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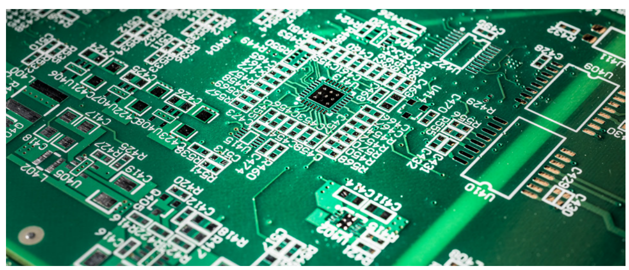
ROYAL CIRCUIT SOLUTIONS

HIGH-SPEED MATERIALS FOR PCBs

INTRODUCTION

Engineers use a number of material parameters for judging the suitability of PCB materials as they relate to the performance at high frequencies including the dissipation factor (Df), and the dielectric constant (Dk) of the materials.



With the predominance of digital circuits, and the fact that their performance speed is steadily rising, choosing the wrong PCB materials can have devastating results ranging from poor plated-through holes to impedance discontinuities in transmission lines on multi-layer circuit boards. However, these same material parameters can help when comparing and selecing various circuit materials for applications of high-speed digital circuits.

This is because a high-speed digital signal is a square-wave signal made up of a combination of several sine waves. Comprising different frequency signal components, a high-speed digital signal actually includes a fundamental-frequency signal, a third-harmonic signal, a fifth-harmonic signal, a seventh-harmonic signal, and a host of other odd-harmonic signals of higher frequencies.

FREQUENCY SIGNAL COMPONENTS

HIGH-SPEED DIGITAL SIGNAL

Fundamental-Frequency Signal
Third-Harmonic Signal
Fifth-Harmonic Signal
Seventh-Harmonic Signal
and Other Odd-Harmonic SIgnals

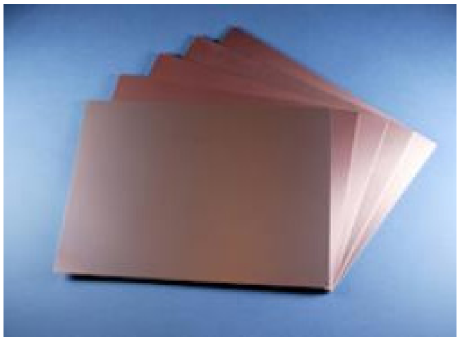
Therefore, for a digital signal to maintain its integrity and the sharpness of its rise and fall times, it is necessary to transfer millimeter-wave signals with the lowest possible loss and distortion. For instance, any PCB material capable of handling analog signals of millimeter wavelengths such as about 25-100 GHz, with low loss and distortion, should be able to maintain the signal integrity of a high-speed digital signal at 10 Gbps.

Although FR-4 is the most popular circuit board material, it fails to perform satisfactorily—introducing insertion loss and distortion—for analog microwave and millimeter-wave signals, and therefore, is not suitable as PCB material for high-speed digital circuits as well.

Typically, the dissipation factor of the circuit material defines its support for high-speed digital applications where insertion loss is critical. Mid-loss substrates with dissipation factors of 0.010 or less may cause high insertion-loss for digital signals at 10 Gbps speeds, and low-loss material with dissipation factors of 0.005 or lower may be more suitable. However, with high-speed digital designs rising to the 25-28 Gbps range, newer, very low-loss material will be necessary, with dissipation factors in the range of 0.003 or less. Experiments with 56 Gbps digital signals show ultra-low loss material with dissipation factors of 0.0015 or less are necessary.

DISSIPATION FACTOR

Dissipation factor, also known as loss tangent, provides invaluable insight into the behavior of a circuit material when loss is an important concern, when signal distortion must be minimized, and when it is necessary to preserve signal integrity. For instance, where circuit materials are transporting mixed signals, or a combination of different technologies such as RF/microwave signals and high-speed digital signals, the materials dissipation factor can indicate how a specific material will handle complex signal routing. In simple terms, Df is the measure of the tendency of the dielectric material to absorb some of the energy from the waveform passing through the material.



Rogers RO3003 High Frequency Materials

Selecting a PCB material with a low Df value ensures that the high-speed circuits fabricated on that material will exhibit minimal losses. Although dielectric losses dominate, other losses may be more significant depending on circuit configuration and thickness. These may include conductor loss, which again depends on frequency, material dielectric constant, conductor finish, conductor thickness, and the surface roughness of the conductor.

