It's a Material World

Beyond Design

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Years ago, when clock frequencies were low and signal rise times were slow, selecting a dielectric material for your PCB was not difficult; we all just used FR-4. And we didn't really care about the properties of the materials.

However, with today's multi-gigabit designs and their extremely fast rise times and tight margins, precise material selection is crucial to the performance of the product. Materials used for the fabrication of the multilayer PCB absorb high frequencies and reduce edge rates, and that loss in the transmission lines is a major cause of signal integrity issues. But we are not all designing cutting-edge boards and sometimes we tend to over-specify requirements that can lead to inflated production costs.

Over the years, a huge range of materials have been developed for multilayer PCB fabrication. In fact, to give you an idea, iCD now has a choice of over 700 series of dielectric materials from more than 60 different manufacturers, in its dielectric materials library. When each material is used for the right target application, the resultant PCB will have the lowest possible cost while still satisfying the design and performance goals of the project. There's no doubt that we live in a material world and selecting the best material for an application is often a daunting task. In this month's column, I will look at how to quickly sort through the vast array of choices to make an informed decision.

The electrical properties of a dielectric material can be described by two terms:

1. The dielectric constant (Dk) or relative permittivity (Er) is the ratio of the amount of electrical energy stored in a material by an applied voltage. It describes how the material increases the capacitance and decreases the speed in the material.
2. The dielectric loss–dissipation factor (Df) or loss tangent (tan δ) is a parameter of a dielectric material that quantifies its inherent dissipation of electromagnetic energy.

