Understanding Dielectric Constant for Microwave PCB Materials

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This article discusses how the dielectric constant (Dk) of microwave PCBs may vary for different applications, and describes the typical test methods used in determining Dk values for these materials

One of the most important properties of a laminate used in microwave PCB technology is the dielectric constant, also known as relative permittivity or ε_r. Many electrical engineering courses teaching microwave technology will use this property as a constant for a given material when discussing a PCB related topic. Because of that experience, some engineers are under the impression that the dielectric constant (Dk) of a laminate is a fixed value for all microwave scenarios. In reality this is not the case. The Dk value found on datasheets for laminates is a number that was generated by a specific test method, which may or may not apply to a specific microwave application.

This article discusses several topics and begins with the basic theory as to why the Dk value of a PCB material can vary for different microwave scenarios. Some of the common test methods used for determining the Dk of microwave laminates will be explained as well. Lastly, analogies will be given between the various test methods and some general microwave applications.

It is well known that the relative permittivity of free space is defined as a fixed number of 1. In this case the relative permittivity value doesn't depend on the applied electric field (E), frequency or the field properties of an electromagnetic wave in question. However, when a material is subjected to an electric field, the field causes polarization of the molecules, which establish electric dipole moments and augments the electric flux. This reaction to the applied field is unique for a material and is dependent on frequency as well as other electromagnetic properties. Free space obviously will not react to the applied field in this manner. When a material is a composite that is made up of several other materials, then the dipole moment reaction to the applied field can be complicated. This is because each of the raw materials making up the composite may form dipole moments differently with the applied electric field. The materials used in the PCB industry are typically a composite, therefore their reaction to applied electric fields may be more complex than one would initially imagine. The basic equation which accounts for the material reaction to the applied electric field is:

$$\mathbf{D} = \varepsilon \mathbf{E}$$

Where **D** is the electric field flux or displacement vector, **E** is the electric field intensity and ε is the permittivity. To be more specific with the interaction of materials and the applied electric field there is a polarization vector (**P**) that is to be added to the formula.

$$\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P}$$

In a linear medium, which most dielectric materials used in the PCB microwave industry are, the polarization is linear and related to the applied electric field by:

$$\mathbf{P} = \varepsilon_0 \chi \mathbf{E}$$

Where χ is the electric susceptibility, can be complex and ε_0 is the permittivity of free space.

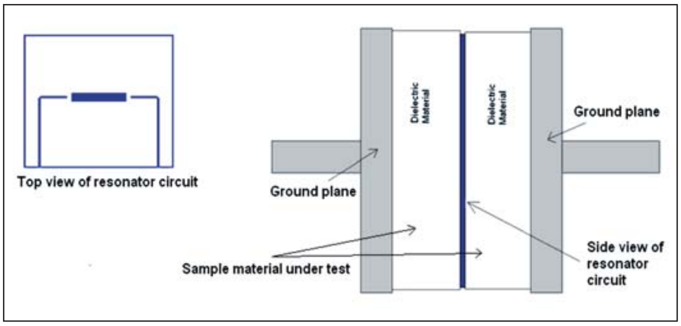

Figure 1 · Drawing of clamped stripline resonator test fixture.

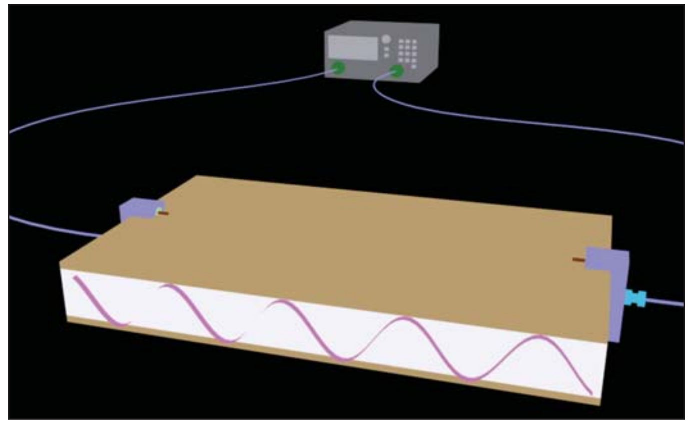

Figure 2 · Graphical representation of the FSR test method.

Expanding the definition of complex permittivity to include the effects of susceptibility and polarization:

$$\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P} = \varepsilon_0 (1 + \chi)\, \mathbf{E} = \varepsilon\, \mathbf{E}$$

$$\varepsilon = \varepsilon' - j\varepsilon'' = \varepsilon_0 (1 + \chi)$$

ε' is the real value of the complex permittivity and is associated with the Dk of the material, and ε'' is the imaginary part and related to material losses or dissipation factor.

