5G/mmWave Materials Assessment and Characterization Project

Report 1: Benchmark Current Industry Best Practices for Low Loss Measurements

November 2020
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1. Introduction

Circuit designers urgently need dielectric properties data for materials at millimeter-wave (mmWave) frequencies to optimize device performance of new 5G hardware and for quality assurance. Unfortunately, there are no standard reference materials or even agreed upon characterization test methods for materials at mmWaves. Without reliable mmWave materials data, manufacturers are forced to extrapolate materials data from low frequencies to high frequencies, which can lead to mistakes that have potentially devastating costs.

In response, iNEMI members organized the 5G/mmWave Materials Assessment and Characterization project to develop guidelines and best practices for a standardized measurement and test methodology that can be shared with industry and relevant standards organizations. The initial focus is to benchmark current available test methods and provide pro/con analysis, identify gaps (if any) for extending test methods to 5G/mmWave frequencies, and develop reliable reference standard materials for setup and calibration.

There are two tasks for the benchmarking phase. Task 1 (presented in this report) introduces some of industry’s ‘go-to’ measurement techniques with a narrowed scope focused on materials for 5G, scalable measurements with high reproducibility, and relevant sample sizes (Figure 1). Other impacts include materials characterization for automotive radar applications, which overlaps some 5G bands. Task 2 (to be presented in Report 2) introduces emerging test methods that are poised to be relevant in the near future.

This Task 1 report discusses the following measurement techniques: rectangular cavity resonator (RCR), split-post dielectric resonator (SPDR), split cylinder resonator (SCR), balanced circular disk resonator (SCR), and Fabry-Perot open resonator (FPOR).
Low loss materials are increasingly relevant for mmWave 5G. The licensed bands are around 24 GHz and 38 GHz, with unlicensed bands around 40 GHz, 45 GHz, 70 GHz, and 82 GHz. All have slightly different bandwidths. The various cavity techniques have different limits for the lowest ‘resolvable’ loss tangents because of the amount of intrinsic losses in the cavity (metal losses, dielectric losses, leakages, etc.). They have different maximum resolvable loss tangents because of the maximum allowed perturbation.

The scope of this document is to:

1) Survey mmWave materials characterization (Section 4)
2) Discuss standard reference materials (Section 5)
3) Outline best practices (Section 6)
4) Discuss the dominant sources of uncertainty (Section 7)

1.1. Materials characterization techniques

This section introduces the different mmWave materials characterization techniques discussed in this document, which will be expanded in later sections.

When it comes to dielectric materials characterization, manufacturers routinely rely on cavity perturbation for ‘right,’ ‘easy,’ and ‘fast’ measurements. However, the dimensions of the cavity are inversely proportional to the resonance frequency used to measure a material’s dielectric response. As 5G technologies push toward higher frequencies, the dimensions of the cavity and the sample size (especially the thickness) must shrink, which increases the fractional uncertainties and sensitivity to measurement error.

Each new material for mmWave 5G applications requires careful consideration to determine the best measurement methodology, fixture, sample fabrication and test instrument. There are dozens of different methodologies that could be used, but which to choose is often not obvious. Table 1 summarizes a comparison of different ‘go-to’ techniques. The table is not intended to be exhaustive or overly detailed. It is a high-level overview of common measurement techniques.
### Table 1. Comparison of Common Material Measurement Techniques

<table>
<thead>
<tr>
<th>Technique</th>
<th>Frequency</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Task 1</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(SPDR)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Split cylinder resonator (SCR)</td>
<td>Discrete frequency points from 10 GHz up to 80 GHz</td>
<td>● High measurement precision&lt;br&gt;● Can be sensitive to many user errors&lt;br&gt;● Typically interpolated to 5G mmWaves&lt;br&gt;● Typically in-plane component of permittivity&lt;br&gt;● Typical sample thicknesses around 100 um&lt;br&gt;● Support temperature sweep measurement&lt;br&gt;● IPC-TM-650 2.5.5.13&lt;br&gt;● <a href="https://www.keysight.com/us/en/assets/7018-06384/brochures/5992-3438.pdf">https://www.keysight.com/us/en/assets/7018-06384/brochures/5992-3438.pdf</a></td>
</tr>
<tr>
<td>Balanced-type circular disk</td>
<td>Multiple discrete frequency points from 10 GHz up to 120 GHz</td>
<td>● High measurement precision&lt;br&gt;● Requires full 2-port calibration (mechanical to 110 GHz or electrical to 67 GHz)&lt;br&gt;● Typically out-of-plane component of permittivity&lt;br&gt;● Typical sample thicknesses less than 1 mm&lt;br&gt;● IEC 63185&lt;br&gt;● <a href="https://www.qwed.com.pl/resonators.html#ResonatorFPOR">https://www.qwed.com.pl/resonators.html#ResonatorFPOR</a> &lt;br&gt;● <a href="https://www.keysight.com/main/editorial.jspx?cc=US&amp;lc=eng&amp;ckey=2276755&amp;nid=null&amp;id=2276755">https://www.keysight.com/main/editorial.jspx?cc=US&amp;lc=eng&amp;ckey=2276755&amp;nid=null&amp;id=2276755</a></td>
</tr>
<tr>
<td>resonator (BCDR)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(FPOR, also called open-cavity)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technique</td>
<td>Frequency</td>
<td>Features</td>
</tr>
<tr>
<td>-----------</td>
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</tr>
</tbody>
</table>
| Coplanar waveguide (CPW) | Continuous frequencies between 1 kHz up to 1000 GHz | ● Moderate measurement precision  
    ● User-selected frequency points  
    ● Can be hard to use  
    ● Can be sensitive to user errors  
    ● Requires microfabrication and multiple measurements  
    ● Uncertainty typically decreases with increasing frequency  
    ● Typically in-plane component of permittivity  
| On-chip resonators | Discrete frequencies between 1 GHz up to 50 GHz | ● Moderate measurement precision.  
    ● Can be hard to use  
    ● Can be sensitive to user errors  
    ● Requires microfabrication and multiple measurements |

**Common quality assurance tools used for permittivity estimation**

<table>
<thead>
<tr>
<th>Technique</th>
<th>Frequency</th>
<th>Features</th>
</tr>
</thead>
</table>
| Stripline, Bereskin, or other transmission line methods | Continuous frequencies between 1 GHz up to 1000 GHz | ● Moderate measurement precision  
    ● User-selected frequency points at continuous frequencies between 1 kHz up to 67 GHz  
    ● Recommended for quality assurance rather than permittivity measurements  
    ● Typically not compatible with standard reference materials certified by national metrology institutes  
    ● [https://www.ipc.org/TM/2-5_2-5-5-5.pdf](https://www.ipc.org/TM/2-5_2-5-5-5.pdf) |

### 2. Problem Statement

Many of the commercial implementations of mmWave technologies involve planar transmission lines and distributed element structures fabricated on high density interconnect (HDI) board or organic package technologies. The iNEMI 5G/mmWave Materials Assessment and Characterization project addresses the characterization of these materials. The geometries of these devices create unique characterization challenges that differ from more traditional ‘bulk’ characterization methods. Many of the methods described in literature utilize large 3-dimensional material samples that are capable of being precisely machined to fit into test fixtures. This form factor is generally not the case with the materials that are the focus of this iNEMI effort.

