Understanding Circuit Material Performance Concerns for PCBs at Millimeter-Wave Frequencies

John Coonrod, Rogers Corporation

Abstract

Millimeter-wave (mmWave) frequency applications are becoming more common. There are applications utilizing PCB technology at 60 GHz, 77 GHz and many other mmWave frequencies. When designing a PCB for mmWave frequency, the properties of the circuit materials need to be considered since they can be critical to the success of the application. Understanding the properties of circuit materials at these frequencies is very important. This paper will give an overview of which circuit material properties are important to mmWave frequency applications using PCBs. There will be data supplied which demonstrates why these properties are essential to the circuit material selection for mmWave applications. Some properties discussed will be dielectric constant (Dk) control, dissipation factor, moisture absorption, thickness control and TCDk (Temperature Coefficient of Dk). Measured comparisons will be shown for insertion loss and Dk versus frequency for different types of circuit materials up to 110 GHz. As part of the test data, the impact on circuit performance due to TCDk and moisture absorption will be shown at mmWave frequencies.

Introduction

There are many material properties which are a concern for most RF applications, but at higher frequencies some of these concerns become more critical. Additionally, some material properties have more impact on RF performance for a thin substrate as compared to a thick substrate. The material properties which can be critical for millimeter-wave (mmWave) circuit performance are the dielectric constant (Dk, ε_r) and the tolerance, Dissipation Factor (Df, tanδ), moisture absorption, thickness tolerance and TCDk (Thermal Coefficient of Dk). Copper surface roughness is another critical material property for good RF performance at mmWave frequencies and this will be discussed briefly. Insertion loss at mmWave frequencies, Df and associated subjects will not be discussed in this paper, however, a reference [1] for this topic was given previously. This paper will give an overview of which circuit material properties are important to mmWave frequency applications using PCBs.

Evaluation and Discussion

The nominal Dk of the material can be very influential for the design of the circuit at mmWave frequencies and the majority of mmWave PCB applications will use circuit materials with relatively low Dk values. This is true because many RF applications use circuit features which have physical sizes that are determined by wavelength and at mmWave frequencies, wavelengths are very small. Using a higher Dk circuit material will cause the wavelength to be even smaller. Since very small circuit features are more problematic for PCB fabrication, high Dk materials are typically avoided for mmWave designs, however, there are exceptions.

As a general statement, circuit materials with a Dk value of 2 to 4 are used at mmWave frequencies and materials with a Dk value of 3 are common. The Dk value itself is important for the circuit design and modeling; however, when considering mass production of a mmWave PCB design it is the Dk tolerance which can be critical for consistent RF performance. The cause of the Dk variance can be from different sources and depending on the circuit design, these variations can have more or less impact on the RF performance at mmWave frequencies. Additionally, there are several different considerations for Dk variation, as it relates to how it occurs. More specifically, the Dk variation within a panel of circuit material is important but there is also Dk variation from panel-to-panel and from lot-to-lot. All of these issues can be important depending on the circuit design and desired properties.

It is common for mmWave PCB circuits to have controlled impedance and / or circuit features which are based on impedance. With this in mind, impedance and impedance variation can be very important. The impedance variation is influenced by several material and circuit fabrication properties. Furthermore, the substrate thickness can make some of these properties more or less significant. To illustrate this point, information is shown in Table 1 which compares the same material and circuit, but uses different substrate thickness.

Table 1. Using the same substrate, but at different thicknesses showing the sensitivity of different variables to the impedance response of the circuit.

Microstrip transmission line circuit using 20mil thick high frequency laminate

Dk	Substrate Thickness (mils)	Copper Thickness (mils)	Conductor width (mils)	Characteristic Impedance (ohms)	Difference of impedance (ohms)	Comment
3.50	20	2	43	50.07		Baseline for comparisons
3.50	18	2	43	46.86	3.21	Substrate is 10% thinner than baseline
3.45	20	2	43	50.39	0.32	Dk lower by 1.4% from baseline
3.50	20	1	43	50.70	0.63	Copper thickness reduced by 1mil from baseline
3.50	20	2	42	50.78	0.71	Conductor width reduced by 1mil from baseline

