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Measuring the Impact of Test Methods for High-Frequency Circuit Materials

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High-frequency materials are characterized by several important parameters, including the dielectric constant or relative permittivity (ε_r) and the dissipation factor (Df). For those parameters to have meaning for circuit designers, they must be measured using methods that deliver accurate, repeatable results. However, circuit materials are characterized by many different test methods: For measuring ε_r, IPC has 12 different test methods. Many other organizations, including ANSI and IEEE, have their own test standards for characterizing ε_r. Each measurement method provides detailed insights into the properties of the material it is testing, and the results of each test method may be correct, but they also may not agree. What follows is a review of different methods for measuring ε_r along with useful modifications and even some suggestions for new Dk measurement approaches.

How can two different test methods provide Dk measurement results that are correct but different? It can occur when the two methods measure the same circuit material in two different directions. Some Dk measurements are performed through the thickness or z-axis of the material while some are performed across the length and width or x-y plane of the material. Since most high frequency materials are anisotropic, the two different measurements will typically provide different results at a given frequency, such as 10 GHz, although both Dk values are correct.

The choice of test frequency can also make a difference in the results of a material Dk measurement, since a material's dispersion characteristics affect that material's Dk as a function of frequency. For example, the same Dk measurement method and testing the same material and testing through the z-axis of the material will provide different results at different test frequencies, such as at 1 and 10 GHz.

Even when two test approaches are evaluating circuit material through the z-axis at the same frequency, the test fixture or apparatus that interfaces the material to the test instruments can make a difference in the Dk measurement results. For example, measurements of Dk can be performed on the raw material (without copper cladding) inside of a clamped test fixture as opposed to measurements made with the aid of a reference circuit fabricated on the material. The variables that must be considered as part of the Dk extraction can differ in both cases, leading to different Dk measurement results, even when testing is performed through the same direction of the material and at the same test frequency. For example, the clamped test fixture will have some amount of entrapped air (with the same Dk as a vacuum, around 1) which will contribute its own low Dk value to the measurement of the material's (higher) Dk; there is no entrapped air when performing Dk measurements with a reference circuit.

In general, different Dk measurement methods can generate different Dk values for a material under test (MUT), and those Dk values should not be compared. For example, Dk measurements using a test circuit on the material will generate different Dk results than measurements made on raw material (with no copper cladding) with a test fixture. Even when the same test method is being used, such as with a test fixture, unless the test fixture is the same in each case, the results may differ. Similarly, circuit based Dk measurements on the same material may differ with any variations in the test circuit. For example, using a ring resonator as the test circuit will typically lead to different Dk results than when extracting a material's Dk from measurements of microstrip transmission lines with precisely known dimensions. A resonator test method is typically considered the more accurate of the two circuit approaches.

In addition, the two circuit types have different sensitivities to the characteristics of the circuit material and to the circuit fabrication process resulting in different Dk values even at the same test frequency. As an example, the loss or dissipation factor (also known as Df, loss tangent, or tan δ) varies widely among different materials, and can be difficult to measure accurately for materials with low Df. But for materials with higher Df, such as FR-4, more measurement methods are available to yield accurate results.

Measuring the Methods

Test methods based on raw material measurements include the X-band clamped stripline test (per the IPC-TM-650 2.5.5.5c standard)[1], the Bereskin test method, split cylinder test method (per IPC-TM-650 2.5.5.13)[2], and the split post dielectric resonator (SPDR) test method [3]. Circuit-based material measurement methods include the microstrip ring resonator, transmission-line, gap coupled resonator, and delay-line measurement approaches. Some of these methods will be explored in detail to show differences among the various test methods and how some methods might be modified for making higher frequency measurements. Figure 1 shows how the Dk measured for the same material can differ when using different test methods: one measurement approach is a raw material test technique (the full sheet resonance or FSR method) and the other two are circuit-based material measurements (the transmission line test method and the ring resonator test method).

