Microwave Journal

eBook

Circuit Material Design Guide for mmWave Radar Applications

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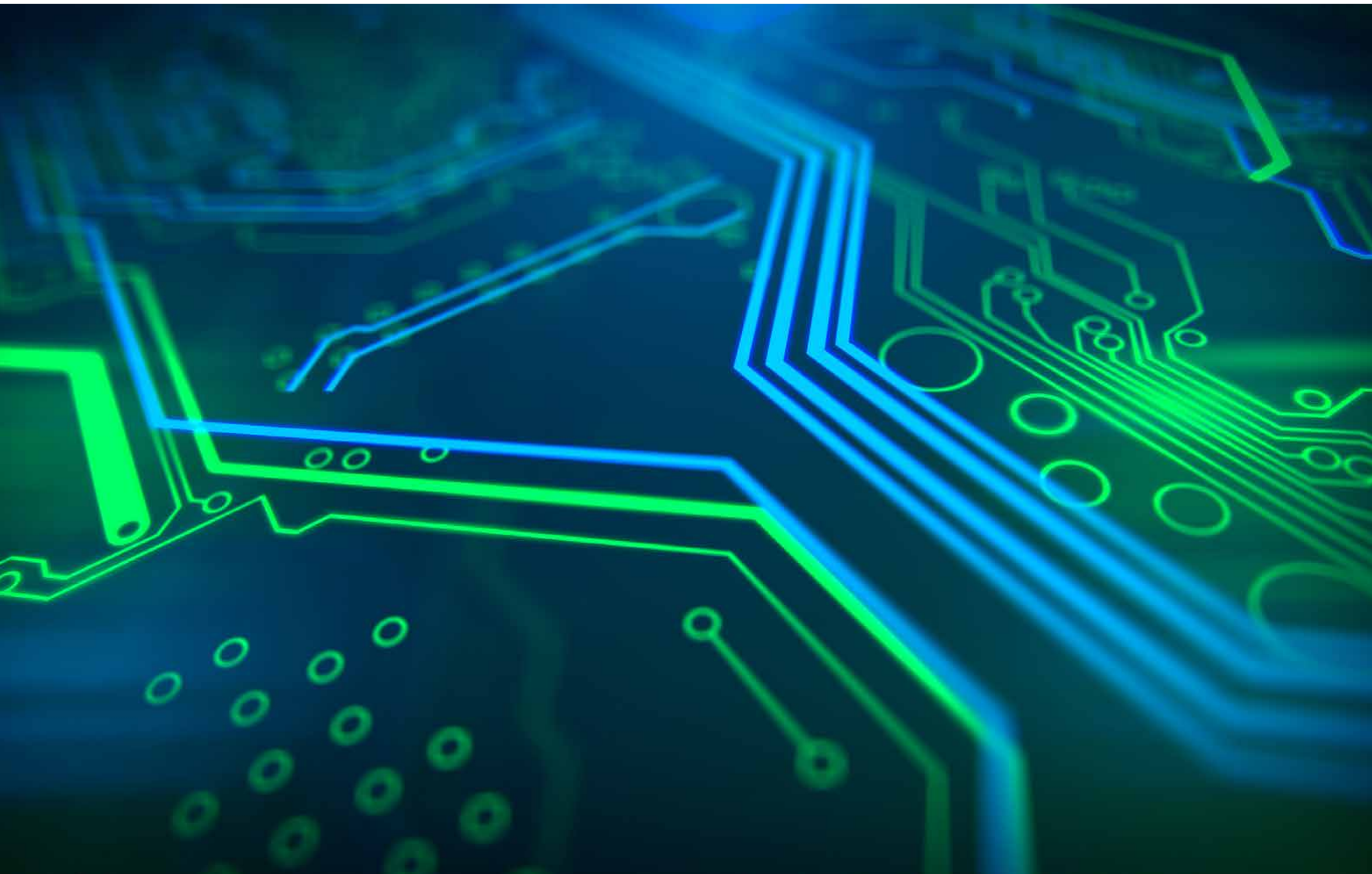

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Introduction

Circuit Material Design Guide for Radar and mmWave Applications

mmWave applications are expanding rapidly in many commercial markets such as automotive radar, for vehicle autonomy and advanced safety systems. Yole Développement estimates the automotive radar market alone will reach US$8.6 billion by 2025, at a 2015 CAGR of 15.6 percent. There are many other mmWave applications such as body scanners, satellite communications and material properties/defect measurements that are also expanding. But designing mmWave circuits is far more challenging than traditional RF circuits as design parameters are much more sensitive at these higher frequencies.

This eBook covers the design considerations for PCB laminate circuits and how to take these issues into account when designing for mmWave applications. Dielectric constant is a key material parameter that can vary due to temperature changes, within a substrate material due to the construction material, or over frequency. Dissipation factor is another key parameter that can affect the losses in a circuit and become very significant at mmWave frequencies. Metal surface roughness is another important consideration that can increase signal loss that is not significant at lower frequencies. The woven glass within the circuit material also causes changes in dielectric constant that can affect mmWave signals differently depending on the direction of the metal transmission lines. In addition, datasheets might not provide all of the information you need to simulate a circuit accurately.

The articles in this eBook address these issues in designing mmWave circuits on PCB laminates and covers how to mitigate or adjust your design for these effects. The articles have measured data and examples that show the effect of each parameter on design examples, providing a practical guide for mmWave designs. We hope that you will learn about these effects and more by reading this design guide brought to you at no cost due to the sponsorship of this eBook by Rogers Corporation.

Pat Hindle, Microwave Journal *Editor*

Understanding mmWave Circuit RF Variations due to Changes in Temperature

Rogers Corp., Chandler, Ariz.

Changes in temperature can cause variations in the performance of high frequency circuits. Whether those temperature variations come from heat dissipated within the circuit itself, from devices mounted on the circuit, or from the environment, they can have impact on the performance of the circuit. For example, motor vehicles are increasingly equipped with the mmWave circuitry of automotive advanced driver assistance systems (ADAS) to provide protection against collisions. Fortunately, the circuit material property known as thermal coefficient of dielectric constant (TCDk) gives a circuit designer a way of knowing how much the material's dielectric constant, Dk (relative permittivity or ε_r) will vary from a nominal value as a function of temperature. The parameter can be used to predict the operating tolerances of a circuit material at mmWave frequencies, when that circuit board must be mounted in an environment with widely varying tem-

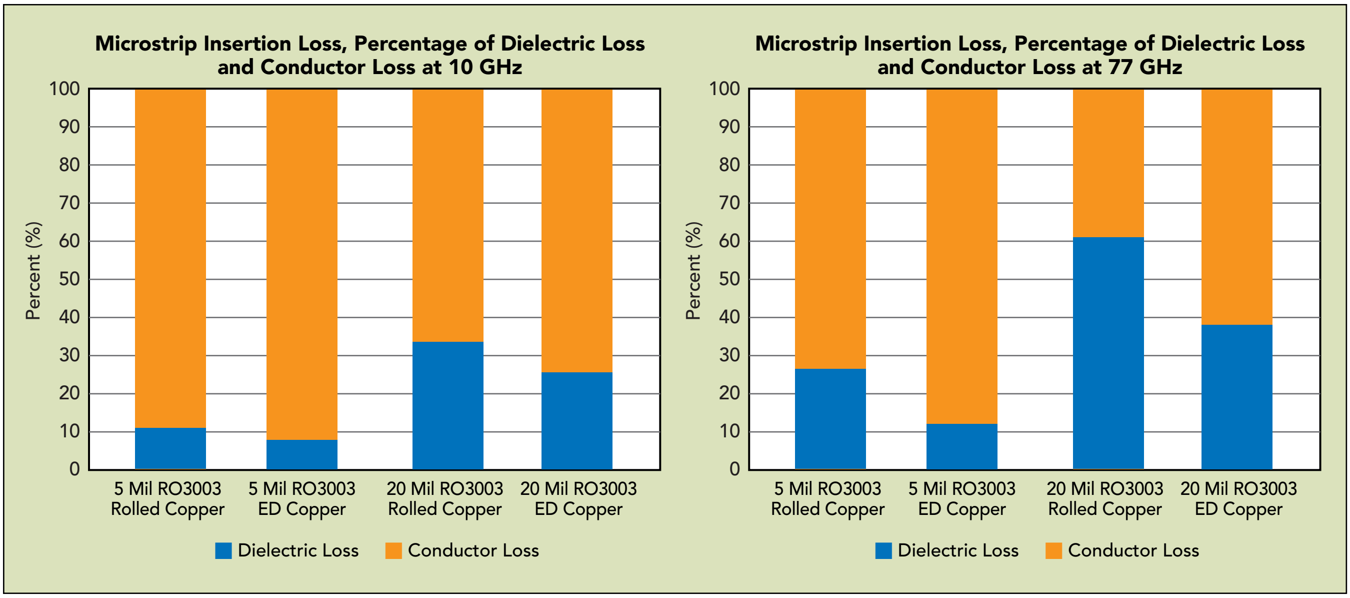


Fig. 1 Comparing insertion loss of 50 ohm microstrip transmission line circuits using different substrate thicknesses and the percentage of the insertion loss for dielectric and conductor loss.

peratures, such as in automotive electronics or 5G base stations.

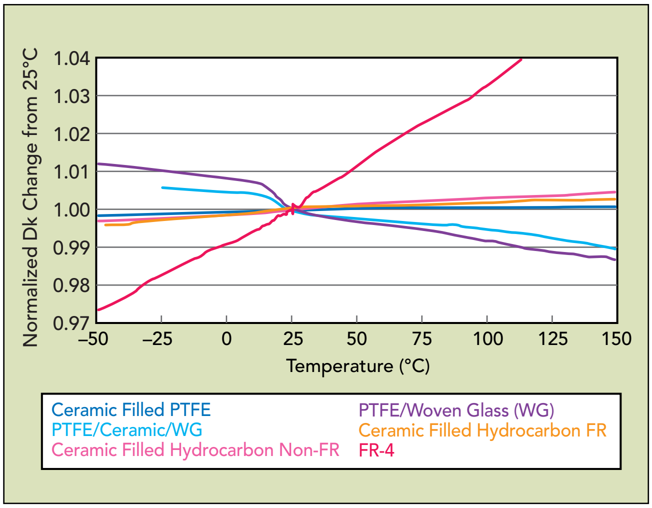
Thermal variations in an RF/microwave printed circuit board (PCB) can be caused by several factors. The operating cycle of a circuit can cause thermal variations (with resulting performance variations), as the circuit switches from power on to power off. The thickness of the PCB material is one of these factors. A PCB based on a thinner substrate will have more RF performance sensitivity to conductor effects than a circuit based on a thicker substrate. In contrast, a circuit based on a thicker substrate is more sensitive to dielectric effects. Typically, conductor effects can have an impact on the insertion loss of a high frequency circuit while the circuit's dielectric characteristics affect the phase response of the circuit; however there are exceptions. Insertion loss is critical in passive components, such as filters and power combiners, while the phase response is needed for phased-array antennas and systems.

As shown in ***Figure 1,*** insertion loss is a summation of four losses: dielectric loss, conductor loss, radiation loss and leakage loss. For this example, leakage loss and radiation loss have been ignored. Leakage loss is typically not an issue for most PCB applications using high frequency materials because these materials have very high volume resistivity. However, there can be exceptions with high power applications, although high power applications will not be covered in this article. Radiation loss is also not considered in Figure 1; many variables impact radiation loss and circuit design can mitigate a lot of these issues. Figure 1 is included to help a reader realize the impact that conductor effects have on a thin circuit compared to a thicker circuit.

For the 50-Ω transmission line circuits in Figure 1, conductor effects are much more significant for a thinner circuit than a thicker circuit. In turn, dielectric effects are more significant for a thicker circuit than a thinner circuit. Why is this important? With bandwidth having been exhausted at lower frequencies, and a growing number of mmWave applications, those mmWave circuits will typically be based on thinner substrates. At mmWave frequencies, circuit designers should be concerned about conductor effects, caused in part by the copper surface roughness[1] and the final plated finish of the conductor[2].

Thicker substrates are typically used at lower frequencies: the conductor effects are minimized but the dielectric effects are increased. The major consideration for dielectric effects is the dissipation factor of the material and any nonmetal added to the circuit. Examples of nonmetals added to a circuit which can impact dielectric loss are soldermask and conformal coatings. Figure 1 compares a thin circuit (a 5-mil-thick substrate) to a thicker circuit (a 20-mil-thick substrate) but 20 mils is not considered thick for some applications. For a 30-mil-thick substrate, for example, the dielectric losses would be more significant while the insertion loss of a 60-mil-thick substrate would be dominated by dielectric loss.

Understanding the variables that can impact a circuit's performance based on the thickness of the circuit material is good to know for different frequency applications but also when trying to understand the potential impact that TCDk can have on a circuit. In theory, a thicker circuit should be influenced more by TCDk than a thinner circuit, because TCDk is a dielectric property. Also, as the circuit cycles through different temperatures, its copper conductivity will change slightly and variations in performance caused by those changes should be more obvious for RF circuits based on thin substrates than those based on thick substrates.

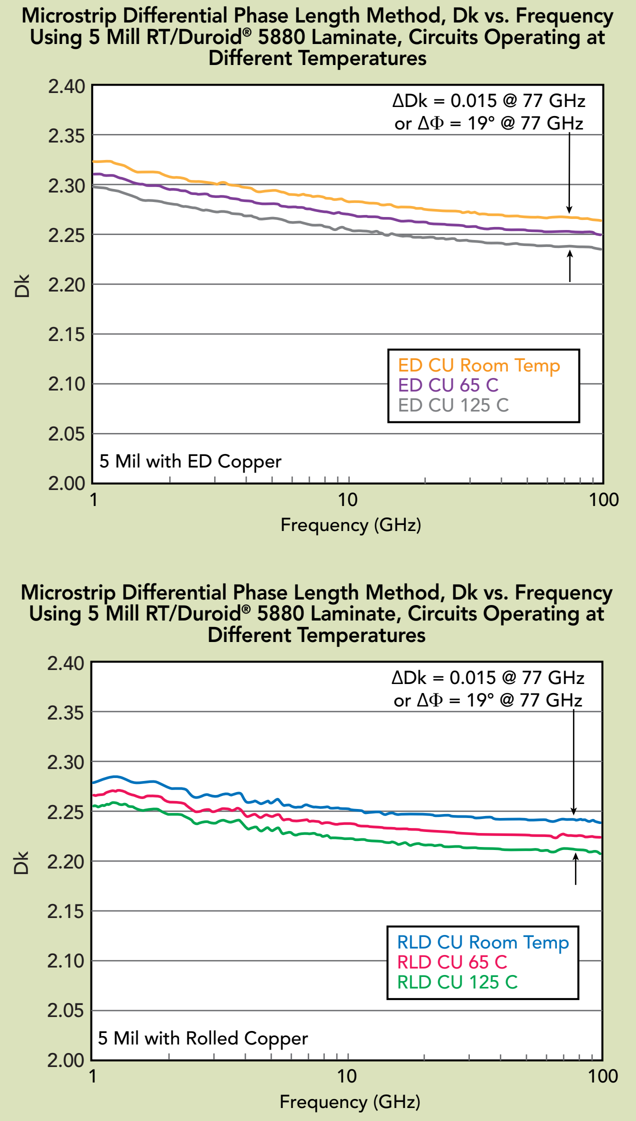


▲ **Fig. 2 TCDk curves for several different circuit materials used with PCB technology.**

All circuit materials have the TCDk property, although due to formulation differences, the amount of Dk variation due to temperature change can be very different. ***Figure 2*** provides a look at several TCDk behavior curves for different circuit materials.

The data for these TCDk curves was collected by testing raw substrate materials and not fabricated circuits. Testing was done at 10 GHz per the X-Band clamped stripline resonator test defined by IPC-TM-650 2.5.5.5c; several materials of different TCDk behavior were evaluated. The brown curve is FR-4 which is typically not used at higher frequencies. It has a very poor TCDk and FR-4 has not been formulated to account for good TCDk performance. The purple curve shows a significant change around room temperature, which is the correct response for PTFE. This curve is based on a material which is PTFE and woven glass reinforcement only. However, when ceramic filler is added to the formulation (light blue curve), the room temperature TCDk response is greatly decreased.

