# iNEMI-IMAPS
# Benchmarking Resonator Based Low $d_K$-$d_F$ Material Measurements

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# Industry Collaboration Brought Together by iNEMI

- This session will provide 5 presentations outlining the status of the benchmarking phase as shown in the paper titles below

| | Title | Author(s) |
|---|---|---|
| **Paper 1** | Challenges for High Dk/Df measurements | Urmi Ray, iNEMI<br>Urmi.ray@inemi.org |
| **Paper 2** | Benchmarking resonator based low dk/df material measurements | Richard Stephenson<br>richard.stephenson@emdgroup.com |
| **Paper 3** | Recent developments of resonator measurements for emerging materials and technologies | Małgorzata Celuch, QWED<br>mceluch@qwed.eu<br>Marzena Olszewska-Placha<br>molszewska@qwed.com.pl |
| **Paper 4** | High Frequency measurements using wafer level techniques | Nathan Orloff, NIST<br>nathan.orloff@nist.gov |
| **Paper 5** | Optimizing Measurement accuracy and repeatability for high frequency measurements | Say Phommakesone,<br>say_phommakesone@keysight.com;<br>Daisuke Kato , daisuke-kobe_kato@keysight.com;<br>Keysight |





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# Agenda

- Benchmarking “current resonators”
- Benchmarking “emerging techniques”
- Next steps

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# Project Goals

- Gather industry experts to understand needs and try to address these problems
- Encourage development of traceable material references by standards organizations
- Better linkage between equipment manufacturers and end users

### Task 1

Benchmark
- Current techniques
- Typical material samples
- Potential reference materials
- Common practices & issues

Report complete

### Task 2

Benchmark
- Emerging techniques
- Possibilities beyond 100GHz

Report complete

### Task 3

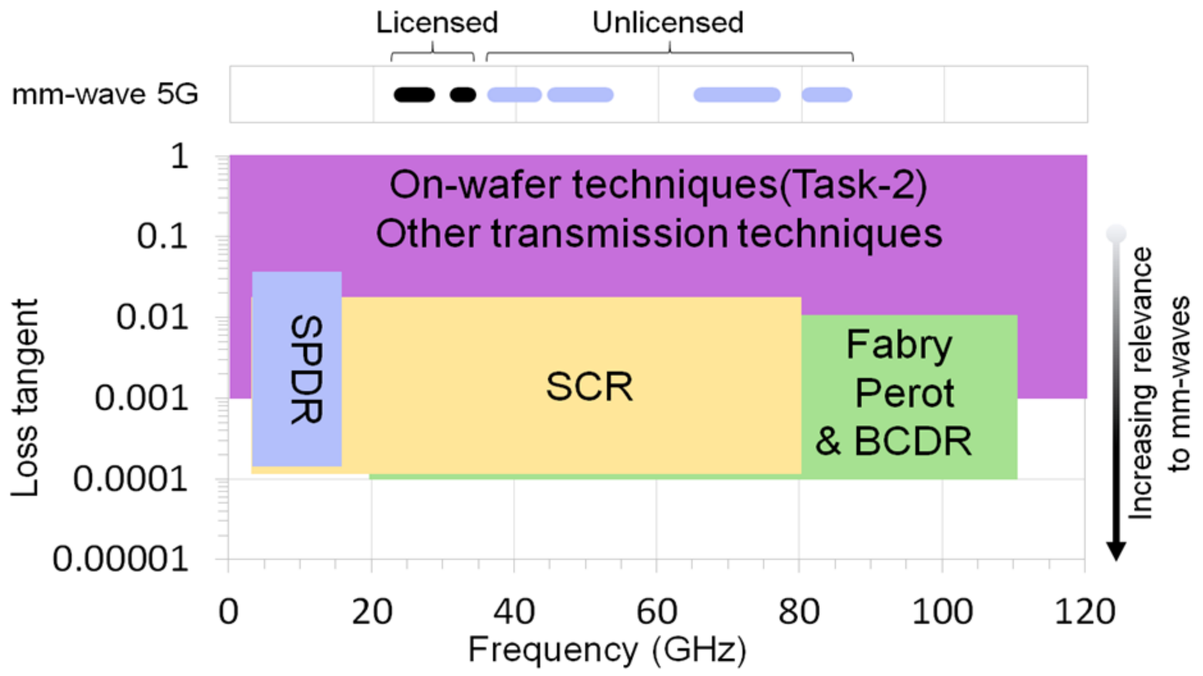
Round Robin Tests
- Create reference samples
- Test metrology differences
- Study lab to lab variations

In Progress Round 1

This presentation

# 5G Initiative Report – Benchmark Current Measurement Techniques

- 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.
- iNEMI Report  focuses on the following ***resonator based*** measurement techniques: split-post dielectric resonator (SPDR), split cylinder resonator (SCR), balanced circular disk resonator (BCDR), and Fabry-Perot open resonator (FPOR).
- The Figure maps these available techniques against frequency.