Although selecting PCB materials with low Df values can help minimize losses, circuit materials with lower dissipation factors tend to be more expensive than materials with comparatively higher dissipation factor values. Therefore, engineers are faced with a tradeoff between price and performance.

DIELECTRIC CONSTANT

The dielectric constant (Dk) of the PCB material affects the impedance of circuits fabricated on that material. As the material's Dk can change with frequency, temperature, and other reasons, it affects the performance of high-speed digital circuits as it changes the impedance of transmission lines on the PCB adversely, and in unexpected ways.

$$\varepsilon = \frac{C}{C_o} \quad , \quad C_o = \frac{\varepsilon_o A}{t}$$

Specifically, unwanted changes in impedance and Dk tend to distort the higher-order harmonics making up the high-speed digital signal, resulting in the loss of digital signal integrity. Therefore, for low distortion of higher-order harmonic signal components one needs to use PCB materials with Dk values that are low and stable with frequency and temperature. Measurements on high-speed digital circuits using clean and clear eye diagrams support this observation.

DISPERSION

Dispersion is another characteristic of the PCB material and is closely related to its Dk. Dispersion refers to a change in Dk with frequency, and all PCB materials exhibit this to some extent. It naturally follows that PCB materials that exhibit minimal changes in Dk with frequency, will also display minimal dispersion.

Low dispersion is a good characteristic for high-speed digital circuits, as dispersion can be the result of different traits of the PCB material, such as loss of the material, polarity of the dielectric material, and the surface roughness of the copper conductor.

Dispersion causes signal losses at increasing frequencies. If these losses are at the higher-order harmonic signal components needed by a high-speed digital circuit, its higher harmonic signals may suffer excessive losses in their amplitudes, causing significant distortion of the high-speed digital signals.

TOTAL LOSSES

The length of the track carrying a high-speed digital signal on the PCB can also affect the integrity of that signal. That is because signal losses increase with the length of travel of the signal. For instance, a 5 GHz signal traveling a distance of 10 inches, may suffer only 0.5 dB loss per inch for the first inch, but is likely to suffer a loss of 5 dB across the entire length of its travel. Moreover, losses for PCB material are more a function of frequency and increases with increasing frequencies.

That means the total losses for the length of travel for high-speed digital signals are considerably higher for the higher-order harmonic frequencies. For instance, although a 5 GHz signal may be facing low losses for the fundamental and the third-harmonic signal component, it will face considerable signal losses for the fifth- and seventh-harmonic signal components of the signal. Therefore, some PCB materials may introduce losses of the order of 10 dB or more for the fifth- and seventh-harmonic signal components of the 5 GHz signal as it traverses the 10-inch distance, resulting in considerable distortion to the high-speed digital signal as it crosses the PCB material.

Apart from the losses from dissipation, dielectric constant, and dispersion of PCB materials, physical details can also distort high-speed digital signals. For instance, right-angled bends in transmission lines represent a change in the effective width of the transmission line. This causes a discontinuity of impedance of the transmission line, resulting in an increase in the capacitance at that point. PCB design engineers avoid such discontinuities in the signal path by using mitered 45-degree bends or arcs for minimizing the reflections that high-speed signals passing through them may face.

SUBSTRATE MATERIAL FOR HIGH-SPEED CIRCUITS

Commercially, PCB materials are available in various formulations at numerous performance levels, and usually, they represent a tradeoff between price and performance. The performance of a circuit material depends on numerous parameters, with dielectric constant or Dk as the most likely starting point when comparing materials.

Panasonic Megatron6 High Frequency Materials

When specifying PCB materials, engineers use various sizes, thicknesses, and dielectric constants. Material suppliers characterize their materials in terms of Dk in the z-axis or in the x-y plane and at a typical test frequency, such as 1 or 10 GHz. High speed circuit design often requires channels closely matched in phase and or amplitude, or otherwise need tight performance tolerances. Manufacturers often specify PCB materials with varying degree of Dk tolerance across the circuit board. This helps designers minimize the variations in performance in transmission lines and other circuit structures they fabricate on those circuit boards.

CONCLUSION

PCB substrate material capable of handling high-speed digital signals must be able to handle signals rich in harmonic content. To maintain the signal integrity, the PCB material must faithfully reproduce the essential harmonic contents without distorting them. Material parameters such as Dk and its uniformity provide insight into the capability of the material to maintain consistent impedance characteristics in the transmission lines. This is vital for achieving high signal integrity in high-speed digital circuits.