Recent Developments and Cross-Calibration of Resonator-Based Techniques for Microwave and mmWave Materials Assessment

Malgorzata Celuch and Marzena Olszewska-Placha
QWED Sp. z o.o., Warsaw, Poland

12th International Conference on Microwave Materials and their Applications
Mainz, 27 September 2023
(1) QWED celebrating 25 years in May 2022

(2) 75th birthday of W.Gwarek at MIKON 2022 (cake featuring pioneering paper of 1985)

All photos © QWED.


QWED’ beginning, founders (right to left): W.Gwarek, M.Celuch, M.Sypniewski, A.Wieckowski

Awarded by Prof. Jerzy Buzek
Prime Minister of Poland 1997-2002
President of the European Parliament 2009-2012

Sale of 1000th resonator based on designs of J.Krupka

Prime Minister of Poland Award for QWED 1998

QWED
We would like to thank all the participants of MMA2010 for their contribution in Microwave Materials and Their Applications Conference. We have uploaded few photos, and we invite you to take a look below.

We would also like to inform you that the next - MMA2012 Conference will be held in Taiwan - Taipei. For more information check MMA2012 website.

https://www.qwed.eu/mma2010/
Outline:

1. QWED: from Computational Electromagnetics to Modelling-Based Materials’ Characterisation.
2. iNEMI: Setting-Up 5G/mmWave Benchmarking Projects.
3. Resume of Round-Robin Results of Resonator-Based Techniques for Characterising 5G Substrates.
5. Summary.
6. Invitations and Acknowledgements.
QWED origins in Computational Electromagnetics since 1980s...
IEEE- awarded research of Prof. Wojciech Gwarek on 2D FDTD modelling (with novel conformal meshing)
Fellow, Pioneer Award, DML

M.Celuch joins the above research, leading to PhD in 1996
1996 Beta-Version of QuickWave at Univ. Chalmers, Kent, Helsinki
1997 first commercial licences sold by QWED
... by 2000, QuickWave-3D by QWED used worldwide
for industrial & research applications from RF to optical bands

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Mainz, 27.09.2023
since 1998 annually at IEEE IMS

Anaheim, CA, 1999

San Francisco, CA, 2006

Denver, 2022

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QuickWave original applications in cosmic research & SATCOM

Septum polariser by SES

design & measurements: Saab Ericsson Space
modelling: QWED, 1997

below: differential phase-shift

E-plane Y-junction by NRAO

after A. R. Kerr, Elements for E-Plane Split-Block Waveguide Circuits, ALMA Memo 381

propagation of two polarisations at centre frequency
Applications for Materials Processing with Microwaves

Simple microwave heating benchmarks & microwave heating phenomena studies*

- heat transfer & load dynamics
- Load rotation & arbitrary movement during heating
- Source parameters tuning – regime for solid state sources
- Temperature dependence of material parameters

Freezing to file the state of the simulation

De-freezing on arbitrary computer & at convenient time

Design & analysis of real-life microwave oven cavities, incl. complicated cavity shapes and advanced feeding system*

With QuickWave EM computation as fast as 1 min 18s on a low-cost video card – supporting all graphic cards with OpenCL

Material Measurements coming to QWED since 1980s...

awarded research of Prof. Jerzy Krupka (IEEE Fellow) on dielectric resonators (best known: Split-Post Dielectric Resonator)

... by early 2000s:
QWED commercialises the SPDRs
endorsement by Agilent / Keysight
publication of standard IEC 61189-2-721:2015

by Donald Tusk
Prime Minister of Poland 2007-2014
President of the European Council 2014-2019

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Agilent Both
IEEE IMS 2006, San Francisco, CA

MMA-2010, Warsaw PL
co-organised by QWED & Warsaw Univ.Tech.
Popular Resonators Offered by QWED

SPDRs for laminar dielectric materials

typical units: 1.1 GHz - 15 GHz

TE01δ cavities, typically 1 – 10 GHz
for bulk low-loss dielectrics

5 GHz SiPDR for resistive sheets

modified SiPDR for graphene

T. Karpisz, B. Salski, P. Kopyt, and J. Krupka,
doi: 10.1109/TMTT.2019.2905549.
Bridging Computer Modelling with Material Measurements

**Commercial since 1997**

**QuickWave Simulation Software**

- ~1000 licences implemented

**Modelling** (EM, MW, multiphysics, ...)
- waves in free space is "easy" Maxwellian
- wave interaction with matter is "complicated"...