The material sets generally used to fabricate HDI and organic package substrates are provided as either curable liquids or curable thin film sheets. Often the materials’ electrical characteristics are dependent on the details of the curing process. Because of this, large, thick, machinable
material samples are generally not available and any suitable metrology has to be able to work with thin (10 um - 250 um) sheets that are frequently fragile, flexible, and brittle. Furthermore, the thickness uniformity of these samples may not be ideal and metrologies that can tolerate or incorporate non-uniformity of the samples into the measurement may have advantages.

Many of the techniques used for material characterization heavily rely on knowledge of the sample thickness. Although the typical samples available are not generally soft, they are frequently compliant under pressure. Contact thickness measurements like hand-held micrometers can lead to significant measurement errors due to operator mistakes, particularly for more compliant materials.

Table 2 contains a list of example materials used in organic packaging and HDI board industries along with sample characteristics. Because of the lack of easy-to-use metrologies for mmWave frequencies, the electrical data in this table was collected using a split-post dielectric resonator (SPDR) at 10 GHz, and extrapolated with a Debye model to 50 GHz as described in [1], [2].

Standards organizations typically quantify the performance of a metrology against traceable dimensional standards and perform detailed error analyses of the physical measurement equipment. This is not practical for most industrial users. A common practice in industry to assess the performance of a metrology involves examining measurement outcomes of reference standard samples across operators and measurement sessions. This process is sometimes referred to as a metrology capability analysis (MCA). A typical MCA involves a single operator measuring a reference material many times in one measurement session and comparing the average of that data against the known value of one or more reference standards. This quantifies the accuracy of the metrology and, by examining the standard deviation of those measurements, the best case precision or repeatability of the metrology is assessed.

Finally, the sample(s) are measured by 3 operators over the span of 3 days to assess the reproducibility of the metrology. During the reproducibility measurements each operator on each day assembles the metrology equipment, performs any needed calibrations or adjustments and measures the test sample(s). In this way, all of the dynamic ‘real world’ variations that would occur during actual use are included in the data. The variation between operators and between days can then be studied to understand, quantify and potentially improve the metrology performance. Frequently, the results from such a study are reported in terms of standard deviations of measurement quantities, and repeatability and reproducibility are documented as separate qualities of the metrology. It is also common to see these quantified as 3 times the standard deviation divided by the mean value of the data as this leads to a value in percentage that is easy to communicate and remember. For example, if the standard deviation of a set of reproducibility data is 0.05 and the mean value is 4, this is sometimes reported as a reproducibility of 3.75%.

For the SPDR metrology at 10 GHz, multi-day, multi-operator reproducibility studies have shown that with well controlled procedures this can be a highly reproducible technique. For example, assuming a stable sample thickness measurement, standard deviations of 0.02 and 0.0004 for permittivity and loss tangent, respectively, for these types of materials can be achieved. Single operator, single day repeatability almost 10x better can be shown. When sample thickness measurement variability is included the reproducibility is dramatically worsened, particularly for
thin samples, resulting in overall standard deviations that can be an order of magnitude higher, highlighting the importance of robust thickness measurements. Due to lack of accuracy standards, the accuracy of these data, with the exception of the Rexolite reference material, is unknown.

Additional difficulties of permittivity measurement at mmWave include:

- DK/DF over temperature (and humidity)
- Continuous frequency measurement (since most available solutions are resonant methods)
- One material under test (MUT) preparation for various fixtures (cavities, resonators)
- The measured results are different from standard methods (fixtures, cavities, resonators)

Table 2. Industry Samples of Typical Materials Used for 5G (Task 1)

<table>
<thead>
<tr>
<th>Material type</th>
<th>Available sample thickness</th>
<th>Typical use thickness</th>
<th>Isotropic</th>
<th>Dielectric constant 10 GHz/50 GHz*</th>
<th>Loss tangents 10 GHz/50 GHz*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Build-up material A</td>
<td>100 um</td>
<td>25 um</td>
<td>Yes</td>
<td>3.71 / 3.67</td>
<td>0.0106 / 0.0106</td>
</tr>
<tr>
<td>Build-up material B</td>
<td>100 um</td>
<td>25 um</td>
<td>Yes</td>
<td>3.43 / 3.42</td>
<td>0.0043 / 0.0043</td>
</tr>
<tr>
<td>Package core material</td>
<td>200 um</td>
<td>100 um</td>
<td>No</td>
<td>4.19 / 4.14</td>
<td>0.0080 / 0.0081</td>
</tr>
<tr>
<td>Solder resist, dry 25C</td>
<td>50 um</td>
<td>20 um</td>
<td>Yes</td>
<td>3.48 / 3.40</td>
<td>0.0224 / 0.0228</td>
</tr>
<tr>
<td>Solder resist, dry 90C</td>
<td>50 um</td>
<td>20 um</td>
<td>Yes</td>
<td>3.57 / 3.41</td>
<td>0.0327 / 0.337</td>
</tr>
<tr>
<td>Mold</td>
<td>450 um</td>
<td>200 um</td>
<td>Yes</td>
<td>3.80 / 3.75</td>
<td>0.0117 / 0.0117</td>
</tr>
<tr>
<td>Die underfill</td>
<td>50 um</td>
<td>50 um</td>
<td>Yes</td>
<td>3.42 / 3.39</td>
<td>0.0096 / 0.0096</td>
</tr>
<tr>
<td>HDI RF material</td>
<td>200 um</td>
<td>30 um</td>
<td>Yes</td>
<td>3.55 / 3.54</td>
<td>0.0023 / 0.0023</td>
</tr>
<tr>
<td>Rexolite reference material</td>
<td>750 um</td>
<td>-</td>
<td>Yes</td>
<td>2.534</td>
<td>0.00046</td>
</tr>
</tbody>
</table>

*50 GHz extrapolated using Debye model
3. Scope

There are several dozens of ways to measure permittivity and loss tangents for dielectric materials, each with its own trade-offs, features, advantages, and disadvantages. It is not our intention for this report to be exhaustive nor to include every measurement technique available in the industry or laboratories. Rather, the scope of this document is to benchmark some of the most common techniques. When selecting what should and should not be included, we decided to narrow the scope based on the following criteria:

1) Must be commercially available, because all participants must have the ability to measure the proposed materials for their own use should they choose to.