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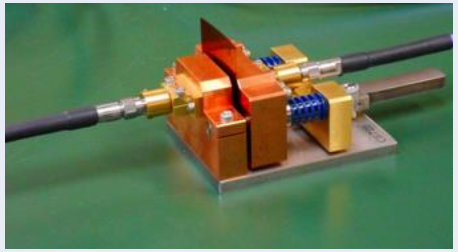
# 5G Initiative Report – Standard Reference Material Development

| Material type | Approximate thickness | Structure | Approx. $\varepsilon_r$, Tan $\delta$ | Important notes |
|---|---|---|---|---|
| Cyclo olefin polymer (COP/ Zeonex®) | 100 μm | Isotropic, homogeneous | 2.3, 5e-4 | Can degrade with finger oil - avoid handling unless using gloves |
| Cross linked polystyrene (Rexolite®) | 700 μm, 250 μm | Isotropic, homogeneous | 2.534, 4.6e-4 | Easy to machine, difficult to make flat, stable with temperature and humidity |
| PTFE / Teflon® | 100 μm, 200 μm | Isotropic, homogeneous | 2.1, 2e-4 | Easy to machine |
| Fused silica | 500 μm | | 3.8 / 1e-4 | Easy to machine, preferred by project team |
| Sapphire | 365 μm | Anisotropic (c-plane) | 9.4 / 11.6, 5e-5 | Hard to machine |

# 5G Initiative Report – Standard Reference Material Development

| | Preferred techniques with sample dimensions | | | Optional |
|---|---|---|---|---|
| Technique → | Split cylinder resonator (SCR) | Balanced-type circular disk resonator (BCDR) | Fabry-Perot open resonator (also called open cavity) | Split-post dielectric resonator (SPDR) |
| Sample dimensions → | 20 um ~ 300 um (best for 100 um), 34 mm x 45 mm > 20G | 0.1 mm ~ 1 mm, Best for 0.2~0.5 mm, 50 mmΦ x 2 each | 0.050 – 3 mm, min. diameter: 75 mm max diameter: 150 mm | max 0.6 mm, min. 15 mm x 15 mm max 40 mm x 40 mm @15G |

# 5G Initiative Report – Resonator-based Measurement (1 of 2)

| Technique | Frequency | Features |
|---|---|---|
| | | |
| Split-post dielectric resonator (SPDR)<br> | Discrete frequency points from 1 GHz up to 15 GHz | • High measurement precision<br>• Easy to use<br>• Insensitive to many user errors<br>• In-plane component of permittivity (typically)<br>• Typically extrapolated to 5G mmWaves<br>• Typical sample thicknesses less than 1 mm<br>• IEC 61189-2-721:2015<br>• https://www.qwed.com.pl/resonators_spdr.html<br>• https://www.keysight.com/us/en/assets/7018-01416/application-notes/5989-5384.pdf |
| Split cylinder resonator (SCR)<br> | Discrete frequency points from 10 GHz up to 80 GHz | • High measurement precision<br>• Can be sensitive to user errors<br>• Typically interpolated to 5G mmWaves<br>• In-plane component of permittivity (typically)<br>• Typical sample thicknesses around 100 um<br>• Support temperature sweep measurement<br>• IPC-TM-650 2.5.5.13<br>• https://www.keysight.com/us/en/assets/7018-06384/brochures/5992-3438.pdf |



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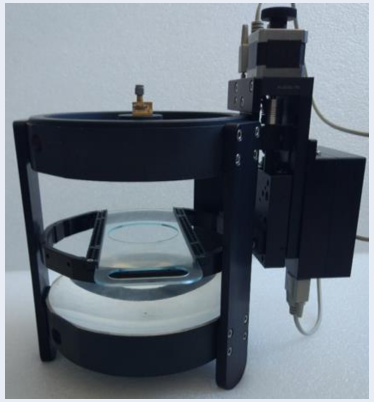
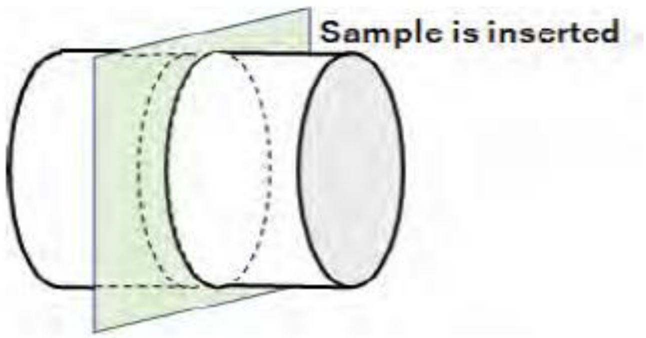
# 5G Initiative Report – Resonator-based Measurement (2 of 2)