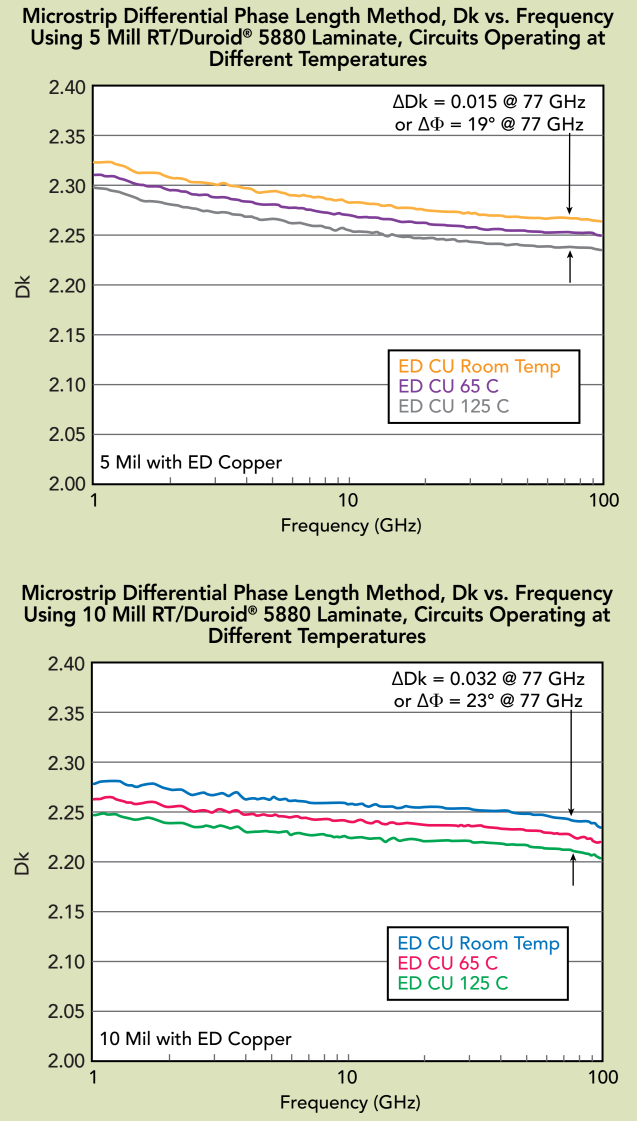
Not all ceramic filler is the same, however, and understanding the intricacies of ceramic engineering can pay off, which the dark blue curve demonstrates. This curve is for RO3003™ circuit material, which is a ceramic-filled PTFE material and it has minimal TCDk of 3 ppm/°C and no response at room temperature. An ideal TCDk would be 0 ppm/°C, which is basically stating there is no change in Dk with a change in temperature. A good reference for TCDk is that a value of |50| ppm/°C or less is considered good. The absolute value


Microstrip Differential Phase Length Method, Dk vs. Frequency Using 5 Mill RT/Duroid® 5880 Laminate, Circuits Operating at Different Temperatures

Microstrip Differential Phase Length Method, Dk vs. Frequency Using 5 Mill RT/Duroid® 5880 Laminate, Circuits Operating at Different Temperatures

These two copper types are very different and the copper differences do not appear to be a significant factor for circuit-TCDk.

▲ **Fig. 3 Comparisons showing circuit-TCDk at different temperatures and using the same material with a poor TCDk, but with different copper types.**


Microstrip Differential Phase Length Method, Dk vs. Frequency Using 5 Mill RT/Duroid® 5880 Laminate, Circuits Operating at Different Temperatures

Microstrip Differential Phase Length Method, Dk vs. Frequency Using 10 Mill RT/Duroid® 5880 Laminate, Circuits Operating at Different Temperatures

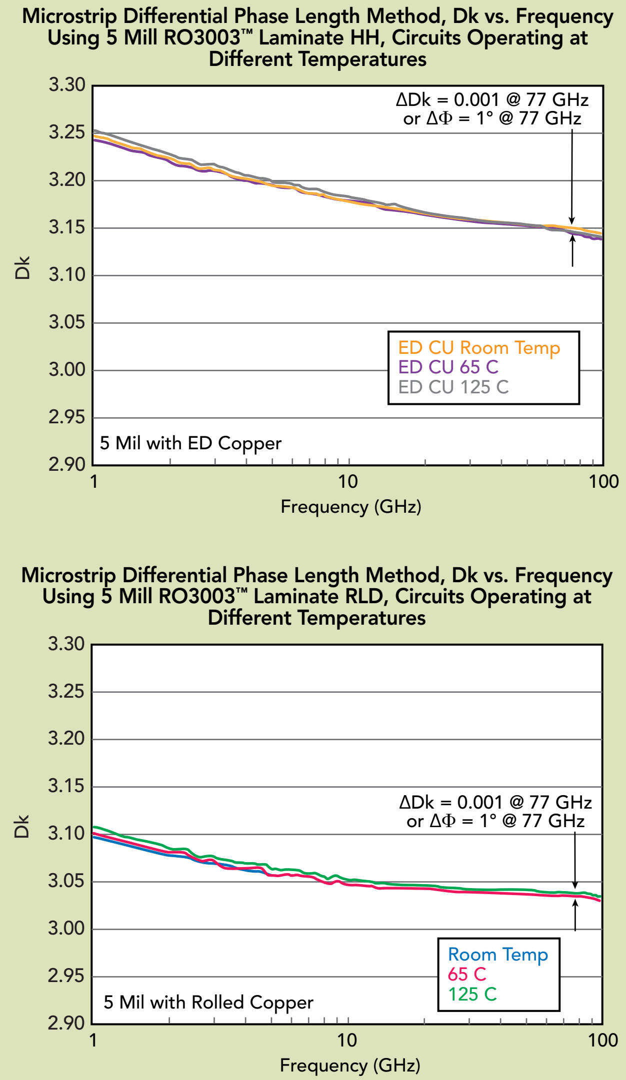
Thin circuits are dominated by conductor effects and thicker are more sensitive to dielectric effects. Even though 10 Mil isn't that thick, it appears that the thicker circuit is more impacted by the Dk difference due to TCDk.

▲ **Fig. 4 Comparisons showing circuit-TCDk at different temperatures and using the same material with poor TCDk and the same copper type, but with different substrate thicknesses.**

of this number was used because some materials have a TCDk trend which has a negative slope and other materials have a positive TCDk slope. For reference, the magenta curve has a TCDk of +50 ppm/°C.

Even though the chart shown in Figure 2 is helpful to understand a material's TCDk performance, it is still limited to several aspects due to that test method. One aspect is that the test method is limited in frequency and another aspect is the testing was not using an actual circuit. Rogers Corporation has developed a test method which allows the evaluations of circuits at elevated temperatures and is called the circuit TCDk test method. It uses the microstrip differential length method[3] with a special setup to evaluate circuits at a controlled temperature.

The circuit-TCDk test method is as follows. For evaluating one material, two 50-Ω microstrip transmission-line circuits are used which are identical in every way except for physical length. One circuit is 2 in. long and the other is 8 in. long. The circuit is first assembled and placed on a heat block, with the heat block being off and at room temperature. Several sweeps on the mmWave vector network analyzer (VNA) are performed to ensure stable RF performance with the initial reading at room temperature. After the data from the initial reading has been captured, the heat blocked is turned on and adjusted


Microstrip Differential Phase Length Method, Dk vs. Frequency Using 5 Mill RO3003™ Laminate HH, Circuits Operating at Different Temperatures

Microstrip Differential Phase Length Method, Dk vs. Frequency Using 5 Mill RO3003™ Laminate RLD, Circuits Operating at Different Temperatures

This is a duplication of the same experiment done using circuits with different copper types on RT/Duroid® 5880 laminate. The RO3003 laminate has nearly ideal TCDk.

Fig. 5 Comparisons showing circuit TCDk at different temperatures and using the same material, with the same substrate thickness, with excellent TCDk, but with different copper types.

to +65°C. After the circuit has reached this temperature, there is time to ensure thermal equilibrium and this is monitored with a thermocouple mounted next to the circuit and with a FLIR® thermal imaging camera. Once the circuit is stable at +65°C, more sweeps are performed on the VNA and the data is captured. The heat block is then adjusted to +125°C and again thermal equilibrium is reached and a stable RF sweep is performed, and data is collected. The process is complete for the 2-in. circuit and then repeated for the 8-in. circuit. Numerous details of this test method are not covered in this article but can be shared upon request.

Many different circuits have been evaluated with the circuit-TCDk test method, although an overview of only one study will be presented in this article. Testing was performed to evaluate several different materials which had poor TCDk vs. those with good TCDk to better understand the effects of TCDk on circuit performance. Evaluating the materials at different substrate thickness and different copper types also made it possible to see if the effects of TCDk on RF performance varies due to different substrate thicknesses or copper types.

PUT TO THE TEST

The high frequency materials chosen for this evaluation were RT/duroid® 5880 and RO3003™ laminates. RT/duroid 5880 material has a good, long history as one of the lowest-loss circuit materials ever introduced to the market, although it also has a poor TCDk of -125 ppm/°C. RO3003 materials have been used for many years in different applications and have been the material of choice for 77 GHz automotive radar sensors. RO3003 materials have a TCDk of 3 ppm/°C. The thicknesses of substrates in this study was 5 and 10 mils thick. Copper foils used were rolled copper with an average surface roughness of 0.35 μm RMS and ED copper with an average roughness of 2.0 μm RMS.

Figure 3 presents a summary of test results comparing circuits made with 5-mil RT/duroid 5880 laminate with rolled copper to circuits made with 5-mil RT/duroid 5880 laminate with ED copper.

Figure 3 shows no difference in the circuit-TCDk performance due to copper type even at different temperatures. The two copper types have very different grain structures and slightly different conductivity, although the small differences in conductivity due to different temperatures are not apparent. Also, the shift in the extracted Dk, which is the data on the y-axis for the charts, is a normal shift when comparing circuits based on this substrate and with these two different copper types. The rougher copper (ED) will cause a slower wave propagation than the smooth rolled copper and the slower phase velocity causes increase in effective dielectric constant and ultimately the extracted Dk, which Rogers calls Design Dk.

To continue this study on TCDk, the same material with the same copper type will be compared with different substrate thicknesses, to evaluate the effects of temperature on circuit materials of different thicknesses. The results of the evaluation are shown in ***Figure 4*** for measurements performed at 77 GHz.

As Figure 4 shows, there is a difference in the circuit-TCDk behavior depending upon the thickness of the substrate. Circuits with the thicker substrate had a larger difference in Design Dk with temperature than the circuits using the thinner substrate. The change in Dk due to the TCDk of the material at different operating temperatures is an indication that a thicker circuit material will be more dominated by the dielectric properties than the conductor properties.

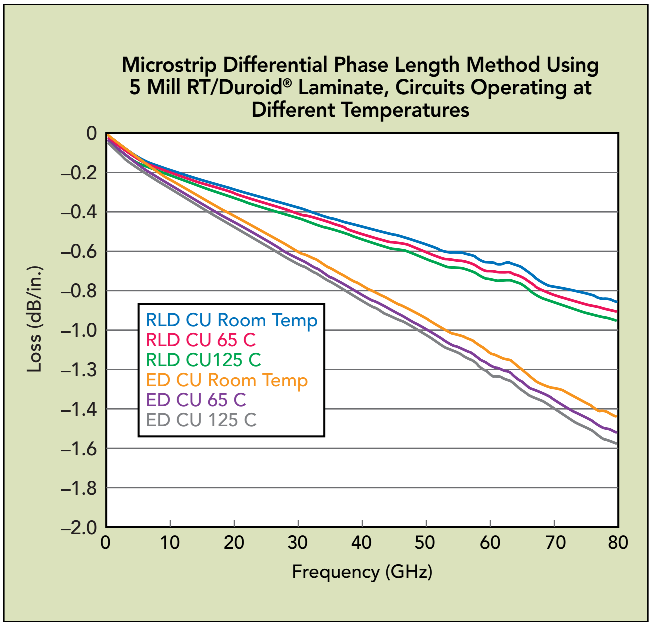
Figure 5 shows the results of circuit-TCDk testing for circuits using a material with excellent TCDk properties.

As the data shows in Figure 5, there is no difference in Dk between the circuits using a material with excellent TCDk and different copper types. Figure 3 shows the different copper types do not affect Dk when using a material with poor TCDk. However, the difference in Dk or phase angle is minimal for circuits based on a laminate material with very good TCDk as shown in Figure 5 and compared to circuits using material with poor TCDk as shown in Figure 3.

Another temperature-dependent circuit material property, thermal coefficient of dissipation factor (TCDf), may also be affected by the relative thickness of a circuit material. But this parameter is extremely difficult to measure accurately due to limits of conventional test methods. Methods such as the IPC clamped stripline resonator test method, for example, are sensitive to the metals involved with the makeup of the test fixture. As these metals expand and contract at different temperatures, that causes one aspect of inaccuracy for the test method. Another issue is the change in conductivity due to changes in temperature. Then considering test methods which use circuit testing to extract Df, those methods also have issues with the type of test vehicle and the sensitivity of the test vehicle to physical dimensional changes caused by temperature changes. They can also be impacted by the small change in copper conductivity, which is a small value, but considering the very sensitive nature of extracting the Df from a material's dielectric losses and trying to accurately account for the other losses (conductor losses and radiation losses), then the slight conductivity changes of copper due to temperature change can cause Df extraction accuracy issues.

A more real-world approach to considering changes in circuit material loss due to temperature changes is to perform insertion loss testing at different operating temperatures. As part of the circuit-TCDk experiments, other circuit properties were evaluated. The circuit properties associated with change in Dk, such as phase response and impedance, did respond in a predictable manner in accordance with the change in Dk from temperature exposure. However, insertion loss was also evaluated; specifically, changes in insertion loss due to temperature were evaluated. ***Figure 6*** compares circuits based on 5-mil RT/duroid 5880 laminates with two different types of copper. This is the same testing that was done for the circuit-TCDk evaluations and the data was collected at the same time, with insertion loss responses presented in Figure 6.

As Figure 6 shows, the effects of copper surface roughness are apparent on these circuits. Rolled copper has an extremely smooth surface and does not impact conductor loss as much as ED copper with its much rougher surface. The same testing was done with circuits on 5-mil-thick RO3003 laminate; however, the trends were like the results shown in Figure 6 and not shown here because the data did not add to the discussion. Insertion loss testing had been performed to see if material that had poor TCDk also had poor TCDf or a wider range of Df due to changes in temperature compared to materials with better TCDk values. Unfortunately, and since these materials (RT/duroid 5880 and RO3003 laminates) have very low dissipation factor (0.001 or less), any change in Df across this range of temperatures and frequencies was not obvious during the testing of the transmission lines. A similar comparison using higher-loss materials with good and poor TCDk could yield different results and it is believed that a material with poor TCDk will also have poor TCDf. However, the investigation can be much more complicated due to how different material formulations behave with changing temperatures and PTFE base materials will likely behave much differently than most hydrocarbon-based materials. And to complicate matters, different PTFE materials can behave very differently based on the different fillers that could be used and the different glass styles or amount of glass reinforcement used to make the laminate.



▲ **Fig. 6 Comparisons showing insertion loss differences for circuits built on 5 mil RT/duroid 5880 laminate with two different copper types and at different operating temperatures.**

In summary, all circuit materials can be defined by TCDk and it is an important parameter that should be considered in the design phase of any new application that will be exposed to varying temperatures. The thickness of a circuit substrate can affect circuit performance, where circuits based on a thicker substrate could be more impacted by changes in Dk according to a material's TCDk parameter with varying temperature. Differences in copper type, which were limited in this study, do not appear to be a significant factor for circuit performance regarding TCDk. Additionally, as a review of Figures 3, 4, and 5 will show, a circuit material's TCDk is not frequency dependent. Small differences can be seen in the figures but basically the Dk shift due to changes in temperature at 10 GHz will be about the same shift as those at 77 GHz. TCDk values found on data sheets are typically tested at 10 GHz; however, that is for raw substrate. When considering TCDk effects in circuit form, substrate thickness has been shown here to affect how the TCDk will impact circuit performance. This would suggest, when a designer is running circuit simulations, they should try several simulations with different Dk values according to how much the Dk of the raw substrate could change across the operating temperatures in which it will be used, to better understand the impact of those changes in Dk on the circuit being simulated. ■

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2. John Coonrod, "Insertion Loss Performance Differences Due to Plated Finish and Different Circuit Structures," APEX / IPC Expo 2019, Feb. 2019.
3. John Coonrod, "Characterizing Circuit Materials at Millimeter-Wave Frequencies," *Microwave Journal,* Vol. 62. No.5, May 2019.

