Tuning the Dielectric Constant (Dk) of Electronic Materials to Meet the Demands of Any Application

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Abstract
Applications for dielectric materials are becoming ever more demanding and complex, requiring careful planning & material selection by original equipment manufacturer (OEM) designers that wish to build reliable products. Some applications may be purely digital and benefit from a very low dielectric constant (*e.g.,* Dk < 3.0) while others, such as radio frequency (RF) applications with high power requirements may benefit from having a higher Dk (*e.g.,* >5). An emerging trend now is the rise of hybrid product designs that combine both traditionally digital and RF materials, especially in the case of high-density interconnects (HDIs). In this paper, methods for tuning the material Dk by careful selection of specialty resins and filler material combinations will be reviewed. The use of mineral fillers for achieving high Dk is a well-established practice that comes with certain considerations such as safety, drilling compatibility, and effects on signal integrity. By contrast, the use of hollow fillers to achieve low Dk is a more recent development that comes with similar considerations, along with chemical composition and morphology concerns. Each of these concerns must be addressed by the product designer, and careful, reliable measurement of the Dk is critical to validating product performance.

Introduction
The demands of the PCB market are forever pushing the envelope of dielectric material performance, and as technology advances to meet the needs of artificial intelligence powered devices, the designs drawn up by OEM engineers are asking for unique combinations of properties. The goal of some designs is to provide as much signal as possible through as small of a device as possible. Hence, there is significant demand for lowering the Dk of new materials, which will allow for easier miniaturization of certain constructions. At the same time that designers are demanding low Dk, there is also a demand for higher Dk materials to form capacitance layers or to further manipulate the loss tangent (*tanδ*), which is given by equation 1:

$$tan\delta = \frac{\omega D_f + \sigma}{\omega D_k} \qquad \text{Equation 1}$$

where Df is the dissipation factor of the material and Dk is the dielectric constant. Equation 1 illustrates how a designer might select material with a given Dk that would allow traces to be sized and spaced a certain way, but then would need to demand a certain Df to maintain acceptable signal loss (*tanδ*). For this reason, it is essential that copper-clad laminate (CCL) makers have the ability to provide materials that span a wide range of dielectric properties. In Figure 1, we see that by reducing the Dk from 3.3. to 2.6, the dielectric thickness is reduced roughly 19%, and the same reduction in Dk allows for traces to be 19% wider. In Figure 2, we see another example of how the incorporation of low Dk, low loss material layers can allow HDI designs to support higher wiring density.

In this study, we will show how careful matching of specialty resins and fillers can lead to a wide array of possible Df and Dk values in digital dielectric materials. Of course, the supporting materials, whether fiberglass, quartz, or other materials, will also impact the final dielectric properties, but that is beyond the scope of this study. Another additional factor for determining dielectric performance is the amount of cured resin in the final construction, typically measured by volume and expressed as percent resin content (%RC). This is another factor that will be considered as a constant for the purpose of this review, though it may be discussed in more detail in later work.

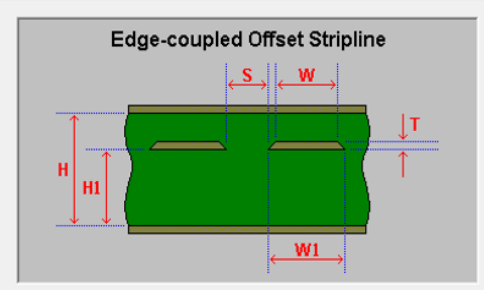
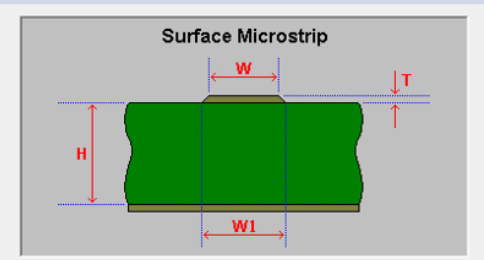
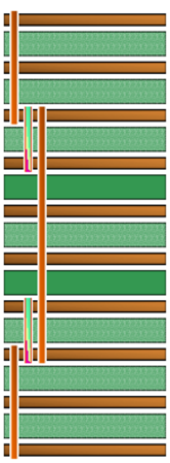
Model (feature sizes in mils)	Feature	Before	Increased Trace	Thinner Dielectric
	Height (H):	6.6	6.6	5.3
	Height (H1):	3.0	3.0	2.4
	Cu Thk (T):	0.6	0.6	0.6
	Space (S):	6.0	6.0	6.0
	Width (W1):	2.7	3.5	2.7
	Dk (Er):	3.3	2.6	2.6
				