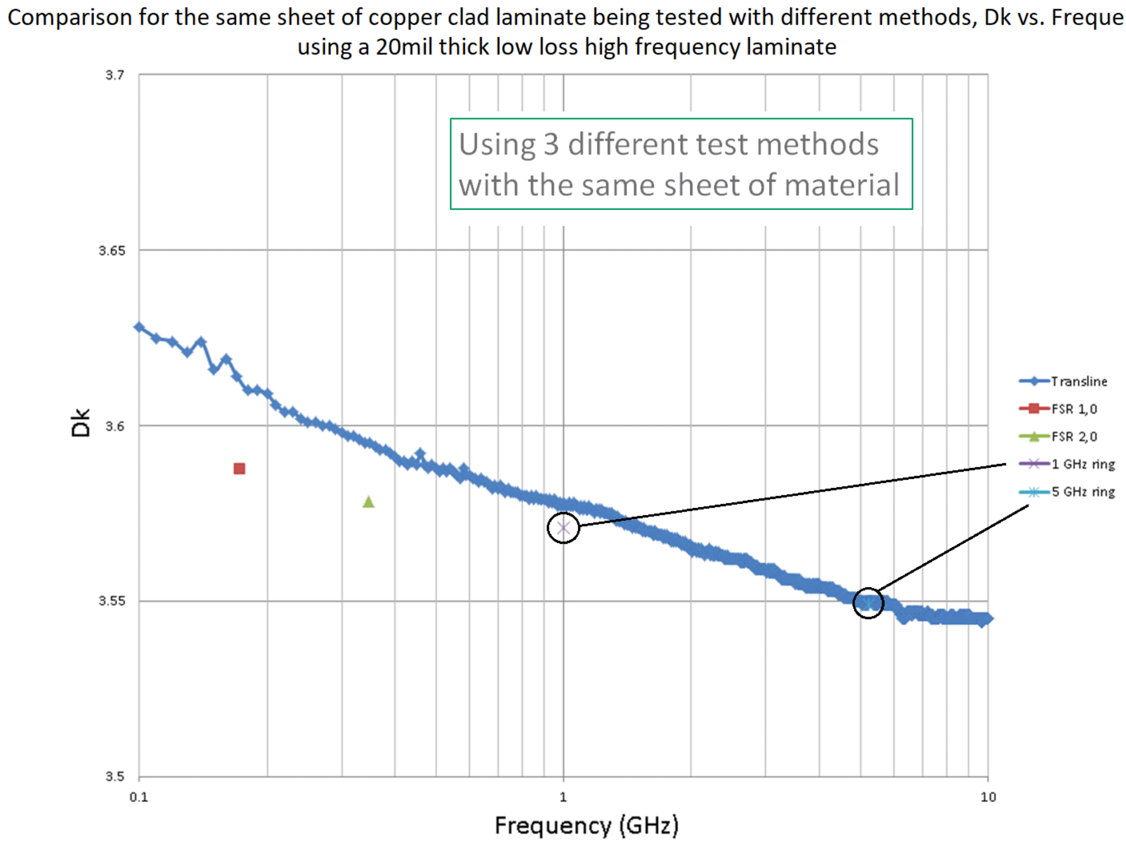


Figure 1. The use of three different test methods can yield three different Dk values for the same piece of circuit material.

In Figure 1, the FSR method is as defined by the IPC-TM-650 2.5.5.6 standard [4]. This test method measures the Dk of a circuit material in copper-clad laminate form. FSR 1,0 and 2,0 refer to resonator nodes. Node 1,0 has a half-wavelength resonance (the "1) along the length of the material under test, with no half-wavelength resonance (the "0") along the width. Node 2,0 has two half-wavelength resonances along the length of the material under test and no resonances along the width. The 1 GHz ring is a ring resonator designed to resonate at 1 GHz while the 5 GHz ring is a ring resonator designed to resonate at 5 GHz. The microstrip transmission line or "Transline" method used in Figure 1 is the microstrip differential phase length method [5] [6].

All three test methods were used to make measurements of Dk through the thickness or z-axis of the material, yet their Dk results do not agree. The smallest differences in the Dk measurements are between the two circuit-based measurement methods: the microstrip transmission line method and the ring resonator method. Greater differences are found between the circuit-based methods and the FSR test, a raw material test method.

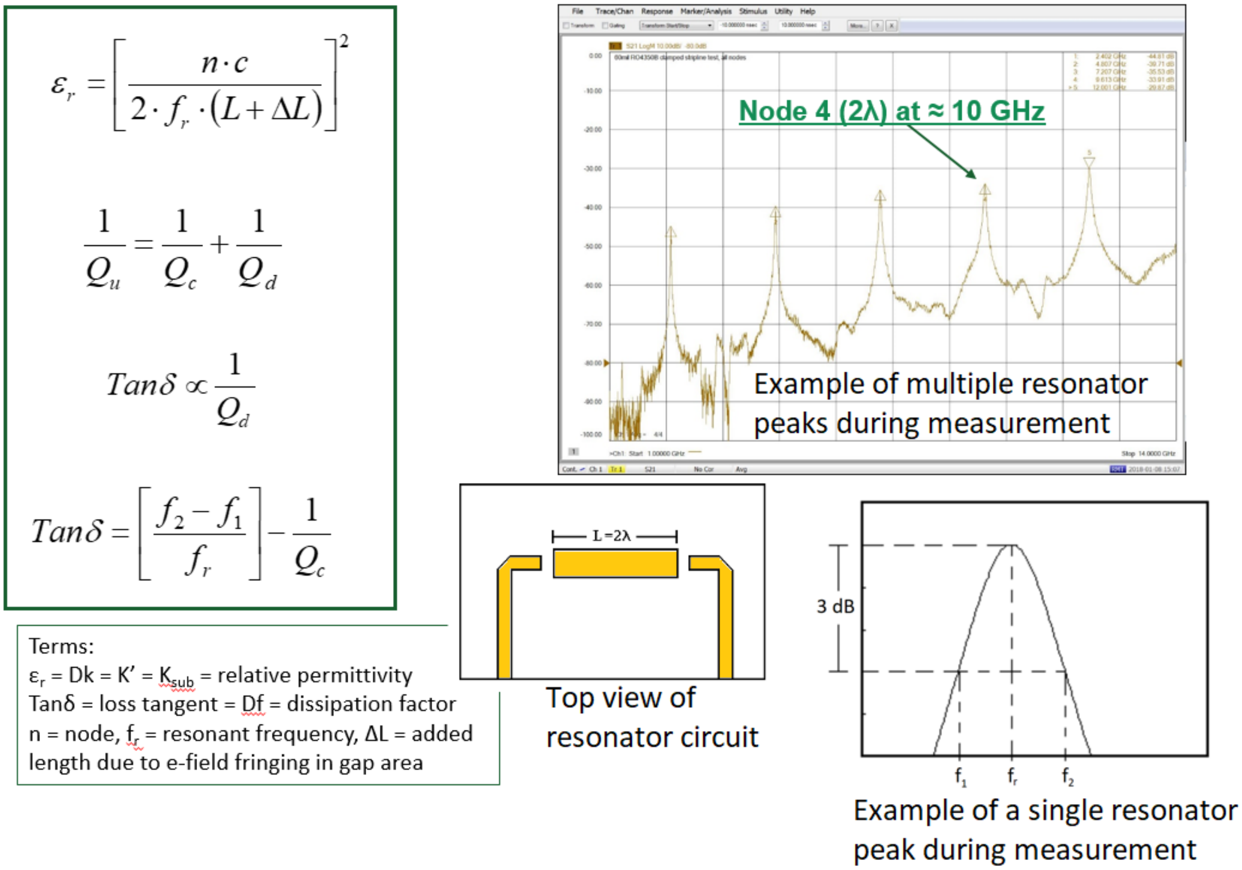
The FSR test is basically a resonator measurement in a large format. It was performed with a copper-clad laminate measuring 18 × 12 in., with node 1,0 one-half wavelength along the 18-in. dimension of the laminate. For the FSR test, a half-wavelength standing wave with a single frequency is used to determine the Dk of the material under test. The Dk value is actual the average Dk along a relatively long section of material.