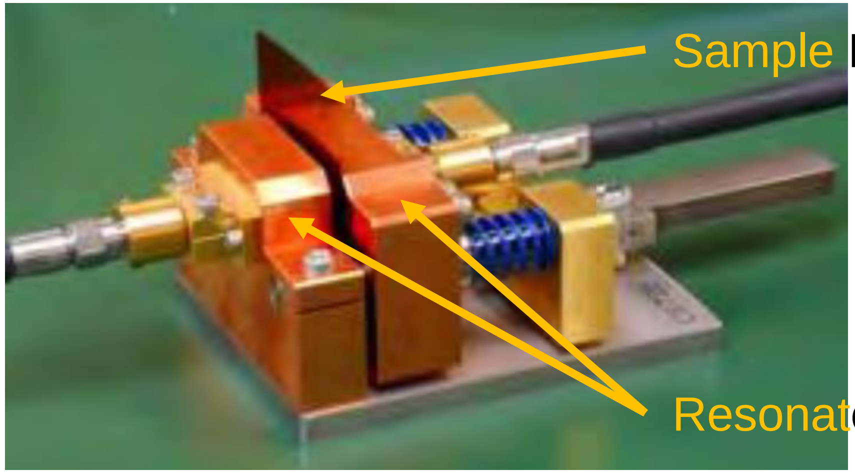
| | | |
|---|---|---|
| Balanced-type circular disk resonator (BCDR)  | Multiple discrete frequency points from 10 GHz up to 120 GHz | • High measurement precision<br>• Requires full 2-port calibration (mechanical to 110 GHz or electrical to 67 GHz)<br>• Out-of-plane component of permittivity (typically)<br>• Typical sample thicknesses less than 1 mm<br>• IEC 63185<br>• https://www.keysight.com/us/en/assets/7120-1214/flyers/N1501AE11-67-Balanced-Type-Circular-Disk-Resonator-BCDR.pdf |
| Fabry-Perot open resonator (FPOR, also called open-cavity)  | Discrete frequencies between 20 GHz up to 110 GHz | • High measurement precision<br>• Can be sensitive to user errors<br>• Uncertainty increases with increasing frequency<br>• In-plane component of permittivity (typically)<br>• JIS R1660-2<br>• https://www.qwed.com.pl/resonators.html#ResonatorFPOR<br>• https://www.keysight.com/main/editorial.jspx?cc=US&lc=eng&ckey=2276755&nid=null&id=2276755 |

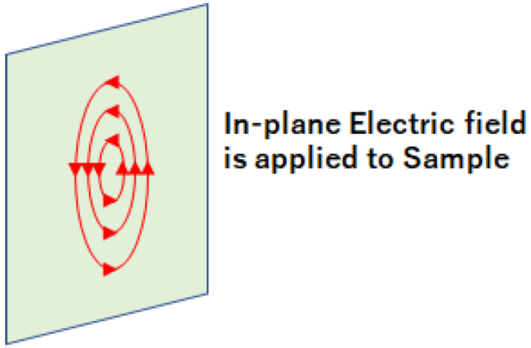
# Benchmarking Resonator – Split Cylinder Resonator (SCR)