Microstrip transmission line circuit using 10mil thick high frequency laminate

Dk	Substrate Thickness (mils)	Copper Thickness (mils)	Conductor width (mils)	Characteristic Impedance (ohms)	Difference of impedance (ohms)	Comment
3.50	10	2	21	49.74		Baseline for comparisons
3.50	9	2	21	46.57	3.17	Substrate is 10% thinner than baseline
3.45	10	2	21	50.05	0.31	Dk lower by 1.4% from baseline
3.50	10	1	21	50.78	1.04	Copper thickness reduced by 1mil from baseline
3.50	10	2	20	51.16	1.42	Conductor width reduced by 1mil from baseline

Information in Table 1 is based on a circuit material with a nominal Dk of 3.5 and a Dk tolerance of ± 0.05 or ± 1.4%. The material substrate thickness is controlled to ± 10%. The group of information in the top 5 rows is related to circuits which are built on this material. The material in row 1 assumes a 20mil (0.51mm) thick laminate. The first row of information is the baseline result and is intended to show the parameters for obtaining a microstrip transmission line with 50 ohm characteristic impedance. The rows of information immediately following the baseline information are similar, however they show scenarios which vary different circuit fabrication attributes or material properties and the response to the impedance values of the circuit. The bottom group of information in Table 1, is using the same materials and circuit design, however the substrate is thinner (10mils or 0.25mm) and the variations on impedance is shown.

It can be seen in Table 1 that the thickness variation has the largest impact on impedance values when considering either the thick or thin group of circuit information. The next most significant variable is the conductor width and for a given conductor width tolerance (± 1 mil), a thinner circuit will have its impedance value impacted more than a thicker circuit. The third most impactful variable is copper thickness and again a similar trend is shown, where the copper thickness variation has more influence on the impedance value of the thin circuit than the thick circuit. The Dk variation has the least impact on impedance stability of the circuit in the examples shown in Table 1 and that is generally true but there can be exceptions.

There are other Dk related issues beside impedance, which can be important at mmWave frequencies. These include: phase response, propagation delay (or phase velocity) and dispersion. For many applications at mmWave frequencies used for radar sensor circuitry, the phase response can be critical and more specifically, a variation of the phase angle can be the major concern. An analysis was done similar to the impedance analysis shown in Table 1; however, this analysis focused on phase response at mmWave frequencies.

Table 2 showing similar differences as shown in Table 1, however due to mmWave frequencies the nominal substrate thickness of the circuit needs to be thinner to avoid spurious wave mode propagation issues.

Microstrip transmission line circuit and modeling a circuit segment 0.049" (1.25mm) in length, using 5mil thick circuit material with a nominal Dk value of 3.0

Dk	Substrate thickness (mils)	Copper thickness (mils)	Conductor width (mils)	Characteristic impedance (ohms)	Phase angle (deg) at 78 GHz	Difference in phase angle (deg)	Comment
3	5.0	2	11	50.05	180.08	0	Baseline for comparison
3	4.5	2	11	46.85	180.46	0.38	Substrate is 10% thinner than baseline
2.96	5.0	2	11	50.33	179.01	-1.07	Dk is lower than 1.4% from baseline
3	5.0	1	11	51.69	181.34	1.26	Copper thickness reduced by 1mil from baseline
3	5.0	2	10	52.77	179.13	-0.95	Conductor width reduced by 1mil from baseline

Table 2 shows the hierarchy of impact on the phase angle, due to the influence of the same variables as shown in Table 1. The variable with the most impact on phase angle is the copper thickness. The next most impactful variable is Dk variation, followed by conductor width changes and finally substrate thickness variation has the least impact on changing phase angle. The length on the line segment for table 2 used for the models is approximately ½ wavelength at 78 GHz. That is the reason why the phase angle values are about 180 degrees and also this is a common fraction of wavelength used for circuit features in RF circuit design.

The variable of copper thickness noted in Tables 1 and 2 is more significant for the PCB fabrication process than the property of the laminate. The typical thickness tolerance for copper used in making a laminate is ± 10% and for a laminate using ½ oz. copper there is a potential thickness variation of about ± 0.07mils. In the PCB fabrication process it is common for the copper to be plated thicker and it is that variation which is more concerning than the copper tolerance on the laminate.
The next most impactful variable is the Dk tolerance and there are more potential issues in this category than most designers may commonly consider.