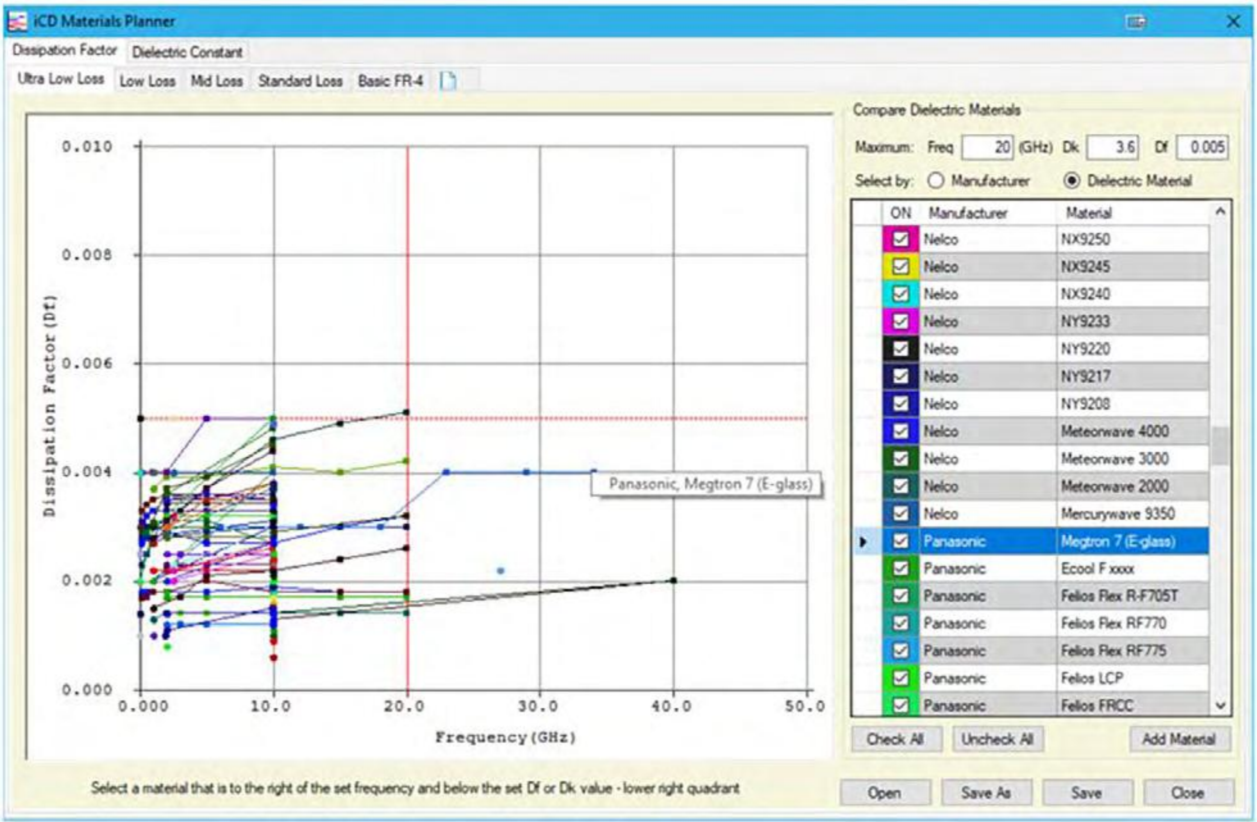

Figure 1: Loss profile for ultralow-loss dielectric materials (source: iCD Materials Planner).

Dielectric constant and dielectric loss are not a function of the geometry of the transmission line—they are a function of the dielectric material in which the signal propagates, their distribution in the PCB stackup, and the applied frequency. These mechanisms contribute to the frequency-dependent loss and degrade the bandwidth and speed of the signal. The signal quality transmitted through the medium and picked up at the receiver will be affected by any impedance discontinuities and by the losses of the dielectric materials.

The glass epoxy material (FR-4) commonly used for PCBs has negligible loss for digital applications below 1 GHz. But at higher frequencies the loss is of greater concern. Also, the entire bandwidth of the signal needs to be considered. For instance, a 10Gbps square wave is made up of a series of odd harmonics. It will have a fundament frequency of 5GHz, a third harmonic of 15GHz, a fifth of 25GHz and possible higher odd harmonics. These high harmonics can suffer excessive losses in amplitude and a degradation of edge sharpness which results in distortion of the signal eye. Plus, when the frequency exceeds 1GHz, copper roughness, conductor loss, skin effect and skew, due to variations of glass weave in the dielectric, begin to come into play.

Also of interest is the glass transition (Tg) temperature, which is the point at which a glassy solid changes to an amorphous resin/epoxy. If the reflow temperature exceeds the Tg, for an extended period, the material rapidly expands in the Z-axis. Plus, the mechanical material properties—strength and bonds in the material—degrade rapidly. A high Tg guards against barrel cracking and pad fracture during reflow. Standard FR-4 has a Tg of 135-170C, whereas the high-speed materials are generally over 200°C. Therefore, Tg is not a factor that needs to be considered for high-speed design but is certainly worth checking.

With so many materials to choose from which is the best for your specific product? Low cost generally means low quality. But also, the price of poor yields drives up the final material cost. Dielectric material selection is usually driven

Profile	Bit Rate (Gbps)	Frequency (GHz)	Dissipation Factor (Df)
Ultralow Loss	≥ 50	≥ 25	≤ 0.005
Low Loss	25 - 50	12.5 - 25	0.005 - 0.010
Mid Loss	10 - 25	5 - 12.5	0.010 - 0.015
Standard Loss	2 - 10	1 - 5	0.015 - 0.02
Basic FR-4	≤ 2	≤ 1	≥ 0.02

Table 1: Loss profile ranges for various materials.

by the frequency and rise time of the digital signal with lower values of loss most suitable for high-frequency applications. These materials generally exhibit lower values of dielectric constant resulting in faster signal propagation.

Figure 1 depicts the profile for dielectric materials with a Df < 0.005. The iCD Materials Planner has five default profiles ranging from basic FR-4 to ultralow-loss materials as in Table 1. This enables the designer to compare dielectric materials based on manufacturer, fabricator, frequency, dissipation factor (loss) and dielectric constant.