	Height (H):	3.0	3.0	2.6
	Cu Thk (T):	0.6	0.6	0.6
	Width (W1):	6.3	7.5	6.3
	Dk (Er):	3.3	2.6	2.6

Figure 1: Based on the models shown above on the left, we can see the effect of reducing the Dk from 3.3 to 2.6 on the overall construction thickness and on the width of the traces.



Name	Thick (mils)	Dk	Trace (mils)	Trace/Space (mils)	Ref Layers	SE (Ω)	Diff (Ω)	Thick (mils)	Dk	Trace/Space (mils)
Solder Mask	0.40	4.00						0.40	4.00	
Copper L1	1.40		5.2		L2	50.64		1.40		
Prepreg	3.01	3.30						4.00	3.30	
Copper L2	1.00			2.5/8.0	L1/L3		97.95	1.00		3.0/5.0
Prepreg	3.16	3.30						4.50	3.30	
Copper L3	1.00							1.00		
Prepreg	3.10	3.30						4.90	3.30	
Copper L4	0.60			2.5/4.0	L3/L5		98.00	0.60		3.0/3.0
Core	3.00	3.30						5.00	3.30	
Copper L5	0.60							0.60		
Prepreg	5.00							5.00		
Copper L6	0.60							0.60		
Core	3.00	2.60						5.00	3.30	
Copper L7	0.60			3.0/3.0	L6/L8		98.09	0.60		3.0/3.0
Prepreg	3.10	2.60						4.90	3.30	
Copper L8	1.00							1.00		
Prepreg	3.16	2.60						4.50	3.30	
Copper L9	1.00			3.0/5.0	L8/L10		99.64	1.00		3.0/5.0
Prepreg	3.01	2.60						4.00	3.30	
Copper L10	1.40		6.5		L9	50.15		1.40		
Solder Mask	0.40	4.00						0.40	4.00	
Total Thickness (mils)	39.5							51.8		

Figure 2: An example of a 1.0 mm thick, controlled impedance, HDI 2-6-2 build-up board. For demonstration purposes, the material is 3.3 Dk on the top half and 2.6 Dk on the bottom half. We can see how a lower Dk can reduce the pitch of differential pairs supporting an even higher wiring density per unit area. Right of the red line, to match this pitch using 3.3 Dk material, the required increased dielectric thickness may not support smaller microvia diameters and increases the PCB total thickness by 24%.

Experimental Methodology

PCB Modeling

The calculations used to illustrate the effects of Dk on the size of PCB features such as trace width and dielectric thickness were performed using a Controlled Impedance Calculator.

Laminate Creation

Dielectric laminates investigated in this study were made by first creating a resin dispersion, coating the resin dispersion on glass cloth to make “prepreg”, and then laminating the prepreg under vacuum using a heated hydraulic press. First, a curable composition was prepared by dissolving the soluble resin components in compatible solvent (*e.g.* methyl-ethyl ketone, toluene, dimethyl formamide, etc.). Next, the insoluble materials such as solid flame retardant and silica or mineral fillers were added and dispersed in the resin varnish using a combination of low and high-shear mixing techniques (*e.g.,* Cowles blade, rotor-stator, or milling). Then, the resin dispersion was poured into a suitable vessel and a glass cloth was impregnated with the curable composition by pulling through a gap of pre-determined width set between two metal bars. The coating thickness was adjusted by changing the gap width. The prepreg was dried with air flow at room temperature for 10 minutes and then heated up to 130-160°C to form a dried prepreg. Two to twelve layers of prepreg were laminated with copper foil on the outside of the prepreg layers (*i.e.,* the copper forms the top and bottom of the stack) to form a laminate. The laminate was cured at 200-225 °C for 1-3 hours at 350-450 psi.