In contrast, the microstrip transmission line test measures a material's Dk according to the electromagnetic (EM) propagation of transmission lines with known dimensions. It is subject to material variations, such as variations in the thickness of the substrate, and circuit fabrication variations, such as variations in copper thickness and width of the microstrip conductors. In addition, the microstrip transmission lines have EM fields fringing in the air around the circuit material under test, combining the low Dk of air (about 1) for those portions of the EM fields with the Dk of the material being measured. Material testing based on transmission lines will be sensitive to normal variations in substrate thickness for the material under test, although such variations in substrate thickness do not significantly impact Dk measurements performed by the FSR method.

In general, ring resonator tests will yield different results than transmission line tests. The ring resonator produces a standing EM wave while an EM wave propagates through a transmission line, with transmission and reflections through the line. Differences in how these EM waves respond to the dielectric medium under test will result in differences in Dk measurements for ring resonator and transmission line test methods. Although the three test methods represented in Figure 1 yield different Dk values, they all show the same trend of decreasing Dk with increasing frequency. This trend is associated with dipole relaxation moments,[6] which refer to changes in electric flux with frequency.

The clamped stripline resonator measurement method (per IPC-TM-650 2.5.5.5 Rev. C) has been an effective means of evaluating the Dk and Df of raw circuit materials or substrates to about 12.5 GHz for some time. It uses a loosely coupled stripline resonator with half-wavelength nodes at approximately 2.5, 5.0, 7.5, 10.0, and 12.5 GHz. Typically, node 4 (at about 10 GHz or at four half wavelengths or 4 × 0.5λ) is used for testing high frequency materials. This test method requires a test fixture which is clamped together to form the stripline ground-signal-ground (GSG) configuration for the three conductive layers.

To make measurements, the copper is first etched off the laminate which is the MUT. The copper free material is placed inside the clamped test fixture. One piece of substrate is placed on both sides of a thin resonant circuit in the middle of the test fixture. The fixture is then clamped together to form a stripline resonator circuit with the MUT serving as the substrate for the stripline resonator (Figure 2).



$$\varepsilon_r = \left[\frac{n \cdot c}{2 \cdot f_r \cdot (L + \Delta L)}\right]^2$$

$$\frac{1}{Q_u} = \frac{1}{Q_c} + \frac{1}{Q_d}$$

$$Tan\delta \propto \frac{1}{Q_d}$$

$$Tan\delta = \left[\frac{f_2 - f_1}{f_r}\right] - \frac{1}{Q_c}$$

Terms:
ε_r = Dk = K' = K_{sub} = relative permittivity
Tanδ = loss tangent = Df = dissipation factor
n = node, f_r = resonant frequency, ΔL = added length due to e-field fringing in gap area

Node 4 (2λ) at ≈ 10 GHz

Example of multiple resonator peaks during measurement

Top view of resonator circuit

Example of a single resonator peak during measurement

Figure 2. These illustrations provide details about the clamped stripline resonator test method.