**Open Platform Examples & Tools**

- QW-Modeller for QuickWave
- Free general purpose 3D CAD/CAE modeller for QuickWave

**Material measurements**
- Accurate material parameters (constitutive relations)

**Applicator design & model for parameter extraction**

**Commercial resonator test-fixtures since 2001**

- 1000th unit sold in 2020

**European Standard:**
- IEC 61189-2-721:2015
- CEN-CENELEC Workshop 2021

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Why Resonators for Material Measurements?

Circuit theory interpretation (for newcomers to the field):

given fixed strength of Signal(in),
at resonance Signal (out) is strongest

given fixed strength of U_{in},
at resonance U_R is strongest (U_{LC} = zero)
Examples of canonical examples of resonators *(for newcomers to the field)*

**Eigenvalue problems:** analytical solutions exist for cuboidal and cylindrical cavities:

$$\frac{Q}{P_q T} = 2\pi \frac{\overline{W}}{f_{r,mnp}^2}$$

$$f_{r,mnp} = \frac{v}{2} \sqrt{\left(\frac{m}{W}\right)^2 + \left(\frac{n}{L}\right)^2 + \left(\frac{p}{H}\right)^2}$$

$$v = \frac{1}{\sqrt{\mu \varepsilon}} = \frac{c}{\sqrt{\varepsilon_r}}$$ *(in non-magnetic, low-loss dielectrics)*

$$f_{r,mnp} = \frac{v}{2} \sqrt{\left(\frac{\kappa_{mn}}{\pi R}\right)^2 + \left(\frac{p}{H}\right)^2}$$

→ application of cavities to Dk measurements appears straightforward!

*(but cavity losses should be minimised & 100% filling factor is difficult to achieve)*
QuickWave Modelling of a Cuboidal Cavity

Transmission $|S_{21}|$ simulated between weakly coupled source and probe in a cube 8x10x10 [mm]

$\varepsilon_r=1$ $\sigma=0.00833$ S/m  
@21.2GHz: $\tan\delta=0.071$  
$Q_{SUT}= 1 / 0.0071 = 141$  
$Q_{S21}=21.2/0/1496= 141$

$\varepsilon_r=1$ $\sigma=0.0833$ S/m

$\varepsilon_r=4$ $\sigma=0.0166$ S/m

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QuickWave model of a cylindrical cavity

**TM011 mode**

**TM021 mode**

compared to rectangular (cuboidal) cavities, typically:
- lower contribution of wall losses
- easier standard manufacturing

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How do dielectric resonators work (with QuickWave illustration)

Dielectric resonator (top left) as a multimode device (see transmission diagramme, top centre) including TE01 mode (top right) and many higher modes (lower row)
**Split-Post Dielectric Resonator method** – as illustrated by QuickWave

- resonant mode with EM fields mostly confined in and between those ceramic posts → minimal losses in metal enclosure
- H-field is only vertical at the side wall of the enclosure → only circumferential currents in side wall → no radiation through slot
- E-field tangential to SUT → air slots between SUT and posts have negligible effect
- easy SUT insertion through slot, no dismatling, NDT method

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Table 2. Typical ranges of applications of SPDRs and SPDRs

<table>
<thead>
<tr>
<th>Range of SPDR applications</th>
<th>Range of SPDR Conductivity (V/g/m)</th>
<th>Range of SPDR Resistivity (Ohm)</th>
<th>Range of SPDR Surface resistivity (Ohm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 to 10^{-6}</td>
<td>from 2 x 10^{-3} to 0.5</td>
<td>from 10^{-4} to 10^{-3}</td>
<td>from 10^{-1} to 10^{-4}</td>
</tr>
<tr>
<td>from 10^{-4} to 10^{-3}</td>
<td>from 2 x 10^{-5} to 5 x 10^{-4}</td>
<td>from 10^{-2} to 10^{-1}</td>
<td>from 10^{-2} to 10^{-1}</td>
</tr>
<tr>
<td>from 10^{-1} to 2 x 10^{-1}</td>
<td>from 2 x 10^{-4} to 10^{-3}</td>
<td>from 10^{-3} to 10^{-2}</td>
<td>from 10^{-3} to 10^{-2}</td>
</tr>
</tbody>
</table>


CAD models and EM field distribution: QuickWave™ software by QWED

Which Scanner: SPDR or iSiPDR

Test Fixtures and Setups

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Modelling-Based Materials’ Characterisation Setup

2D scanner designed with a modified 10 GHz SPDR
Finalist of the European Innovation Radar Prize 2021

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Modelling-Based Materials’ Characterisation Setup

2D 10 GHz iSiPDR Scanner for Resistive Sheets

Example application:
battery anodes before & after cycling (SEI formation).