Dielectric Measurements

Dk and Df were measured using a split post dielectric resonator at 10 GHz connected to a Network Analyzer. Dk and Df against different frequencies were measured via Balanced Type Circular Disk Resonator (BCDR) from 14 GHz to around 100 GHz.

Particle Size Analysis

Particle size distribution was measured via laser diffraction with a particle size analyzer.

Results & Discussion

Specialty and proprietary base resins are, of course, the industry’s “secret sauces” for making the low-Df or low-Dk substrate material, and it is these same secret structures that become the basis of patents and products. It is for this reason that the resins we used in this work will be masked as “Type A, B, or C” in the ensuing discussion and Table below. Likewise, we assign the labels “X, Y, Z_1, and Z_2” to the different types of fillers tested. Considering that the resin content for some CCL products is only ~50%, this means that the base resins might account for less than a third of the total product volume when the use of fillers is considered. It is no secret then, that the use of high purity mineral fillers and other specialty products will allow the final electrical properties of the material to be tuned to hit performance targets. In fact, RF products such as the RF-30A (Dk = 2.97) and RF-10 (Dk = 10.2) have been made to span a wide range of dielectric constants using unique combinations of proprietary resins and various fillers. Applying the lessons learned from these RF products to digital products, it is possible to accomplish a wide range of Dk values while maintaining good signal integrity via low loss (Table 1 & Figure 3).

Table 1: List of dielectric materials with various Dk and Df values; all data was collected from dielectric laminates.

Product	Resin Type	Filler Type	Dk @ 10 GHz	Df @ 10 GHz
AX	A	X	3.3	0.0024
AY	A	Y	6.0	0.0049
BX	B	X	3.28	0.0016
BZ-1	B	Z_1	3.0	0.0025
CX	C	X	3.05	0.0012
Experimental-01	C	Y	6.4	0.0019
Experimental-02	B	Z_2	2.7	0.0015
Experimental-03	C	Z_2	2.7	0.0012