When the polarization vector (**P**) is in the same direction as **E**, then the material is said to be isotropic. Most PCB materials are not isotropic (they are typically anisotropic) and there is usually a complicated relationship between **P** and **E** as well as **D** and **E**. An anisotropic laminate is one in which the Dk in the *z*-axis (thickness) is different than the Dk in the *x-y* plane.

By the nature of how the material reacts to the applied electric field, that will dictate how sensitive the Dk value is with a change in frequency. It will also determine the isotropic or anisotropic behavior of the material. Of course when the material is heated, the molecular structure will change and this change combined with the polarization properties of the material will have an influence on the TCDk (thermal coefficient of Dk) of the material. All of these considerations are unique for a particular microwave PCB material. When these considerations are combined with the many different possible electromagnetic field scenarios of microwave applications, it becomes apparent why determining the proper Dk of a PCB material for a particular application is not trivial.

There is no shortage of test methods for determining the Dk value for microwave PCB materials. The most common test method is the X-band clamped stripline resonator. This test is typically done in accordance with an IPC test method, which details the test; IPC-TM-650 2.5.5.5c and can be found at http://www.ipc.org. The test is tailored to the needs of a laminate supplier where a large number of samples are tested on a daily basis. This test is excellent for repeatability regarding the testing of raw laminate, however, there are aspects of the test that are not real-world for an actual microwave application. The test will essentially clamp two samples of the raw laminate on both sides of a resonator circuit and form a clamped stripline resonator as shown in Figure 1.

The material being tested was initially a copper clad laminate, and the copper was etched off prior to the test. The mirror image of the copper treatment is the surface roughness of the samples and with the sample having more surface area that will relate to an increase in entrapped air in the clamped fixture. The addition of air in the sampling area of the fixture will cause the test to under estimate the Dk value of the material being tested. This is one concern with this test method, which will not relate to a "true" stripline circuit. Another issue with this test is related to the loosely coupled stripline resonator circuit. The resonator is purposely designed to be loosely coupled, and in the gap coupled area there are strong E fields that are sensitive to the *x-y* plane properties of the material under test. This test is intended to determine the Dk value of the material in the *z*-axis (thickness), however, if the material under test has a high degree of anisotropy then the *x-y* properties detected in the gap coupled area can alter the calculated Dk value.

Another test that is common in the microwave PCB laminate industry is the Full Sheet Resonance (FSR) test. This test is also detailed on the IPC website and is test method IPC-TM-650 2.5.5.6. The FSR test uses the copper clad panel as an open walled parallel plate waveguide, establishes a standing wave, measures the resonant peak and determines the Dk value of the material. A graphical representation is shown in Figure 2.

The FSR test offers some advantage over the clamped stripline test. This test does not have the potential issue with entrapped air and is not sensitive to the anisotropic nature of the material being tested. Another possible

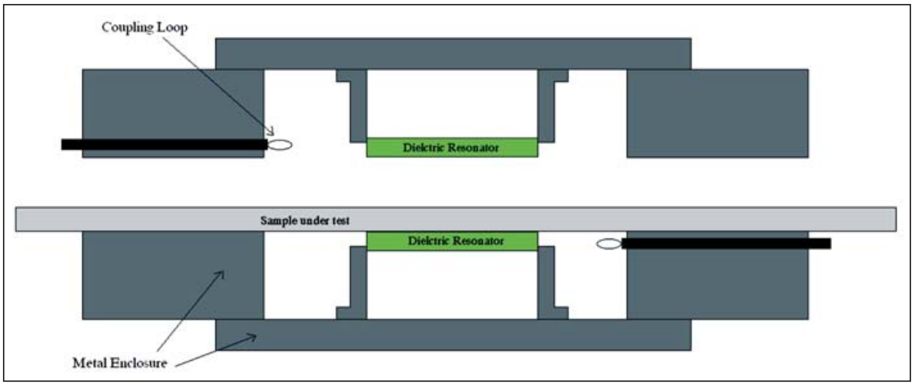

Figure 3 · Simple drawing of a typical SPDR test method fixture.

advantage is that this test can give the circuit fabricator a copper clad panel with its own distinct Dk value as compared to the sampling Dk value, which is necessary with the destructive stripline test. The drawback for the FSR test is that it is a low frequency test. Because the resonant peak of the standing wave being evaluated for Dk is related to the physical size of the panel by wavelength, this test is a low frequency test. The clamped stripline test is typically done at 10 GHz where this test will generally be less than 1 GHz. The low frequency Dk value can be an issue for microwave applications using the material at higher frequencies. It has been found [1] that the copper roughness can have an effect on the Dk value of a laminate and the lower frequency testing of FSR does not fully capture these effects.

