IWWE6

mmWave Permittivity Standard Reference Material Development

International Electronics Manufacturing Initiative

Outline

Review of the iNEMI project objectives and goals in a view of 5G industry needs for traceable materials' characterization

Say Phommakesone (Keysight Technologies, USA)

Review of the efforts on developing traceable permittivity standard reference material

Nate Orloff (NIST, USA)

Review of the iNEMI round-robin SRM candidate material characterisation results and challenges

Marzena Olszewska-Placha (QWED, Poland)

5G/6G mmWave Materials and Electrical Test Technology Roadmap

Urmi Ray (INEMI, USA)

Acknowledgement

Special thanks to the entire working group

Lucas Enright[1], Michael Hill[2], Charles A. Hill[3], Hanna Kähäri[4],
Chiawen Lee[5], Daisuke Kato[6], Chang-Sheng Chen[5]

[1] *National Institute of Standards and Technology, USA*

[2]*Intel Corporation, USA*

[3]*3M Company, USA*

[4]*Nokia Corporation, Finland*

[5]*Industrial Technology Research Institute, Taiwan*

[6]*Keysight Technologies, USA*

Review of the iNEMI project objectives and goals in a view of 5G industry needs for traceable materials' characterization

Say Phommakesone (Keysight Technologies)

Say_phommakesone@keysight.com

iNEMI International Electronics Manufacturing Initiative
intel
QWED
3M
KEYSIGHT TECHNOLOGIES
Panasonic
SHOWA DENKO
ITRI Industrial Technology Research Institute
NOKIA

5G/mmWave Materials Assessment & Characterization

Motivation:

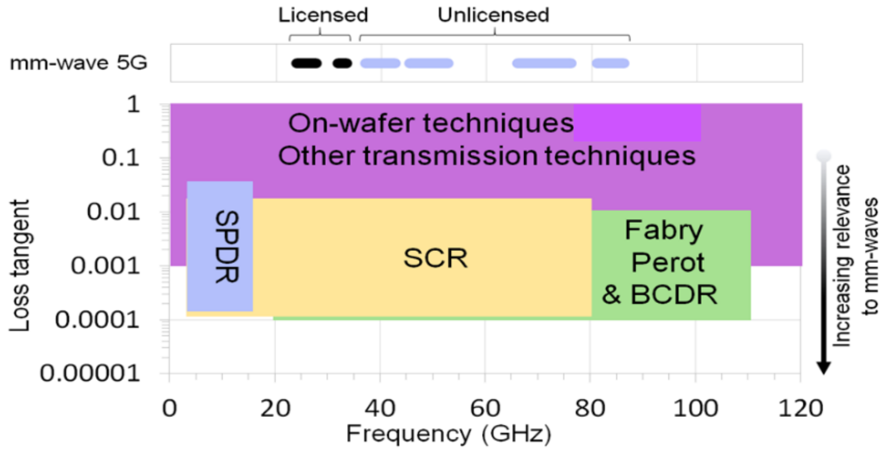
- 5G Solutions require ultra-low loss laminate materials and PCBs/substrates for efficient design of 5G communications equipment
- The existing transmission loss or Df/Dk measurement methodology lacks consistency, especially for higher frequency measurements (such as 30-100GHz)
- Many different test methods currently in the industry, require different fixtures and test methods/sample preparation/data analysis/extraction
- Industry needs standardized measurement methods and reference materials

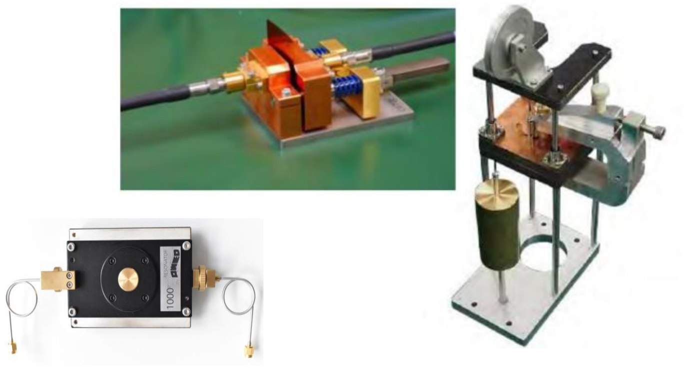
Objective:

- Develop consistent Df/Dk measurement methodologies for characterizing ultra low loss laminate materials in the range of 30 – 100GHz
- Provide guidelines and best practices to the industry

Strategy/Approach:

- Benchmark existing measurement methodologies and reference materials
- Develop guideline of standardized method of Dk, Df measurement based on round robin testing
- Propose “standard” test coupons for industry wide application (Phase 2)





Industry Collaboration Brought Together by iNEMI

Approach for Solving Problem:

- Bring together Cross-functional team spanning industry Value Chain
- iNEMI Project team members cover wide range of industry, academia and equipment suppliers