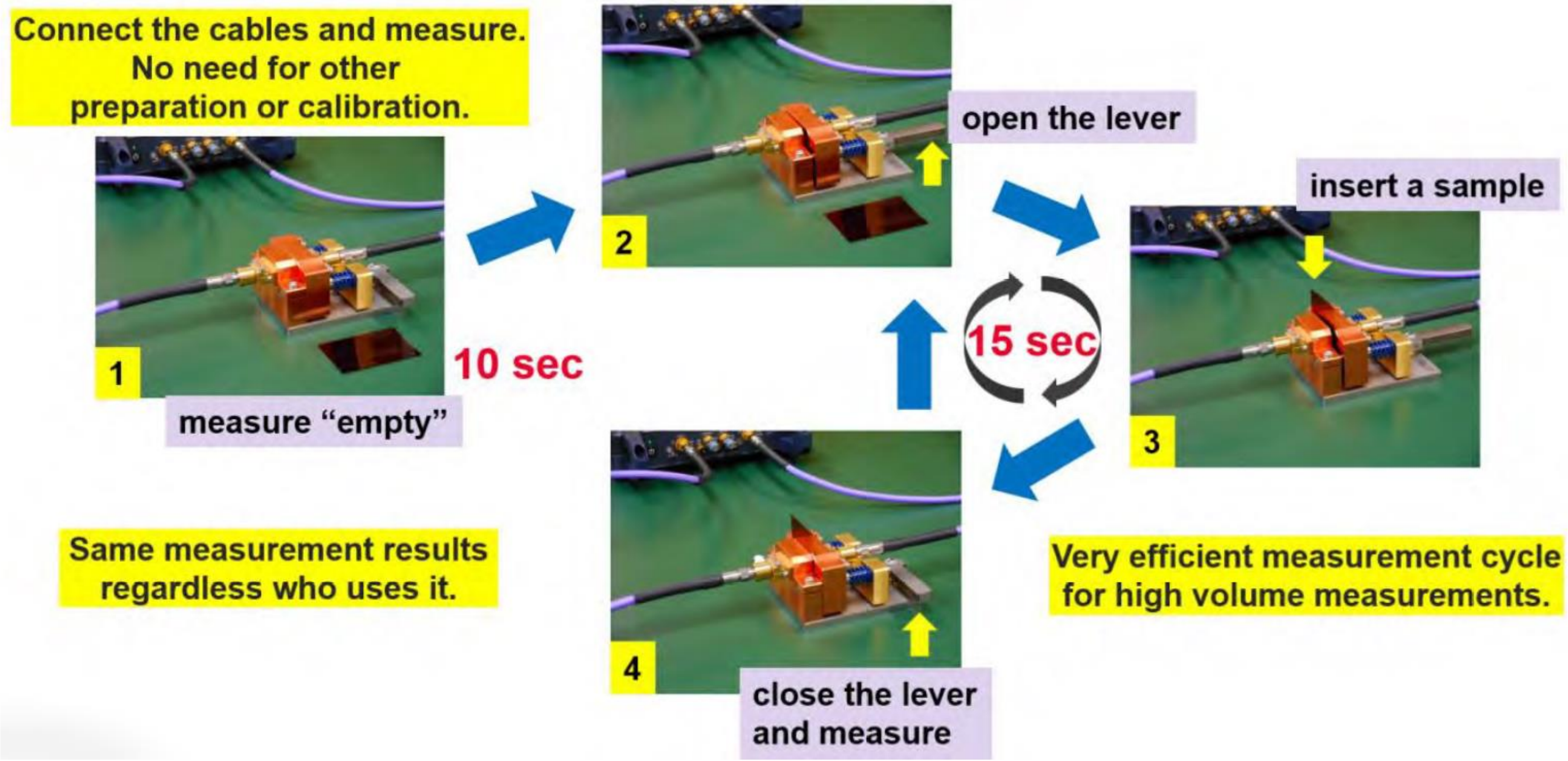

- SCR consists of two halves of a cylindrical cavity
- Sample material is inserted between the two cavities
- Sample perturbs the resonance of the TE011 mode by shifting the resonance lower and decreasing the quality factor
- The field samples the material in the plane of the film
- The shifts are used to produce the permittivity
- Permittivity by SCR is impacted by thickness determination
- Sample must be thin (less than several hundred micrometers)

