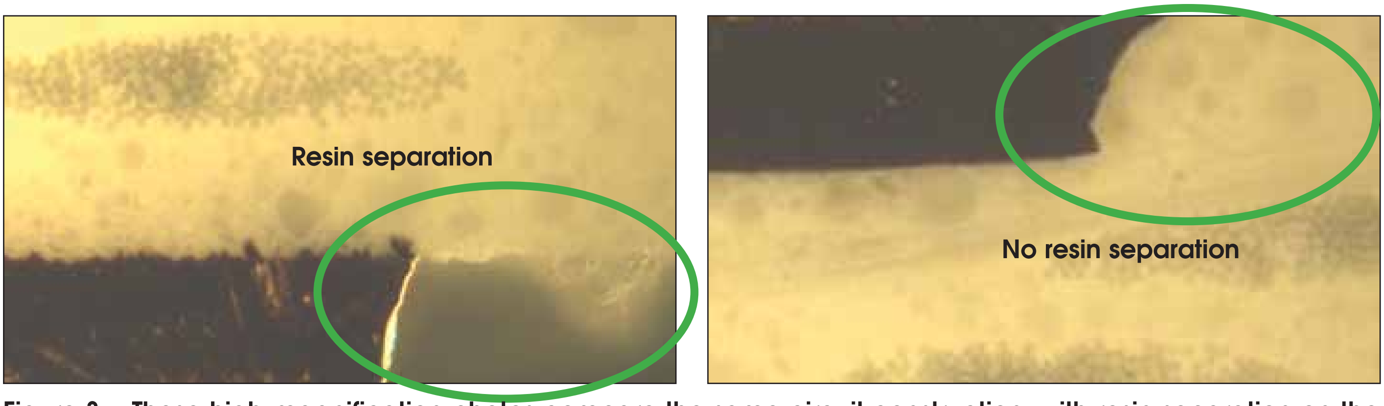

Figure 3 • These high-magnification photos compare the same circuit construction, with resin separation on the left using a low-flow prepreg material. This resin separation does not occur on the right using an optimized prepreg material.

tion with low-flow prepreg materials when the pressure is insufficient to cause a uniform flow of material at the process temperature. Figure 2 shows an example of resin separation that can occur in these low-pressure circuit areas.

Circuit lamination processes have been optimized to minimize or eliminate this resin separation that can occur when fabricating hybrid multilayer PCBs. However, improvements to a prepreg material that has been used extensively for hybrid multilayer PCBs has also helped. This prepreg material, RO4450F™ prepreg from Rogers Corporation (www.rogerscorp.com), does not exhibit the poor resin flow problems and associated resin separation associated with many low-flow prepreg materials. Figure 3 compares a prepreg material on the left that is sensitive to the effects of low-pressure areas during multilayer PCB processing to the RO4450F prepreg material on the right using the same circuit. As Fig. 3 shows, the standard low-flow prepreg material suffers resin separation. This does not occur with the RO4450F prepreg material.

When design engineers work with hybrid multilayer PCBs composed of materials with different Dk values, they are usually interested to know what the composite Dk of the multilayer circuit structure will be, especially how that Dk might impact RF/microwave performance. When two materials with different Dk values are stacked between conducting planes, the parallel plate capacitance and associated Dk of that stack can be determined by a simple summation formula[1]:

$$Dk_{layered} = \frac{1}{\sum_{n=1}^{all\_layers} \frac{h_n}{h_t \; Dk_n}}$$

Figure 4 shows a cross-sectional view of an edge-coupled microstrip circuit formed of two stacked dielectric materials with different Dk values. Figure 4 shows examples of the nomenclature for the variables in the layered Dk formula. This type of composite laminate is not typically offered by circuit laminate suppliers, although this type of construction is often part of a hybrid multilayer PCB.

