Innovative Approaches to Solve Low Loss Materials Characterization Challenges
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Acknowledgements:
Intel: Michael J. Hill
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Keysight: Say Phommakesone
Nokia: Hanna Kähäri
NIST: Nate Orloff
5G Electronics: Major Challenges
5G/6G Electronics Hardware: Design and Manufacturing Challenges

- 5G: major elements:
  - 5G systems will have more integrated, smaller antennas @ mmWave frequencies
  - AiP devices require radical change to existing contact test solutions
- Select Gaps / Challenges Drivers
  - Antenna in Package (AiP)
  - Heterogenous Integration (SiP)
  - High Speed/Ultra Low Loss Materials
  - Testing Complexity/Capabilities
  - Co-design/simulation
  - Thermal Challenges

- 5G solutions require complex integration approaches
  - and require close collaboration.
5G Electronics: Mobile applications

- Support advanced beam forming, beam steering, and beam tracking
- Integrated 5G NR radio transceiver, power management IC, RF front-end components and phased antenna array
- Support up to 800 MHz of bandwidth
- With compact footprint, up to four of them can be integrated in a smartphone

Source: Qualcomm
5G and mmWave – Industry Needs

• ‘5G’ extends beyond wireless applications, including automotive and industrial radar – many forward-looking wired applications need material data spanning DC to 100+GHz

• Selection of package materials may involve measurements of 50 or more test materials

• Errors in characterization limit accuracy of modeling resulting in time consuming iterations

• Traditional methods of microwave trimming & tuning are difficult to tolerate in today’s environment

• Development of new materials requires the ability to evaluate the performance of those materials at use conditions

Current Material
Advanced Material

Semiconductor products, equipment suppliers, material manufacturers have significant exposure if characterizations are incorrect

Cost to switch: ~$2 per CPU substrate x 20M units = $40M

Source: Intel
One potential problem is with the materials.

Thermal Management
Performance at High Frequencies

Vendor measures here
5G works here
Industry Collaboration for Solving Materials Measurement Challenges at High Frequencies

Brought Together by iNEMI

www.inemi.org
5G Materials Project: Industry Collaboration

Approach for Solving Measurement Challenges @ High Frequencies:
• Bring together Cross-functional team spanning industry Value Chain
• Develop a guideline/best practice for a standardized measurement and test methodology that can be shared with industry and relevant standards organizations

Project Team

- 3M
- AGC-Nelco
- Ajinomoto USA
- AT&S
- Centro Ricerche FIAT-FCA
- Dell
- Dupont
- EMD Electronics (Co-Chair)
- Flex
- Georgia Tech
- IBIDEN Co Ltd
- IBM
- Intel
- Isola
- ITRI (Co-Chair)
- Keysight (Co-Chair)
- MacDermid-Alpha
- Mosaic Microsystems
- NIST
- Nokia
- Panasonic
- QWED
- Shengyi Technology Company
- Sheldahl
- Showa Denko Materials
- Unimicron Technology Corp
- Zestron
iNEMI 5G Materials GLOBAL Project Members

- Precision Teflon
- Cyclo Olefin Polymer

Future additions:
- Rexolite
- Fused Silica
• Task 1 – Benchmarking permittivity methods, potential reference materials
• Task 2 – Emerging technologies / 100GHz & beyond
• Task 3 – Multi Lab Round Robin Reference Experiment
• Task 4 – Extension to advanced substrate materials
Project Goals

• Gather industry experts to understand needs
• Development methodology to address and solve
• Independent Validation
• Provide Linkage between end to end supply chain: materials suppliers, 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

Testing complete ✅

Task 4
Round Robin Tests
• Commercial Material
• Validation of Test methods

Ongoing
Materials Test Methods: Task 1

- Task 1 identified the most common tool sets available to participants
  - Mirrors wider industry – few vendors in this space
- Equipment methods used
  - Actual device / vendors varied by lab

Discrete frequency points
1 GHz → 15 GHz

Discrete frequency points
10 GHz → 80 GHz

Discrete frequencies
10 GHz → 120 GHz

Continuous frequencies
10 GHz → 120 GHz

SCR
(Split Cavity Resonator)

SPDR
(Split Post Dielectric Resonator)

BCDR
(Balanced Circular Disk Resonator)

FPOR
(Fabry-Perot Open Cavity Resonator)
Task 1: Current Industry Best Practices for Low Loss Measurements

Resonator-based measurement

SPDR
- High measurement precision
- Easy to use
- Insensitive to many user errors
- In-plane component of permittivity (typically)
- Typically extrapolated to 5G mmWaves
- Typical sample thicknesses less than 1 mm
- IEC 61189-2-721:2015

SCR
- High measurement precision
- Can be sensitive to user errors
- Typically interpolated to 5G mmWaves
- In-plane component of permittivity (typically)
- Typical sample thicknesses around 100 um
- Support temperature sweep measurement
- IPC-TM-650 2.5.5.13
### Task 1: Current Industry Best Practices for Low Loss Measurements

**Resonator-based measurement**

<table>
<thead>
<tr>
<th>BCDR</th>
<th>FPOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>• High measurement precision</td>
<td>• High measurement precision</td>
</tr>
<tr>
<td>• Requires full 2-port calibration (mechanical to 110 GHz or electrical to 67 GHz)</td>
<td>• Can be sensitive to user errors</td>
</tr>
<tr>
<td>• Out-of-plane component of permittivity (typically)</td>
<td>• Uncertainty increases with increasing frequency</td>
</tr>
<tr>
<td>• Typical sample thicknesses less than 1 mm</td>
<td>• In-plane component of permittivity (typically)</td>
</tr>
<tr>
<td>• IEC 63185</td>
<td>• JIS R1660-2</td>
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</tbody>
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Task 3: Round Robin Experiment