Commercial SCR Example

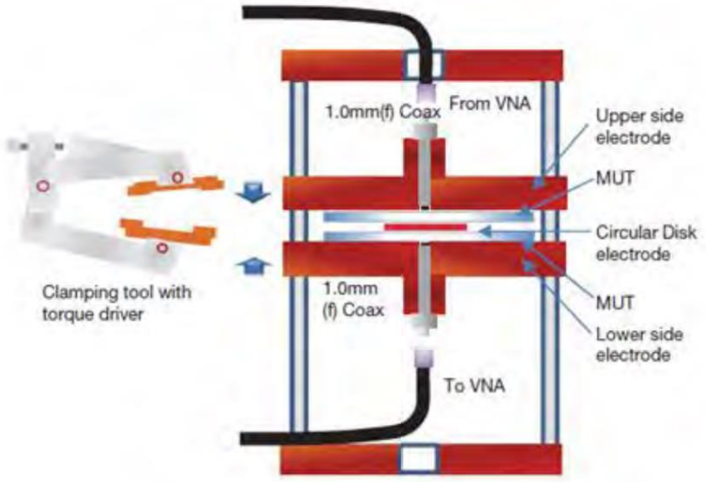


# Benchmarking Resonator – Split Cylinder Resonator (SCR) – Operation/Use

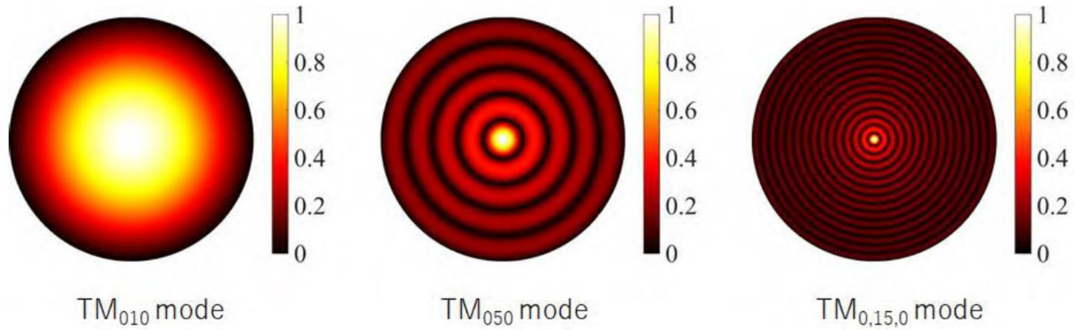


# Benchmarking Resonator – Balanced-type Circular Disk Resonator (BCDR)



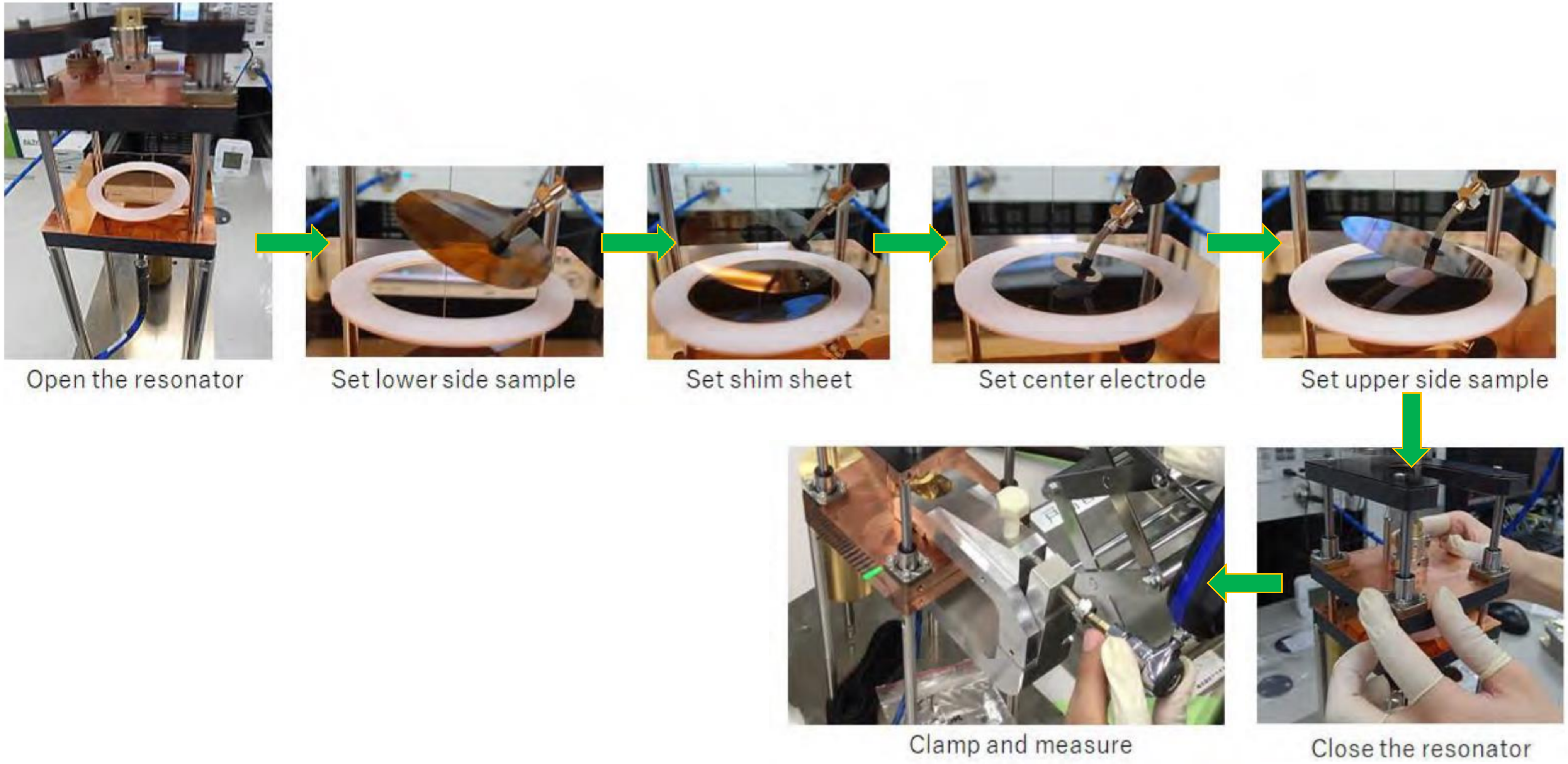

Commercial BCDR Example

- BCDR consists of a thin circular conductor disk between two dielectric plate samples
- Dielectric plate samples must be identical (thickness, roughness, size)
- BCDR creates a region where multiple standing waves resonate at different frequencies
- Multiple resonances are transmitted through the mode structure and occur at different harmonics
- Well-suited for high frequency measurements (maximum frequency is limited by the lines used to excite the resonator, apertures excitation holes, etc.)
- Method standardization is applicable for frequencies 10 – 120 GHz, $\varepsilon_r$ 1.1 – 10, and tan δ $10^{-4}$ – $10^{-2}$




E-field in-plane of the sample as a function of increasing frequency at different harmonic numbers (left-to-right)