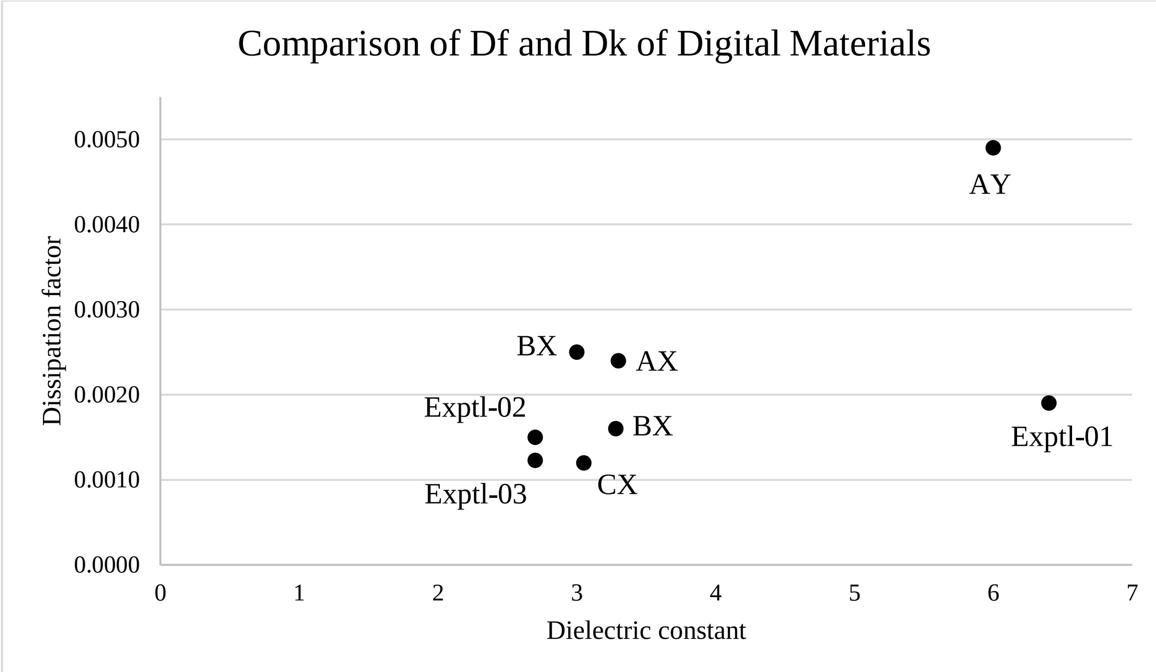


Figure 3: The data from Table 1 is plotted to show the range of Dk and Df values achieved by changing the base resin and/or filler.

In Table 1 and Figure 3, we see the progression of changing the resin type, changing the filler, and changing both simultaneously. Beginning with the first two rows of Table 1, we see the effect of changing the main filler type to a high purity mineral filler. The Dk was nearly doubled when converting from commercial product AX to AY, but this change came at the cost of raising the Df. Then, when comparing AX versus BX, we see how changes to the resin formula maintained a similar Dk (~3.3) while reducing the Df by 33%, providing better signal integrity for advanced products. With the development of BZ-1, which is discussed in more detail below, we again see the effects of changing the filler to reach a target Dk that was demanded by newer product designs. Finally, we see the change from BX to CX, which represented a new approach to resin formula design, discussed in detail in a separate white paper by T. Nakanishi e*t al*. When we then applied our new filler types to more advanced resin systems, we were able to achieve the experimental-02 and -03 results shown in Table 1 and Figure 3.

On the higher end of the Dk spectrum, high-Dk applications are demanding better signal integrity. To address this demand, the AX formula was adapted and achieved a much higher Dk (6.0) than the standard version, while maintaining a rather cromulent Df at 0.0049. In Figure 3, we can see just how much the dielectric properties of AX changed with the use of this new filler. While most of the materials in Table 1 are clustered around (3.0, 0.0020), AY and our Experimental-01 material appear as outliers simply due to their high Dk values, which are the product of identifying a new type of filler. Looking closer at Experimental-01, we see that combining an advanced resin with a high purity mineral filler puts us in new territory again: high Dk with very low loss. This change in the Df while maintaining the high Dk desired by OEM designers should allow better capacitance layers with improved power integrity. Combining these elements required balancing base resin performance, filler performance, and glass cloth type to achieve, but the possible applications for a product that has this unique Dk/Df performance are exciting certain product designers working in specialized fields.

In some newer cases, instead of relying on mineral fillers which may give undesired effects on certain properties, the best fillers for reducing the Dk include those that contain air. Since air has a low dielectric constant (~1.0006), adding air to dielectric materials naturally lowers the Dk. In Figure 3, we see the typical performance of BX contrasted with BZ-1. Both formulas rely on the same low-loss resin system (Type B), but the 8300 variant has achieved a slightly lower Dk, albeit with an increase to its Df; this is accomplished with the use of hollow glass spheres. Indeed, a cross-section of BZ-1 reveals “glass bubbles” that are around 20 µm in diameter, nominally (Figures 4 & 5). The glass bubbles are manufactured in a way that traps air, which allows them to be used to adjust the Dk of a given formula. These spheres are also quite durable, withstanding a crushing force of 16,000 psi. This resistance to crushing allows them to be pressed into CCLs and other products without fear of damage.