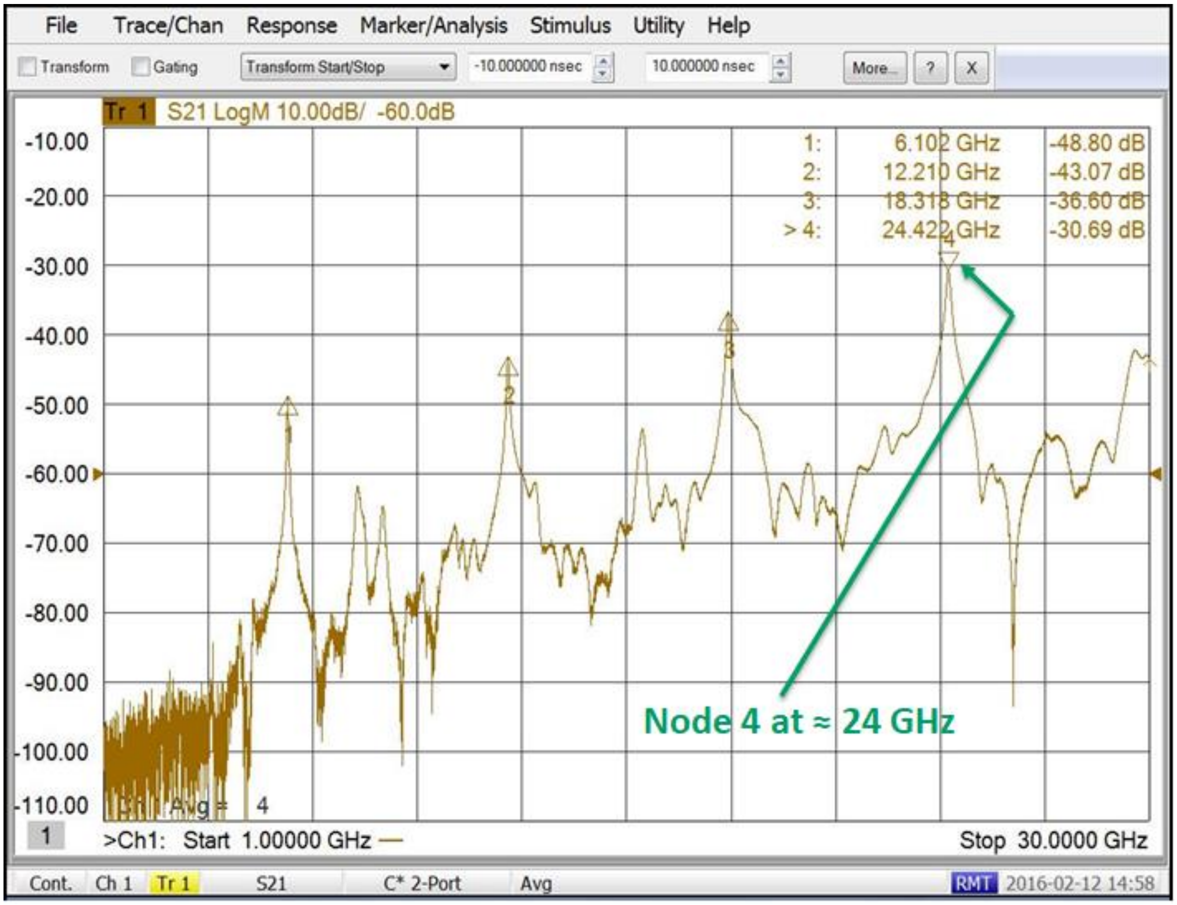
As shown in Figure 2, several equalities are used to determine the Dk and Df for a MUT. Parameter L in the equality for relative permittivity, ε_r, represents the physical length of the thin resonator circuit in the middle of the clamped test fixture. Parameter ΔL is the extension of the electrical length of the resonator due to electric field fringing. Because the resonator is loosely coupled, measurements of the resonator's quality factor (Q) can be considered equal to the unloaded quality factor (Q_u) and the equality for Q_u can be used to determine conductor losses related to the Q (Q_c) and dielectric losses related to the Q (Q_d). The conductor losses can be approximated in these calculations since conductor effects are minimal in thick stripline circuits, such as this clamped stripline resonator. In this case (Figure 2), the clamped stripline resonator is formed with 60-mil-thick circuit materials, resulting in 120-mil ground-to-ground spacing. The ground-to-ground spacing for the clamped stripline resonator is 128 mils, with 8 mils thickness attributed to the resonator circuit.

The clamped stripline resonator measurement method can determine material Dk values with enough accuracy for quality assurance (QA) or process control applications, but it may not yield the Dk results which are appropriate for circuit design and simulation. The approach has some variables that are not related to an actual circuit. For example, air can become entrapped in the resonator structure during testing and shift the Dk measurement results. As noted earlier, measurements of a stripline resonator with entrapped air (and its Dk of approximately 1) will yield lower Dk values than measurements of the same stripline resonator structure with no entrapped air.

Due to the types of coaxial connectors and cables used in the test fixture, the standardized clamped stripline material measurement method is limited to about 12.5 GHz. Type N connectors are typically used with 3.5-mm coaxial cables to set the upper frequency limit. By using higher frequency coaxial cables and connectors, in theory it should be possible to extend this measurement approach to higher frequencies.

In fact, efforts to modify the clamped stripline test method for Dk measurements to 24 GHz were achieved by using higher frequency cables and connectors and redesigning the resonator circuit. The 3.5mm cables were changed to 2.4mm cables, with an upper frequency limit of 50 GHz, while the Type N connectors were swapped for 2.4mm connectors, capable of operation to 50 GHz. The resonator circuit was redesigned to have the first half-wavelength resonance occur at about 6 GHz so that node 4 would be at about 24 GHz. The resonator circuit's chamfered feedline was modified to have to a very large radius to accommodate wideband operation through 24 GHz.