# Benchmarking Resonator – Balanced-type Circular Disk Resonator (BCDR) – Operation/Use



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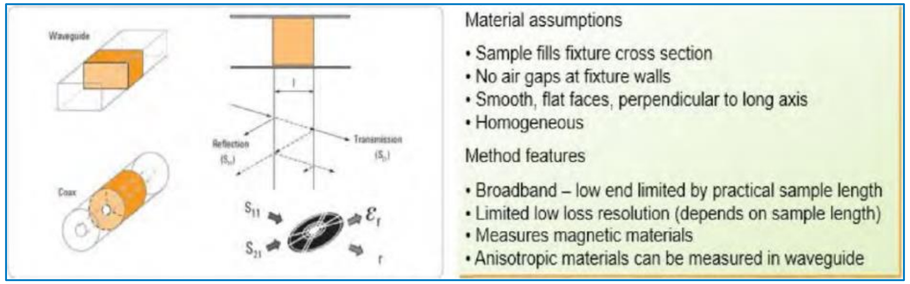
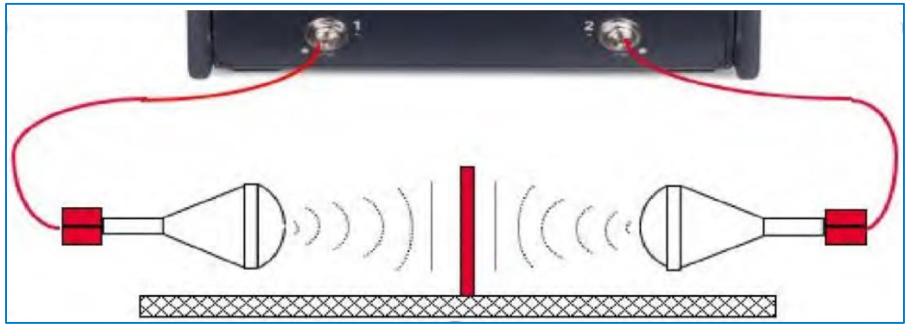
# Benchmarking Emerging Measurement and Characterization Methods

- Transmission Line Method
- Free Space Method
- Split Cylinder Cavities
- Microstrip Ring Resonator



# Benchmarking Emerging Measurement and Characterization Methods

Wafer Level Measurements

- Permittivity (ε) and permeability (μ) define the electromagnetic properties of microwave materials
  - Dielectric – materials that stores energy upon application of an electric field
  - Permittivity – expressed as a complex number

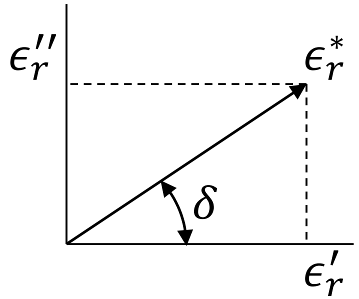
$$\kappa^* = \varepsilon_r^* = \frac{\varepsilon^*}{\varepsilon_0} = \varepsilon_r' - j \cdot \varepsilon_r'' = \left(\frac{\varepsilon'}{\varepsilon_0}\right) - j \cdot \left(\frac{\varepsilon''}{\epsilon_0}\right)$$

Dielectric Constant

Complex Relative Permittivity

Real (energy storage)

Complex (dielectric loss)




Dissipation Factor → $\tan\delta = D = \dfrac{\varepsilon_r''}{\epsilon_r'}$

Permittivity of Free Space → $\varepsilon_0 = \dfrac{1}{36\pi} \cdot 10^{-9} [F/m]$