2) Must have a traceability path to a standard reference material, which extends only for the techniques discussed in this document rather than to what participants use.

3) Must be relevant for materials with loss tangents less than 0.01 and permittivity less than 10.

4) Must be relevant to 5G mmWave.

We relaxed these criteria for the singular case of split-post dielectric resonators. This technique is ubiquitous in industry and often the ‘go-to’ technique for many commercial labs. Its prevalence and clear traceability path make it relevant for this program's activities. Cross-validation with low frequency measurements seemed logical, since many labs use extrapolation to obtain mmWave properties. Importantly, all the techniques discussed herein provide average materials properties integrated over the sample-under-test based on the mode structure of the electric field in the sample, rather than local material properties.

The following sections describe the basic working principles behind most of the techniques, how they work, and how the theory connects the things we measure to the material properties we want. We also describe specific details about each of the selected measurement techniques. We provide a schematic of the measurement technique, a photograph of a commercial instrument, a graph of how the fields interact with the sample, and a figure that shows step-by-step how to measure a sample.

4. Extended Summary of Common Test Methods

This section expands on a handful of ‘go-to’ techniques in more detail. These are: split-post dielectric resonators, split cylinder resonators, balanced-type circular disk resonators, and Fabry Perot open resonators. Many of these methods share common features, a general use, and basic theory. In the next section, we discuss the common features, math, and usage. Following this broad overview, we discuss some of the key differences, providing images of instruments commonplace in industry, field patterns, and any other key differences that require additional explanation.
4.1 Common features

Most of the ‘go-to’ techniques are variants of a measurement technique called ‘cavity perturbation’ [3]. Developed in the 1940s [4], cavity perturbation is perhaps the most widely used materials characterization technique. It's widely used because it can be ‘easy’ to perform, ‘fast’ to measure samples, and often produces the ‘right’ value for the dielectric properties.

In the earliest instantiations of cavity perturbation, the working principle was very simple [4]. To start, consider a simple cavity with metal walls. For example, a metal box of any shape is a cavity. This cavity has a resonance frequency where an incident electromagnetic wave creates a standing wave that does not vary spatially but does vary as a function of time.

At this resonance frequency, the transmission through the cavity is maximum and the relative phase shift between the incident and transmitted wave is zero [5]. The resulting frequency dependence of the transmission is often approximated by a damped harmonic oscillator, which is parameterized by a resonance frequency and quality factor. If the shape of the cavity is simple, like a cylinder or rectangle, then electromagnetic fields, standing waves, resonance frequencies, and quality factors are calculable by analytical expressions.

![Figure 2. Prototypical transmission through a resonant cavity.](image)

In Figure 2, the transmission (left) peaks at the resonance frequency and then decreases to either side. The phase (right) goes from a 90 degree phase shift through zero at resonance and then to -90 degrees above resonances. The thin line is a fit to a damped harmonic oscillator. Quality (Q-) factor is either directly computed from the fit or approximated by a three-point technique. The three-point technique computes the 3 dB bandwidth around the resonance frequency and takes the ratio of the resonance frequency to the bandwidth.
Measuring a material’s permittivity amounts to cutting a hole in the cavity and inserting a sample into the cavity to cause a small change or perturbation in the resonance frequency and quality factor. Bethe and Schwinger (with Slater and others coming later) are perhaps the first to relate this perturbation to the electrical properties of the material inserted into the cavity [4]. We include this derivation only to give insight into how the measurands relate to the desired materials properties.

Subsequent advancements made at NIST and other institutions used mode-matching techniques to attain more analytical expressions for complex permittivity, which accounted for perturbations of the complex electromagnetic field due to the introduction of the sample into the cavity and sample slot in the metal side walls. While an important distinction, providing a complete description mode-matching is beyond the scope of this document.

Figure 3 shows how the peak in the transmission (right) without a sample moves to the left when a sample perturbs the field. The thin line is a fit to a damped harmonic oscillator. Quality (Q-) factor is either directly computed from the fit, or approximated by a three-point technique. The three-point technique computes the 3 dB bandwidth around the resonance frequency and takes the ratio of the resonance frequency to the bandwidth.

4.2 General procedure
The following general procedure outlines how to measure cavity perturbation. Our intent is to clearly communicate how the measurements are performed and what steps are involved to complete the measurements.

- Step 1: Connect the cavity to a network analyzer.
- Step 2: Measure S-parameters of the empty cavity.
• Step 3: For the empty cavity, compute the resonance frequency and quality factor either by fitting or three-point techniques.

• Step 4: Insert sample-under-test.

• Step 5: Measure S-parameters of the cavity with the sample-under-test.

• Step 6: For the cavity with the sample-under-test, compute the resonance frequency and quality factor either by fitting or three-point techniques.

• Step 7: Either by means of analytical expressions, vendor software, or numerical computations, compute the permittivity of the sample using Steps 2 (or 3), Steps 5 (or 6), and the sample geometry.

4.3 Methods for computing permittivity from the measurement

Most treatments of cavity perturbation start with the Slater Perturbation Theorem [6]. Slater’s equation is often written as follows

\[ \frac{\bar{\omega}_c - \bar{\omega}_{cs}}{\bar{\omega}_c} = \frac{\int_{V_c} [(\vec{E}_c \cdot \vec{D}_s - \vec{E}_s \cdot \vec{D}_c) - (\vec{H}_c \cdot \vec{B}_s - \vec{H}_s \cdot \vec{B}_c)]dV}{\int_{V_c} (\vec{E}_c \cdot \vec{D}_c - \vec{H}_c \cdot \vec{B}_c)dV} \]

In this equation, the subscript ‘c’ indicates the unperturbed cavity and the subscript ‘cs’ indicates the unperturbed cavity with a sample. The other variables in the equation are the electric field \( E \), the displacement field \( D \), and the angular resonance \( \omega \). For a nonmagnetic material, Slater’s equation simplifies to

\[ \frac{\omega_c - \omega_{cs}}{\omega_c} = i \left( \frac{1}{2Q_{cs}} - \frac{1}{2Q_c} \right) \frac{\int_{V_c} [(\vec{E}_s \cdot \vec{D}_c - \vec{E}_c \cdot \vec{D}_s)]dV}{2 \int_{V_c} |\vec{E}_c|^2 dV} \]

Here, we expanded the left side to explicitly show how the quality factor and resonance frequency are treated in this expression.