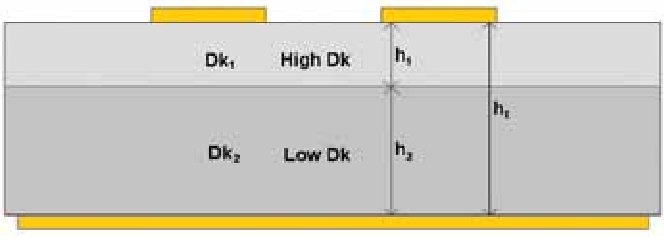

Figure 4 • This cross-sectional view shows an edge-coupled microstrip circuit based on two stacked circuit materials with different Dk values, resulting in a composite, layered Dk value determined by the formula.

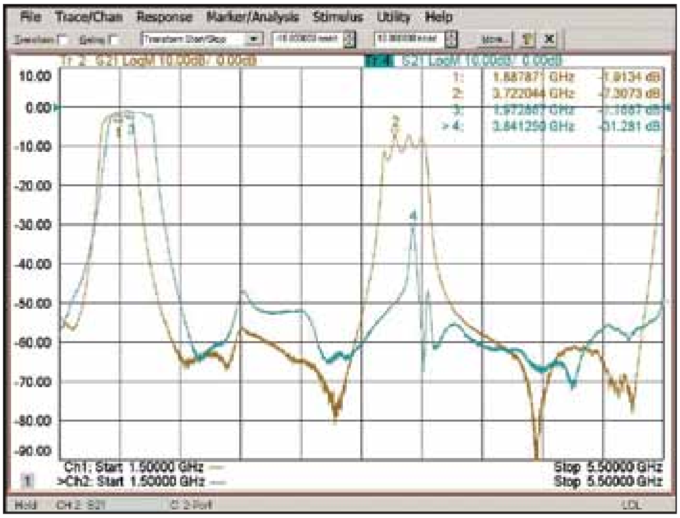

Figure 5 • Experimental results from an edge-coupled bandpass filter of the same design using a composite laminate construction as shown in figure 4 and comparing to a homogeneous laminate; composite laminate is the blue curve and homogeneous is the yellow curve.

The type of edge-coupled multilayer circuit structure shown in Fig. 4 offers numerous benefits with the higher-Dk material near the signal layer and the low-Dk materials near the ground layer. Such a configuration can help to equalize the even- and odd-mode phase velocities in the circuit, which can minimize the spurious harmonic responses of the coupled feature[2]. Figure 5 compares edge-coupled bandpass filters fabricated with a homogeneous circuit laminate and with the type of composite circuit laminate depicted in Fig. 4. As the plots show, the composite laminate contributes to excellent harmonic rejection.

As the curves in Fig. 5 show, the main difference between the bandpass filter responses for the composite and homogeneous laminates is the reduction of second-harmonic response at about 3.7 GHz. For the filter using the composite laminate (the blue curve), the harmonic response level is relatively low at -31 dB; this harmonic response level is much higher for the bandpass filter based on homogeneous laminate, at -7 dB. The composite circuit was based on the configuration of Fig. 4, using 5-mil-thick RO3010™ laminate (Dk of 10.2 at 10 GHz) and 25-mil-thick RO3003™ laminate (Dk of 3.0 at 10 GHz), both from Rogers Corporation.

Another advantage of using such a composite laminate is the overall lower Dk achieved for the thickness of these two materials, while still receiving the benefit of the high Dk value in the coupled area. The lower Dk in the thickness axis will allow wider conductors for transmission-line features which use the z-axis Dk and enables lower conductor losses.

Hybrid multilayer PCBs with mixed dielectric materials and Dk values can offer numerous benefits in high-frequency applications. But to reap the greatest benefits from such circuit constructions, it is recommended to consult with the circuit material supplier for guidance on material selection and processing approaches in order to achieve the most satisfactory results.

About the Author:

John Coonrod is Market Development Engineer for the Advanced Circuit Materials Division of Rogers Corporation, Chandler, AZ. He can be reached at john.coonrod@rogerscorp.com.

References:

[1] Brian C. Wadell, *Transmission Line Design Handbook,* Artech House, Norwood, MA, 1991.

[2] John Coonrod, “Harmonic Suppression of Microstrip Edge Coupled Bandpass Filters using Composite Substrates,” *Microwave Journal,* September 2012.

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