The other issue is that different materials are available locally compared to off-shore and also vary from fabricator to fabricator. Typically, prototype boards are fabricated locally, whereas Asia is a more economical option for mass production. A profile for each PCB fabricator that you usually deal with can be set up. This will display the complete range of materials that each Fab shop stocks. This also enables the comparison of competitive fab shop capabilities.

Figure 2 plots the loss properties of dielectric materials from an Asian fabricator. One can easily see which materials are best for high-speed applications and can choose a few materials from this that are in stock. Cost-to-performance evaluations must still be done to ensure the lowest cost material, that will do the job, is selected. Also, keep in mind that material costs vary with quantity.

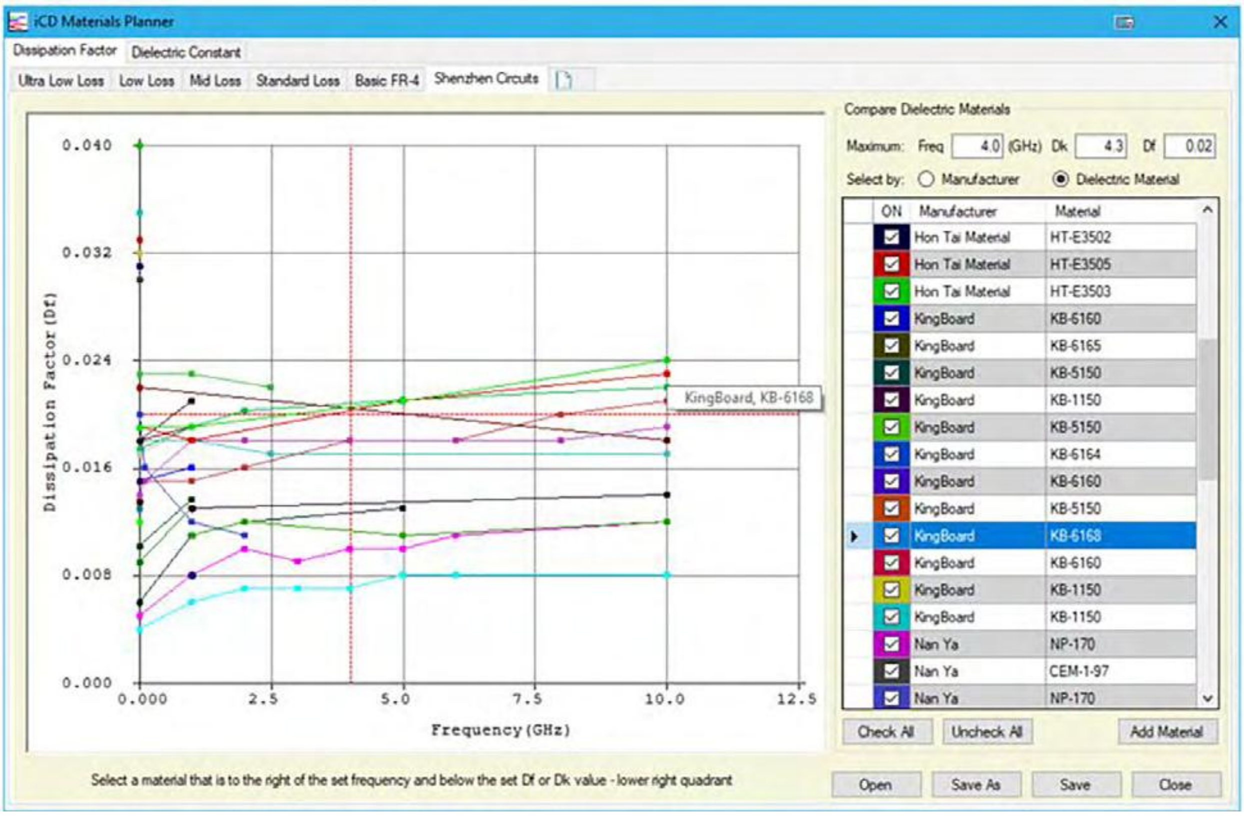

Figure 2: Example of a fabricator's dielectric materials loss profile.