To avoid unwanted resonances at higher frequencies, the MUT had to be thinner in the higher frequency clamped stripline test method. It was implemented with an overall ground-to-ground spacing of 45 mils, of which 5 mils is the thickness of the resonator circuit and two pieces of 20-mil-thick circuit material complete the resonator structure. Figure 3 shows measurements made with this higher frequency version of a clamped stripline test fixture, where much attention was paid to the signal launch area to achieve clean resonant peaks.



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1:    6.102 GHz  -48.80 dB
2:   12.210 GHz  -43.07 dB
3:   18.318 GHz  -36.60 dB
> 4: 24.422 GHz  -30.69 dB
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>Ch1: Start 1.00000 GHz — Stop 30.0000 GHz

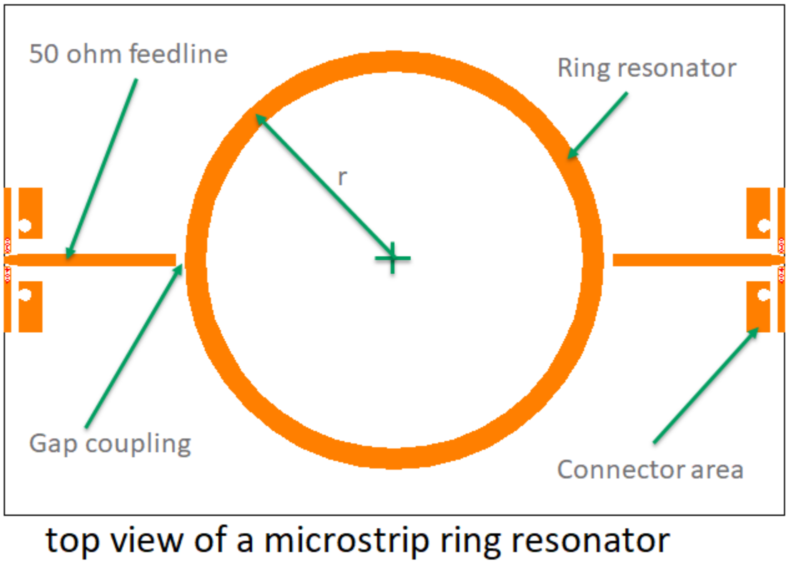
Figure 3. This screen shot shows measurements made with the modified higher frequency clamped stripline resonator test fixture at 24 GHz.

Various studies performed on this modified clamped stripline test fixture and material measurement method have found the accuracy and repeatability at 24 GHz equal to or better than that of the standard clamped stripline test method at 12.5 GHz or lower frequencies. Correlations were done but could only be approximated since the standard test method uses 60 mil thick materials while the modified test method uses 20 mil thick materials. Correlations were made by stacking three pieces of 20 mil thick materials on both sides of the resonator structure in the standard test method to achieve the normal 60 mil thickness.

The modified test was designed to have lower nodes that would be close in frequency to the nodes of the standard clamped stripline test method so that the same material could be tested using both versions of the test method at approximately the same frequencies. For example, node 2 of the modified clamped stripline test method is at about 12.2 GHz while node 5 of the standard clamped stripline test method is at about 12.6 GHz.

Checking Circuit Test Methods

In contrast to raw material Dk measurement methods, circuit based Dk measurement methods rely on a well characterized circuit fabricated on the MUT. The microstrip ring resonator is commonly used for measurements of material Dk and Df, although it is sensitive to normal PCB material and fabrication variations. For circuit-based material measurements, a ring resonator provides the highest accuracy at lower frequencies, with accuracy decreasing at frequencies above around 12 GHz.



$$2\pi r = n\lambda_g \qquad (1.)$$

$$\lambda_g = \frac{c}{f\sqrt{Dk_{eff}}} \qquad (2.)$$

$$Dk_{eff} = \left(\frac{c\,n}{2\pi r f}\right)^2 \qquad (3.)$$

Figure 4. This diagram shows the basic layout of a microstrip ring resonator along with some basic associated equalities to help in determining material Dk.

Figure 4 provides basic information about a microstrip ring resonator and equalities for determining the effective dielectric constant, Dk_{eff}, for MUT with a microstrip circuit. Symbol λ_g represents the wavelength associated with the ring resonator at its effective dielectric constant. In addition to the circuitry shown in Figure 4, a real-world microstrip ring resonator has coaxial connectors on the left and right sides attached to the feedlines, for transferring energy into and out of the resonator.

Gap coupling can cause accuracy issues with a ring resonator, since the coupling influences the center frequency of the resonator. When using a ring resonator to measure the Dk of a circuit material, it is desirable that the resonator's center frequency only be affected by the Dk of the material. If the effects of the gap coupling alter the center frequency, they will also alter the accuracy of calculations of material Dk based on center frequency.