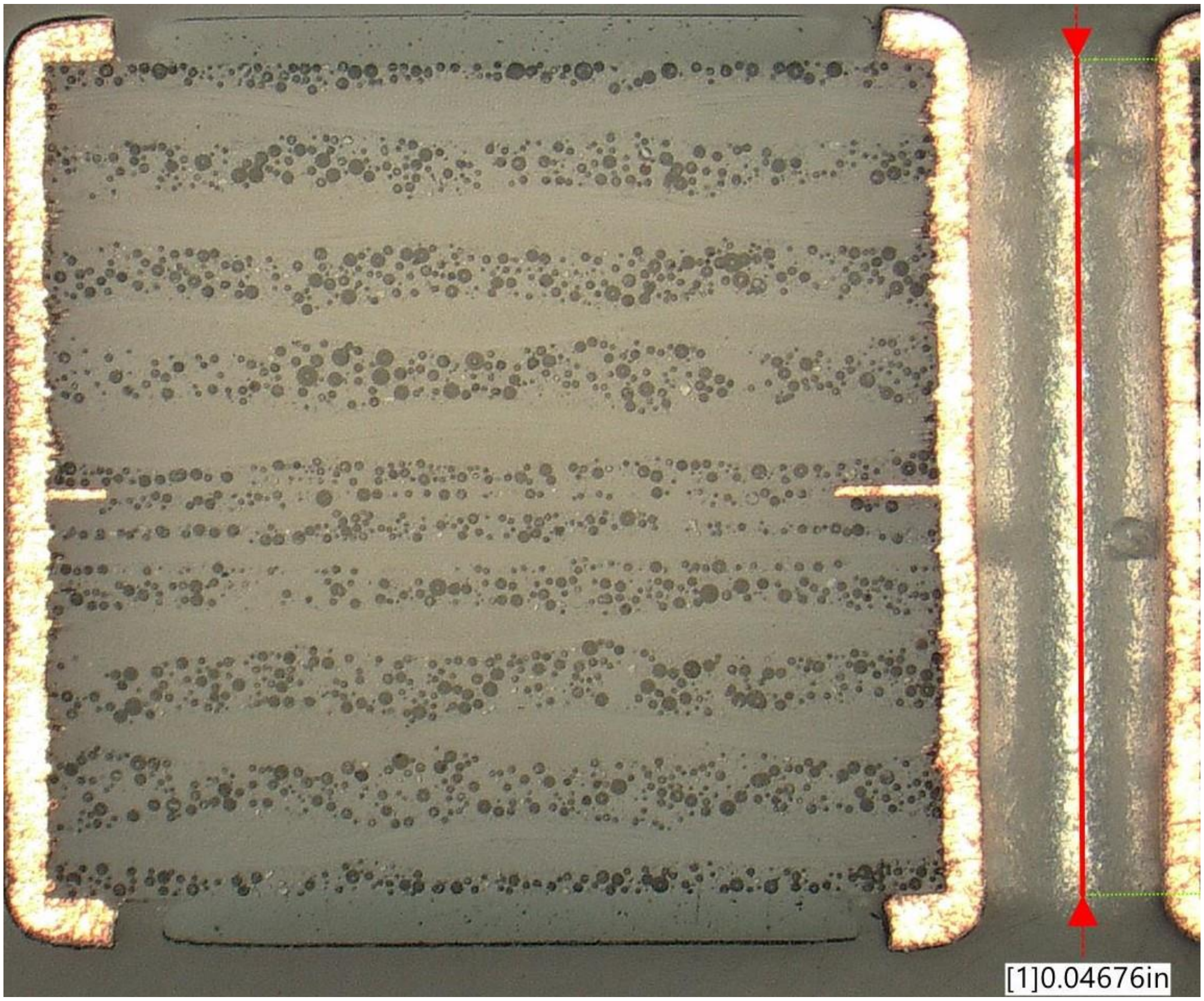


Figure 4: the cross-section of a multi-layer BZ-1 PCB; 100x magnification. At this scale, the presence of hollow glass spheres is easily observed.