One obvious issue is the normal Dk variation of the raw substrate and in the example shown in table 2,that is being held to about ± 0.04 which is considered a good and very tight Dk tolerance. However, there are other issues which can vary the Dk and one is the Thermal Coefficient of Dk (TCDk), which is a property that all materials possess and it is the Dk variation with a change in temperature. Moisture absorption is another material property that can alter the Dk of the material and it has been demonstrated [2] that copper surface roughness can alter the effective-Dk of the circuit.

TCDk is most appropriately evaluated with a measurement of the raw substrate and within a controlled environment with different temperatures. This is often done using a clamped stripline resonator test method as defined in IPC-TM-650 2.5.5.5c [3]. This test method uses a raw substrate, placed inside a fixture and when under clamped pressure it behaves as a stripline resonator circuit. A simple illustration of this fixture is shown in Figure 1.

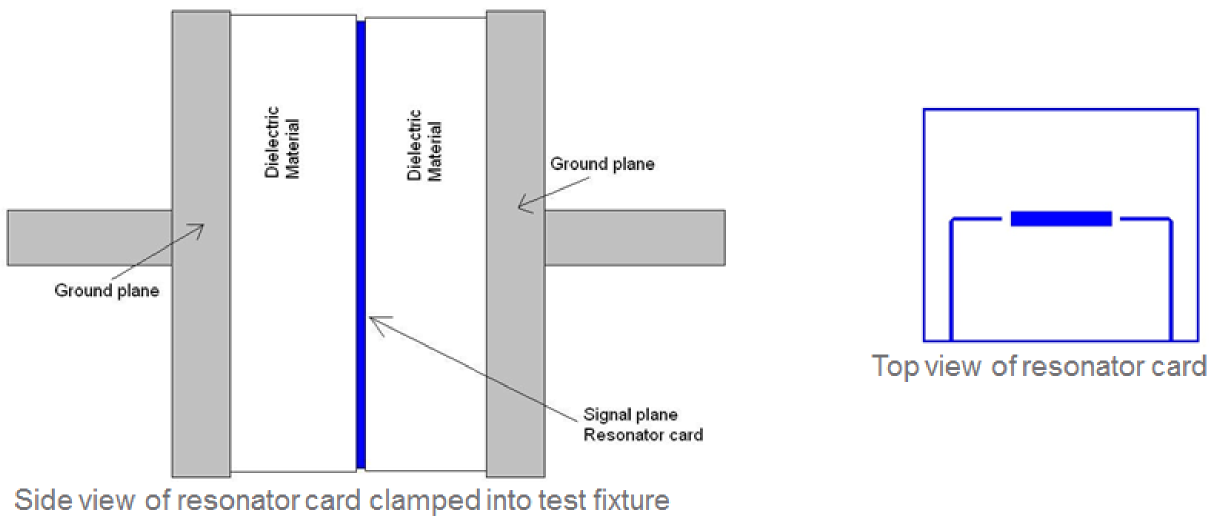

Figure 1. Clamped stripline test fixture to measured Dk of the raw substrate (dielectric material).

The IPC procedures for the clamped stripline test are used in testing the TCDk of a material, however, there are special precautions which are necessary for testing at elevated temperatures. Special cables are used that go into the oven. These cables need to have very good RF stability with changes in temperature and are robust to the temperatures which will be evaluated. Also, the clamping mechanism is made of thick metal which can impact the actual temperature of the material being tested and special attention needs is needed to ensure the material is at a thermal equilibrium prior to testing at a specific temperature. With these considerations applied and testing at approximately 10 GHz, the following graph in Figure 2 shows the TCDk behavior of several different materials used in RF PCB applications.