Task 3 TWG
(Technical Working Group)
Members

Intel: Michael J. Hill
QWED: Malgorzata Celuch
    Marzena Olszewska-Placha
Keysight: Say Phommakesone
ITRI: Chang-Sheng Chen
    Chiawen Lee
Nokia: Hanna Kähäri
NIST: Nate Orloff
EMD Electronics: Richard Stevenson
iNEMI: Urmi Ray

Round Robin Test Labs

3M: USA
Dupont: USA
Intel: USA
ITEQ: Taiwan
ITRI: Taiwan
QWED: Poland
Keysight: USA
Nokia: Finland
NIST: USA
Showa-Denko: Japan
Shengyi Electric: China
Materials Test Method: Round Robin Studies Using “Reference” Samples

- Initiated and completed Round Robin Experiments with 10 global sites
  - ~2200 Data points in data set
  - Spanning 10 labs, 4 methods, 10-110GHz
  - 2 Materials: COP, Teflon

- Goals
  - High level – how much agreement is there in results
  - Thickness – how closely do labs assess thickness
  - Understand sample quality, handling and sizing / compatibility
  - Understand practicality of techniques
  - Look for obvious biases between equipment types
  - Look for frequency dependency at higher frequencies
  - Average value for kit samples – usable as references for labs
  - Drive & demonstrate need for standards labs to develop SRMs
Representative Results

- Very good consistency across measurement methods and sites

Results generally:
- $\pm 2\%$ range for $\varepsilon_r$
- $\pm 0.0002$ to $\pm 0.0004$ for $\tan\delta$
Key Learnings: Sample sizing, compatibility & practical issues

- Common BCDR, SCR, FPOR, SPDR compatible with 2 different sample sizes 90x90 mm, 35x45 mm
  - Implications for traceable standard geometry
- Recommendations for equipment suppliers & end users
  - Make devices capable of arbitrarily large samples where possible
  - End users: Include in purchasing requirements

Importance of sample & device geometry compatibility can not be understated

![Sample size limited](image1)

![Sample size unlimited](image2)
Key Learnings: What about sample thickness?

- Sample thickness is critical to results
  - Any errors in thickness assessment impact extracted $\varepsilon_r \sim 1:1$
  - TanD is impacted but not technically significant by comparison
- Labs generally have good agreement of an individual sample’s thickness
  - $\sim 0.2 – 0.5 \%$ of thickness value
Key Learnings: Sample Quality

- Samples have to be thin (typically <250um) – 1% variation only 2.5um
- Commonly available thickness variation is often unknown but this order
- Surface topology can be a factor
  - Difficult to assess
  - Easily on the order of thickness variation – potentially similar effects on results

Sample surface quality and thickness variation is important
Traceable, uniform & smooth SRM needed
Key Learnings: Need for Traceable Standards

- Experiment a good demonstration of need for traceable standard
- Industry is functionally limited to $\pm 2\%$ without an accuracy standard
- Additional biases may exist because vendors may be relying on Teflon & COP for calibrations
- Usable SRM would allow improvement of accuracy and removal of biases

Proposed Fused Silica based Reference Material Development: Partnership with NIST
**Summary and Next steps**

- Expect ±2% limitation in Er measurement reproducibility (accuracy unknown)
  - Results appear to be independent of resonator type

- Several contributions to this – none dominant
  - Sample surface and thickness variation
  - Ability to measure thickness in reproducible way
  - Slight equipment variations

- 35mm x 45mm & 90mm x 90mm sample sizes fit most equipment sets
  - Thickness requirements vary by Er and specific device but 100-250um is commonly useful for many organic dielectrics
  - Recommend these sample sizes if specific measurement equipment is not known

- Individual labs - repeatability within a lab is much better than across labs

- Need for traceable standards is clear from this study

- **Next steps:** Project with NIST for Reference Material Development – coming soon
Path Forward

• Collaboration is the key to solving complex problems
• Organizations such as iNEMI have years of bringing everyone to the table and solving complex industry problems and working with industry standard organizations
  • Participation from end-to-end supply chain stakeholders, based on mutual respect and trust
  • minimize risk and ensure supply chain readiness
• Breadth of expertise and perspective
• Leverage industry wide expertise - “best” of the “best”
• Significantly accelerate Time to Market and ROI
• Leverage resources to minimize time, cost and risk

Collaboration: A process, NOT an event
Who's iNEMI

The International Electronics Manufacturing Initiative (iNEMI) is:

- a not-for-profit,
- industry-led,
- highly efficient

R&D consortium of approximately 80 leading electronics manufacturers, suppliers, associations, government agencies and universities.

Forecast and Accelerate improvements in the Electronics Manufacturing Industry for a Sustainable Future via Collaborative Innovation

**Roadmap**
- Anticipate technology requirements
- Identify gaps
- Focus R&D priorities

**Collaborative Projects**
- Eliminate gaps
- Deliver learning & critical data
- Leverage efforts & participants’ resources

**Forums & Workshops**
- Share solutions & best practices
- Prioritize key challenges
- Network with customers & suppliers

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