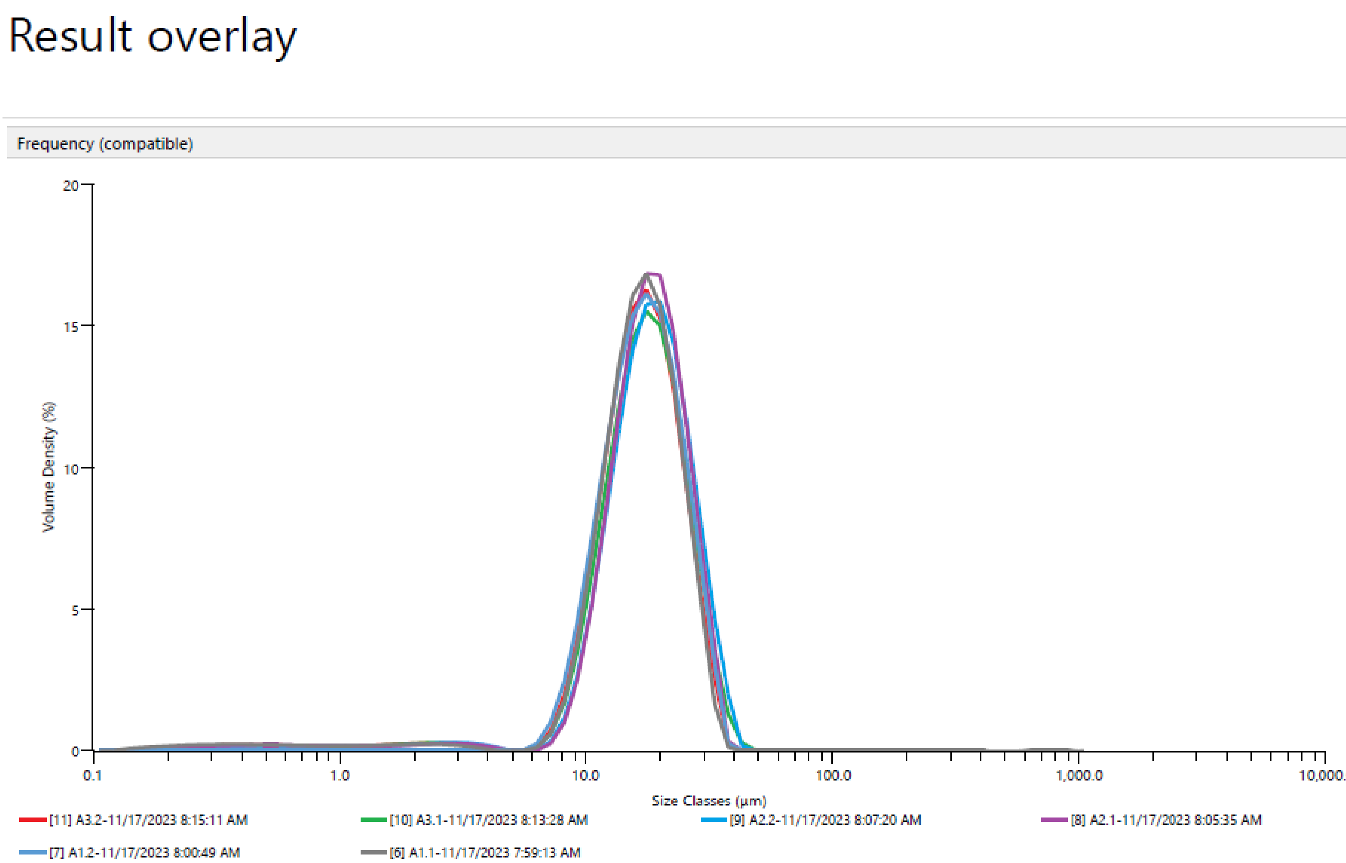


Figure 5: Particle size analysis of glass bubbles used for BZ-1.