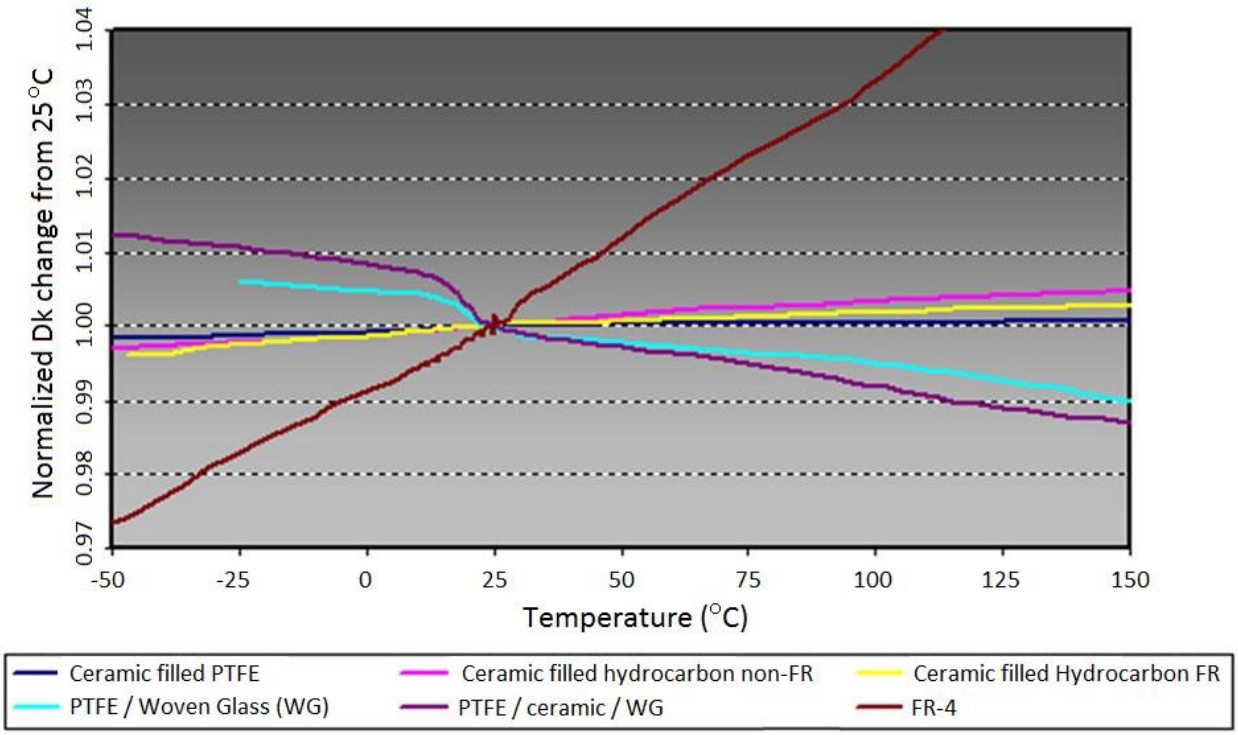

Figure 2. TCDk behavior of several different materials used in PCB circuits for RF applications.

The TCDk behavior shown in Figure 2 has several different curves which can be important to understand when considering materials for RF applications, where the circuit may vary in temperature during operation. The FR-4 TCDk curve is shown as a reference and is considered very poor. Most FR-4 materials are not formulated to have good (low) TCDk values and they are also not typically used in the PCB where good RF performance is needed. On the other side of this rating spectrum for TCDk is a material with very good TCDk and it is the dark blue curve, which is a specially formulated ceramic filled PTFE material without woven glass reinforcement. This material is currently used in very large volume for automotive sensor applications at mmWave frequencies and it can be seen that it has a nearly perfect TCDk curve, where perfect would be a constant 1.00 across the range of temperatures being evaluated.

The PTFE / Woven glass (WG), light blue curve, has a transition at room temperature which is common for most PTFE materials, regardless if the material is glass reinforced or not. If the proper ceramic filler is used, this room temperature transition can be eliminated which is demonstrated with the dark blue curve of the ceramic filled PTFE material.

Although the information is important to understand in Table 2, it is limited to testing at 10 GHz, which is far below mmWave frequencies and it is testing raw material only. Of course most PCB applications operating at mmWave frequencies are circuits and it may be helpful to evaluate the TCDk effects in circuit form. This can be done but it needs to be understood that when evaluating TCDk properties in circuit form, there are more variables than just raw material. Circuit form testing across a range of temperatures has the variable of the copper changing conductivity as the temperature changes. Additionally, the copper treatment will also change conductivity, which may be different than the bulk copper change. To be clear, the copper treatment is a thin layer that is typically a non-copper alloy and is at the copper-substrate interface of the laminate. The impact of copper conductivity changing with temperature is difficult to assess the effect at mmWave frequencies because there are Direct Current (DC) and RF properties impacted. As a side effect, the skin depth is also altered by a change in conductivity as well as surface impedance. Considering these conductor variables which are difficult to account for accurately, it is best to look at results of circuit testing for TCDk as approximate and put more attention on the trends when comparing circuits of differing materials.