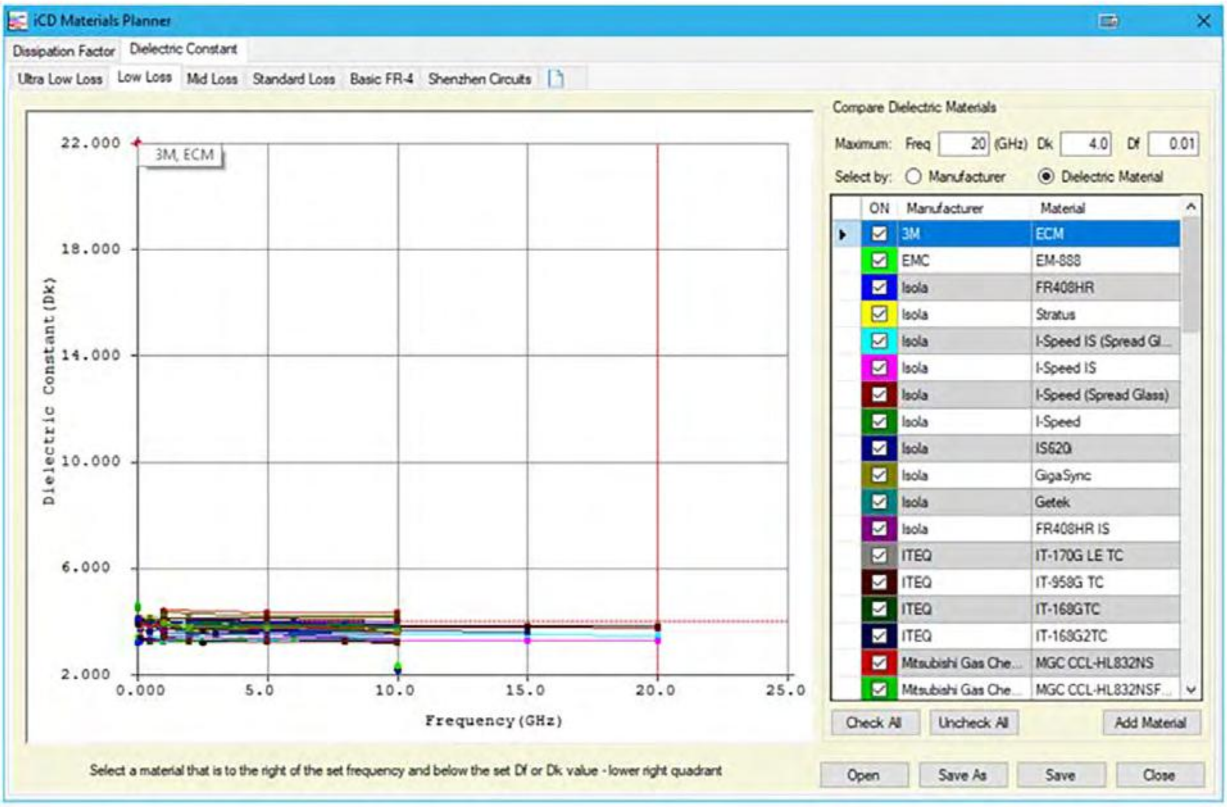

Figure 3: Dielectric constant vs. frequency of low-loss materials.

Matching material performance numbers of the dielectric constant is also important. A small difference in this value between materials can impact impedance, line widths/clearances, and thus losses significantly. Also the dielectric constant, of a material, determines the propagation speed of the signal in the medium. So, if Dk values vary, on different layers of the substrate, then bus timing may also be an issue. One should consider construction options that allow a drop-in material that matches the impedance for each layer of the stackup.

With the continuous trend to smaller feature sizes and faster signal speeds, planar capacitor laminate or embedded capacitor materials (ECMs) are becoming a cost-effective solution for improved power integrity. This technology provides an effective approach for decoupling high-performance ICs whilst also reducing electromagnetic interference.