While the use of hollow glass filler has allowed a breakthrough in reaching low Dk in digital materials, one of its limitations is the Df of certain types of glass (*e.g.*, borosilicate), which can be relatively high compared to the low-loss resins. Hence, adding glass filler can raise the Df of the resin formula, even as the Dk is reduced by the inclusion of air. If we wish to combine the effects of hollow filler and maintain the lowest possible Df, then new materials, such as hollow silica are the next logical step. Low-Df silica is already on the market, so making a hollow version was a natural progression for raw materials suppliers looking to serve the high-performance dielectric materials markets. Building on the concept proven with the use of glass spheres, we are currently working on next-generation materials that target Dk < 3.0 by using hollow silica. This new filler material also contains air trapped in "silica bubbles" but the average size is about 1 order of magnitude less than the aforementioned glass bubbles, and the Df is also sufficiently low enough to maintain extremely low loss performance. Indeed, a typical cross-section may not reveal the presence of this type of silica, but microscopes capable of >2000x magnification will see them (Figures 6 and 7).

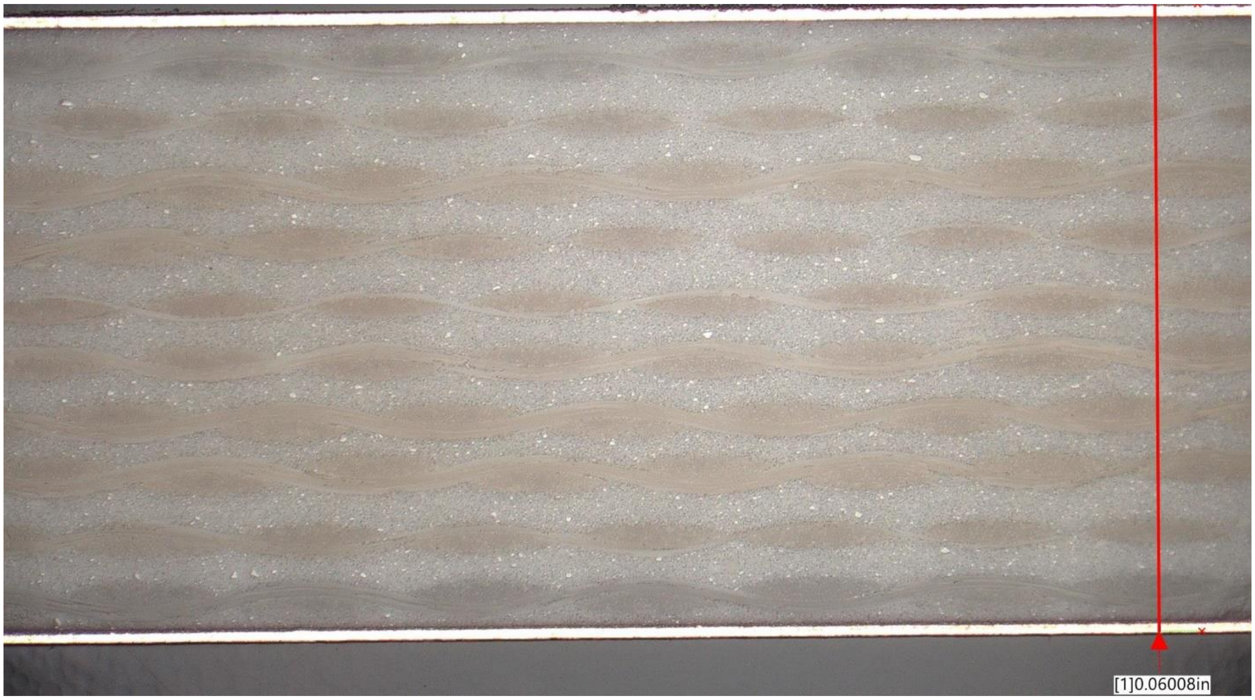


Figure 6: Cross-section of a 10-ply 2116SI dielectric CCL using hollow silica filler; 100x magnification.