Circuit testing was done and comparison trends made between room temperature conditions and conditions at 65°C. Besides the previously mentioned conductor variables, there are also variables associated with the testing, such as connectors and cables changing performance with a change in temperature.

For the testing done here, special cables were used which were rated well above the testing temperature as well as the connectors. Additionally, the connectors were compression connection end launch connectors (non-soldered connectors), which allows the same physical connectors to be used on the different circuits evaluated. This helps to minimize connector differences when comparing results of different circuits in this test. The graph in Figure 3 shows testing of microstrip transmission line circuits, using two different circuit materials which have significantly different TCDk performance.

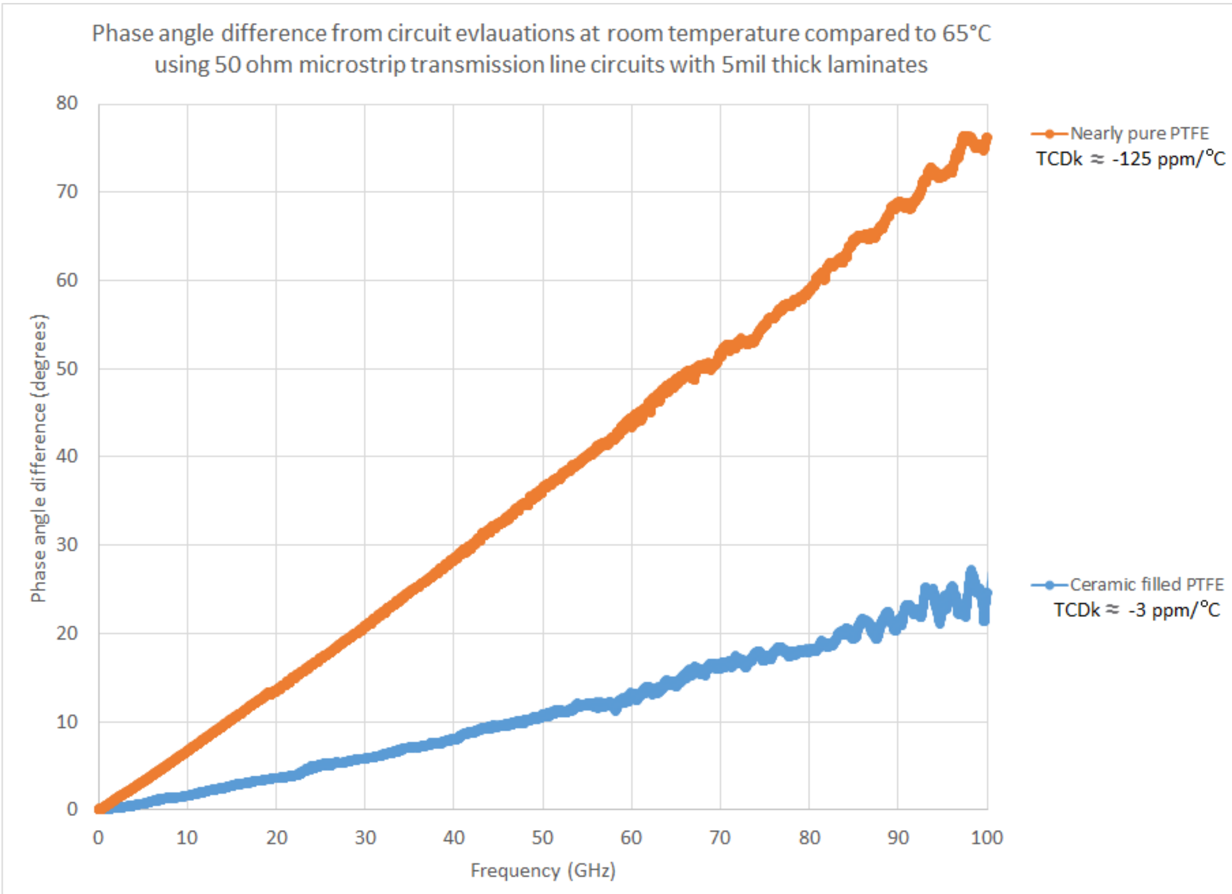

Figure 3. Phase angle testing of 8" (203mm) long 50 ohm microstrip transmission line circuits, comparing room temperature conditions to operating at 65°C.