The reference to the FLIR thermal imaging camera was from FLIR® Systems, Inc.

Material Solutions for mmWave Radar: From ADAS to Smart Cities and Factories

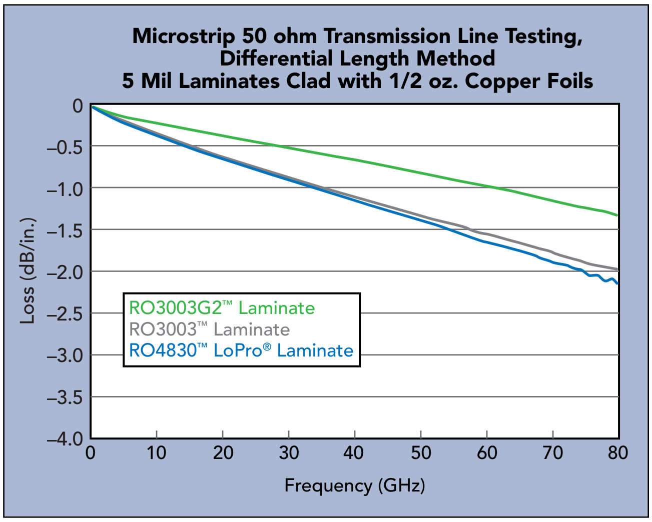
Rogers Corp., Chandler, Ariz.

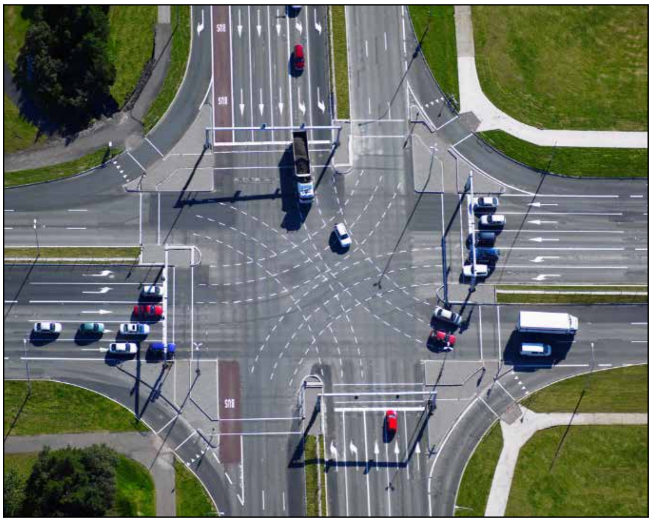
Over the last two decades, radar technology has been widely applied to commercial automotive applications to make driving safer and more convenient. With the development of Industry 4.0 and Smart Cities, radar applications have found even more diverse usage in traffic management, security and building automation. As radar PCB applications have grown and evolved, Rogers Corporation has blazed the trail with high performance, reliable, and cost-effective RF material solutions.

RADAR SENSORS FOR ADAS AND AUTONOMOUS DRIVING

Today, radar sensors are a key component of advanced driver assistance systems (ADAS). As ADAS expands to meet the increasing functional safety requirements driven by regulatory and NCAP roadmaps, radar technology will be applied to additional applications, such as corner radars for motorcycle and pedestrian detection, as well as in-cabin occupancy sensing to reduce the incidence of heat stroke tragedies. Additionally, high resolution radar technologies are being developed and deployed in Level 4 and Level 5 autonomous vehicles for personal mobility as well as last mile delivery vehicles. Radar technology is expected to grow and evolve to meet the increasing performance requirements of these automotive applications.

Along the way, Rogers' high frequency laminates have provided the RF performance and reliability required by the PCB patch antennas used in these safety-critical automotive radar applications. RO4000® materials, such as RO4835™ laminates are widely used for 24 GHz applications. For 77/79 GHz automotive radar applications, RO3003™ laminates are the industry leader, due to their exceptionally reliable RF and thermomechanical performance. To address the evolving needs of automotive radar antenna designers, Rogers continues to develop and launch new products to enable automotive radar designers, radar chip set suppliers, and PCB fabricators to optimize the cost and performance of their automotive radar applications. Compared to the first generation RO3003 laminates, next generation RO3003G2™ laminates provide lower insertion loss, even more stable dielectric constant, and optimized PCB fabrication performance. Rogers RO4830™ laminates with LoPro® copper foil provide an excellent balance of RF properties and total cost of ownership. RO4830 thermoset laminates provide competitive





RF material and enable reduced PCB fabrication costs, while also delivering low insertion loss (similar to legacy RO3003 laminates), and stable dielectric constant through environmental exposures.

RADAR TECHNOLOGY FOR SMART CITIES AND INDUSTRY 4.0

Now we see these same radar technologies, which are being applied to autonomous vehicles, being applied to create Smart Cities and Smart Factories to improve efficiency and quality of life. Globally, more than 4.2 billion people live in urban areas. The United Nations is projecting that this will grow to 68% of the world's population living in dense urban areas by 2050. This large urban population will be concentrated in mega cities. High population density is good for cities' economies to thrive and flourish by higher efficiency and productivity, providing opportunity for all its citizens and businesses. Maximum utilization of cities' road infrastructure, electricity, buildings and social services are key to providing benefits for everybody, by creating a safe and clean environment to live in.

In Smart Cities, digital sensors, and in particular, radar will be the eyes and the ears of the city. These sensors will help to maximize the operational efficiency of roads. This is to help people to travel from home to work in a minimum amount of time. Reduced traffic congestion makes maximum use of existing road infrastructure and increases traffic flow.

Further, radar sensors in building or home automation minimizes the amount of electricity being used by automatically adapting heating, ventilation and air-conditioning (HVAC) systems, controlling lighting, door opening and gates. This is to keep balance between comfort, cost and energy consumption. In automated office room planning systems, radar provides crucial data about presence and the amount of people to optimize the utilization of buildings and space. In Smart Factories, radar sensors are helping people to manage robotic systems in a safe and secure environment by predictive safety and health systems.

In Smart Cities, traffic management systems are tracking real time traffic conditions via radar sensing intensity, queues, speed, and position of road users including pedestrians and bicyclists. Radars provide reliable data input in all weather conditions to adjust traffic speed and traffic lights to reduce travel time. In case of incidents, traffic management systems must react quickly to prevent hazardous situations and reduce delays caused by traffic jams. Radars detect incidents in a split second, and cameras zoom in to analyze the situation. Prediction of traffic conditions is done by combining all sensor data over the air via 5G and vehicle to infrastructure communications.

Radar technology has an edge over other traffic sensors, in both performance and cost. Radar functions effectively in all weather conditions, and performs more accurate measurements than conductive loops. Radar sensors are not intrusive which makes them easily accessible for road maintenance workers, resulting in lower system cost. Similar to automotive ADAS applications, radar in traffic requires high-performance PCB antennas for transmitting and receiving functions. The PCB antenna must achieve angular and high lateral resolution and repeatable performance. These requirements call for Rogers' circuit materials with the characteristics that support operation at such high frequencies and in such operating environments.

Key PCB antenna performance parameters include gain, directivity, and electrical efficiency, and low circuit material loss is essential for achieving good PCB antenna performance. These compact antennas and their high frequency transmitter and receiver circuits must operate continuously and reliably in challenging city and factory operating environments.

In Smart Factories, the fourth industrial revolution has begun. Industry 4.0 is about connectivity and a smart, interconnected, pervasive environment using cloud computing, artificial intelligence, additive manufacturing, co-robots, drones, block chain and mixed reality. Sensors like radar are used to generate data which will create insights to do fast product improvements, increase plant utilization, predictive safety and decrease environmental impact. Products will also become Smart via internet of things (IoT), transferring data to businesses to do real time product improvements during the lifetime of a product, offering additional value to customers. In these harsh product and production environments, radar measures presence, speed and distance and is equipped with GPS for positioning and Wi-Fi for fast data transfer.

Whether at 24, 60 or 77/79 GHz, the performance of PCB antennas is vital to these applications. As the market leader for RF materials used in the automotive radar market, Rogers is ready to support ease of use materials solutions to the industry. Providing optimum and reliable RF materials for antenna systems tailored to every radar use case of the Smart city. RO4835™ laminates from Rogers Corporation are well established as reliable circuit materials for 24 GHz radar for traffic management, and factory, building, and home automation applications like door opening and automatic lighting and air conditioning systems.

When we move to higher frequencies to achieve higher resolution for object classification, movement detection and people counting applications, sizes of circuit features shrink with increasing frequencies, becoming quite fine at operating frequencies of 60 to 77/79 GHz as those signal wavelengths become quite small. Various circuit transmission-line formats are used at those frequencies, including microstrip, stripline, and coplanar-waveguide (CPWG) circuits. These fine circuit features require extremely consistent and predictable circuit materials, such as RO3003G2™ and RO4830™ laminates. RO4830 thermoset laminates are well suited for price-sensitive mmWave applications. Rogers RO3003G2 laminates provide the tightly controlled dielectric constant performance across a circuit board and across changing environments, along with the lower insertion loss essential for maintaining scarce signal levels at mmWave frequencies.

Radar sensors are a cost effective, versatile, and indispensable technology enabling increased safety and mobility for society. Their versatility also makes a great fit for applications which improve safety, security, and efficiency in our home, offices and industries. As radar sensors become ubiquitous, Rogers Corporation continues to innovate and lead the market with high performance, cost effective materials solutions.■

How Do Circuit Material Parameters Impact mmWave Radar Performance?

Rogers Corp., Chandler, Ariz.

Millimeter-wave (mmWave) frequency spectrum contains wide available bandwidth for many applications. To take advantage of the bandwidth, circuits are being developed at much higher frequencies than traditional wireless applications, at frequencies from 24 to 77 GHz and beyond, for everything from 5G cellular wireless communications networks to collision-avoidance radar systems in advanced driver assistance systems (ADAS). The frequency range was once considered off limits for all but the military, with frequencies beyond the range of affordable and practical circuits. But mmWave frequencies are quickly being brought to the masses in millions of 77 GHz automotive radar systems, applying radar and robotic technologies to make roads safer. One of the keys to developing circuits for these systems is understanding what is required to make the printed-circuit-board (PCB) materials work best at these frequencies.

PCB materials are a starting point for many circuit designers, although circuits operating at mmWave frequencies may represent unknown territories for many of those designers. But understanding how various circuit material parameters affect mmWave performance can ease the task of finding a circuit laminate for 77 GHz or other mmWave circuit applications. In simplest terms, consistency is everything. A low loss, high performance circuit material with characteristics that are consistent with time, temperature, and other operating conditions will provide repeatable performance at mmWave frequencies.

The dimensions and features of PCB transmission lines for mmWave circuits, whether microstrip, stripline, or grounded coplanar waveguide (GCPW), of necessity are quite fine. Signal wavelengths shrink with increasing frequency, so the higher the frequencies, the finer the details of the transmission lines. The circuit material's behavior can set the limits for the performance of the transmission lines at mmWave frequencies, and PCB material inconsistencies can result in signal losses, phase shifts, and propagation delays in the transmission lines. For systems such as radars that rely on timing and signal phase, delays and phase distortion degrade ultimate system performance. By knowing more about the circuit material parameters that affect mmWave performance, PCB materials can be intelligently specified for the growing number of mmWave circuit applications, including 77 GHz automotive radar systems and Fifth Generation (5G) cellular wireless communications systems.

When reviewing circuit material candidates for a design, specifiers often begin by comparing familiar material parameters, such as dielectric constant (Dk) and dissipation factor (Df). Dk is an indication of a circuit material's electromagnetic (EM) charge storage capability while Df refers to a material's energy loss. A PCB's dielectric material is an insulator for its metal conductors, and the EM field propagates along the conductors, through the material, and through the air around it. For materials with copper conductors, lower Dk values translate to faster wave propagation with minimal delays and changes in signal phase—important behavior for mmWave radar circuits.

Dk is typically characterized through the thickness or z-axis of a circuit material. It is usually determined according to industry-accepted standards developed by organizations such as the IPC (www.ipc.org) and at a single frequency, such as 10 GHz. Every circuit material will have some amount of variation in Dk, ΔDk, according to changes in frequency or temperature, and this will affect circuit performance.

The Dk value is usually associated with the composition of a circuit material's dielectric materials, such as polytetrafluoroethylene (PTFE). But the Dk that determines the performance of a circuit is a composite value resulting from such things as the fillers used in the material, such as glass fiber reinforcement, the material thickness, and even the quality of the copper conductors. For circuit design and computer modeling, this is the Dk that is more important than the nominal Dk of the material because this is the Dk that will determine how the circuit on that material and with those conductors behaves. It is typically known as "the circuit-perceived Dk" or what Rogers Corp. refers to as "Design Dk."

PROBING THE PARAMETERS

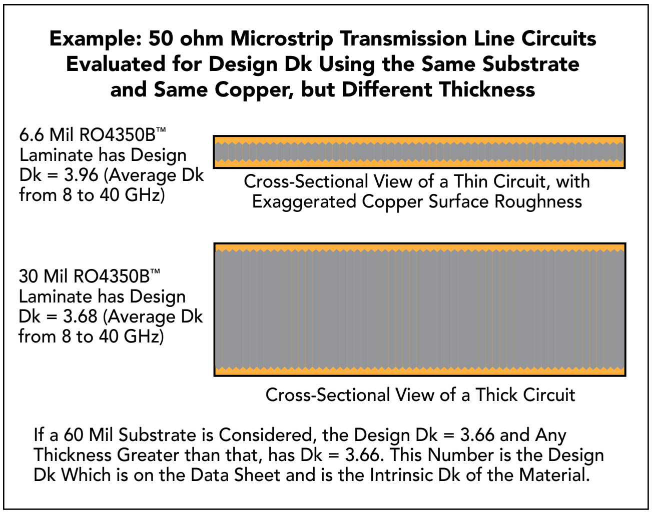
Dk is one of many circuit material parameters to review when considering circuit materials for mmWave circuits such as 77 GHz automotive collision-avoidance radars. How tightly the Dk is controlled to a nominal value may be as important as the Dk value itself. Additional circuit material parameters that can impact mmWave circuit performance are Df, material thickness, copper conductor quality, moisture absorption, and the "glass weave" effect caused by glass fiber reinforcement. Again, consistency is essential, especially at mmWave frequencies and excess variations in these parameters will impact circuit performance at mmWave frequencies.

These various circuit parameters can all play a part in what is a circuit material's Design Dk. To ensure clarity of terms, the "effective Dk" refers to the overall Dk experienced by the propagating wave. For microstrip, the effective Dk is a combination of the Dk of the substrate and the Dk of the air around the substrate. The "Design Dk" uses "effective Dk" data to extract the Dk of the material itself and remove the effects of the Dk of the air around it.

A microstrip circuit using 5-mil-thicksubstrate based on RO3003™ materials, using electrodeposited (ED) copper, will have an effective Dk (including the effects of air) of 2.54 and the Design Dk will be 3.16 when tested at 77 GHz. The Dk of the raw circuit material is 3.00 through the thickness or z-axis of the material but this is a standardized test of the raw material and does not include the effects of circuitry. The effective Dk and Design Dk are circuit properties while the raw material Dk is a material property and is the intrinsic Dk of the substrate material.

For example, a material's Design Dk (the Dk of the material tested in circuit form) can change with thickness. The variations in Design Dk with material thickness are also often dependent upon frequency, with Dk typically decreasing at higher frequencies. For a circuit designer, such Dk variations can lead to unexpected impedances for mmWave transmission lines with physical dimensions based on a calculator or computer simulator.

A microstrip circuit using a thin laminate will have little distance between the signal conductor plane and the ground plane. Thinner circuits are more dominated by the properties of the conductor than the dielectric material and the conductors can play their part in determining the effective Dk and the Design Dk. Capacitance increases and impedance decreases for transmission lines on thinner substrates while capacitance decreases and impedance increases for transmission lines on thicker substrates. An increase in capacitance can also be achieved with wider transmission lines, which increases the conductive area on the PCB.



▲ **Fig. 1 This depiction compares circuits with thin and thick dielectric materials and rough copper conductors.**

For many high frequency applications, including 77 GHz radars, transmission-line impedance must be consistent and tightly maintained to minimize reflections. Deviations from a characteristic impedance of 50 Ω, for example, can result in signal reflections, losses, and phase shifts. For a given variation in Dk, those shifts can impact phase response more at mmWave frequencies than at lower frequencies and become a source of radar performance degradation at mmWave frequencies.