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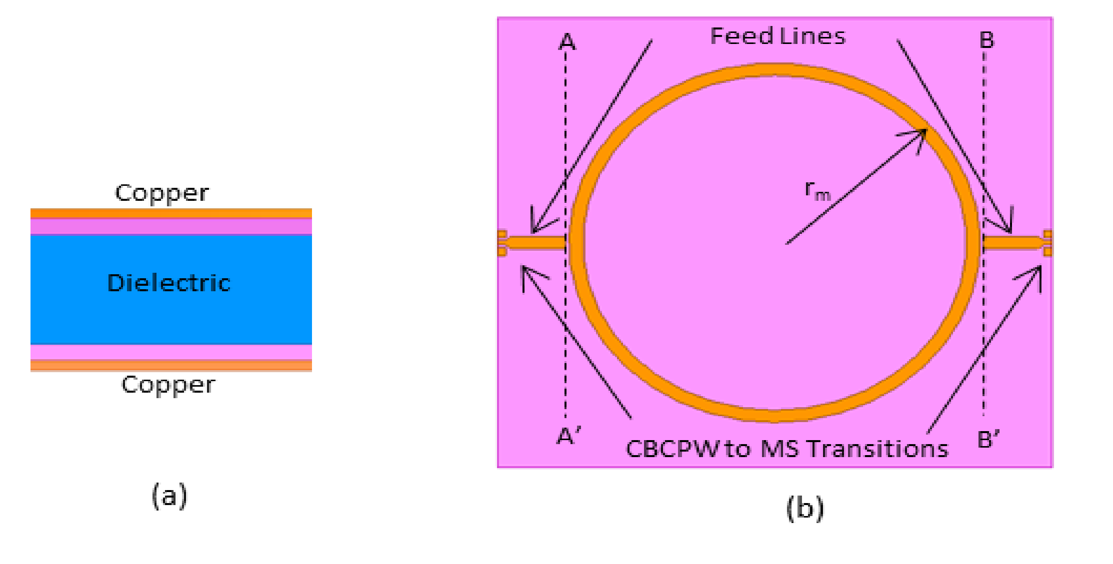
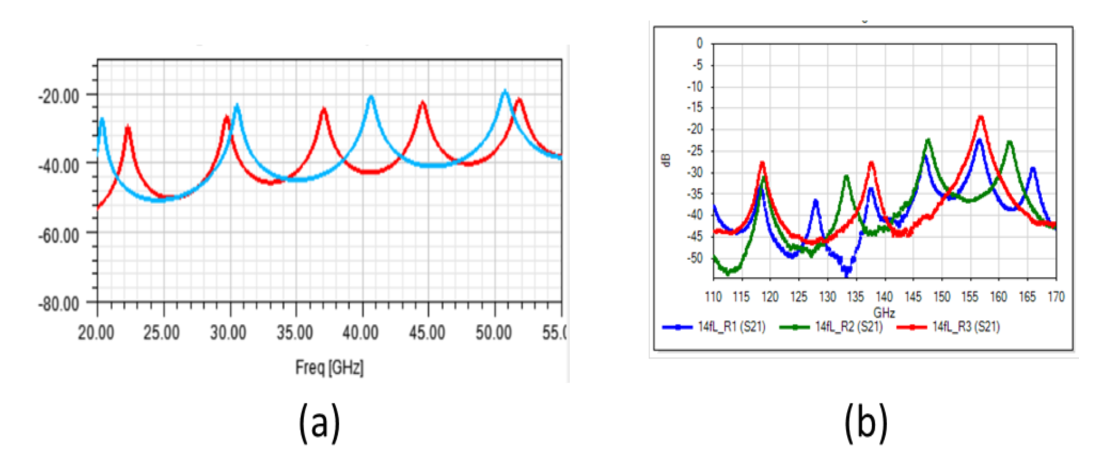
# Wafer Level Measurements – Microstrip Ring Resonator (MRR)

- Electrical characterization using microstrip ring resonator (MRR) method




(a) material stack-up and

(b) (b) MRR with feed lines and CBCPW (conductor-backed coplanar waveguide) to MS transition.

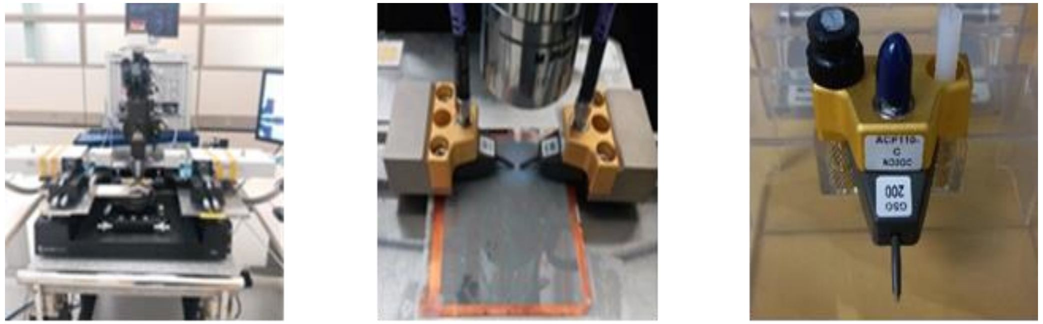



(a) simulation in frequency range of 20 GHz to 50 GHz

(b) (b) measurements of MRRs in D-band 110 GHz to 170 GHz.