To keep the circuit design variables at a minimum, 50 ohm microstrip transmission line circuits were used when collecting the data shown in Figure 3. The transmission line circuits were relatively long at 8 inches (203mm), and both ends of the circuits were protected from the heat as much as possible. The ends of the circuits had the end launch connectors and the connection to the cables, so these areas were purposely closer to room temperature conditions. The bulk of the length of the 8-inch-long circuit was subjected to the elevated temperature and the area of the circuit exposed to that temperature was constant for the different circuits evaluated. The y-axis of the chart is the difference of phase angle when the circuit was tested at room temperature (25°C, ≈ 20% RH) as compared to the same circuit being tested at 65°C and approximately 20% RH. The circuits were allowed to come to a thermal equilibrium before the data was collected.

The blue curve in Figure 3 is the same "ceramic filled PTFE" material mentioned in Figure 2 as the dark blue curve. This material has a TCDk value of -3 ppm/°C when measured at 10 GHz and in accordance with testing per the IPC clamped stripline test described earlier in this paper. The material noted as the "nearly pure PTFE" material in Figure 3, has a TCDk value of -125 ppm/°C when tested in the previously mentioned IPC test.

In an effort to clarify the data shown in Figure 3, the phase angle difference at 80 GHz for the ceramic filled PTFE material is approximately 18 degrees. Meaning, there was an 18-degree difference in phase angle from the circuit being measured at room temperature as compared to being measured at 65°C. The nearly pure PTFE material, with the poorer TCDk, is shown as the orange curve in Figure 3 and at 80 GHz there is a phase angle difference of about 59 degrees. Again as a reminder, circuit testing has more variables than raw material testing at elevated temperatures, so the circuit TCDk trends should be used in a comparative sense or as an approximate trend. Also mmWave automotive radar sensors are sensitive to differences in phase angle but it very much depends on the sensor design. In some cases, a phase angle difference of a few degrees can be significant and in other cases it may only be sensitive to 10's of degree differences. As a general comment for phase angle in mmWave automotive sensors, the differences shown in Figure 3 for the ceramic filled PTFE material are considered good and the angle differences for the nearly pure PTFE material are considered poor.

Another concern at mmWave frequencies can be Dk variation due to moisture absorption and its impact on phase angle. Basically, a material which can readily absorb moisture from the environment, can change Dk properties. Water has a Dk value of about 70 and when more water is absorbed into the substrate by moisture absorption, the Dk of the substrate will increase. A test that is being used more recently and is simply known as 85/85 testing, is an evaluation of material or circuits in an environment which is at 85°C and 85% RH for some significant period of time. Results from phase testing at 85/85 for 72 hours are shown in Figure 4.