While the above expression is exact, there are numerous publications in the literature where one neglects the perturbation on the field structure due to the presence of the sample. In this approximation, the electric field distribution in the sample is approximated as the electric field distribution in the cavity at the region of the sample with a prefactor, relating to the permittivity of the sample. The approximate expression is as follows

\[ \frac{\omega_c - \omega_{cs}}{\omega_c} = i \left( \frac{1}{2Q_{cs}} - \frac{1}{2Q_c} \right) \approx \frac{(\bar{\varepsilon}_s - 1) \int_{V_s} |\vec{E}_c|^2 dV}{2 \int_{V_c} |\vec{E}_c|^2 dV} + \ldots \]

After simplifying the Slater equation to an expression of the electromagnetic field in the cavity, one simply evaluates the integral. Depending on the cavity geometry and field structure, the
The integrand in the numerator typically evaluates to the volume of the sample ($V_s$) and the denominator evaluates to the volume of the cavity.

Manipulating both sides, one obtains expressions for the real and imaginary parts of the permittivity as

\[
\varepsilon_{r,s} \approx \left( \frac{V_c}{2V_s} \right) \left( \frac{\omega_c - \omega_{cs}}{\omega_c} \right) + 1 + \ldots
\]
\[
\varepsilon_{i,s} \approx \left( \frac{V_c}{4V_s} \right) \left( \frac{1}{Q_{cs}} - \frac{1}{Q_c} \right) + \ldots
\]

A note of caution — neither of these expressions is explicitly used in the comparisons here. Rather, for the following resonator-type cases, we use a mode-matching approach that has fewer approximations. Mode-matching resolves several of the approximations here, by exactly computing the electromagnetic fields even in the presence of the sample and the currents near the slot for the sample. This approach remains the most accurate analytical treatment. However, more recent efforts to develop full-wave simulations may prove more accurate as the 3D models may capture small differences in a given cavity dimension that are assumed to be symmetric. These models might improve the accuracy of the cavity perturbation beyond the benchmarks today.

The next sections discuss some of the more commonplace resonator-based measurement techniques. Each section includes the following figure elements: a schematic of the device, a picture of a device, a picture or illustration of the fields, and pictures of usage. They detail any key differences or features that make a given technique unique.

### 4.4 Split-post dielectric resonator

The split-post dielectric resonator (SPDR) device is arguably one of the most widespread and popular dielectric measurement techniques. Prof. J. Kupka developed the most popular instantiation of this widespread tool [7], now under continued development and sold by QWED and Keysight, among others. Noted for its ease of use, reliability, and resilience to user error, the main drawback of this technique is that there are no commercial instruments above 15 GHz. While this technique does not extend to the mmWave bands, it is relevant because industry often relies on it for cross validation, using permittivity models to extrapolate results to mmWaves.

SPDR is almost identical in use to all the other techniques. A metal cavity has two dielectric posts that load the cavity and impose specific mode structure (Figure 4). A sample (purple rectangle) in the cavity perturbs the mode structure, shifting the resonance frequency and decreasing the quality factor.
As shown in Figure 4, the “heart” of the SPDR is two dielectric cylinders or posts (red) separated by a slot, and hence typically considered as one “split-post.” A major part (80-90%) of the electromagnetic energy of the whole resonator is confined in the posts and in the slot between them (see also Figure 5). A metal enclosure (orange) protects the resonating region mechanically and from external electromagnetic interferences. It is important to note that losses in the enclosure are relatively low, compared to other resonating cavities, as fields decay fast in the radial direction away from the dielectrics (Figure 6). A planar sample (purple) is conveniently moved in and out of the resonator through the fixed slot in the enclosure, without any dismantling of the resonator. This is additionally facilitated by the fact that currents in the cylindrical wall are only circumferential, hence the slot does not disturb electric current paths and does not cause radiation. The dielectric posts (red) are mounted to the enclosure by auxiliary supports (blue) made of low permittivity and having a negligible effect on the resonant field pattern. Of crucial importance, however, is ensuring axial symmetry of the complete assembled structure. The sample (purple) should ideally cover the cross-section of the enclosure (as in the picture) though measurements with reduced accuracy can be performed for samples just covering the area between the posts (red).
Figure 5. Photograph of a commercial SPDR unit — top view of the 1000th unit sold by QWED. There are coaxial cables at the input and output. A network analyzer or Q-meter measures the resonance in transmission, which results in a plot similar to the example data shown earlier.

Figure 6. Schematic of the electric and magnetic fields in the SPDR operating in its TE_{01\delta} mode, as obtained with QuickWave-3D software.

In Figure 6, the air-filled cavity interior is marked blue with a split-post dielectric resonator (two dielectric posts) marked in red; the cavity walls are not shown. A planar sample is placed in the slot between the two posts (its geometry is not marked in the picture, so as not to hide the field lines). Both fields (E-field in the left pictures and H-field in the right pictures) are marked with black arrows. They are shown in the sample plane (horizontal section at the half-height of the cavity, upper pictures) and in the vertical section across the cavity diameter (lower).
SPDR devices can be used to determine material parameters. “Loading” the resonator with a material sample causes changes in the resonant frequency and Q-factor of the device. As explained earlier those changes may be directly linked with material parameters (complex permittivity and permeability) of the sample under test (SUT).

Practically, the determination of material properties is performed with the aid of dedicated software using results of rigorous electromagnetic simulation (e.g., Rayleigh-Ritz [8] or BOR FDTD [9] methods) of empty and loaded resonators, relating actual material parameters and sample thickness with changes in resonant frequency and Q-factor of the resonator device.

The material properties extraction is performed in a two-step measurement: the resonant frequency and Q-factor are measured with a vector network analyzer (VNA) or a dedicated scalar analyzer, for an empty resonant device and afterwards, for a device in the presence of a material sample of known thickness. Standard operating procedures ([10] or [7] for SPDRs) must be followed. The differences in the measured parameters serve as an input to the software that converts them to the sought material parameters. Note that such conversion software is typically dedicated to a particular resonator unit, incorporating its calibration upon manufacturing.
4.5 Split cylinder resonator (SCR)

The split cylinder resonator consists of two halves of a cylindrical cavity that face each other to form one complete cylindrical cavity resonator. One measures the permittivity just as in the other cases, simply inserting a sample into the narrow slit between the two halves of the cavity. The sample must be held securely to avoid air gaps that can affect the accuracy of the measurement.