Another test that has gained much interest over the years is the split post dielectric resonator (SPDR) test. This test is not currently defined per IPC, however, there have been several application notes written [2]. The SPDR test is a fast test with minimal operator influence. It uses a fixture that is a resonator tuned to a specific frequency. The empty resonator is measured first, then the sample is introduced into the resonator and the center frequency shift noted. The Dk is determined from the center frequency shift along with an accurate measurement of the sample thickness. A drawing of a typical SPDR fixture is shown in Figure 3.

The accuracy of this test is directly related to the accuracy of the measurement of the sample thickness. The SPDR test determines the Dk value for the sample under test in the *x-y* plane only, and because of this it is sometimes used in combination with other tests to understand the anisotropy nature of a material. The SPDR test would be used to understand the *x-y* plane Dk properties while FSR or some other test that evaluates the *z* axis properties is used. It should be understood when comparing SPDR to other tests, such as FSR, there are many differences in these test methods so the comparisons for Dk data related to anisotropic properties of a laminate should be viewed as approximate only.

There are many different types of microwave applications. How the electromagnetic fields for a particular application will use the microwave PCB laminate is important to consider when using a Dk value from a specific test method. As it has been mentioned, some test methods will report the Dk value of a microwave laminate in the *z*-axis only, and other methods will report *x-y* plane only.

Many microwave PCB applications will have E fields, which primarily use the *z*-axis of the material. An example may be a simple microstrip transmission line circuit. If the circuit is used at relatively low frequency (less than 1 GHz), then the Dk data generated from the FSR test should be appropriate. If the circuit is used at higher frequencies, the stripline test may be of interest, however, knowing the material would be very important. If the material does not have a rough copper treatment and/or a high degree of anisotropy, then the stripline test may be appropriate. If the material uses rough copper and/or has a high degree of anisotropy, then it should be understood that the clamped stripline test will report a lower Dk value than an actual circuit. In this case, it may be best to use Dk data from a microstrip differential phase length method [3]. This method uses microstrip circuits of two different lengths and calculates the Dk value over a wide range of frequencies. An example of a microwave PCB laminate using this test method is shown in Figure 4.

Some microwave PCB applications will have E fields which are in the *x-y* plane only, however, this is unusual. For these applications, the Dk values of microwave materials generated by the SPDR method would be appropriate. The SPDR fixtures can be made for testing at different frequencies, so the application frequency should match

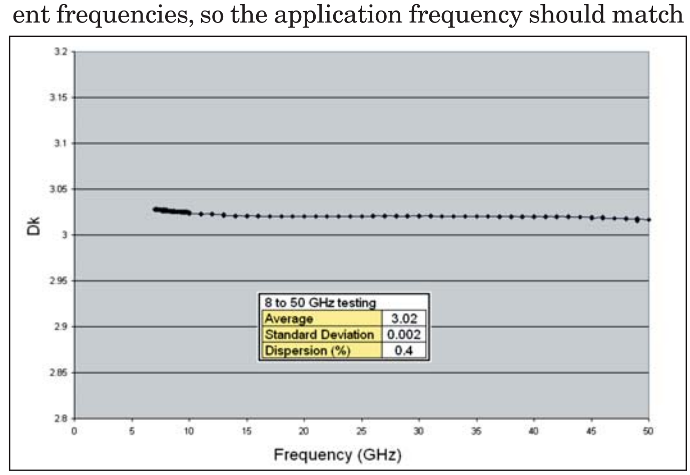

Figure 4 · Microstrip differential phase length method for determining Dk values.

the SPDR data as close as possible.

There are several applications where the E fields are in the *x-y* plane as well as the *z*-axis. Most edge coupled applications will fall in this category, and this type of circuit is a little more difficult to pick the appropriate test method for the proper Dk value. Understanding the *x-y* plane Dk value of the material is important, and in that regard, the SPDR test data will be helpful. The *z*-axis Dk is also important. As previously mentioned, if it is a lower frequency then a Dk value from the FSR test would be appropriate, and if higher frequency then the differential phase length method results would be suitable. The challenge with this application is that the overall Dk value to be used is a combination of the *z*-axis number and the *x-y* plane number. What ratio of which number to use will vary by the nature of the circuit. An edge coupled circuit that is tightly coupled will not use as much of the *x-y* properties of the material as a loosely coupled design. In this case, the best scenario is to collect the Dk data from the appropriate test methods and use a field solver that can accommodate anisotropy in the design.

It has been a surprise to some engineers when they learn that a particular microwave PCB laminate has a Dk value that is different than what is given on the datasheet. This often comes after the engineer has built a circuit on a laminate, back calculated the Dk value from the circuit performance and determined the difference in the Dk value from the laminate datasheet. Understanding the different test methods and how the fields are used in the test will help the engineer pick the Dk value from the test method that is most appropriate to his circuit.

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