# Measurement Equipment and Probes

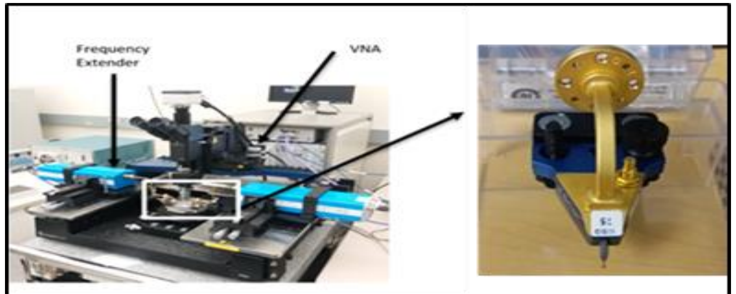
- Broadband Set up (110MHz→110GHz)



(a) (b) (c)

Broadband measurement setup:
(a) VNA with extenders and probes
(b) TV and probes
(c) ACP110 probe with 200 um GSG pitch.

- D-band (110 GHz to 170 GHz) measurement setup




(a) (b)

D-band measurement setup:
(a) VNA with extenders and probes
(b) Cascade Infinity Probe with 75 um GSG pitch.

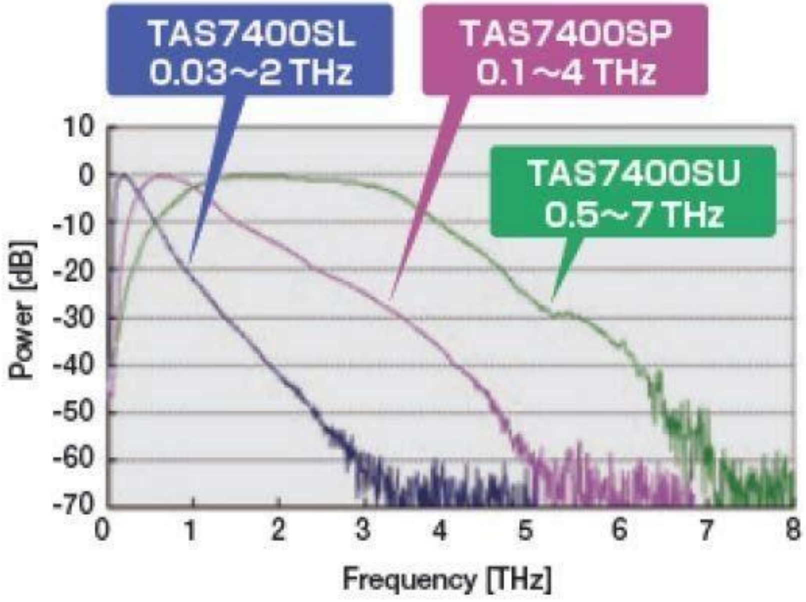
# Time Domain Spectroscopy: for THz Solutions

## Advantages

- Dielectric properties can be extracted as a continuous function of frequency. This is in contrast with a frequency domain method (using resonators) where the properties can only be extracted at discrete frequencies.
- Do not have to explicitly satisfy Kramer-Kronig relationship since the complex parameters are extracted using a single measurement.
- Dielectric properties over a broad frequency range can be supported (30 GHz – 2 THz).
- Can directly measure the properties of the dielectric sample without the need for any conductive structures.

## Potential sources of error

- Need to precisely account for scattering effects; otherwise, this approach can lead to larger loss tangents than the true values.
- Need precise thickness measurement (d) of the sample as this parameter is used for extracting the refractive index.
- Around 30dB SNR (signal to noise ratio) may be required to keep errors low. As shown in the Figure, this measurement system works well over a range of frequencies. If the frequency is too low, however, the errors can increase.




Power vs frequency in TDR measurements

# Conclusions and Next steps

- 5G expansion (and beyond) requires benchmarking of low Dk-Df materials for meaningful understanding of performance characteristics

- Various characterization methods are available and are being compared and contrasted with selected materials in the iNEMI study

- Choice of method and equipment are dependent on features and advantages of the materials being evaluated (and equipment!)

- Emerging measurement techniques will become increasingly relevant as new spectrum auctions open communication bands above the current industry release for 5G mmWave
  - 5G → 6G
  - 80x increase of mobile traffic (>75% video traffic)
  - Zero perceived latency
  - High (massive) degree of interconnectivity