2D iSiPDR scanner based on inverted 10 GHz SiPDR
Now coming to iNEMI projects...
5G/mmWave Materials Assessment and Characterization

*Further referred to as “5G Dielectrics” our “5G Substrates” project*

- 5G: Common to only think in terms of ‘radio’ applications
- ‘5G’ extends beyond wireless applications

**CPU Clock Speeds**

- <1GHz
- 3GHz
- 4GHz
- 5GHz
- 24.28GHz
- 37.40GHz

**High Speed I/O**

- 600MHz (220MHz)
- 1.2GHz (440MHz)
- 1.8GHz (660MHz)
- 2.4GHz (880MHz)

**Dielectric constant measurements**

- Many forward-looking wired applications need material data spanning DC to 100+GHz
- Dielectric constant measurements are key enables for many different industries & technologies

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Industrial Motivation

- Traditional methods of microwave design rely on trimming & tuning difficult to tolerate in today’s environment...
- Faster & less costly “virtual prototyping” is achieved with today’s modelling & simulation tools...
- …but accurate material data is still required
- …errors in materials’ characterisation limit accuracy of modelling resulting in time consuming iterations

“errors may cost $10’s of millions for a single program, or worse, unexpected product failures”
Gaps & Practical Challenges

No standards & SRMs for mmWave Permittivity measurements >20 GHz:
- Challenges for ISO and quality control

Few vendors for mmWave Permittivity measurement equipment >10 GHz:
- Explain vendor to vendor differences
- Whom to trust?
- On whom to rely?

Useful 5G materials are typically very low loss:
- Eliminates many traditional transmission line techniques

Increasing frequency:
- Severe limitations on sample thicknesses
- Incompatible sample dimension requirements between techniques
- Higher sensitivity to operator

Our project:

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

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Sample Material Requirements
- Stable, Low loss
- Low moisture absorption / temperature dependency
- Isotropic
- Good mechanical & handling properties

1\textsuperscript{st} Project Stage
- Precision Teflon
- Cyclo Olefin Polymer

2\textsuperscript{nd} Project Stage
- Rexolite
- Fused Silica

Techniques Included
- Split Post Dielectric Resonator
- Split Cavity Resonator
- Fabry-Perot
- Balanced Circular Disk Resonator

\( \rightarrow \) Frequency Span : 10GHz – 100GHz with overlaps

10 Sample Kits Created
- Sample sizes 35 mm x 45 mm, 90 mm x 90 mm

10 Laboratory Round Robin

Industrial
- Automotive

Results for in-plane measurements first reported at EuMW 2021
3 resonator techniques
2 sample kits
3 labs, each using 2+ techniques

BCDR results & concerns reported herein.
Split Cylinder Resonator (SCR) - Basics

TE011 mode modelling result in this frame is by QWED

**Split cylinder resonator (SCR)**

- High measurement precision
- Can be sensitive to many user errors
- Typically interpolated to 5G mmWaves
- Typically in-plane component of permittivity
- Typical sample thicknesses around 100 um
- Support temperature sweep measurement
- IPC-TM-650 2.5.5.13

*Discrete frequency points from 10 GHz up to 80 GHz*
Measurement Procedure: SCR

1. Connect the cables and measure. No need for other preparation or calibration.
2. Open the lever
3. Insert a sample
4. Measure “empty”
5. 10 sec
6. 15 sec
7. Close the lever and measure
8. Very efficient measurement cycle for high volume measurements.

Disclaimer: this slide is NOT about QWED design

Split-Post Dielectric Resonator (SPDR): Basics & Standard

- resonant mode with EM fields mostly confined in and between those ceramic posts → minimal losses in metal enclosure
- H-field is only vertical at the side wall of the enclosure → circumferential currents → no radiation through slot
- E-field tangential to SUT → air slots between SUT and posts have negligible effect
- easy SUT insertion through slot, no dismantling
0. Connect the SPDR to Q-Meter using SMA cables. 
Connect Q-Meter to PC using USB cable.