Thinner PCB materials are typically used for mmWave circuits, which are often multilayer circuits with analog, digital, and power functions. The value of the effective Dk and the Design Dk will decrease for thicker sheets of the same material. For example, for 6.6-mil-thick RO4350B™ circuit material from Rogers Corp., the average value of the Design Dk from 8 to 40 GHz is 3.96 as determined through the thickness or z-axis of the material. But for 30-mil-thick RO4350B laminate, the Design Dk is 3.68 ***(Fig. 1)***. The Design Dk will continue to decrease with thicker RO4350B laminate, dropping to 3.66 average from 8 to 40 GHz for 60-mil-thick material, but will not decrease further with increased thickness. That value represents the intrinsic Dk of the material. At this thickness and beyond, the properties of the dielectric content dominate the circuit's effective Dk and Design Dk. The conductors play a part in determining the effective Dk for thinner versions of the material but less so as it gets thicker.

To further demonstrate how material thickness can impact a circuit design, a different circuit material was evaluated. When three different thicknesses (5, 10, and 20 mil) of RO3003 circuit material from Rogers Corp., with the same type of copper conductor, ½-oz. ED copper, were tested for Design Dk using the differential phase length method with 50-Ω microstrip transmission lines, the results revealed the change in Design Dk as a function of substrate thickness through 50 GHz ***(Fig. 2)***.

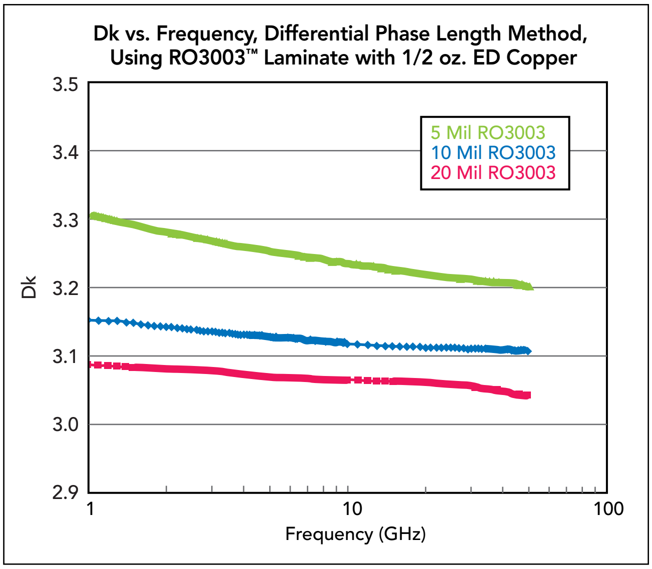


Fig. 2 **As demonstrated for RO3003, material thickness can make a difference in the Design Dk of the material, often consistently across frequencies.**

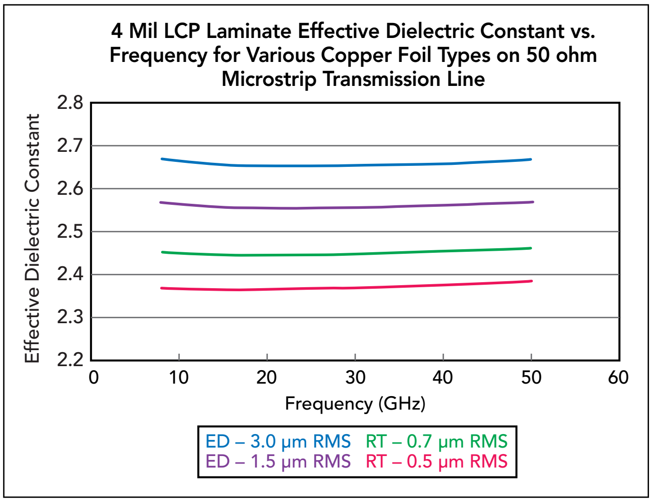


Fig. 3 **The effective Dk of a circuit material can also change with copper conductor type and the surface roughness of the copper.**

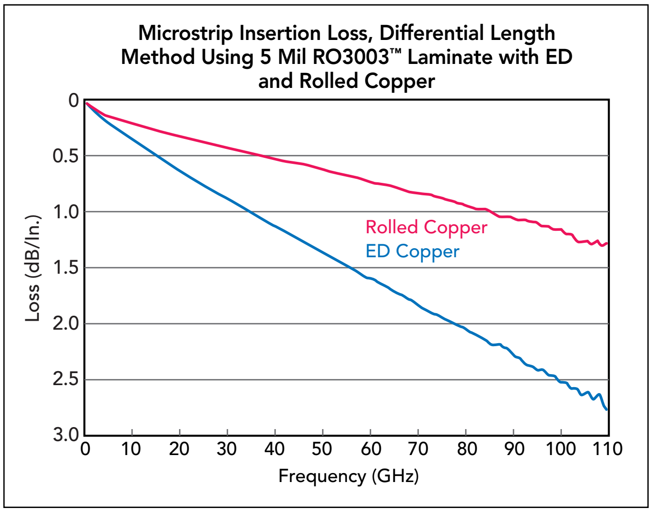


Fig. 4 **The type of copper conductor can also affect a circuit material's loss performance at higher frequencies.**

METERING METAL EFFECTS

All a circuit material's components combine for its Design Dk, so it is important to pay attention to those different components. Copper conductor quality, for example, can make a difference in performance at mmWave frequencies. High quality copper conductor material provides transmission lines with the high conductivity and consistent impedance needed for reliable signal phase characteristics at mmWave frequencies, such as in 77 GHz automotive radars.

The amount of surface roughness in a circuit material's copper conductors can affect mmWave circuit performance. Rougher copper yields transmission lines with slower EM wave propagation than transmission lines produced with similar copper but smoother surface. The copper surface roughness that is a concern is the copper roughness at the substrate-copper interface of a laminate. The slower wave propagation is equivalent to a circuit material with higher Dk.

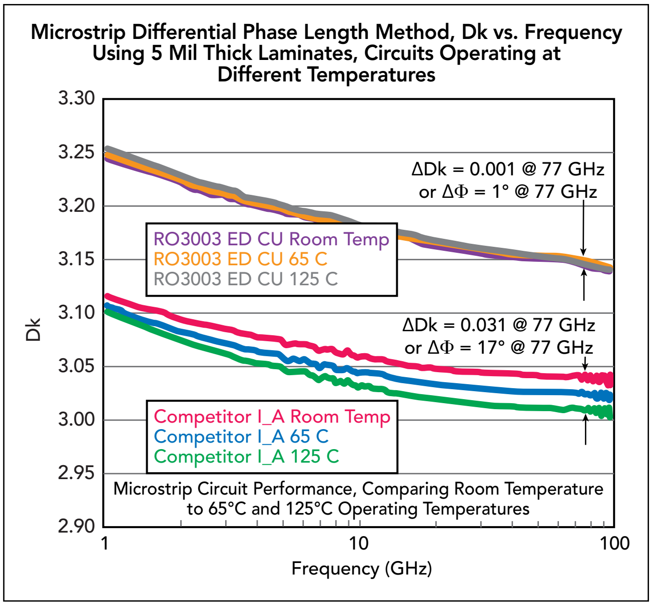
To show how differences in copper surface roughness can affect mmWave circuit performance, one type of circuit material, a 4-mil-thick liquid-crystal-polymer (LCP) substrate, was teamed with different copper conductors. The copper conductors consisted of different types of ED copper, each having different values of surface roughness. The surface roughness refers to the average or root-mean-square (RMS) value across the copper, with value of 0.5, 0.7, 1.5, and 3.0 µm RMS.

To evaluate different copper conductors at higher frequencies, 50-Ω microstrip transmission lines were fabricated on the LCP substrates with the four copper types and measurements were made with a microwave/mmWave vector network analyzer (VNA) from 8 to 50 GHz. The effective Dk changed according to the type of copper, with the differences remaining constant across the frequency range ***(Fig. 3).***

As the measurements show, a single type of PCB material with different types of copper conductors, will yield different effective Dk values. Circuits using materials with rough copper surfaces have higher effective Dk values than the same dielectric materials with smoother copper surfaces. The wave-slowing effects of circuits with higher effective Dk values can have greater impact at the highest frequencies.

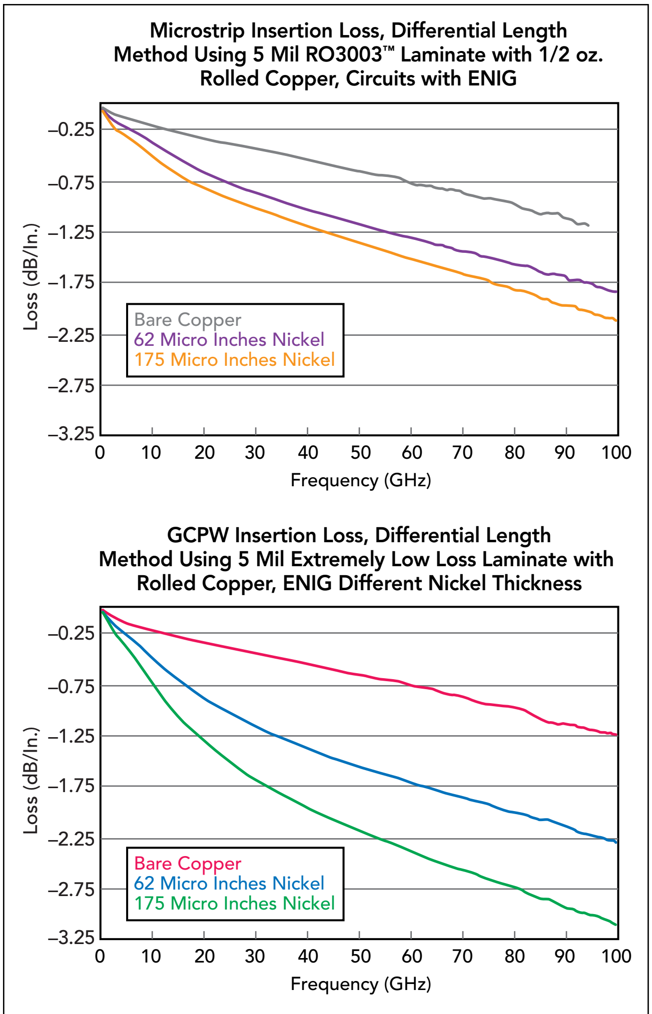
Copper surface roughness can also impact conductor loss, especially at mmWave frequencies, with rougher copper conductor surfaces causing higher conductor losses. To investigate this, the same 5-mil-thick RO3003 laminate was characterized with both ED and rolled copper. The ED copper has a surface roughness of 2.0 µm RMS while the rolled copper has a surface roughness of 0.35 µm RMS.

The insertion losses of 50-Ω microstrip transmission lines were measured from DC through 110 GHz to compare the loss characteristics of the different copper conductors. The impact of the increased copper surface roughness on (increased) conductor loss, including insertion loss and return loss, is apparent ***(Fig. 4)***. A circuit material's thickness will determine the influence of copper surface roughness on loss, with circuits using thinner materials more greatly affected by rougher copper surfaces.



Microstrip Circuit Performance, Comparing Room Temperature to 65°C and 125°C Operating Temperatures

Fig. 5 A circuit material's response to changing temperatures can result in changes in Design Dk and phase angle.



GCPW is much more impacted by final plated finish than microstrip.

Fig. 6 Choice of transmission-line technology and how well it can be manufactured can impact the performance of a circuit at mmWave frequencies.

KEEPING DK CONSTANT

For the small differences in signal phase from reflected objects detected by 77 GHz automotive radars, any variations in a circuit material's Design Dk can impact the phase performance and degrade the accuracy of the system. While a circuit material with no Dk variations under any conditions would be ideal, the Design Dk of real materials will change with frequency, with temperature, and with thickness. To maintain the phase range needed for high system accuracy and reliability, a realistic maximum Dk tolerance for the intrinsic circuit material Dk is ±0.05.

As part of monitoring a circuit material's changes in Dk with temperature, it is specified within a temperature range according to its thermal coefficient of Dk (TCDk) parameter. This is important for applications that must weather wide operating temperature ranges, such as 77 GHz radars. Any circuit material considered for mmWave applications should have minimal TCDk value to minimize the effects of changes in Dk on circuit performance, such as phase shifts.

Some circuit materials, such as those based on PTFE, exhibit an abrupt change in Dk as a function of temperature around room temperature (+25°C). For many applications, a TCDk of 0 ± 25 ppm/°C is considered good. As a real world example, RO3003 circuit material has a TCDk of -3 ppm/°C at 10 GHz through the z-axis for a temperature range of -50 to +150°C. The extremely small value of TCDk results in very little change of Dk with temperature ***(Fig. 5)***, vital for consistent circuit performance at mmWave frequencies and for wide operating temperature ranges.

Additional circuit material properties of concern at mmWave frequencies include Df, moisture absorption, and the glass weave effect, each of which can influence the Design Dk value of a material. As with Dk, material Df has temperature-related behavior, defined by its thermal coefficient of Df (TCDf), so that its effects on circuit design will vary with temperature. Moisture absorption refers to the amount of total weight of water, as a percentage, that a circuit material will absorb. The lowest values are recommended at higher frequencies. Typical values are in the range of 0.1 to 0.2 perecnt; RO3003 laminate has moisture absorption of 0.04 percent.

Because of the small wavelengths at mmWave frequencies, the glass weave effect is a concern when specifying a PCB material. It refers to the way glass reinforcement is distributed throughout the dielectric in a circuit material. The glass reinforcement fabric can be an open weave or a spread weave, where an open weave has some openings between glass bundles. The glass fibers are collected in bundles throughout the material and can be balanced or unbalanced. A glass fabric that is considered balanced has the same density of glass in the x-axis compared to the y-axis and an unbalanced fabric has different glass densities in these two axes. For open weave glass fabric, there are sections of the circuit material with no glass, where the Dk is low. When glass bundles cross and form knuckles, the Dk is at its highest. Small wavelengths can be distorted by the differences.

For a 77 GHz radar, PCB materials with strong glass weave effect can suffer from variations in group delay, propagation delay, and phase angle. Because of the impact on phase, materials with a spread glass weave and minimal Dk variations should be specified for 77 GHz circuits. Circuit materials with open glass weave can have large Dk variation of 0.090 with phase angle differences of 100 deg. at 77 GHz. The large variations in phase angle equate to large differences in group delay and propagation delay for those materials. Ideally, a material with no glass reinforcement, such as RO3003 or RO3003G2™ laminates, will have no concern for glass weave effects.

Even the choice of transmission-line technology can have bearing on the circuit performance ultimately possible for mmWave applications such as 77 GHz automotive radars. The mmWave circuits are usually part of hybrid multilayer PCB assemblies also containing digital, power, and even opto-electric circuitry. The mmWave circuitry is usually fabricated with microstrip or GCPW transmission-line technologies, although PCB fabrication variables can have much greater impact on GCPW, including copper plating thickness, conductor etching tolerance, and final plated finish ***(Fig. 6)***. Computer models are available for both technologies although GCPW tends to be more difficult to produce especially at 77 GHz.

While evaluating different circuit materials and copper conductor types with an E-field simulator or even prototype designs and measurements, can be costly and time consuming, an easier approach is with the aid of a free MS Windows software program, MWI-2019, downloadable from Rogers Corp. The software (see "More on MWI-2019") allows users to experiment with the effects of material thickness, copper conductor surface roughness, and other parameters on Design Dk, using a built-in database of measured Design Dk values for many different materials. Compared to the long computational times of EM simulators, it provides results with somewhat less accuracy but almost instantly for comparing the implications of using different materials and material parameters for mmWave circuit designs.

More on MWI-2019

One way to get a quick idea of the RF performance differences of circuit materials at mmWave frequencies is the free-of-charge MWI-2019 software program. It is downloadable from the Rogers Corp. (www.rogerscorp.com) website to run on most MS-compatible personal computers (PCs). It employs quick-response closed-form equations (versus longer-running EM field solvers) to compute the effects of different materials and different Dk values on the performance of high-frequency transmission lines, including microstrip, stripline, and grounded coplanar waveguide (GCPW).

The straightforward software works according to a material's Design Dk, using a large database of values measured at specific frequencies for different materials and copper conductors. Design Dk considers not just the Dk of the substrate material but factors such a frequency, substrate thickness, and copper surface roughness that can impact the Dk as seen by the circuit's transmission lines. While MWI-2019 cannot match the accuracy of an EM field solver, it can provide results for different transmission-line types, copper types, and substrate thicknesses in a fraction of the time and provides a good first look at different circuit material candidates through 110 GHz.