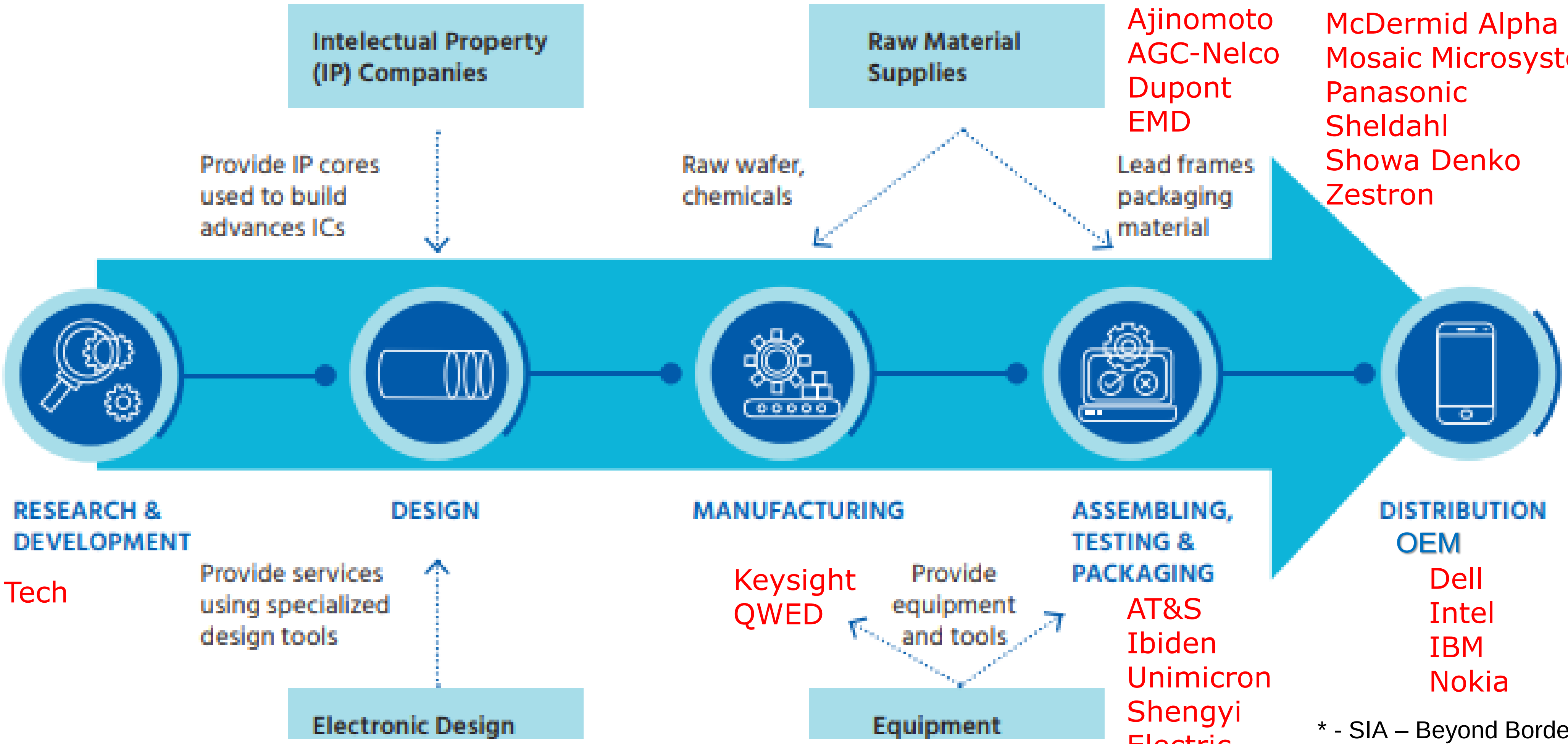
Deliverable:

- 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
- 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

iNEMI 5G Project Team – Spanning across Supply Chain



Georgia Tech
NIST
ITRI
CFT

Keysight
QWED

3M
Ajinomoto
AGC-Nelco
Dupont
EMD

Isola
McDermid Alpha
Mosaic Microsystems
Panasonic
Sheldahl
Showa Denko
Zestron

AT&S
Ibiden
Unimicron
Shengyi Electric

OEM
Dell
Intel
IBM
Nokia

* - SIA – Beyond Borders

iNEMI 5G Materials Project Members

Project Goals

- Gather industry experts to understand needs and address these problems
- Development of traceable material references by standards organizations
- 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

Report complete ✓

Task 4

Extension to advanced substrate materials
- Commercial material testing

Report complete ✓

Reports can be downloaded from project site, using iNEMI login
https://www.inemi.org/5g-mat-assessment