Embedded Capacitance technology allows for a very thin dielectric layer (0.24 - 2.0 mil) that provides distributive decoupling capacitance and takes the place of conventional discrete decoupling capacitors over 1GHz. Unfortunately, standard decoupling capacitors have little impact over 1GHz and the only way to reduce the AC impedance of the power distribution network (PDN), above this frequency, is to use ECM or alternatively on-die capacitance. These ultra-thin laminates replace the conventional power and ground planes and have excellent stability of dielectric constant and loss up to 15GHz. As the supply chain grows and becomes more competitive, the costs associated with the use of these materials will continue to decrease which will make system cost reductions possible in a greater number and variety of applications.

Figure 3 outlines the relative dielectric constant of low loss materials. 3M, embedded capacitor material (top left) is the standout. It is a copper clad laminate that utilizes an ultra-thin, high Dk-value dielectric material, between the copper planes, to deliver a capacitance density of up to 20nF/in^2. Whereas, typical values of Dk, for low-loss materials, vary between 3.2 and 4.0. But, keep in mind that these low loss dielectrics are placed adjacent to signal traces in which case a low Dk is required to improve signal propagation speed through the medium. However, for planar capacitance, a high Dk creates a high value of capacitance, between the planes, to effectively decouple the PDN at high frequencies.

ECMs offer many benefits when used for decoupling high-speed digital circuits, including:

- Lowers the impedance of the PDN
- Dampens plane resonance
- Reduces power plane noise and thus coupling of plane noise to signals
- Reduces radiated emissions
- Replaces large numbers of discrete decoupling capacitors

From an engineering perspective, noise margins are increased, which can translate into improved performance and less time devoted to troubleshooting and fixing issues further down the track. In addition, the component count reduction saves time in board layout and assembly which reduces cost.

In conclusion, the designer needs to be able to quickly evaluate the best, most cost-effective material for their application based on the vast array of choices available. Sorting through numerous datasheets is a very time-consuming process. And an extensive table of numbers does not paint a memorable picture. However, a direct visual comparison, of dielectric materials, based not only on manufacturer's product lines but more importantly on what one's preferred fabricators stock is undoubtedly the most efficient approach.

Key Points:

- Materials, used for the fabrication of the multilayer PCB, absorb high frequencies and reduce edge rates causing signal integrity issues.
- Dielectric constant and dielectric loss are a function of the dielectric material, their distribution in the PCB stackup and the applied frequency.
- The glass epoxy material (FR-4) has negligible loss for digital applications below 1 GHz. But, at higher frequencies the loss is of greater concern.
- High harmonics of the fundament can suffer excessive losses in amplitude and a degradation of edge sharpness which results in distortion of the signal eye.
- When the frequency exceeds 1GHz, copper roughness, conductor loss, skin effect and skew, due to variations of glass weave in the dielectric, begin to come into play.
- Standard FR-4 has a Tg of 135°-170°C, whereas the high-speed materials are generally over 200°C.
- Dielectric material selection is usually driven by the frequency and rise time of the digital signal with lower values of loss most suitable for high frequency applications.
- A small difference in dielectric constant between materials can impact impedance, line widths and clearances, and thus losses significantly.
- Embedded capacitance technology provides distributive decoupling capacitance and takes the place of conventional discrete decoupling capacitors over 1GHz.

References

1. Barry Olney's Beyond Design columns: Material Selection for Digital Design, Material Selection for SERDES Design, Effects of Surface Roughness on High-Speed PCBs.

2. Selecting PCB Materials for High-Speed Digital Circuits, by John Coonrod, Rogers Corporation.

3. Using Embedded Capacitance to Improve Electrical Performance, by Joel Peiffer, 3M.

Barry Olney is managing director of In-Circuit Design Pty Ltd (iCD), Australia, a PCB design service bureau that specializes in board-level simulation. The company developed the iCD Design Integrity software incorporating the iCD Stackup, PDN and CPW Planner. The software can be downloaded from www.icd.com.au. To contact Olney, or read past columns, click here.