1. Measure “empty SPDR” – app invoked measurement.

2. Measure thickness of the sample

3. Insert the sample into SPDR

4. Insert the sample thickness into the PC app

5. Material parameters are extracted automatically

Total measurement time: 30sec
Fabric-Perot Open Resonator (FPOR): Basics & Standard


Measuring in-plane anisotropy:

Resonances detected for BoPET sample ($t = 0.100$ mm), turned in xy plane.

Measurement Procedure: FPOR

1. Connect the FPOR to VNA and PC with control app.

PC app invoked and controlled measurement – fully automatic
Total measurement time: 10min

2. Measure “empty FPOR” (resonant frequency and Q-factor at M..N modes)

3. Insert the sample into FPOR

4. Automatic procedure finds M..N modes of sample-loaded FPOR

5. Material parameters at consecutive frequencies (modes) are extracted automatically
First Round-Robin Results: Consistency

3 labs, 3 techniques
14 laboratory setups

Resonators:
- Intel - SCR at 10 / 60 GHz and SPDR at 10/ 20 GHz
- Keysight - SCR at 10 / 20 / 28 / 40 / 80 GHz
- QWED - SPDR at 10/ 15 GHz and FPOR over 10-110GHz

VNA, software:
- Intel, Keysight – benchtop VNA with Keysight Option N1500A
- QWED FPOR – benchtop VNA with customised FPOR software
- QWED SPDR – handheld VNA, extraction based on abs(S21)

dot colours denote testing sites

visually good results, with reference to standards and practices in the microwave range
(e.g. IEC 61189-2-721:2015 for SPDRs < 20GHz dictates 0.3% for Dk assuming perfect determination of thickness, relaxed to 1% in industrial practice)
First Round-Robin Results: Repeatability

3 labs, 3 techniques, 14 laboratory setups
1 operator per setup

Intel - SCR at 10 / 60 GHz and SPDR at 10/ 20 GHz,
Keysight - SCR at 10 / 20 / 28 / 40 / 80 GHz
QWED - SPDR at 10/ 15 GHz and FPOR over 10-110GHz.

Each symbol denotes an average of 16 measurements; error bar = repeatability = triple of standard deviation

repeatability of SCR ±1%
repeatability of SPDR, FPOR better than ±0.5%
First Round-Robin Results: Discussion

3 labs, 3 techniques, 14 laboratory setups

3 labs, 3 techniques, 14 laboratory setups

Dk spread < 1% (within ± 0.5% from average)
(< 2% incl. outliers)

> 40GHz 2x increase in Df compared to 10GHz

Intel - SCR at 10 / 60 GHz and SPDR at 10/ 20 GHz,
Keysight - SCR at 10 / 20 / 28 / 40 / 80 GHz
QWED - SPDR at 10/ 15 GHz and FPOR over 10-110GHz.

dot colours denote testing sites

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Modelling Based Characterisation of Materials

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Round-Robin – 2nd Material

3 labs, 3 techniques, 14 laboratory setups

- Intel - SCR at 10 / 60 GHz and SPDR at 10/ 20 GHz
- Keysight - SCR at 10 / 20 / 28 / 40 / 80 GHz
- QWED - SPDR at 10/ 15 GHz and FPOR over 10-110GHz.

Dk spread < 1% (within ± 0.5% from average)
Divergence of BCDR Measurements More Pronounced for Fused Silica*

Considered causes of BCDR divergence:
- material anisotropy,
- error inherent in out-of-plane measurement,
- error in particular BCDR instrument.

* for further info on “iNEMI 5G SRM Project”, see talk (5.47) by Marzena this afternoon
Notes on BCDR

Disclaimer: this slide is NOT about QWED designs

Note: in the iNEMI benchmarking, different BCDRs are used by two project partners.

The photos and figures on this slide concern:

Open the resonator
Set lower side sample
Set shim sheet
Set center electrode
Set upper side sample

Close the resonator
Clamp and measure
Notes on BCDR: Air slots in In-Plane and Out-of-Plane Measurements – Small Air Slot in a Paralel-Plate Capacitor

- Error

Colour – material:
- Water
- Sapphire
- Teflon

Dashed lines: in-plane
slot tangential to E-Field

Continuous lines: out-of-plane
slot perpendicular to E-Field

in-plane: even for high Dk dielectrics, % error in Dk is significantly smaller that % of air gap
out-of-plane: % error in Dk increases faster than linearly with % air gap (here, 10% gap -> ~40% error in Dk of sapphire)
Notes on BCDR: QWED’s Electromagnetic Insight

green curve: sample $\varepsilon_r=3 \tan(\delta) = 0.005$ @ 80 GHz

red curve: air
Our BCDR prototype has been manufactured and works. Measurements confirm BCDR sensitivity to air gaps, even small, caused by roughness of metallic surfaces (electrodes). This is not a problem in SPDR (and other standard out-of-plane measurements)!