In addition, gap coupling is sensitive to frequency. When using a ring resonator with multiple nodes across a wide range of frequencies, the capacitance of the gap coupled area will vary with a change in frequency. Unless the frequency dependent gap capacitance is accounted for, it can affect the accuracy of Dk calculations. If field-solving software is used for the Dk extraction, the frequency dependent gap capacitance can be accounted for. But when using the basic equations of Figure 4 to determine Dk, the frequency dependent gap capacitance will have some bearing on the accuracy of the Dk calculations.

The actual extraction for the Dk of the MUT uses the effective dielectric constant, Dk_{eff} shown in figure 4. With accurate circuit dimensions, a field solver software can be used to find what Dk value of the material will cause the field solving softwares' effective dielectric constant to match the RF measurement of effective dielectric constant. This can also be done using closed form equations. However, the accuracy is typically not as good as the field solver solution.

Variations resulting from circuit fabrication processes are also causes of concern for achieving high accuracy when determining material Dk when using gap coupled ring resonator circuits. For example, for circuits with plated through holes (PTHs), the copper plating thickness will vary from circuit to circuit, and these variations can affect the gap coupled capacitance. For circuits with thicker plated copper (or taller sidewalls for the gap coupling), more electric fields are coupled into air in the gap region, resulting in a lower effective Dk. When the plated copper is thinner, where there is less electric fields coupled in air around the gap region, the perceived Dk will be higher for the same circuit design.

Trapezoidal effects can influence the gap capacitance of a gap coupled ring resonator, and the effects can vary significantly from one circuit to another of the same design. The trapezoidal effects of circuit conductors result from normal circuit fabrication processes, where conductors typically thought of as rectangular in shape are trapezoidal in shape. The trapezoidal shape causes the EM fields to condense lower on the coupled sidewalls of the gap and alter the gap capacitance and the value of Dk extracted for the MUT.

Another circuit fabrication step that can affect the accuracy of a Dk extraction has to do with plated finish. A plated finish protects a circuit's conductors from rust and environmental effects but can increase conductor loss and may affect phase response [7]. Electroless nickel immersion gold (ENIG) is an example of a very good final plated finish. It provides protection but also increases conductor insertion loss and alters the phase response of a circuit. The application of ENIG does have normal thickness variation for the nickel layer and that layer can impact the capacitance in the gap coupled area, which could affect the Dk extraction accuracy. Figure 5 shows two microstrip gap coupled ring resonator circuits built on the same sheet of material, with the same PCB process. The only difference was the thickness of the nickel applied for the ENIG finish.

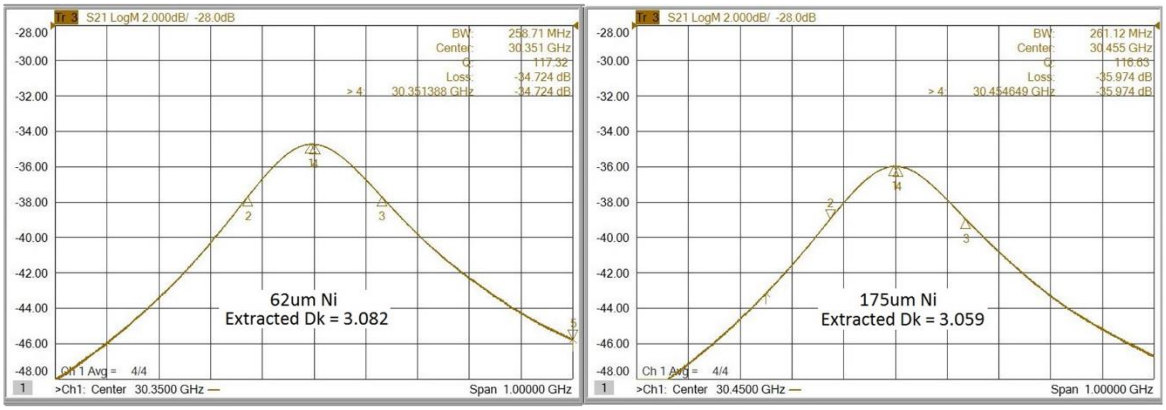
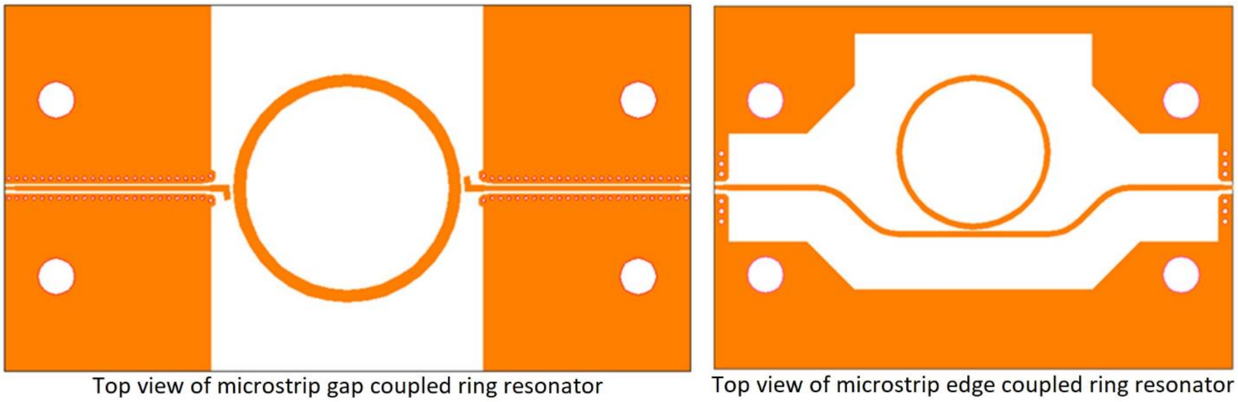


Figure 5. Extraction errors when determining Dk can take place as a result of differences in nickel plating thickness, with a lower frequency resonant peak occurring on the left with thinner ENIG plating.