Many SCRs use the TE011 mode resonance to measure permittivity. In many instantiations, the TE011 mode resonance generates a circular electric field in parallel with the sample plane and, therefore, interacts with the permittivity in the plane of the sample. The electric current also flows in the circular direction, which keeps the TE011 resonance intact even when the two halves of the cylinder do not touch electrically.

Just like in the example data, a sample perturbs the resonance of the TE011 mode by shifting the resonance frequency lower and decreasing the quality factor. One then compares the shift in the resonance frequency and quality factors and uses them to estimate the permittivity, as discussed in “Methods for computing permittivity” (Section 4.3 of this document). Either a calculation using theoretical equations or an electromagnetic field simulation provides the complex permittivity values. Here, a correct thickness value of the sample is needed for a correct permittivity value. The sample shape is expected to be a thin film with a thickness of less than several hundred micrometers.

There are few limitations to this technique. The sample dimensions simply need to be known and sufficient to fill the active region of the resonator. Perhaps the greatest limitation, common with all resonator-based techniques, is that the perturbation cannot be too large because it can change the mode structure. This requirement places limits on the loss tangent and permittivity to values typically less than 30 and 0.01, respectively. The loss tangent also cannot be too large because the resonance amplitude becomes too low to be under the noise floor of the measurement instrument. These limitations vary according to the measurement frequency and users are encouraged to consult the vendor.

In many cases, SCR is notoriously tricky to use. However, new products solved some of the sample fixturing issues, making the cavities far more reproducible and user-friendly. One example had easy operation for excellent repeatability and test efficiency regardless of operator skills. The repeatability of the real part of the permittivity was 0.0003 and 0.000003 for the loss tangent.

![Figure 8. Schematic diagram of a split cylinder resonator. The split cylinder resonator is simply two metal cylinders cut in the middle to allow for a sample (green).](image)
Figure 9. Photograph of a commercial split cylinder resonator unit. In this instantiation, a spring-loaded sample fixture (blue springs) ensures easy and repeatable sample loading and unloading. The unit has coax at the input and coax at the output. The cylindrical halves of the cavity are in the copper blocks. The sample is the rectangular sheet in the middle of the sample.

Figure 10. Schematic of the electric fields in the sample for a split cylinder resonator. The field samples the material in the plane of the sample.
4.6 Balanced-type circular disk resonator (BCDR)

Complementing the more commonplace SPDR and SCR techniques is the balanced-type circular disk resonator (BCDR). Early investigations of BCDRs include work by Kawabata and Kobayashi, et al. (2006) [11]. They presented a multi-frequency measurement method for measuring the perpendicular E-field complex permittivity with TM_{0m0} modes of a balanced-type circular disk resonator. In this method, a thin circular conductor disk is sandwiched between two dielectric samples.

The biggest requirement for BCDR is that the dielectric plates must be identical. They also must have the same thickness and smooth surfaces. The technique works by sandwiching the metal disk between the two dielectric plates and inserting the sandwich between two parallel conductor plates, which creates a region where there are multiple standing waves that resonate at different frequencies. Like the cylinder cavities, BCDR has multiple resonances that are transmitted through the mode structure and occur at different harmonics. BCDR is particularly well-suited for high frequency measurements because the maximum measurable frequency is only limited by the coaxial lines used to excite the resonator, the apertures of the excitation holes, and other factors.

Just like in previous examples, the measured values of the resonant frequency and the unloaded Q of the TM_{0m0} modes relates to the complex permittivity of the dielectric plates. Analytical models of the fringing fields and conductor’s relative conductivity account for the additional perturbations on the resonance frequency and quality factor. Recently, Y. Kato and M. Horibe (2016) with AIST Japan presented a BCDR solution that works up to 110 GHz [12], [13].

Figure 11. Step-by-step usage for the split cylinder resonator.
commercial version of their solution exists up to 67GHz (typ. 70 GHz) with 1.85 mm coaxial connector to a network analyzer, and another up to 110 GHz (typ. 120 GHz) with 1.0 mm coaxial connector. M. Horibe et al. (2020) presented the capability to extend the BCDR’s operation frequency up to 170 GHz [14].

Two circular metal disks of slightly different radii can also be utilized with BCDR [15]. Use of two resonators corrects the resonator fringing effects and cancels the conductor losses in calculations improving accuracy.

There are a few features that differentiate BCDR from the other techniques reviewed earlier. One key difference is that it measures out-of-plane material properties rather than in-plane properties. This distinction is because of the electric field direction of the TM$_{0m0}$ mode. Unlike many of the other techniques, it can be used to measure multiple points between 10 GHz to 120 GHz. Like SCR and SPDR, its dimensions can be traced to gage blocks from the National Metrological Institute (NMI), giving it a unique traceability path compared to other multi-frequency techniques. The big trade-off is that this approach requires a 2-port network analyzer, and a calibration kit in order to work. Another trade-off is that one needs two samples that are identical which, in practice, is challenging with non-commercial materials.

This method is under standardization in IEC project 63185 and is expected to be published in November 2020. The standardized method is applicable for the measurements in the frequency area from 10 GHz to 120 GHz for materials with relative permittivity of $\varepsilon_r$ 1.1 to 10 and $\tan \delta$ 10$^{-4}$ to 10$^{-2}$.

In 2020, AIST announced in a news release that they had succeeded in measuring conductivity of metal material up to 120 GHz using a BCDR resonator and known dielectric parameter substrate.
Figure 12. Schematic diagram of a commercial balanced circular disk resonator. The top panel shows a schematic of the entire measurement setup. The bottom left shows a close-up schematic of the setup and how one places a sample into the BCDR system. The BCDR consists of two electrical plates. In between the plates, there is a sandwich of the lower sample-under-test, a dielectric shim with an annulus, a metal disk centered about the annulus, and the upper sample-under-test.

Figure 13. Photograph of a commercial balanced circular disk resonator. This BCDR has a counterweight that maintains uniform pressure on the sandwich of the upper and lower samples-under-test and the centered metal disk placed between the conductor plates (electrodes).
Figure 14. Schematic of the electric fields in the sample. From left to right, the images show the electric field in the plane of the sample as a function of increasing frequency at different harmonic numbers. The lowest order mode, TM010, has a maxima in the middle of the sample and an electric field that monotonically decreases radially from the center to the edge of the sample. Increasing the mode number simply adds nodes in the radial standing wave where the dielectric properties of the material do not influence the mode structure.