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QWED’s Novel Design for Thick Samples

patent filed last week
Challenges in Measuring (Thick) Industrial Samples

Relevant industrial samples, provided in iNEMI 5G Dielectrics” project for testing for automotive radar applications, could NOT be measured at mmWaves – they were only measured with low frequency SPDR (@1.1 GHz).

This is because all the available resonator techniques impose limits on sample thickness:
- mechanical – related to design of a particular instrument,
- electromagnetic – due to undesired modes appearing in the measurement band.

Typically:
- SPDR allows thicker samples than SCR, for given frequency,
- but SPDRs are offered only for lower frequencies.

Sample Thickness - SCR

Typically: sample needs to be thinner when:
- Dk is higher,
- frequency is higher.

Example:
In 15GHz SPDR, slot 0.6mm, 0.6mm sapphire can be measured.
In SCR even 10GHz, sapphire sample would need to be < 0.4mm

![Diagram showing sample thickness vs. Dk and frequency]

<table>
<thead>
<tr>
<th>Nominal frequency [GHz]</th>
<th>Maximum thickness of s [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>6.0</td>
</tr>
<tr>
<td>2.45 / 2.5</td>
<td>3.1</td>
</tr>
<tr>
<td>5 / 5.1</td>
<td>1.95</td>
</tr>
<tr>
<td>10</td>
<td>0.95</td>
</tr>
<tr>
<td>15</td>
<td>0.6</td>
</tr>
</tbody>
</table>

SPDR f [GHz] and slot [mm]

SPDR 15 GHz
QWED’s Novel SCR with Q-Choke

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Q-Choke

patent filed last week
Modelling of SCR without and with Q-Choke

- SCR
- SCR with Q-Choke

<table>
<thead>
<tr>
<th></th>
<th>S21</th>
<th>[dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>-110</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>-100</td>
<td></td>
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<tr>
<td>20</td>
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<td>25</td>
<td>-40</td>
<td></td>
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</tbody>
</table>

Frequency [GHz]

TE011
TM110
TM111
TM120
TM210
Measurements in Q-Choked SCR

- Empty
- 0.4 mm Sapphire
- 0.8 mm Sapphire
- 1.2 mm Sapphire

1.2 mm sapphire easily measured at 20 GHz
Conclusions

1. The talk has reported on iNEMI projects concerning assessment of materials and benchmarking of material measurement techniques for 5G/mmWave applications.

2. The “5G Substrates” project initiated rigorous benchmarking for substrate materials:
   - assembled tens of thousands of measurements by 11 labs with 4 techniques (in different implementations),
   - techniques: 3 for in-plane (SPDR, SCR, FPOR) and 1 for out-of-plane (BCDR) permittivity measurement,
   - samples: 2 sample sizes that cover all the techniques: 35mm x 45 mm and 90mm x 90mm,
   - materials: started with COP (186 µm) and Teflon (126 µm, 50 µm); then fused silica, rexolite, and industrial (automotive, electronics,..).

3. For inter-lab, inter-technique comparisons, average of 16 measurements (at a given lab by a given technique for a given sample) was used.
   - For in-plane techniques:
     - Dk spread (between the 3 metrologies) < 1% (2% incl. non-standard outliers),
     - QWED’s SPDR and FPOR well consistent, SCR and other FPORs are sometimes outliers,
     - sample-to-sample variation more significant than lab-to-lab or technique-to-technique (presumably sample thickness variations),
     - for COP at f > 40GHz, 2x increase in Df demonstrated compared to 10GHz loss.
   - For out-of-plane (BCDR), Dk measurements:
     - diverges from in-plane for (presumably) isotropic samples (up to 3-7% for fused silica),
     - vary in frequency,
     - the effects remain to be explained by BCDR designers / vendors or by use of other out-of-plane measurements.