The calculated difference in Dk between the resonant peaks for the two gap coupled ring oscillators in Figure 5 is 0.023. That is solely due to variations in nickel plating thickness, since the two resonator circuits were built on the same sheet of circuit material and fabricated with the same PCB process at the same time. The difference between the resonators is the ENIG finish: when it was applied, one resonator received a thin nickel plating and the other a thicker nickel plating, within a range of nickel-plating thickness considered typical.

Different design methodologies can be used for implementing ring resonators, although one design approach may be less affected by PCB fabrication process variations than another. Such is the case with a standard gap coupled ring resonator versus an edge coupled ring resonator, which is less impacted by PCB fabrication process variations (Figures 6 and 7).


Top view of microstrip gap coupled ring resonator

Top view of microstrip edge coupled ring resonator

Figure 6. Microstrip ring resonators can be implemented as gap coupled (left) and edge coupled (right) designs

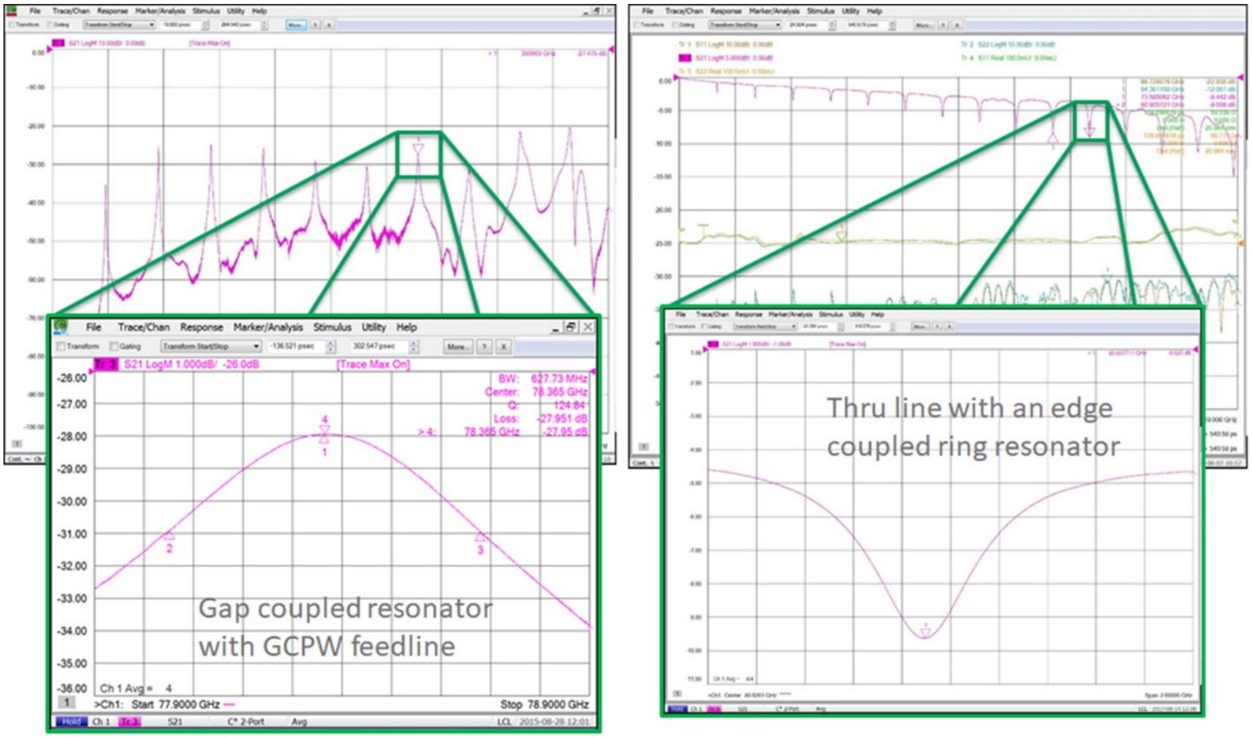
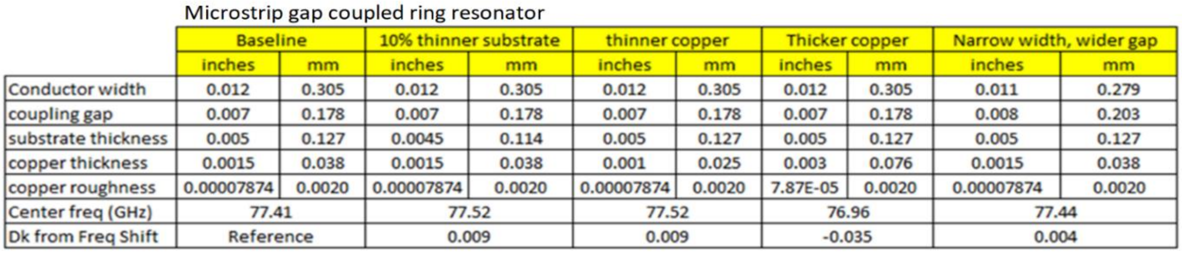