Figure 15. Step-by-step usage of BCDR. The images on the top show how the center electrode is aligned to the middle of two identical sample sheets by using a shim sheet. The resonator is then closed and clamped tightly before the measurement.
Figure 16. Example data. The measurable frequency depends on the sample thickness and permittivity of the sample. These examples are from a BCDR using a 15 mm diameter Cu circular disk electrode.
Figure 17. Example data for cyclo olefin polymers (COPs). $\varepsilon''$ (Dk) and loss tangent (Df) are measured at 9 frequency points from 15.7 GHz to 120.5 GHz from samples with 250 um thickness and with a 15 mm diameter Cu electrode.

4.7 Fabry-Perot open resonator (also called open-cavity)

Fabry-Perot open resonator (FPOR) is a unique tool applicable to accurate characterization of materials at microwave and millimeter frequency ranges [16], where alternative techniques (e.g., based on dielectric resonators) fail. The FPOR is usually made of two concave metallic mirrors, so that resonant modes in the form of a Gaussian beam can be excited. Despite the open structure, the Q-factor of well over 200,000 at consecutive Gaussian modes distributed within the frequency spectrum can be achieved in the FPOR. These properties make the FPOR suitable for the characterization of ultra-low loss dielectric materials in a broad frequency spectrum with a very high accuracy and precision. Insertion of the material under test (MUT) inside the FPOR changes both the resonance frequency and the corresponding Q-factor of each mode of interest which, in turn, can be compared against an electromagnetic model of the FPOR in order to determine the unknown dielectric constant and loss tangent of the MUT. Industry has been
aware of this measurement for decades but it has been rarely used until recently because there are several fundamental and technical challenges. However, due to recent progress in addressing these challenges, FPOR techniques are currently being investigated in commercial applications.

Figure 18. Fabry-Perot open resonator for 20-110 GHz automated measurement of low loss dielectrics.

Figure 19. Exemplary dielectric constant of a few samples as measured with the setup shown in Figure 18.
The FPOR solution commercialized by QWED (see Figure 18) [17], [18], [19] has a few features that make it unique among alternative solutions available on the market. First, the whole measurement is fully automated, so really challenging issues, like mode identification and tracking among plenty of other modes occurring in the FPOR, can be done quickly without the need for user intervention. Consequently, characterization of a single sample in the whole 20-110 GHz frequency band with a total of 60 measurement points can be reduced to a few minutes (see Figure 19). To compare, manual measurement with the FPOR, as typically offered by other vendors, requires about an hour per measurement point, which makes the solution impractical in real industrial processes. This is one of the reasons other vendors usually provide exemplary measurement results at just one frequency, although the FPOR is a broadband device. Second, the FPOR is coupled with adjustable coaxial lines, which allows running single-sweep measurements at frequencies spanning from 20 GHz up to 110 GHz. This is different from alternative solutions available on the market, where either waveguide or dielectric coupling is commonly proposed, thus preventing the use of a single FPOR device in the broadband characterization of materials. And last, but not least, the extraction of complex permittivity of a dielectric MUT is made with the aid of a novel electromagnetic model of the FPOR based on conformal transformation, which allows reducing the FPOR’s model to a scalar one-dimensional multilayer problem (see Figure 20) with better accuracy than alternative solutions based on a characteristic equation. Distance between the mirrors is fixed to maintain accuracy of the measurement better than 0.5% in a short time and the resulting frequency resolution is 1.5 GHz. The total number of measurement points is sufficient to account for dispersion of typical dielectric materials.

Figure 20. Exemplary Gaussian beam in the FPOR with two concave mirrors (left) and the corresponding field distribution in the equivalent planar EM model of the FPOR after conformal transformation with planar mirrors (right).

Despite its relatively short history on the market, the FPOR solution commercialized by QWED has already gained significant attention from large worldwide corporations and companies interested in the measurement of dielectrics in microwave and millimeter wave bands. The measurement procedure scheme is presented in Figure 21.
Figure 21. Step-by-step usage for FPOR (measurement time given for analysis in 20-50 GHz band).

4.8 Other techniques primarily used for quality assurance

There are several techniques commonly used in the PCB industry for screening of materials as well as quality assurance. One commonly used method is referenced by IPC and described in the document, “Stripline Test for Permittivity and Loss Tangent (Dielectric Constant and Dissipation Factor) at X-Band” [20]. As stated in the IPC manual, this method is intended for the rapid measurement of the X-band (8.00 to 12.40 GHz) apparent relative stripline permittivity and loss tangent of metal clad substrates. Measurements are made under stripline conditions using a resonant element pattern card, which is separated from the ground planes by sheets of the material to be tested. The test method warns users of multiple limitations, including accuracy and repeatability. The IPC document also says “The method does not lend itself to use of stable referee specimens of known electric properties traceable to the National Institute of Standards and Technology (NIST).” The stripline method was developed by A. Bereskin [21] and uses a stripline configuration with probes contacting the conductor planes. The planes use a “sandwich configuration” of the dielectric under test and a copper conductor as shown in Figure 21.

For anisotropic materials, this test method can give misleading values of effective stripline permittivity and loss tangent.

Since this document primarily focuses on higher frequencies typical of 5G/mmWave, the stripline method is not considered particularly relevant.
“Users are cautioned against assuming the method yields permittivity and loss tangent values that directly correspond to applications. The value of the method is for assuring consistency of product, thus reproducibility of results in fabricated boards.” [20]

5. Standard Reference Materials for Validation and Intercomparison

National metrology institutes, such as NIST in the United States, once produced reference dielectric material; however, these materials are no longer available. With the recent push to mmWaves, there is a need for national metrology institutes (NMIs) to develop and supply new standards reference materials. Furthermore, this effort must be sustained to support the long term evolution of mmWave technology. It is important that industry needs are communicated to the NMIs.
Manufacturers often must extrapolate low frequency data to 5G frequencies when they accept new material from vendors. This extrapolation leads to disagreements between specified values by the vendor and measured values by the manufacturer for high density interconnect (HDI) boards used in every piece of mobile and other communication technologies. For base station manufacturers this problem has the potential to lead to unpredictable performance of deployed hardware.

The lack of traceable reference material for mmWaves is a serious problem. This lack makes verification of measurement methods and laboratory techniques impossible in an industry setting. For the industrial use case, most laboratories rely on internal or external calibration services to ensure that measurement equipment is accurate and to remain compliant with quality management systems such as ISO 9001. International quality systems such as ISO are an intermediate path on a traceability chain that ultimately ends at a national metrology institute.