4. The work continues in ongoing projects, including on “5G Copper Foils” and “5G SRMs” (see talk 5.47)
Conclusions

1. QWED material measurement methods and instruments have been presented:
   - for different frequency bands (within 1.1 -120 GHz),
   - for different materials (substrates, coper foils, liquids, 2D materials,...)

2. Insight into the physics behind the applied methods and instruments has been provided, by modelling in QuickWave™ simulation software by QWED.

3. In both qualitative and quantitative terms, the presented methods and instruments prove advantageous, in the context of the international benchmarking inititaives coordinated by iNEMI.

4. Recent developments have been indicated:
   - 2D imagining of dielectric surfaces of resistive films with 2D SPDR or iSiPDR scanners,
   - BCDR for out-of-plane measurements (and testing of the BCDR concept),
   - Q-Choked SCR for 20 GHz (scheduled 304, 40, 50 GHz) alleviating the existing limits on sample thickness.

5. QWED is happy to design custom-made instruments and enter into joint R&D projects!!!
Invitations & Acknowledgements.
5G/mmWave
- mmWave Permittivity Reference Material Development
- Also see Roadmap: 5G/6G mmWave Materials and Electrical Test Technology Roadmap (5G/6G MAESTRO)

Board Assembly
- Bi-Sn Based Low-Temperature Soldering Process and Reliability
- Characterization of Third Generation High-Reliability Pb-Free Alloys
- Conformal Coating Evaluation for Environmental Protection against Corrosive Environments, Phase 3
- Connector Reliability Test Recommendations, Phase 3
- Electromigration of SnBi Solder for Second-Level Interconnect
- QFN Package Board Level Reliability

Optoelectronics
- Best Practices for Expanded Beam Connectors in Data Centers

Packaging
- Impact of Low CTE Mold Compound on Second-Level Board Reliability, Phase 2
- Low Temperature Material Discovery and Characterization for First Level Interconnect
- Moisture Induced Expansion Metrology for Packaging Polymeric Materials Project, Phase 1
- FLP Fine Pitch Substrate Inspection/Metrology, Phase 4
- RDL Adhesion Strength Measurement Project
- Warpage Characterization and Management Program
  - High Density Interconnect Socket Warpage Prediction and Characterization

PCB & Laminates
- Reliability & Loss Properties of Copper Foils for 5G Applications
- PCBA Materials for Harsh Environments, Phase 2
- Hybrid PCBs for Next Generation Applications
- PCB Characterization for CAF and ECM Failure Mitigation
- PCB Connector Footprint Tolerance

https://www.inemi.org/in%20progress
New and improved materials and the use of existing materials in new applications are a key factor for the success and sustainability of European industry and society in general.

EMMC considers the integration of materials modelling & digitalisation critical for more agile and sustainable materials & product development.

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Calls for Papers https://ieee-jmmct.org/calls-for-papers/

Special Section on Computational Modeling for Microwave Processing and Characterization of Materials
Modeling Methods for Wave Propagation in Wireless Systems
Quantum Computational Electromagnetics: From Nanoscale Modelling to Algorithms
International Conference on Computation in Electromagnetics (CEM2023)
ANNUAL Special Section on Women in Computational Physics
ANNUAL Computational Electromagnetics for Industry Applications

Quick Facts!

Impact Factor: 2.3
CiteScore: 3.7 ↑
IEEE Xplore Usage: ~100 downloads per paper, 8.4+ citations per paper ↑
Average time from submission to first decision: 47 days
to my Father,
MSc in engineering with PhD in economics,
Sybirak - survivor of Soviet deportation to Siberia

1º because it is his birthday

2º because I find myself more & more following his footsteps

3º with an appeal for a sustained response
to Russia’s invasion of Ukraine
to prevent Siberia happening to my grandchildren
Acknowledgements

The authors wish to thank all the partners of the iNEMI 5G project for their great collaboration in the benchmarking activities.

Our special thanks go to:

Coordinator: Urmi Ray (iNEMI),
Industry: Mike Hill (Intel), Hanna Kahari (Nokia), Charles Hill (3M)
Say Phomakesone and Daisuke Kato (Keysight)
NMIs: Nate Orloff and Lucas Enright (NIST), Chiwen Lee and Chang-Sheng Chen (ITRI)

QWED R&D work is currently co-funded by the Polish National Centre for Research and Development under contracts M-ERA.NET2/2020/1/2021 (ULTCC6G_Epac) and M-ERA.NET3/2021/83/I4BAGS/2022.