Figure 7. Screen shots of the insertion loss behavior for the two different ring resonators

The ring resonator on the left-hand side of Figure 6 is designed for use at millimeter-wave (mmWave) frequencies. The feedlines are open ended structures that can have their own resonance which can interfere with the resonance of the ring. The resonator on the left-hand side of Figure 6 features grounded coplanar waveguide (GCPW) feedlines and, when properly designed, the open-ended resonances can be suppressed. The ring resonator on the left is a gap coupled ring resonator, but with GCPW feedline. The ring resonator on the right-hand side of Figure 6 is basically a microstrip transmission line circuit with a ring resonator in very close proximity of the through-line. At the frequencies where the ring will naturally resonate, the normal insertion loss curve will have a dip or a "suck-out" where the ring resonator will draw energy off the through-line at that specific frequency.

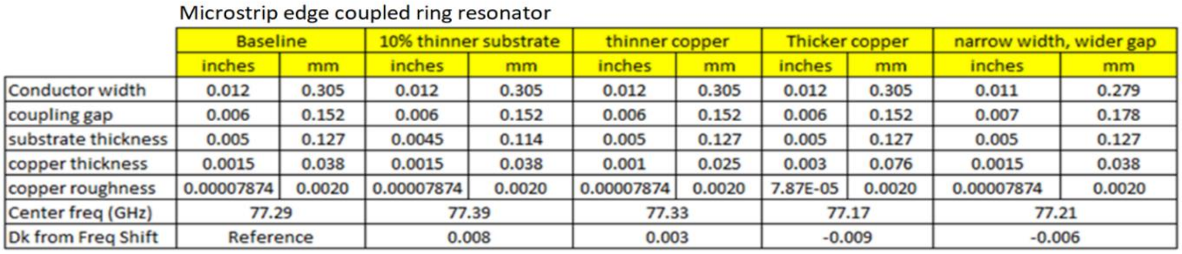
Figure 7 shows the wideband insertion loss responses for the two ring resonators as well as more narrowband responses for each resonator. When the resonator circuits were modeled, the microstrip edge coupled resonator was less affected in RF performance by PCB fabrication variables than the microstrip gap coupled ring resonator. The modeled comparisons are shown in Table 1.

Table 1. This comparison of two types of modeled microstrip ring resonators shows how they are affected by PCB fabrication variables.



Microstrip gap 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	



Microstrip 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	

The data in Table 1 is from models using EM simulation software from Sonnet Software [8]. The circuit material was the same for all models, a low-loss ceramic filled PTFE substrate with no woven glass reinforcement commonly used for 77 GHz automotive radar applications. The first column in Table 1 is the baseline model or reference for the other models. Variations in the other models are based on expected real world variations. The last column presents data for variations in feedline conductor width. These variations impact the conductor width of the ring resonator itself and the gap between the ring and the feedline or the gap between the ring and the through line. A narrower conductor results in a wider gap. As the data in Table 1 show, the microstrip edge coupled ring resonator exhibits less shift in Dk with variations in the model than the microstrip gap coupled ring resonator.

Measuring Material Df

Material Df is difficult to measure accurately especially at higher frequencies. When using a ring resonator to measure Df, it is necessary to use the measured quality factor (Q) or bandwidth to determine the overall losses of the material. As Figure 2 shows, the dielectric Q of the material, Q_d , is related to the Df and can be determined from measurements of the unloaded quality factor, Q_u. However, when using a ring resonator to determine a circuit material's Df, the copper surface roughness of the circuit material can have an impact on the quality factor of the conductors, Q_c . Many models [9] are available to extract the effects of conductor loss due to the copper surface roughness, although they offer varying degrees of accuracy.

The effects of radiation, represented by Q_R which is not mentioned in Figure 2 because stripline structures typically do not have this effect, can also have an impact on Df determinations made with ring resonators. Although ring resonators are not expected to suffer from radiation effects, they can radiate at mmWave frequencies. Even if the main ring doesn't radiate, the circuit's gap coupling may radiate at mmWave frequencies, leading to errors in Df calculations based on measurements with ring resonators. At mmWave frequencies, circuits need to be thinner to avoid unwanted resonances and spurious wave propagation modes, although thinner circuits are more sensitive to copper surface roughness effects and loose coupling can be more difficult to obtain with a thinner circuit. If the coupling is not loose, the measured Q is not necessarily the Q_U required for determination of material Df, and the accuracy of the overall test setup will be more influenced by connectors, cables, and calibration.

In short, different material measurement approaches can yield different results for essential circuit material parameters, such as Dk and Df. Measurements can be made using raw material tests on materials with no conductive layers as well as circuit-based tests using basic circuits, such as transmission lines or resonators, fabricated on a MUT. But because test approaches are different, and employ different structures made differently, they have different variables affecting measurement accuracy resulting in different values of Dk for the same material.

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