These calibration laboratories frequently measure traceable standard reference materials and devices with the equipment discussed herein to verify that the equipment produces the expected result within documented tolerances. For resonators used in dielectric measurements, a national metrology institute may argue that physical dimensions can be used to certify the measurement device; however, this is impractical for most industrial use cases, where a standard reference material is requisite for verification and validation. Furthermore, given the complex geometries of some of the equipment used in the most common techniques, it may be impossible outside of the most sophisticated dimensional labs.

Specifically, reference materials fabricated from mechanically, environmentally and electrically stable materials capable of being formed into samples compatible with a variety of common measurement techniques are needed. Ideally, these reference materials would span a range of dielectric constant and loss tangent values and would be characterized across a wide range of frequencies. Candidate materials include cross linked polystyrene (Rexolite®), polytetrafluoroethylene (PTFE/Teflon), cyclo olefin polymers (COP/ Zeonex®), quartz, and alumina. Furthermore, industry needs to support the maintenance of such materials to make long term availability of references practical.

Without a standard reference material spanning 5G frequencies, industry has little suitable choice for validation and verification, none of which are ISO compliant. Perhaps the best alternative for the 5G Materials Characterization project is to select a number of stable material samples and test them at multiple laboratories using different physical equipment. This would lead to a set of physical artifacts, each with a large amount of measurement data, that could be shared within the project team as quasi reference materials.

To accomplish this, the samples should be sized to be compatible with the measurement setups available in each of the participating laboratories. A common procedure describing the handling of the materials should be developed to ensure the samples are not damaged or contaminated. The samples used should be immune to moisture absorption and should be tested to ensure they are of uniform thickness. Further, each laboratory should make the necessary dimensional measurements using the best method available to each laboratory.
Proposed materials, along with relevant characteristics, are shown in Table 3. Enough samples of each material should be tested to enable each participating laboratory to receive and keep one of each of the fully characterized material artifacts at the end of the experiment. Table 3 summarizes several proposed reference materials. All the materials must be available in standard formats (circular or rectangular), which can be machined down to a user’s fixturing needs.

### Table 3. Proposed Standard Reference Material

<table>
<thead>
<tr>
<th>Material type</th>
<th>Approximate thickness</th>
<th>Structure</th>
<th>Approx. Er, Tand</th>
<th>Important notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyclo olefin polymer (COP/Zeonex®)</td>
<td>100 um</td>
<td>Isotropic, homogeneous</td>
<td>2.3, 5e-4</td>
<td>Can degrade with finger oil - avoid handling unless using gloves</td>
</tr>
<tr>
<td>Cross linked polystyrene (Rexolite®)</td>
<td>700 um</td>
<td>Isotropic, homogeneous</td>
<td>2.534, 4.6e-4</td>
<td>Easy to machine, difficult to make flat, stable with temperature and humidity</td>
</tr>
<tr>
<td>PTFE / Teflon®</td>
<td></td>
<td>Isotropic, homogeneous</td>
<td>2.1, 2e-4</td>
<td>Easy to machine</td>
</tr>
<tr>
<td>Fused silica</td>
<td>500 um</td>
<td></td>
<td>3.8 / 1e-4</td>
<td>Easy to machine, preferred by project team</td>
</tr>
<tr>
<td>Sapphire</td>
<td>365 um</td>
<td>Anisotropic (c-plane)</td>
<td>9.4 / 11.6, 5e-5</td>
<td>Hard to machine</td>
</tr>
<tr>
<td>Alumina</td>
<td>100 um</td>
<td>Isotropic, homogeneous</td>
<td>9.8, 1e-4</td>
<td>Easy to machine, preferred by project team</td>
</tr>
</tbody>
</table>

### 6. Practical Problems Impacting Reproducibility

Much of the published literature on high frequency and mmWave dielectric measurements focus on the numerical stability, mathematical extraction methods, and best case accuracy for a given method. These factors are very useful for determining the acceptable ranges of usability for a given technique; however, industrial scale use of these measurement methods adds complications that can significantly reduce the usefulness or accuracy of these techniques. It is important to consider these issues when evaluating a measurement method.

For 5G and mmWave applications, most use cases relevant to this iNEMI effort will involve transmission-like structures fabricated with thin film dielectrics that are not typically available in large, machinable samples. This end use case limits the methods under project review to techniques compatible with films or stacks of films ranging from 10 um to 500 um. It also places an additional hurdle on many of the techniques. Specifically, almost all of the existing techniques require precise knowledge of the film sample thickness, and require the samples to be smooth.
and uniformly thick. Measurement of this thickness necessarily requires a separate step in the measurement process, and that step often requires an operator to collect a physical measurement on the sample in a location chosen by the operator. In some cases, this step can dominate all the errors in extraction of the dielectric material parameters. Further, the compressibility of the sample material can lead to operator or tool dependence in the thickness measurement. Evaluation of a measurement method must include a study of operator independence to assess all the practical implications of a given technique.

In addition to operator independence, for many applications it is desirable to be able to characterize a material over an operating temperature range. Techniques that are inherently incompatible with data collection at reduced or elevated temperatures may be of lower interest for industry. Material behavior under moisture absorption is often a concern for high volume industrial applications. Techniques that are slow or require lengthy procedures may limit a user’s ability to evaluate materials against moisture absorption. For example, one common method for examining the impact of moisture absorption involves soaking test samples in a controlled humidity environment and then quickly collecting dielectric performance data after removing the sample from the environmental chamber. For many thin (< 100 um) substrate materials sufficient moisture absorption or drying can occur over the course of 10 minutes to alter the performance of the material. Hence, methods that allow for samples to be quickly configured in the test equipment, with minimal alignment requirements and speedy data collection are desirable.