A PCB Laminate Optimized for mmWave Radar Antenna Applications

Rogers Corp., Chandler, Ariz.

Composite material based printed circuit boards (PCBs) constructed from glass fiber cloth with differing glass weave construction styles exhibit localized variation of dielectric constant. At millimeter-wave (mmWave) frequencies, the glass weave construction style in thin laminates causes observable changes in the RF circuit and antenna performance. The impact of PCB construction on the transmission line performance is explored in a 100 μm thick woven glass polytetrafluoroethylene (PTFE) laminate. Depending on the glass weave construction style, a dielectric constant variance between 0.01 and 0.22 is observed. To investigate the effects of different glass weave construction styles on the antenna performance, a series fed microstrip patch array antenna is constructed on Rogers' commercially available RO4835™ and RO4830™ thermoset laminates. The antenna structure produced on the RO4830 laminate exhibits significantly less variation under nominal circuit dimensions and maintains the reflection coefficient ($S_{11} < -10$dB) and bore-sight gain performance.

Autonomous vehicles demand high reliability to help drivers and pedestrians avoid potentially fatal accidents. Millimeter-wave (mmWave) radars are more compact, resilient to environmental effects and provide an accurate solution for object detection in autonomous driving. In commercial radar systems at mmWave frequencies (76-81 GHz), series fed microstrip patch antennas are preferred for their ease of design, compactness, and ability to be manufactured at high volumes and low cost[1]. At high frequencies, the wavelength is very small, hence the transmission line and antenna dimensions are smaller in comparison to lower frequencies. The PCB effects on the transmission lines and microstrip patch antennas need to be investigated to ensure the desired performance for automotive radar. PCB's with consistent material properties across the laminate under environmental exposure (temperature and moisture) are preferred at mmWave frequencies[2]. However, copper foil, glass reinforcement, and ceramic filler used in laminate constructions have a large impact at high frequencies.

In this article, the impact of PCB construction on mmWave radar performance is investigated. PCB laminates are typically constructed by impregnating a glass cloth with a polymeric resin. The effect of glass fiber cloth is significant at mmWave frequencies as the glass bundle width is comparable to the transmission line width. Also, when the antenna structure is manufactured on thin (e.g., 100 μm) PCB laminates, woven glass cloth

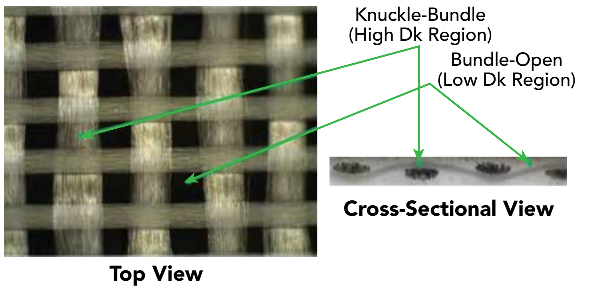


Fig. 1 Microscopic top and cross-sectional views of laminate with glass cloth.

can cause significant changes in the antenna performance and reduce manufacturing yield.

PCB LAMINATE CONSTRUCTION

PCB laminates are constructed using polymeric resin and glass cloth which are cladded with copper foils on two sides. Glass cloth has a typical dielectric constant (Dk) of 6.1, while low loss polymeric resin has a Dk of 2.1-3.0. ***Figure 1*** shows the microscopic top and the cross-sectional illustrations of glass weave in laminates. A conductor over the knuckle-bundle glass region experiences higher Dk from larger glass content. Whereas, a conductor over the bundle-open region experiences lower Dk from larger resin content. The glass cloth style is characterized based on the thickness of the glass weave, the distance between the weave, the spread of the weave, and the glass content along each axis.

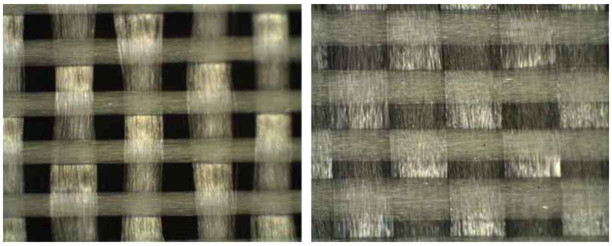

1080 Glass, Standard Weave 1078 Glass, Spread Weave

Fig. 2 Microscopic views of the 1080 (open and unbalanced weave), and the 1078 (spread weave) glass construction styles.

Fig. 3 Microstrip transmission line transitioning from a GCPW.

TABLE 1

MEASURED PERFORMANCE DIFFERENCE BETWEEN THE KNUCKLE-BUNDLE AND THE BUNDLE-OPEN GLASS REGIONS

Glass Construction Style	Average Differences Between the Knuckle-Bundle and the Bundle-Open Glass Region		
	40 GHz to 80 GHz		77 GHz Phase Difference (°)
	Group Delay (ps)	Propagation Delay (ps)	
1078 Spread Weave	1	1.3	20
1080 Standard Weave, Unbalanced	7.3	10.1	149
Ceramic Filled 1080 Standard Weave, Unbalanced	0.3	0.6	10

In thin laminates used for mmWave applications, two of the typical thin glass cloth weave styles used in manufacturing are 1080 and 1078, as shown in ***Figure 2.*** The 1080 standard weave is with unbalanced glass cloth indicating more glass content along one axis than the other axis. The 1078 spread glass weave has a more uniform plane of glass fibers than the 1080 weave, with less variation in Dk across the laminate. Thin laminates with one layer of glass cloth have a more significant variation in Dk than multilayer glass cloth based thick laminates. The laminate material with ceramic filler reduces Dk variation in laminates due to the glass cloth.

IMPACT ON THE TRANSMISSION LINE CIRCUIT

The experimental test vehicle is a microstrip transmission line circuit, which uses 1 mm end launch connectors from Southwest Microwave (model # 2492-04A-6). The end launch connector excites a 50 ohm grounded coplanar waveguide (GCPW) which transforms into a high impedance microstrip transmission line with an impedance transformer. The microstrip transmission line is 5 mils wide and 2" long as shown in ***Figure 3,*** ensuring sensitivity towards the glass weave construction styles. The circuits are fabricated on 100 µm thick woven glass polytetrafluoroethylene (PTFE) laminate using 0.5 oz. rolled copper and a single layer of glass cloth. To compare different glass weave construction styles, the transmission line circuits were fabricated on three different PCB laminate constructions: PTFE with 1080 glass, PTFE with 1078 glass and ceramic filled non-PTFE with 1080 glass laminates. Careful inspection of the fabricated circuits was performed to select the transmission lines aligned with the knuckle-bundle and the bundle-open glass regions of the laminates. A network analyzer is used to measure the magnitude and the phase angle properties of the circuit. Phase angle (unwrapped), group delay (based on phase angle which varies with frequency) and propagation delay (calculated based on phase angle) are the three parameters used to determine the dielectric constant variation across the laminate.

Table 1 indicates the measured raw group delay, propagation delay and phase difference of the transmission lines aligned with the knuckle-bundle and the bundle-open regions of the laminate. A higher Dk slows an electromagnetic wave, which corresponds to increased group delay, increased propagation delay and an increased phase difference. The knuckle-bundle regions have higher Dk than the bundle-open regions of the laminate. ***Table 2*** indicates the dielectric constant variation calculated from group delay, propagation delay and phase difference of the circuits. The 1078 spread weave laminate has a uniform glass plane, consequently a lower Dk variation of 0.03 than the 1080 standard weave laminate with a variation of 0.22. As discussed earlier, the ceramic filled laminate has a much smaller Dk variation of 0.02.

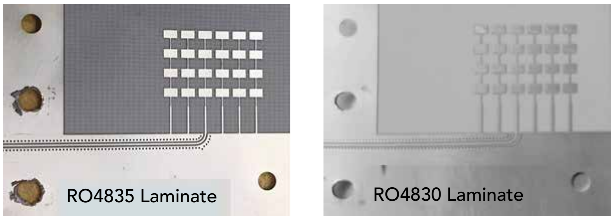
IMPACT ON THE ANTENNA PERFORMANCE

A series fed microstrip patch antenna array is a typical automotive radar antenna at mmWave frequency. The 1×4 series fed microstrip patch antenna is designed to operate in the frequency range of 76-81 GHz.[3] The

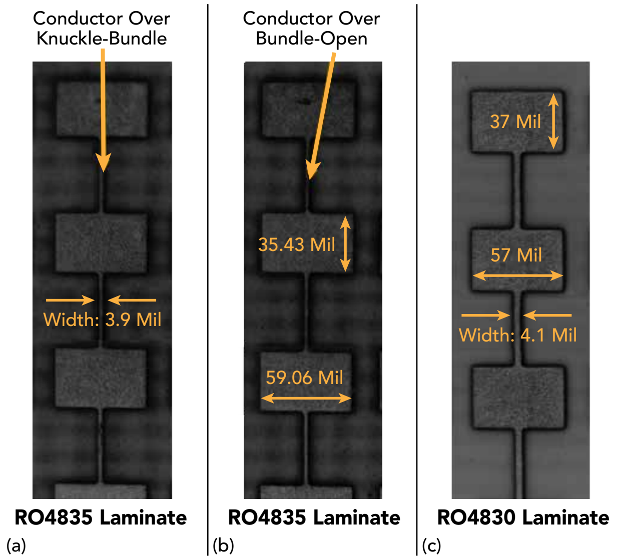
TABLE 2

CALCULATED PERFORMANCE DIFFERENCE BETWEEN THE KNUCKLE-BUNDLE AND THE BUNDLE-OPEN REGIONS

Glass Construction Style	Equivalent Difference in Dk (ΔDk) Between the Knuckle-Bundle and the Bundle-Open		
	40 GHz to 80 GHz		ΔDk from 77 GHz Phase Angle
	ΔDk from Group Delay	ΔDk from Propagation Delay	
1078 Spread Weave	0.02	0.03	0.02
1080 Standard Weave, Unbalanced	0.17	0.22	0.14
Ceramic Filled 1080 Standard Weave, Unbalanced	0.01	0.02	0.01



▲ **Fig. 4 Fabricated series fed microstrip patch array on the RO4835 and the RO4830 laminates.**



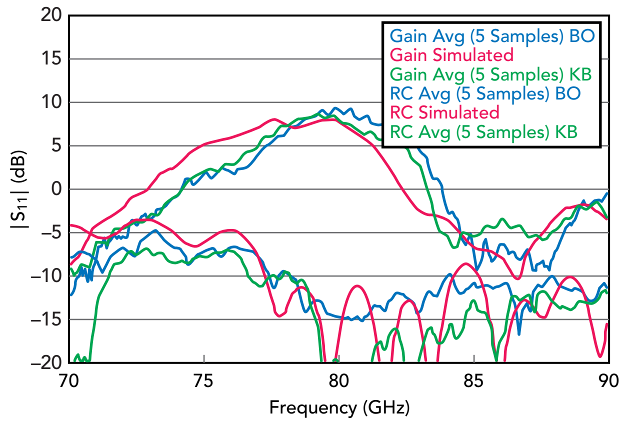
RO4835 Laminate (a) **RO4835 Laminate** (b) **RO4830 Laminate** (c)

▲ **Fig. 5 Antennas over knuckle-bundle and bundle-open glass fabric region on RO4835 laminate, and a sample antenna on RO4830 laminate.**

TABLE 3

COMPARISON OF RO4835 AND RO4830 LAMINATES

Glass Construction Style	RO4835 Laminate	RO4830 Laminate
Dielectric Constant[a]	3.48	3.21
Loss Tangent[a]	0.0037	0.0033
Substrate Thickness	100 µm	125 µm
Ceramic Filler Size	Coarse	Fine and Uniform
Glass Content	High	Low
Laminate Type	Thermoset	Thermoset



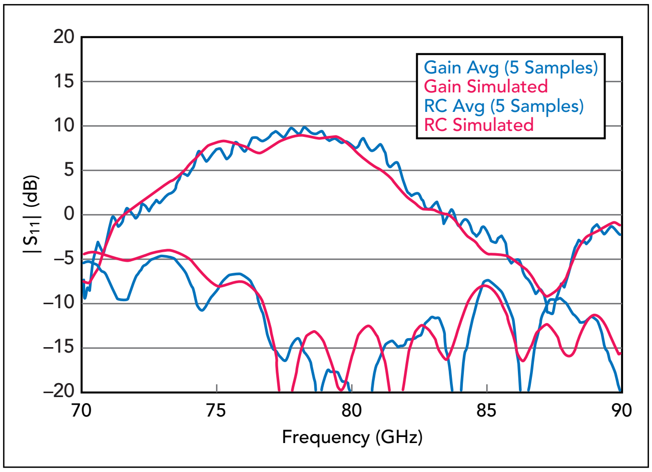
▲ **Fig. 6 Comparison of measured results to simulation for antenna samples on the knuckle-bundle (KB) and bundle-open (BO) glass fabric region of the RO4835 laminate.**

antenna is built on RO4835™ and RO4830™ laminate materials of differing glass cloth construction, as shown in ***Figure 4.*** The antenna is fabricated with grounded adjacent elements to investigate coupling effects. The antenna transitions to a GCPW and then to a 50 ohm Southwest Microwave 1 mm end launch connector (model # 2492-04A-6).

The RO4835 laminates have a dielectric constant of 3.48 and loss tangent of 0.0037 at 10 GHz (determined by IPC TM-650 2.5.5.5 test method). Whereas, the RO4830 laminates have a dielectric constant of 3.24 and loss tangent of 0.0033 (determined by IPC TM-650 2.5.5.5 test method). The RO4835 laminate is reinforced with 1080 standard weave unbalanced glass and ceramic filled, however, the RO4830 laminate is reinforced with 1035 spread weave glass and ceramic filled with smaller particles. ***Table 3*** further compares the RO4835 and RO4830 laminates characteristics.

The fabricated antenna is selected to match the design dimensions and to align with the knuckle-bundle and the bundle-open glass fabric of the RO4835 laminate as in ***Figure 5 (a)*** and ***(b).*** However, due to the spread glass weave construction style, the selection of the antenna to align conductors to glass fabric was not performed in RO4830 laminate, as shown in Figure 5 (c). The antennas were measured for reflection coefficient (S_{11}) and bore-sight gain using a network analyzer. The microstrip patch and series microstrip feed line dimension differ for both laminates as shown in Figure 5.

For brevity, the presented results are from the average of sample data among multiple measured antennas. The measured results are compared to the full-wave ANSYS HFSS simulation. The antennas on the RO4835 laminates (five samples) over the knuckle-bundle and bundle-open region show significant variation both in



▲ **Fig. 7 Comparison of measured results to simulation for antenna samples on the RO4830 laminate.**

the reflection coefficient (S_{11}) and bore-sight gain from the simulation as in ***Figure 6.*** Also, the antenna performance on the RO4835 varies across the laminate depending on the conductor alignment to the knuckle-bundle and bundle-open regions. The shift in gain over frequency indicates variation in dielectric constant. Also, the shift to higher frequency indicates a lower dielectric constant. In contrast, the antenna performance as measured with S_{11} and bore-sight gain shows consistency over samples and much closer match to simulation on RO4830 laminates, as shown in ***Figure 7.*** The consistency of measured results with simulation demonstrates a minimal variation of dielectric constant across the laminate. The boresight gain varies by a maximum of 4 dB in the standard weave as opposed to a maximum of 2 dB in spread weave. Therefore, the antenna performance reflection coefficient and bore-sight gain are preserved by using Rogers RO4830 laminates with a spread weave glass construction style.

CONCLUSIONS

The PCB laminate construction influences the transmission line and antenna performance. The glass cloth construction style varies the dielectric constant across the laminate which degrades the performance and impacts the manufacturing yield. The antenna response is much more consistent across the RO4830 laminate than the RO4835 laminate. The improved antenna performance and manufacturing yield are due to laminate construction, i.e., spread glass weave, less glass content with the conductor farther from glass fiber, and thicker substrate. The improved performance is also attributable to the material's electrical properties i.e., lower dielectric constant and lower loss tangent of RO4830 laminates. The larger dimensional widths of the antennas and the transmission lines also improve the manufacturing yield at high frequencies. Therefore, at mmWave frequencies radar applications, the performance of antennas on Rogers RO4830 laminates is superior to that of antennas with Rogers RO4835 laminates.■

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Characterizing Circuit Materials at mmWave Frequencies: Part I

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Rogers Corp., Chandler, Ariz.