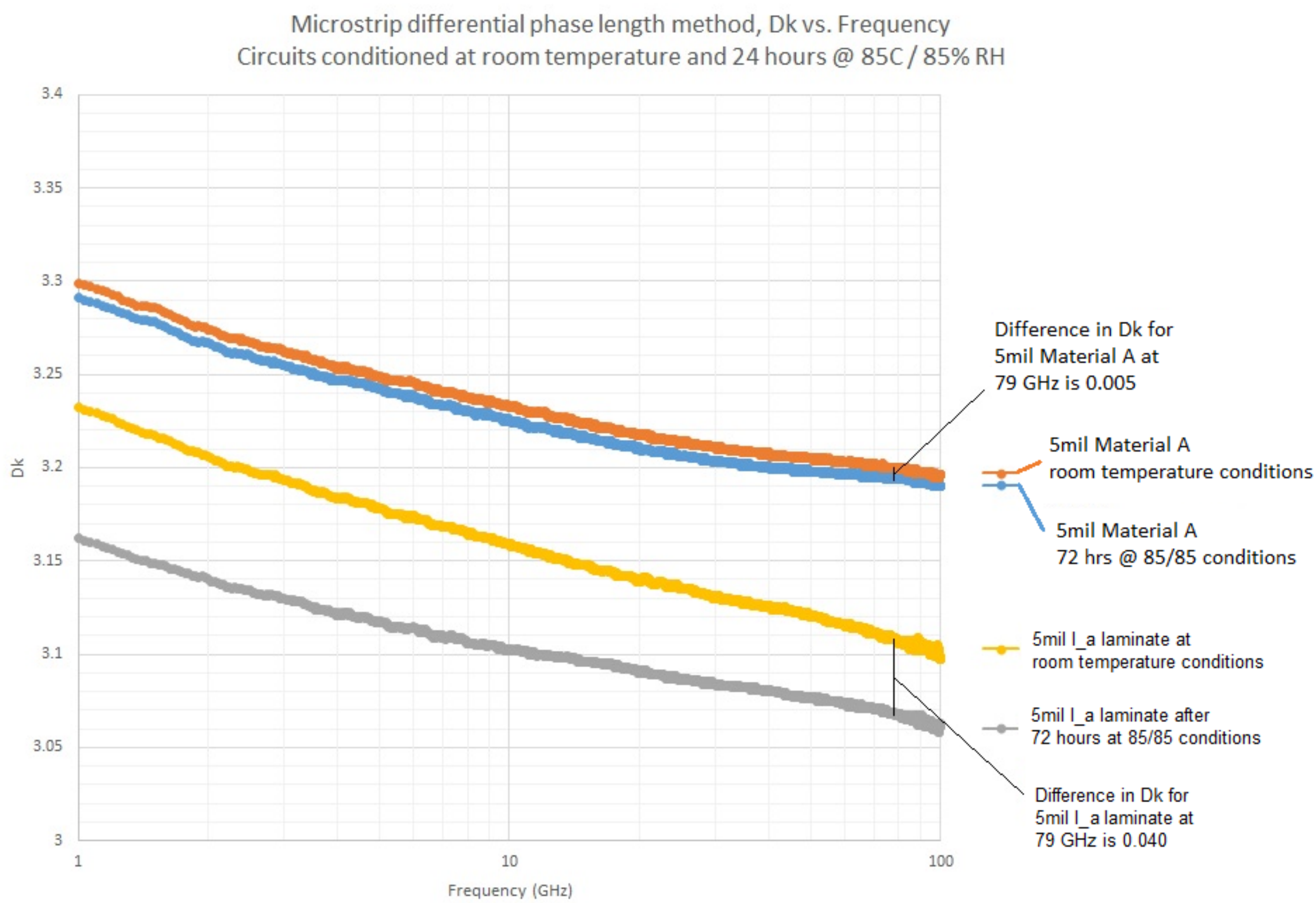

Figure 4. Phase response testing, with calculation of Dk for circuits tested at room temperature and then after the circuits were subjected to 85C/85RH conditions for 72 hours.

The data shown in Figure 4 is with microstrip transmission line circuits and using the differential phase length method [4]. The method uses 2 circuits of different physical length and measures the phase angle across a wide range of frequencies. From the difference of phase angle and the physical length difference, equations [5] [6] are used to back calculate the Dk of the material. Material A noted in the chart of Figure 4 are the same materials as noted in Figures 2 and 3 as the ceramic filled PTFE material with good TCDk. These materials show very good Dk stability in the 85/85 testing as opposed to a different material which shows significant RF performance difference due to the 85/85 conditioning.

The testing done in Figure 4 is always at room temperature. The initial testing is of course after the circuits have been at room temperature for a long period of time; more than 1 week. The room temperature conditions were 25°C and approximately 20% RH. The circuits were placed in a temperature-humidity chamber and conditioned to 85/85 for 72 hours. After the conditioning, the circuits were removed and tested at room temperature. This testing was done very quickly after removal from the conditioning chamber so the circuits did not change from the absorbed humidity. The testing results were completed in less than 5 minutes after removal from the 85C/85RH conditioning, which is a very safe time frame to avoid changes in the humidity content of the circuits.

This is important to note, because the circuits did not have the influence of TCDk, because they were tested at room temperature conditions which means the 85/85 testing is really showing the influence of moisture absorption. In the real-world, the influence of TCDk would also be included if the circuits were actually tested within the 85/85 environment.

The reason the circuits are not tested in the 85/85 environment, is that this type of test needs a calibration done within the environment where the testing is being performed. It is not possible to do a valid calibration within the 85C/85RH conditioning chamber. As a side note, the IPC-TM-650 2.5.5.5c test method used to evaluate raw material TCDk properties as mentioned previously, does not require calibration which makes it is feasible to perform that testing within a test chamber.