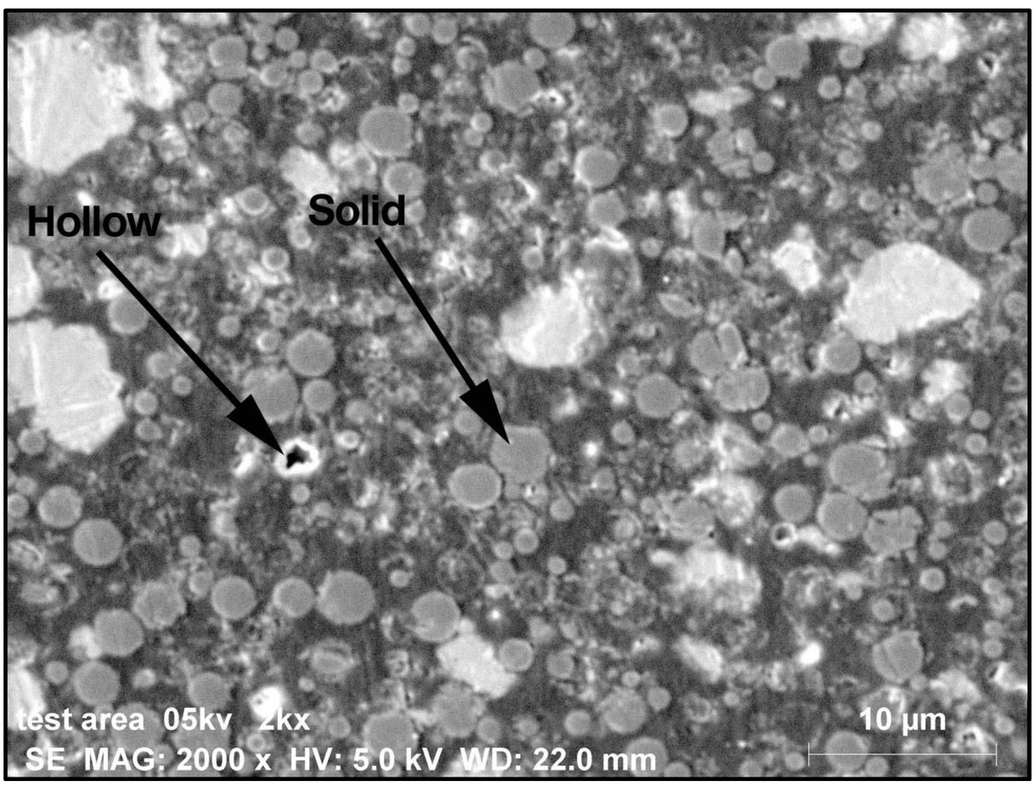


Figure 7: Cross-section of 10-ply 2116SI dielectric CCL using hollow silica filler; 2000x magnification. At this scale, it is possible to observe the spherical, hollow filler and some irregularly shaped pieces of insoluble materials.

Conclusions

As electronic product designs become more complex and demanding, selecting a substrate material that delivers the desired combination of Df and Dk will be even more important. Through careful consideration of base resin, filler materials, and support materials, it is possible to produce a wide range of dielectric materials that offer unique Dk/Df combinations. The design of the resin will always be a primary concern for formulation chemists, but giving more consideration to the impact of the filler material has become critical. By combining air-inclusive fillers with high-integrity polymers, we have shown the ability to dial in Dk and Df to meet any demand. This, in turn, allows the OEM designers more freedom to create next-generation products that will be the backbone of future devices. Indeed, tuning the Dk of a given material allows the OEM designers to build the ideal dielectric construction with the desired trace width & spaces and overall thickness that will meet their needs.

Acknowledgements
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References
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