Different dielectric constant measurement methods provide different results.

The dielectric constant (Dk) or relative permittivity of a circuit material is not a constant—despite what its name might imply. The Dk of a printed circuit board (PCB) material, for example, will change as a function of frequency. Also, using different Dk test methods on the same piece of material, they are likely to measure different Dk values, which are correct for those test methods. As circuit materials are increasingly employed at mmWave frequencies, with the growth of 5G and advanced driver assistance systems, it is important to understand how Dk changes with frequency and which Dk test methods are "best" applied.

No industry-standard best test method exists for measuring circuit material Dk at mmWave frequencies, although organizations such as the IEEE and IPC have committees devoted to this topic. It is not the lack of measurement methods; in fact, more than 80 are described in just one reference by Chen et al.[1] No method is ideal, with each having challenges and shortcomings, especially at frequencies from 30 to 300 GHz.

CIRCUIT vs. RAW MATERIAL TESTS

Tests for determining circuit material Dk or Df (the loss tangent or tanδ) are generally performed in one of two ways: either on the raw material or a circuit fabricated from the material. Raw material tests depend on high quality test fixtures and test equipment to extract Dk and Df values directly from the material. Circuit tests use a common circuit and extract the material parameters from the circuit's performance, such as measuring the center frequency or frequency response of a resonator. Raw material tests introduce uncertainties typically associated with the text fixture or test setup, while circuit tests contain uncertainties from the test circuit design and fabrication techniques. Because the two methods differ, measurement results and accuracy levels typically do not agree.

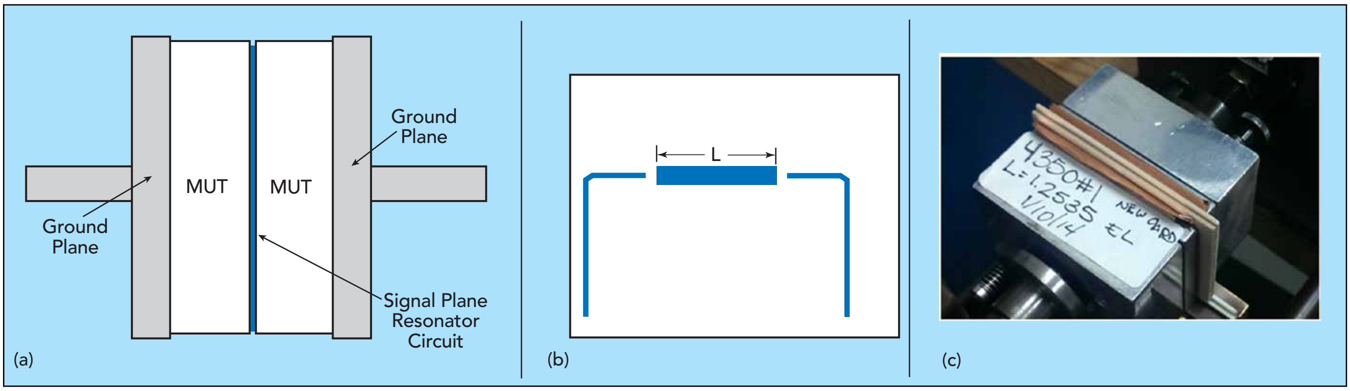

Fig. 1 X-Band clamped stripline test fixture side view (a), stripline resonator (b) and photograph (c).

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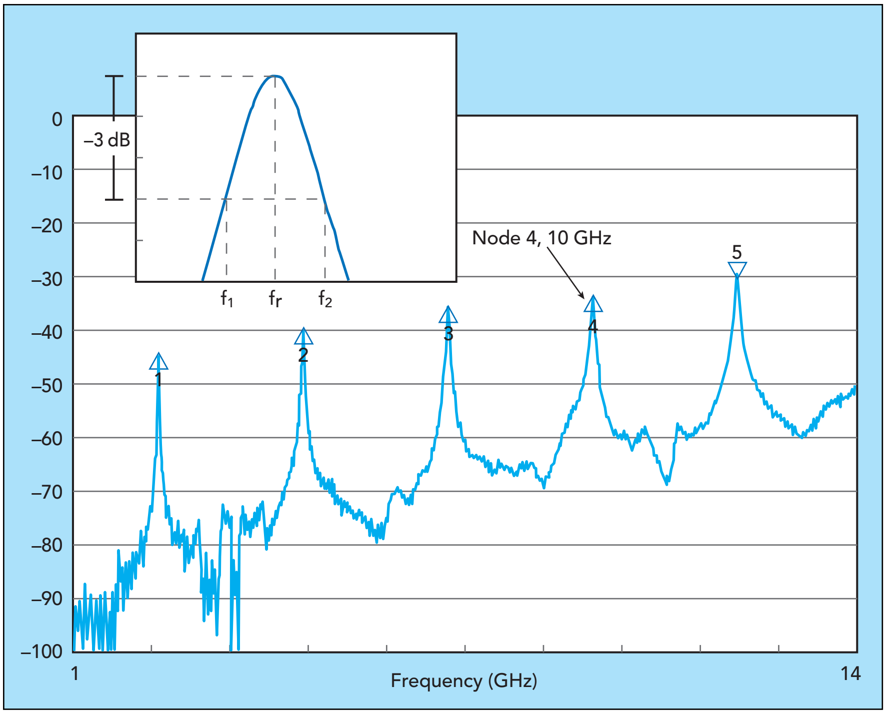


Fig. 2 Wideband clamped stripline measurement of a MUT 60 mils thick, with a Dk = 3.48.

For example, an X-Band clamped stripline test defined by IPC,[2] a raw material test, may not provide Dk results agreeing with a circuit test of the same material. The raw material test creates a stripline resonator by clamping two pieces of the material under test (MUT) in a special test fixture. Air can become entrapped between the MUT and the thin resonator circuit which is part of the fixture. The air becomes part of the measurement and lowers the measured Dk. If a circuit test is performed on the same circuit material, without the entrapped air, the measured Dk will be different. For a high frequency circuit material with a Dk tolerance of ±0.050 determined from a raw material test, a tolerance of ±0.075 may result from a circuit test.

Circuit materials are anisotropic, often with different Dk values in the three material axes. Dk values typically differ little between the x- and y-axis, so for most high frequency materials, Dk anisotropy comparisons are usually made between the z-axis and the x-y plane. For the same MUT, test methods that measure Dk for the z-axis can provide different results than test methods used to evaluate Dk in the x-y plane, although the values of Dk may be "correct" for the given method.

The type of circuit used for a circuit test also influences the value of the measured Dk. In general, two types of test circuits are used: resonant structures and transmission/reflection structures. Resonant structures typically provide narrowband results, while transmission/reflection tests are usually wideband. Methods using resonant structures are typically more accurate.

TEST METHOD EXAMPLES

An example of a raw material test is the X-Band clamped stripline method. It has been used by manufacturers of high frequency circuit laminates for years and is a dependable means of determining the Dk and Df (tanδ) in the z-axis of a circuit material. It uses a clamping fixture to form a loosely coupled stripline resonator from MUT samples. The measured quality factor (Q) of the resonator is the unloaded Q, so it can be measured with minimal impact from cables, connectors and fixture calibration. The MUT is a copper-clad circuit laminate with all the copper etched from the substrate prior to testing. The raw circuit material is environmentally conditioned, cut to size and placed into the fixture on both sides of the resonator circuit at the signal plane (see ***Figure 1***).

The resonators are designed with half-wavelength resonances starting at about 2.5 GHz, so node 4 is around 10 GHz; this is the node commonly used for Dk and Df measurements. Lower nodes and frequencies can be used—even the higher node 5 can be used, although higher nodes are usually avoided due to wave propagation or measurement issues from harmonics and spurious content. The extraction of the Dk or relative permittivity (ε_r) is straightforward:

$$\varepsilon_r = \left[\frac{nc}{2f_r\left(L+\Delta L\right)}\right]^2 \qquad (1)$$

where n is the node, c is the speed of light in free space and f_r is the center frequency of the resonant peak. ΔL compensates for the electrical length extension due to electric fields in the gap-coupled area. Extraction of tanδ (Df) from the measurements is also straightforward. It is a fraction related to the 3 dB bandwidth of the resonant peak after subtracting the conductor losses ($1/Q_c$) associated with the resonator circuit.

$$\frac{1}{Q_u} = \frac{1}{Q_c} + \frac{1}{Q_d} \qquad (2)$$

$$\tan\delta \propto \frac{1}{Q_d} \qquad (3)$$

$$\tan\delta = \left[\frac{f_2 - f_1}{f_r}\right] - \frac{1}{Q_c} \qquad (4)$$

Figure 2 shows a measurement using the clamped stripline test method with a 60-mil thick MUT with Dk = 3.48.

Ring resonators are often used as test circuits.[3] They are simple microstrip structures having resonances at integer multiples of the mean circumference of the microstrip ring (see ***Figure 3a***). They are typically loosely coupled, as loose coupling between the feed lines and the ring minimizes the capacitance of the gaps between the feed lines and the ring. This capacitance changes with frequency, causing the resonant frequency to shift and resulting in errors when extracting the material Dk. The conductor width of the resonator ring should be much smaller than the radius of the ring —as a rule of thumb, one-quarter the dimension of the ring radius or smaller.

The $|S_{21}|$ response of a microstrip ring resonator on a 10-mil thick circuit material with Dk = 3.48 is shown in ***Figure 3b***. An approximate calculation of the Dk is given by

$$2\pi r = n\lambda_g \quad (5)$$

$$\lambda_g = \frac{c}{f\sqrt{Dk_{eff}}} \quad (6)$$

$$Dk_{eff} = \left[\frac{cn}{2\pi rf}\right]^2 \quad (7)$$

Although approximate, these formulas are useful for determining an initial Dk value. A more accurate Dk can be found using an electromagnetic (EM) field solver and precise resonator circuit dimensions.

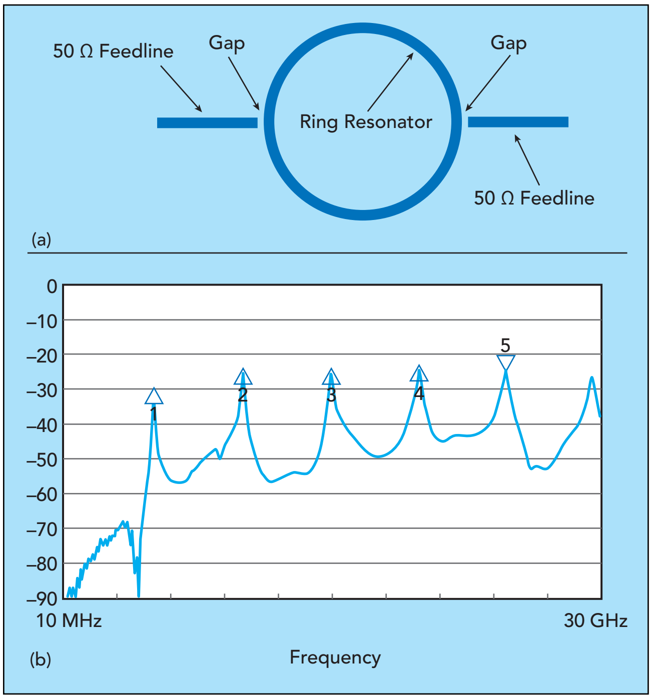
Loosely coupled resonators are often used for Dk and Df measurements to minimize resonator loading effects. Coupling should be loose enough so the insertion loss is 20 dB or less at the resonant peak. In some cases, with extremely weak coupling, the resonant peak may be so weak that it cannot be measured. This typically occurs for resonant circuits with thinner substrates, the types of materials commonly used in mmWave applications, since the high frequencies have small wavelengths and circuit dimensions.

mmWAVE TEST METHODS

While there are many Dk test methods, only some are suitable for mmWave frequencies, yet none are accepted as industry standards. However, the following methods are accurate and repeatable at mmWave.

Differential Phase Length Method

The microstrip differential phase length method has been used for many years.[4] It is a transmission test method in which phase measurements are made on two circuits that only differ by physical length (see ***Figure 4***). To avoid any variations in circuit material properties, the circuits are fabricated side-by-side and as close together as possible on the MUT. The circuits are 50 Ω microstrip transmission lines of different lengths with a grounded coplanar waveguide (GCPW) signal launch. At mmWave frequencies, the GCPW signal launch is important, since the launch area can have a major impact on return loss. End-launch connectors should also be used, to make good pressure contacts between the coaxial connectors and the test circuit without soldering, allowing the same two connectors to be used for the shorter and longer circuits. This minimizes the effect of the connectors on measurement results. For consistency, the same connectors should be oriented to the same ports of the vector network analyzer (VNA). If connector A is oriented to port 1 of the VNA and connector B to port 2 for testing the shorter circuit, the same should be true when testing the longer circuit.



▲ **Fig. 3 Microstrip ring resonator (a) and wideband measurement (b).**

Subtracting the phase angles of the short and long circuits will also subtract the effects of the connectors and the signal launch areas. If the return loss is good for both circuits and the connectors have consistent orientation, most of the effects of the connectors will be minimized. When using this method at mmWave frequencies, return loss at these transitions of better than 15 dB through 60 GHz and 12 dB from 60 to 110 GHz is considered acceptable.

The extraction equations for the microstrip differential phase length method are based on a manipulation of the microstrip phase response formula for circuits with different physical lengths:

$$\Phi = 2\pi f \frac{\sqrt{Eff\_\varepsilon_r}}{c} L \quad (8)$$

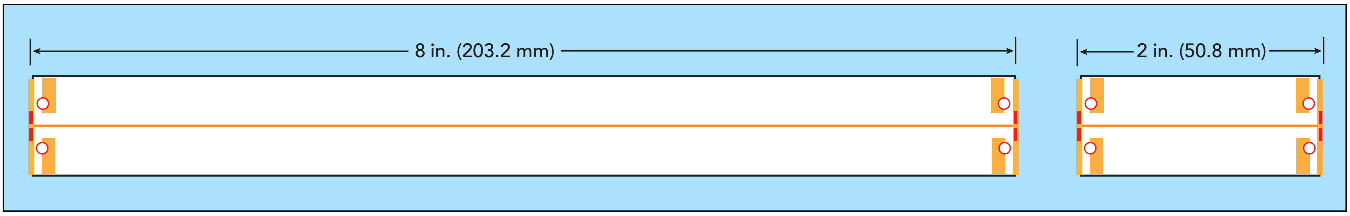
$$\Delta\Phi = 2\pi f \frac{\sqrt{Eff\_\varepsilon_r}}{c} \Delta L \quad (9)$$

$$Eff\_\varepsilon_r = \left[\frac{\Delta\Phi c}{2\pi f \Delta L}\right]^2 \quad (10)$$

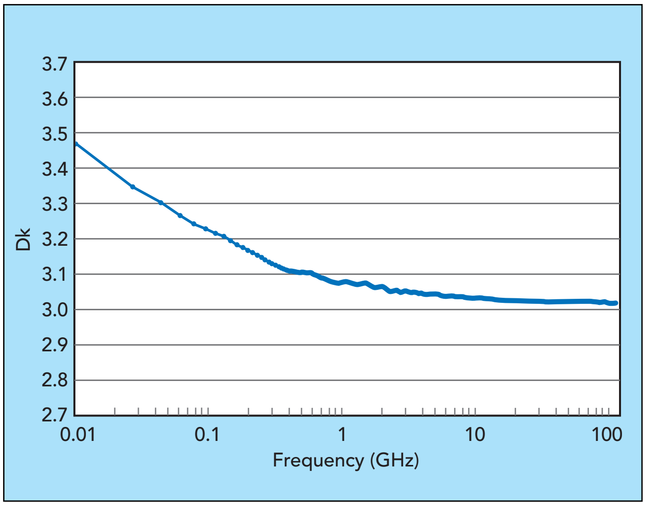
where c is the speed of light in free space, f is the frequency of the S_{21} phase angle, ΔL is the difference in physical lengths of the two circuits and ΔΦ is the difference in phase angle between the shorter and longer circuits.