The copper surface roughness is another issue which can be very influential for mmWave performance of PCBs. However, due to the depth of this topic it is not feasible to include much details in this paper. Reference [7] which gives an overview of this topic shows that the effective-Dk of the circuit can be significantly altered by the copper surface roughness variation at mmWave frequencies. Additionally, surface roughness of all copper foils used in the PCB industry have normal variation. There are roughness variations for copper foil as within-sheet variation, or sheet-to-sheet and lot-to-lot variations and these differences should be considered when modeling circuits at mmWave frequencies. As a quick overview of this topic, Figure 5, shows a comparison of testing microstrip transmission line circuits with two different copper types and the impact on the circuit-perceived-Dk due to copper surface roughness variation.

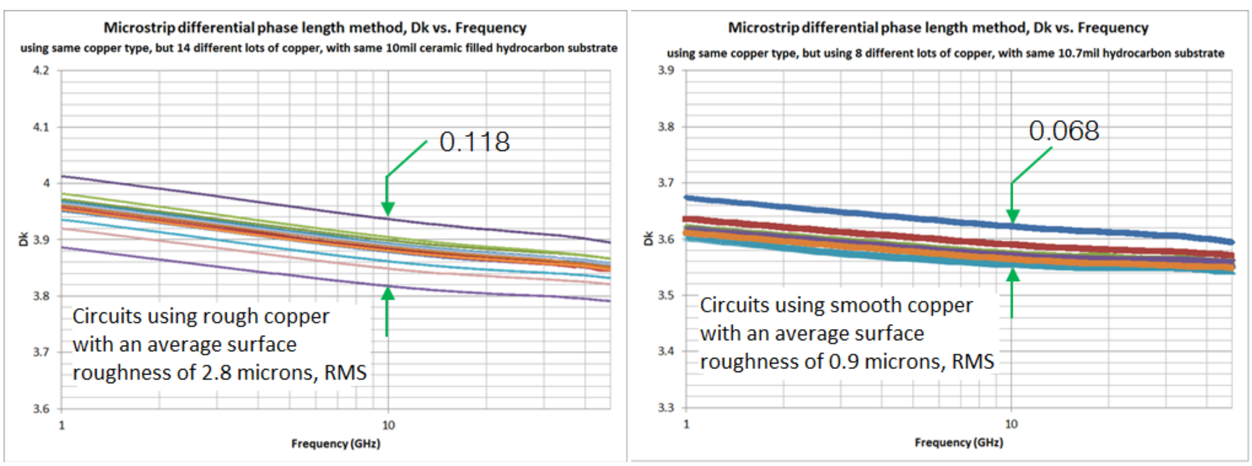

Figure 5. 50 ohm microstrip transmission line circuits using the same substrate, but with 2 different copper types and showing the impact on the circuit-perceived-Dk due to normal lot-to-lot surface roughness variation of the copper foils.

The information shown in Figure 5 is illustrating the impact of normal lot-to-lot surface roughness variation for copper. The type of copper which is the rough copper has an average surface roughness of 2.8 microns when measured as Root Mean Square, (RMS or R_q) and the smooth copper has an average roughness of 0.9 microns RMS. A rougher copper surface will cause the phase velocity to slow and the natural response of the circuit is to perceive a higher Dk with a slower wave, even though the dielectric material is the same. Additionally, the charts shown here are circuits using a substrate that is approximately 10mils thick and if the circuits were thinner the Dk difference shown here would be greater. This Dk variation due to copper surface roughness can be significant for thin circuits used at mmWave frequencies. The copper foil with the rougher surface naturally has a higher range of roughness variation as compared to the smoother foil. As a general statement for PCB applications at mmWave frequencies, it is advisable to use a copper foil with a smooth surface to minimize the circuit-perceived-Dk variation.

Conclusions

There are four significant circuit properties to consider for good PCB RF performance at mmWave frequencies. These properties are conductor width, copper thickness, dielectric constant and substrate thickness. Material properties that need to be considered are TCDk, moisture absorption and copper surface roughness. The designer needs to consider the circuit and material properties when designing circuits at millimeter wave frequencies.

References

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