7. Sample Preparation and Fixturing

Sample sizes and configurations vary with the device used. For the thin film materials commonly used in HDI and package technologies, only thin sheets of material are typically available. There is little limitation in the availability of sample X-Y size — that is, physically small or large samples can be acquired — however, sample thickness is usually limited to dimensions on the same order as used in practice. Polishing or machining these thin samples is usually not practical. For measurement devices requiring large samples, sample bending and flexure can be a problem. Some measurement systems like the Fabry-Perot resonators require the samples to be held flat vertically or horizontally in the exact center of the cavity. With large flexible samples this can be difficult because the middle region of the sample may bow or warp out of plane, introducing errors and/or limiting repeatability. Often the amount of bowing is difficult to measure, particularly if the samples are thin. For example, a 50 um 100 mm x 100 mm sample could easily bow 100 um against the force of gravity and not be visually obvious. This would place the center of the sample multiple sample thickness out of plane of the edges of the sample. Clamping flexible samples like this in a fixture to hold them taut is a frequently used method to try to overcome this problem; however, with such large samples it can still be a challenge.
Table 4. Techniques and Sample Dimensions

<table>
<thead>
<tr>
<th>Task - 1</th>
<th>Preferred techniques with sample dimensions</th>
<th>Optional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technique</td>
<td>Split cylinder resonator (SCR)</td>
<td>Balanced-type circular disk resonator (BCDR)</td>
</tr>
<tr>
<td>Sample dimensions</td>
<td>20 um ~ 300 um (best for 100 um), 34 mm x 45 mm &gt; 20G</td>
<td>0.1 mm ~ 1 mm, Best for 0.2~0.5 mm, 50 mmΦ x 2 each</td>
</tr>
</tbody>
</table>

8. Summary

mmWave applications have historically been limited to niche and low volume products. With the expansion of 5G technologies this is no longer the case. Applications ranging from mid volume base station infrastructure to extremely high volume consumer devices are already entering the market. For engineers designing these products it is critical to start with correct electrical material models. Past development flows that allowed multiple design iterations for the tuning of mmWave structures are generally not tolerable for these high volume applications because of limited design cycle times. To enable functional designs on the first cycle, fast, easy and accurate methods for characterizing materials at mmWave frequencies are required. This document has summarized a candidate set of techniques that may fulfill industrial requirements for measurement of thin film HDI and package build-up materials for 5G and mmWave applications.

9. References


[20] IPC-TM-650 2.5.5.5: Stripline Test for Permittivity and Loss Tangent (Dielectric Constant and Dissipation Factor) at X-Band. [https://www.ipc.org/TM/2-5_2-5-5-5.pdf](https://www.ipc.org/TM/2-5_2-5-5-5.pdf)

APPENDIX 1 — Contributors

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Georgia Tech  Nokia
ShowaDenko Materials  QWED
IBIDEN Co Ltd  Shengyi Technology Company
IBM  Sheldahl
Intel  Unimicron Technology Corp
Isola  Wistron
ITEQ  Zestron
APPENDIX 2 — Reference to Existing Standard Methods from Other Industry Groups (for \( \geq 10 \) GHz)

**ASTM**

ASTM D2520: Standard Test Methods for Complex Permittivity (Dielectric Constant) of Solid Electrical Insulating Materials at Microwave Frequencies and Temperatures to 1650\(^{\circ}\)C.  
[https://www.astm.org/Standards/D2520.htm](https://www.astm.org/Standards/D2520.htm)

- Microwave Dielectric Measurement System: TM mode Cavity Resonator (AET Inc). This method is compliant with ASTM D2520  

ASTM D3380: Standard Test Method for Relative Permittivity (Dielectric Constant) and Dissipation Factor of Polymer-Based Microwave Circuit Substrates  

**GB/T**


- Precise Measurement of Low Loss Dielectric Materials Using Quasi-optical cavity Technique  

- Open resonator technique for measuring multi-layer dielectrics  

**IEC**

IEC 63185: Balanced-type circular disk resonator method to measure the complex permittivity of low-loss dielectric substrates.  

[https://webstore.iec.ch/publication/22343](https://webstore.iec.ch/publication/22343)
IPC

IPC-TM-650 2.5.5.13: Relative Permittivity and Loss Tangent Using a Split-Cylinder Resonator

IPC-TM-650 2.5.5.5: Stripline Test for Permittivity and Loss Tangent (Dielectric Constant and Dissipation Factor) at X-Band. https://www.ipc.org/TM/2-5_2-5-5-5.pdf

IPC-TM-650 2.5.5.5.1: Stripline Test for Complex Relative Permittivity of Circuit Board Materials to 14 GHz. https://www.ipc.org/TM/2-5_2-5-5-5-1.pdf

JIS

JIS C 2565: Measuring methods for ferrite cores for microwave device.
https://global.ihs.com/doc_detail.cfm?document_name=JIS%20C%202565&item_s_key=00269091

- Microwave Dielectric Measurement System: TM mode Cavity Resonator (AET Inc).
  This method is compliant with JIS C 2565

JIS R 1660-2: Measurement method for dielectric properties of fine ceramics in millimeter wave frequency range -- Part 2: Open resonator method.
https://standards.globalspec.com/std/1358824/JIS%20R%201660-2


Other/Miscellaneous

Resonance Method Strip Line Type Dielectric Constant and Dielectric Loss Tangent (Dk/Df) Measurement System for Sheet [Films, Sheet, Dk, Df, εᵣ', tanδ] Model No. DPS50
https://www.keycom.co.jp/eproducts/dps/dps50/page.html

World Leading High-Accurate Dk/Df Measurement System, PCB Measurement, 900 MHz – 15 GHz — Highly accurate in dielectric loss tangent (tanδ) measurement and requires no conductor pattern; Optimum solution for thin film measurement
https://www.keysight.com/main/editorial.jspx?cc=TW&lc=cht&ckey=2309245&nid=-11143.0.00&id=2309245

Resonance method micro strip line type for sheet and ultra thin sheet dielectric constant and dielectric loss tangent measurement system (Dk/Df) Model No. DPS01
https://keycom.co.jp/eproducts/dps/dps1/page.html
## APPENDIX 3 — Glossary

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>BCDR</td>
<td>Balanced-type circular disk resonator</td>
</tr>
<tr>
<td>COP</td>
<td>Cyclo olefin polymers</td>
</tr>
<tr>
<td>EM</td>
<td>Electro-magnetic</td>
</tr>
<tr>
<td>FPOR</td>
<td>Febry-Perot open resonator (also called open cavity)</td>
</tr>
<tr>
<td>HDI</td>
<td>High density interconnect — a printed circuit board technology that</td>
</tr>
<tr>
<td></td>
<td>generally provides finer feature definition, thinner layers and smaller,</td>
</tr>
<tr>
<td></td>
<td>often laser drilled, via sizes compared to traditional PCB technologies</td>
</tr>
<tr>
<td>MCA</td>
<td>Metrology capability analysis</td>
</tr>
<tr>
<td>MUT</td>
<td>Material under test</td>
</tr>
<tr>
<td>NMI</td>
<td>National metrology institute</td>
</tr>
<tr>
<td>SCR</td>
<td>Split cylinder resonator</td>
</tr>
<tr>
<td>SPDR</td>
<td>Split-post dielectric resonator</td>
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<tr>
<td>SUT</td>
<td>Sample under test</td>
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<tr>
<td>VNA</td>
<td>Vector network analysis</td>
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