The test method comprises a few simple steps:

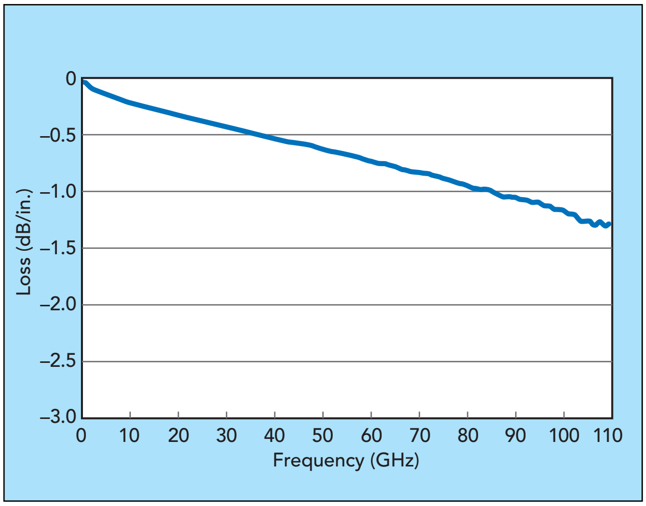
- Measure the S_{21} phase angle as a function of frequency for the shorter and longer circuits.
- Use the formulas to determine the measured effective Dk.
- Obtain precise and accurate circuit dimensions that can be entered into an EM field solver using the initial Dk value for the material.



▲ **Fig. 4** **Top view of the long and short microstrip circuits used in the differential phase-length method.**



▲ **Fig. 5** **Dk vs. frequency measured with the microstrip differential phase length method.**



▲ **Fig. 6** **Insertion loss vs. frequency determined from the microstrip differential length measurements.**

- Use the software to generate a simulated effective Dk value. Change the Dk in the solver until the measured and simulated effective Dk values for the material match at the same frequency.
- By incrementing the frequency into the mmWave region and repeating this process, the Dk value can be determined across a range of frequencies through mmWave.

Figure 5 shows a measurement using the microstrip differential phase length method with 5-mil thick RO3003G2$^{\text{TM}}$ circuit material. The curve was generated using a Microsoft Windows PC program developed by Rogers Corp.[5] The data reflects the usual trend of decreasing Dk with increasing frequency. At lower frequencies, larger changes in Dk occur versus frequency; however, from 10 to 110 GHz, the Dk shows little change. This curve reflects a material with low loss and rolled copper with a smooth surface. A material with high loss and/or higher copper surface roughness will exhibit an increased negative slope in the Dk-frequency relationship. Using this test method, the insertion loss for circuits using the MUT can be obtained by subtracting the S_{21} values of the shorter and longer circuits at each frequency (see ***Figure 6***).

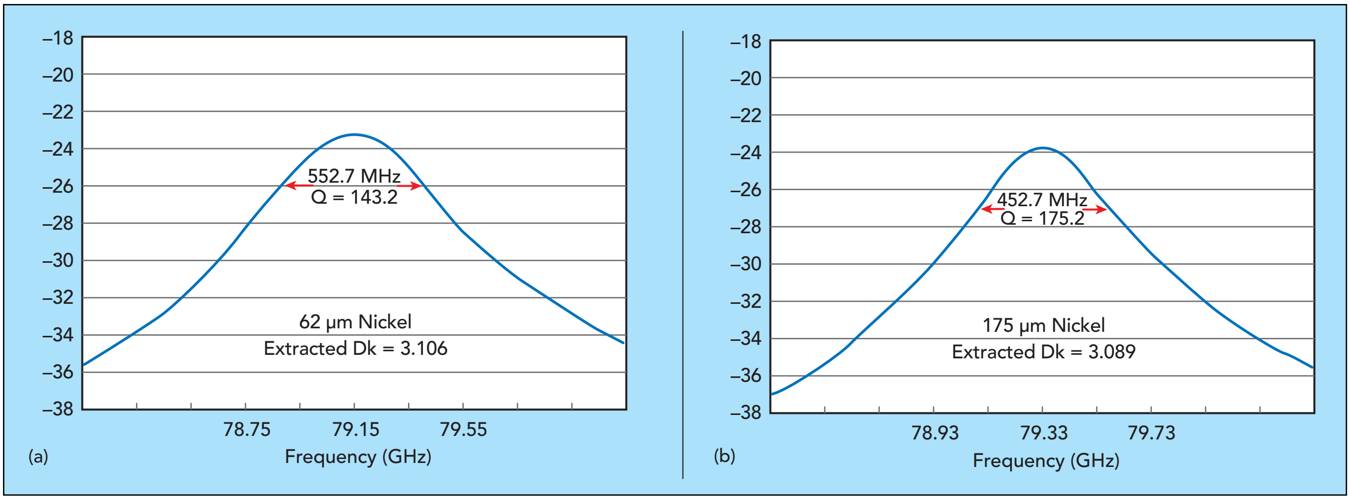
Ring Resonator Method

The ring resonator method is another approach for mmWave characterization. While ring resonators are often used below 10 GHz, with proper fabrication precision they can be used effectively at mmWave frequencies. Fabrication is important because the effects of circuit dimensions and dimensional tolerances are greater at mmWave, with any variation reducing accuracy. The thickness of the copper plating on the circuit material also varies, as does the gap dimension. Most mmWave ring resonators are thin (usually 5 mils), and the gap between the feed line and resonator ring is also small. Thickness and gap variations for a gap-coupled ring resonator will impact both coupling and the resonant frequency.

When comparing two circuits built on the same circuit material and with different copper plating thicknesses, the circuit with the thicker copper will exhibit a lower Dk. The resonant frequencies of the two circuits will also differ, even though they should be the same for the same circuit material and test method. ***Figure 7*** shows an example where the thickness variation in a circuit's final plated finish causes differences in the extracted Dk for the same material. Whether the finish is electroless nickel immersion gold (ENIG) or other plated finishes, the issue remains.

Besides these fabrication issues, conductor width variation, etched-space variation, trapezoidal effects and substrate thickness variation cause similar effects. If all these variations are accounted for, one individual ring resonator measurement can yield the correct Dk value; however, many test routines will assume nominal circuit dimensions and extract an incorrect Dk. At lower frequencies these effects do not impact Dk accuracy as much as at mmWave frequencies.

Another significant variable using ring resonators at mmWave is the gap coupling changing with frequency. It is typical for ring resonators to be evaluated using multiple nodes, with the nodes usually spaced by significant differences in frequency. As a result, gap coupling variation can be a significant source of error. To overcome this, a differential circumference method is used. This approach uses two ring resonators, essentially identical



▲ **Fig. 7 mmWave ring resonator measurements of a MUT with 62 μm thick (a) and 175 μm thick (b) nickel plating.**

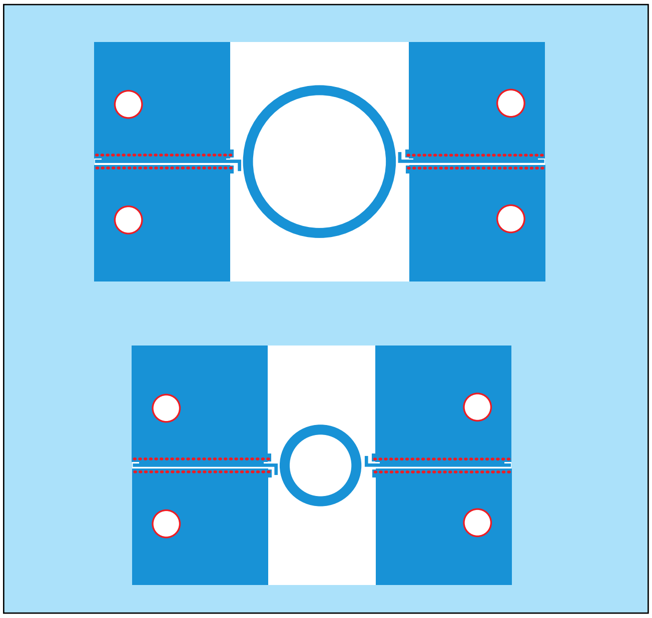
except the ring circumferences differ in size and are integer multiples of each other (see ***Figure 8***). With two ring resonators, the higher order resonant nodes used in the Dk extraction have some frequencies in common. Since the feed lines and gaps are the same, the effects of gap coupling are decreased—theoretically eliminated—which leads to better accuracy in the extracted Dk. The Dk is calculated from the equations:

$$L_1 + \Delta L = \frac{n_1 c}{2f_{r1}\sqrt{\mathrm{Eff\_}\varepsilon_r}} \qquad (11)$$

$$L_2 + \Delta L = \frac{n_2 c}{2f_{r2}\sqrt{\mathrm{Eff\_}\varepsilon_r}} \qquad (12)$$

$$\mathrm{Eff\_}\varepsilon_r = \left[\frac{c\left(n_1 f_{r2} - n_2 f_{r1}\right)}{2f_{r1}f_{r2}\left(L_2 - L_1\right)}\right]^2 \qquad (13)$$

The ring resonators in Figure 8 are microstrip structures, with the feed lines tightly-coupled GCPW to avoid open-end feed line resonances, which could interfere with the ring resonant peaks. If the feed lines were open-ended microstrip, they would have their own resonances. The only way to avoid this is to make the feed lines much shorter or use tightly-coupled GCPW feed lines. Since the differential circumference ring resonator method yields the circuit's effective Dk, it is still necessary to make accurate circuit dimension measurements and use a field solver to extract the material Dk.



▲ **Fig. 8 Test rings used with the microstrip differential circumference ring resonator method.**

CONCLUSION

The mmWave test methods discussed here are circuit-based. Several other methods may be considered, such as raw material tests, but most yield a material Dk for the x-y plane rather than the z-axis (thickness). Circuit designers are more interested in the z-axis Dk, but for those willing to work with x-y material Dk values, free-space measurements, split-cylinder resonator measurements and waveguide perturbation testing are additional test methods.

The clamped broadside coupled stripline resonator test method has also been evaluated for determining circuit material Dk at mmWave frequencies. Unfortunately, this approach is most effective with small pieces of MUT and is not practical for volume testing. The quest continues to find a good raw material test to characterize materials at mmWave frequencies.■

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Characterizing Circuit Materials at mmWave Frequencies: Part II

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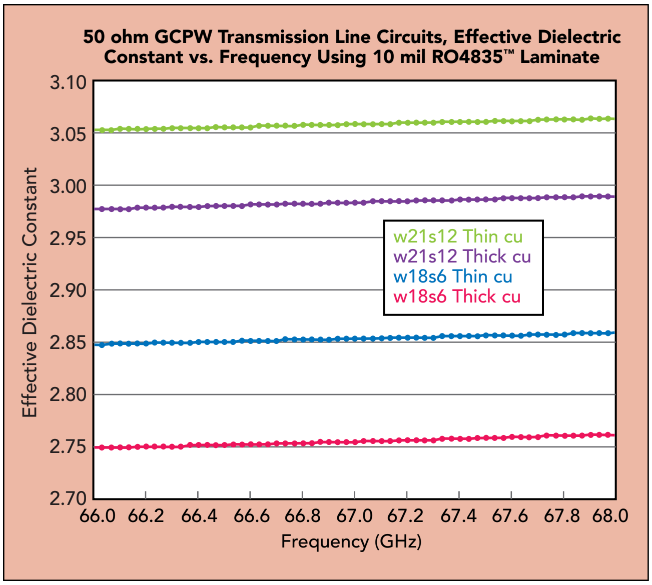
Different Dk measurement methods can provide different test results, depending upon the many variables involved.

The first part of this article (See page 14 in this ebook) explored several methods for measuring the dielectric constant (Dk) or relative permittivity of a circuit material at mmWave frequencies, including by means of ring resonators. Part 2 will take a closer look at ring resonators and how they can be used to determine the Dk and the loss tangent (Df) of a high frequency printed circuit board (PCB) material. The importance of characterizing circuit material properties at higher frequencies increases steadily as interest grows in potentially large applications at mmWave frequencies, including automotive radar and 5G wireless communications.

Ring resonators are often used to determine the Dk and Df of high frequency circuit materials. While they are typically used to characterize materials at frequencies less than 12 GHz, they can be used at higher frequencies provided that several issues are addressed. One of these concerns is the RF/microwave performance variations that occur in a ring resonator as a result of normal process variations that can impact the fabrication and construction of the resonator PCB, such as variations in the thickness of the PCB's copper plating.

Electrical connections between different conductor layers of PCBs are typically made by plated thru hole (PTH) viaholes formed through the z axis (thickness) of the circuit material. Conductive paths through the viaholes are formed with electroless copper plating and then final electrolytic copper plating. Copper plating is also performed on the outer conductive layers of the PCB, increasing the thickness of the copper supplied with the circuit laminate material. The plating process is subject to normal variations in copper plating thickness.



▲ **Fig. 1 Excerpt from article [1] showing effective dielectric constant versus frequency for the four groups of GCPW, with tight coupling (s6), loose coupled (s12), and thin and thick copper.**

Depending on frequency and design, the performance of some circuits can be impacted by these variations in copper plating thickness. Normally, circuits formed with microstrip transmission lines will not be affected. But coupled circuits and circuits with different

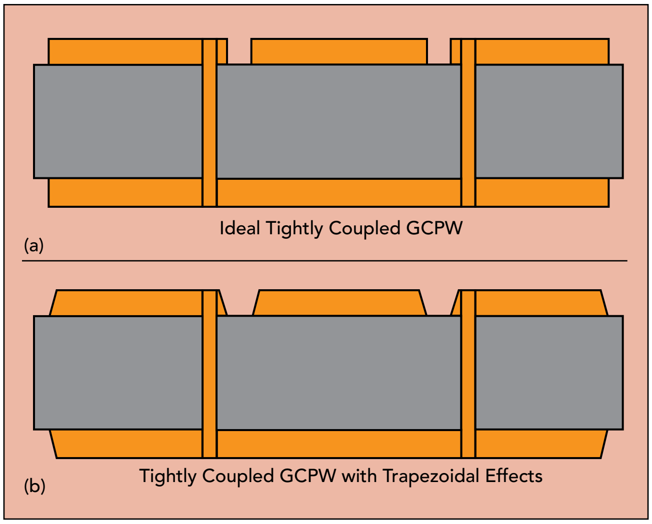


Fig. 2 Cross-sectional views of GCPW circuits with ideal, rectangular shaped conductors (a) and trapezoidal-shaped conductors (b).

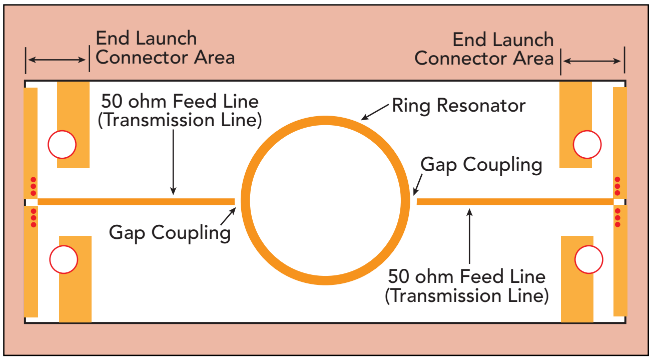


Fig. 3 Description of a microstrip ring resonator circuit.

transmission-line technologies, such as grounded coplanar waveguide (GCPW), can exhibit performance variations as a result of variations in the PCB copper thickness. A good example of this was published previously (see ***Figure 1***).[1]

The naming convention for the effective Dk curves of the GCPW circuits in Figure 1 refer to the signal conductor width (w) and the space (s) between the signal conductor and the neighboring coplanar ground planes. The curve for w18s6 refers to a circuit with an 18-mil-wide signal conductor and space or gap between both sides of the signal conductor and the neighboring ground planes that is 6 mils wide. All circuits in this study were built on the same panel of circuit material to minimize material variations which could impact measurement results.

As can be seen in Figure 1, there is an approximate difference of 0.1 in the values of effective Dk determined when using the same design (w18s6) for circuits with thin copper (about 1 mil thick) compared to circuits with thick copper (about 3 mils thick). This design (w18s6) is considered tightly coupled: the gap between the signal plane and neighboring coplanar ground planes is relatively small. As Figure 1 also shows, the loosely coupled design (w21s12) was less impacted by the difference in copper thickness, with a difference of about 0.075 in effective Dk for circuits with thin and thick copper.

As shown in ***Figure 2,*** another concern with PCB copper thickness variations is related variations of trapezoidal effects.

Most electromagnetic (EM) simulation software will assume rectangular-shaped conductors for a GCPW circuit (see Figure 2a). But a cross-sectional view of a GCPW circuit would show that most of the conductors will vary between rectangular and trapezoidal shapes (see Figure 2b). Depending upon the PCB fabrication process, the trapezoidal shape could be inverted compared to what is shown in Figure 2b, being narrower at the base of the conductor, which is the interface between the PCB's copper conductor and dielectric substrate.

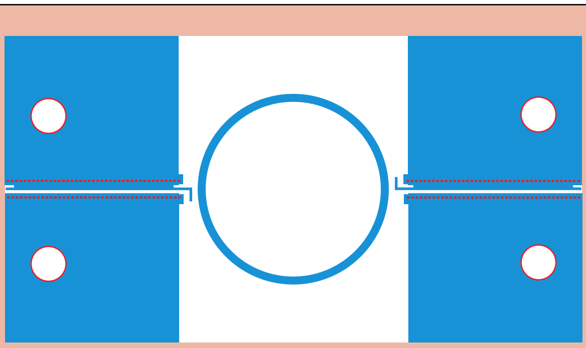
A typical consequence of thicker copper is to have conductors with more of a trapezoidal shape than a rectangular shape. Variations from rectangular to trapezoidal conductor shapes can impact the electrical performance of coupled circuits. For tightly coupled GCPW circuits, rectangular shaped conductors have significant current density along the sidewalls of the coupled conductors, with increased electric fields along the coupled area. When the conductor shape changes to trapezoidal, the current density changes, with increased current density near the base of the conductor and lower current density along the coupled sidewalls. This results in decreased electric fields in the air around the trapezoidal shaped conductors. Having more or less electric fields in air will impact the capacitance in gap coupled areas and alter the effective dielectric constant as determined from measurements of such circuits.

The formation of trapezoidal conductors and their effects on circuit performance cannot be predicted or included in a circuit simulation as a standard procedure. However, for troubleshooting or evaluating a circuit, a small section of that circuit can be analyzed to determine the impact of trapezoidal conductor effects. The results of the partial circuit analysis will then be available for use in an EM simulator to better predict the overall effects of variations in conductor shape on circuit performance.

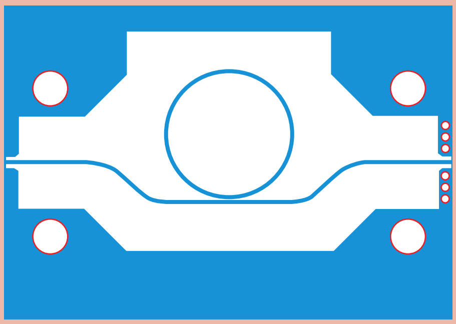
Because they are coupled structures, ring resonators can be impacted by certain PCB fabrication variations; copper plating thickness and trapezoidal conductor effects are among the concerns related to PCB fabrication variations. Most ring resonators are gap coupled (see ***Figure 3***).

Feedlines bring energy into and out of a ring resonator circuit (see Figure 3). The feedlines are gap coupled to the ring resonator and the gap coupling can impact the resonant frequency. The gap coupling is sensitive to PCB copper thickness variations. When the copper is thin, less of the electric fields will occupy the air around the conductors and more electric fields will be in the substrate; the distribution of the electric field impacts the capacitance in the gap area and can alter the frequency of the ring resonator circuit. When the same circuit design is fabricated with a PCB having thicker copper, more of the electric field is in air and the capacitance in the gap area and the center frequency of the resonator will change. Although the ring resonator design is the same, it can exhibit significant variations in resonant frequency due to normal variations in PCB copper thickness and trapezoidal conductor effects. Because the same ring resonator can yield different results depending upon copper thickness and trapezoidal conductor effects, it can also provide a range of Dk values (some incorrect) when used as a test circuit.

Coupling is a key part of any ring resonator design and variations in PCB copper thickness and conductor shapes will impact the performance of a ring resonator depending upon the amount of coupling in a design. The effects have more impact when the coupling is tight than when it is loose. As a rule, the coupling should be relatively loose to avoid the impact of copper thickness and trapezoidal shape variations. Additionally, when the ring is very loosely coupled, the resonator circuit will behave more like an unloaded resonator and the effects of the gaps, feedlines, connectors, and cables are less significant. The coupling should be loose enough to where the resonant peak amplitude is no greater than -20 dB.



(a) Thru-Coupled Ring Resonator



(b) Thru-Line with Edge Coupled Ring Resonator

Fig. 4 Illustrations of a thru-coupled ring resonator (a) and a thru-line edge coupled ring resonator (b).

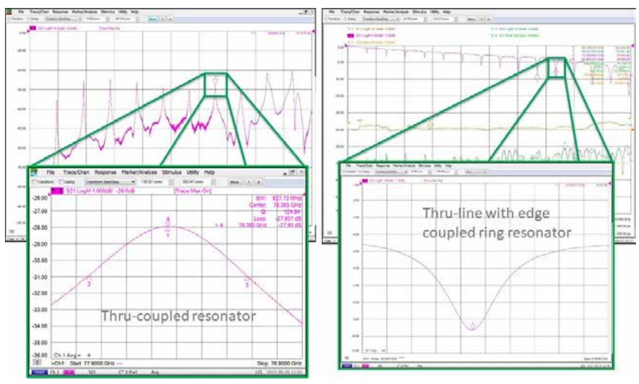


Fig. 5 Screen shots from a network analyzer show typical ring resonator performance for the thru-coupled ring resonator and the thru-line edge coupled ring resonator.

Most mmWave circuits are fabricated on thin substrates. Thinner substrates help minimize radiation, dispersion, and spurious wave propagating modes. Fabricating a loosely coupled ring resonator on a thin substrate with a resonant peak that can be measured is very difficult. For a thin substrate, the differences between a gap coupled ring resonator that is loosely coupled compared to tightly coupled, at mmWave frequencies, can be a dimensional difference of less than 1 mil in the gap coupled area. Since most circuit fabricators can maintain an etching tolerance of at best ±0.5 mil (a 1-mil variation), coupling variations for mmWave circuits can be significant from one circuit to the next when fabricating multiple circuits of the same design.

Not all ring resonator designs have the same sensitivity to gap coupling. For example, a thru-coupled ring resonator (see Figure 3) is sensitive to gap coupling variations but a thru-line design with an edge coupled ring resonator is less sensitive to gap coupling variations. Figure 4 provides illustrations of these two types of coupled resonators.

As was shown in Figure 8 of Part 1 of this article, feedlines for thin mmWave ring resonator circuits are best implemented in GCPW to prevent any open-ended feedline resonance which can interfere with the resonance of the ring. ***Figure 4a*** shows a thru-coupled ring resonator structure while Figure 4b depicts a thru-line edge coupled ring resonator. The thru-line transmission line in ***Figure 4b*** uses a GCPW structure in the end-launch connector area to optimize the signal launch. The signal launch is the transition from the connector to the PCB. It must be optimized for good return loss across the frequency range of interest for a ring resonator design.

The thru-coupled ring resonator will exhibit resonant peaks as expected. However, the thru-line with ring resonator that is edge coupled will have a "suck-out" in measured amplitude-versus-frequency response at the frequencies where the ring resonates. The thru-line with edge-coupled ring resonator should have an S21 response much like that of a transmission line, although it will have periodic dips in its insertion loss versus frequency response where the ring resonates (see ***Figure 5***).

Table 1 provides a comparison to show potential differences in RF performance between these two different ring resonators due to normal variations in material properties and circuit fabrication processes.

Data in Table 1 is from models run in Sonnet Software,[2] a popular EM simulation software tool. The EM field solver has been shown to have excellent accuracy for planar circuits when simulation results are compared with measured results. The resonator models are based on 5-mil-thick RO3003™ circuit laminate with electrodeposited (ED) copper from Rogers Corp. The ring resonator designs were moderately coupled. The resonant peak for each resonator was tuned to -10 dB at the center frequency noted in Table 1. Several variations related to circuit material properties and PCB fabrication processes were modeled and the results are shown in Table

TABLE 1

THRU-COUPLED RING RESONATOR

	Baseline		**10% Thinner Substrate**		**Thinner Copper**		**Thicker Copper**		**Narrow Width, Wider Gap**	
	Inches	**mm**	**Inches**	**mm**	**Inches**	**mm**	**Inches**	**mm**	**Inches**	**mm**
Conductor Width	0.012	0.305	0.012	0.305	0.012	0.305	0.012	0.305	0.011	0.279
Coupling Gap	0.007	0.178	0.007	0.178	0.007	0.178	0.007	0.178	0.008	0.203
Substrate Thickness	0.005	0.127	0.0045	0.114	0.005	0.127	0.005	0.127	0.005	0.127
Copper Thickness	0.0015	0.038	0.0015	0.038	0.001	0.025	0.003	0.076	0.0015	0.038
Copper Roughness	0.00007874	0.0020	0.00007874	0.0020	0.00007874	0.0020	7.87E-05	0.0020	0.00007874	0.0020
Center Freq. (GHz)	77.41		77.52		77.52		76.96		77.44	
Dk from Freq. Shift	Reference		0.009		0.009		–0.035		0.004	

THRU-LINE EDGE COUPLED RING RESONATOR

	Baseline		**10% Thinner Substrate**		**Thinner Copper**		**Thicker Copper**		**Narrow Width, Wider Gap**	
	Inches	**mm**	**Inches**	**mm**	**Inches**	**mm**	**Inches**	**mm**	**Inches**	**mm**
Conductor Width	0.012	0.305	0.012	0.305	0.012	0.305	0.012	0.305	0.011	0.279
Coupling Gap	0.006	0.152	0.006	0.152	0.006	0.152	0.006	0.152	0.007	0.178
Substrate Thickness	0.005	0.127	0.0045	0.114	0.005	0.127	0.005	0.127	0.005	0.127
Copper Thickness	0.0015	0.038	0.0015	0.038	0.001	0.025	0.003	0.076	0.0015	0.038
Copper Roughness	0.00007874	0.0020	0.00007874	0.0020	0.00007874	0.0020	7.87E-05	0.0020	0.00007874	0.0020
Center Freq. (GHz)	77.29		77.39		77.33		77.17		77.21	
Dk from Freq. Shift	Reference		0.008		0.003		–0.009		–0.006	

Table 1 Comparisons of the thru-coupled ring resonator and the thru-line edge coupled ring resonator in relation to variables which can potentially impact RF/microwave performance.

1. The description of most of the different models in the column headers is self-explanatory. However, the far right-hand column labeled "Narrow width, wider gap" shows the difference for a ring conductor with narrower width. With PCB fabrication and in a discrete circuit area with a conductor and open circuit-board area, a narrower conductor results in more open circuit-board space. The far right-hand column of Table 1 shows the effects of a narrower ring conductor and resulting increased gap coupling space.

The Dk extraction is shown on the bottom row of Table 1 for each of the different scenarios. In summary, the thru gap coupled ring resonator has a worst-case Dk shift of 0.035. When subjected to the same material and process variations, the thru-line edge coupled ring resonator has a worst-case Dk shift of 0.009. This indicates that the thru-gap coupled ring resonator is more affected by material and PCB fabrication process variations in terms of RF performance than the thru-line edge coupled ring resonator.

Copper surface roughness is yet another circuit material quality that can affect the accuracy of material Dk characterization efforts. Copper surface roughness can impact transmission-line insertion loss and phase response at high frequencies.[3] The quality of the copper surface at the circuit material substrate-copper interface can affect the phase velocity of a high-frequency circuit's signals, with a rougher copper surface resulting in slower phase velocity. An EM wave with a slower phase velocity is an effect like a PCB material with an increase in Dk. Even if the Dk of a circuit substrate has not changed, if using circuits like ring resonators for Dk characterization, circuits with smoother copper will exhibit a circuit-perceived Dk or Design Dk that is lower than the same circuits having a rougher copper surface.

In addition, a rougher copper surface will result in increased conductor loss compared to a smoother copper surface. The increase is dependent upon frequency, substrate thickness, and the amount of copper surface roughness. The effects of copper surface roughness will be more pronounced for circuits on thinner substrates than for circuits on thicker substrates. When evaluating the effects of copper surface roughness on insertion loss at lower frequencies with thick skin depth, the effects will be minimal compared to the more significant effects on loss at higher frequencies with thinner skin depth.

Circuit material copper surface roughness effects can impact the values of Dk and Df extracted from ring resonator circuits. Some amount of surface roughness is to be expected, although it is hoped to be within normal limits. Variations in roughness will occur within a single sheet of copper foil and from sheet to sheet, although for some copper, such as rolled copper, the surface roughness variations will be minimal. For standard ED copper, the normal surface roughness can have significant variation. For example, ED copper with a specified average surface roughness of 2.0 µm RMS can vary as much as 1.8 to 2.2 µm within the same sheet of copper.

Since a microstrip ring resonator has two substrate-copper interfaces, it is unlikely that the signal plane copper surface roughness will be the same as the ground plane for most copper types. If a RF/microwave engineer was trying to account for the effects of copper surface roughness during material Dk and Df extraction, not having the same copper roughness on each interface is problematic and unpredictable. It is generally assumed that the signal plane copper surface roughness has more impact on RF performance than the ground plane copper surface roughness. The copper surface roughness can vary within a small area and the roughness for the ring conductor may vary and it may not be what is assumed.

The copper surface roughness must be part of any extraction process for Dk and Df using circuit structures such as ring resonators because of the impact of the copper surface roughness on test circuit performance. Errors due to copper surface roughness can be minimized by using rolled copper. It is smooth, with minimal variations in surface roughness, and minimal effect on phase or insertion loss of transmission lines in test circuits.

Ring oscillators can be effective test devices for extracting material Dk and Df at microwave frequencies; however, accurate extraction of Dk and Df at mmWave frequencies can be very challenging. Ring resonators are assumed to have no radiation since the ring is a closed structure, but there are always exceptions. For a tightly coupled ring resonator that is a thru-coupled resonator, the radiation in the gap coupled area can affect the quality factor (Q) of the resonator which can cause errors in Df extraction.

SIW TEST CIRCUITS

As circuits move higher in frequency, substrate integrated waveguide (SIW) transmission lines are being used more in support of PCB-based mmWave applications. SIW provides some benefits at mmWave frequencies, although there are also some concerns when using this type of circuit structure for the extraction of material Dk and Df values.

Several methods can be used to extract Dk from a material with an SIW structure. One technique is based on using the 3-dB cutoff frequency of the SIW to extract the Dk of the circuit material. Another method involves phase angle measurements in the passband frequency range of the SIW to extract the Dk of the material. When using SIW structures at mmWave frequencies, the location of drilled holes in the circuit material must be extremely precise. Most PCB fabricators can hold a drilled hole location tolerance within ±1 mil, which is considered good. But because the hole patterns form the sidewalls of the SIW, any variations in the hole spacings or locations can make a difference in the 3-dB cutoff frequency, especially at mmWave frequencies.

As an example, for an SIW designed for a 3-dB cutoff frequency of 70 GHz using a 5-mil-thick substrate with Dk of 3.0, a variation in wall hole location of 1 mil (one-half of the ±1 mil tolerance) will change the 3-dB cutoff frequency by 1.5 GHz. If this frequency shift is assumed to be due to Dk only and not the SIW drilled hole tolerance, it will result in a shift/error of 0.12 in the extracted Dk value.

In addition, the 3-dB cutoff frequency of transitions of other transmission-line technologies to SIW can be sensitive to circuit fabrication variables. Transitions may be from microstrip to SIW or GCPW transmission lines to SIW. A microstrip-to-SIW transition is less affected by PCB fabrication variations than a GCPW-to-SIW transition. Multiple PCB fabrication variables can impact the RF performance of GCPW and these variations can certainly impact the 3-dB cutoff point. Because of these issues, extracting the Dk of the material by using the 3-dB cutoff frequency for SIW at mmWave frequencies is not recommended.

The phase angle response for the SIW in the passband frequency region is somewhat less sensitive to the drill location tolerance but it is still a concern. One design trick which could be advantageous for phase measurements in the passband for SIW is to use a dual row of grounding viaholes for each sidewall of the SIW structure. The drilled hole location tolerance requirement will still exist but having dual rows for each sidewall seems to give an averaging effect and minimizes the impact of variations in hole location on phase response.

Specific recommendations for measurements that can help determine circuit material Dk and Df at mmWave frequencies have not been made in either part 1 or part 2 of this article mainly because an industry-defined standard test method does not exist at mmWave frequencies (30 to 300 GHz). Different methods are available, although caveats must be made regarding accuracy under certain conditions. Measurements based on ring resonators have great value at mmWave frequencies but, without understanding the many variables related to these circuit structures, the accuracy of test results and Dk and Df characterizations can be greatly compromised.■

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