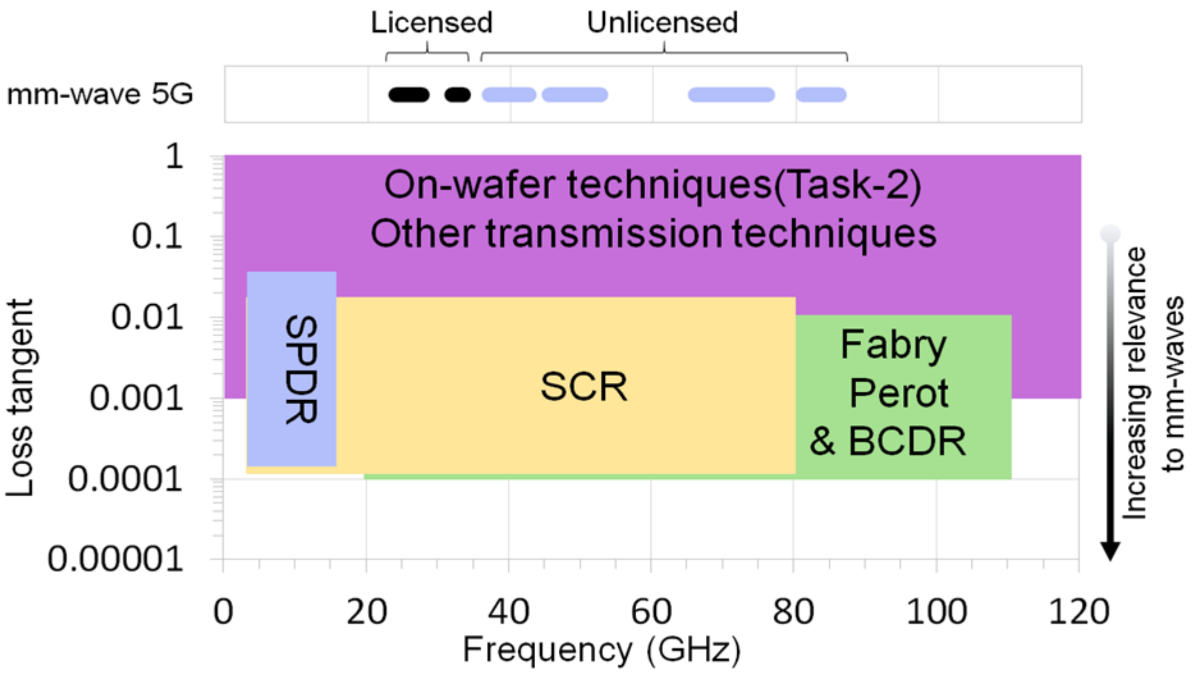
Task 1 Report Oct 2021

Benchmarking Available Measurement Methods

Task 1: 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).

Map of available techniques vs Frequency



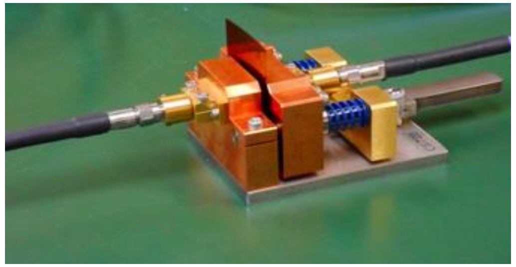
Resonator-based measurement

Split-post dielectric resonator (SPDR)

Discrete frequency points from 1 GHz up to 15 GHz

Split cylinder resonator (SCR)

Discrete frequency points from 10 GHz up to 80 GHz

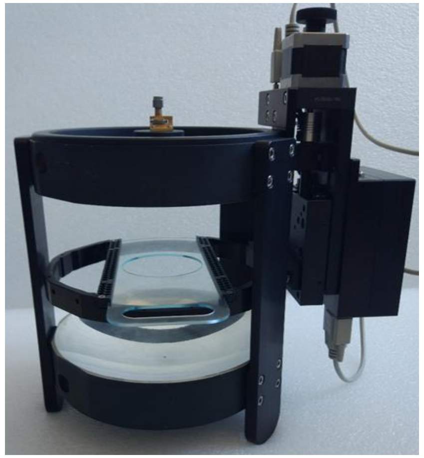


Balanced-type circular disk resonator (BCDR)

Multiple discrete frequencies from 10 GHz up to 120 GHz

Fabry-Perot open resonator (FPOR, also called open-cavity)

Discrete frequencies between 20 GHz up to 110 GHz



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**
- https://www.qwed.com.pl/resonators_spdr.html
- https://www.keysight.com/us/en/assets/7018-01416/application-notes/5989-5384.pdf

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**
- https://www.keysight.com/us/en/assets/7018-06384/brochures/5992-3438.pdf

Resonator-based measurement

BCDR

- High measurement precision
- Requires full 2-port calibration (mechanical to 110 GHz or electrical to 67 GHz)
- Out-of-plane component of permittivity (typically)
- Typical sample thicknesses less than 1 mm
- **IEC 63185**
- https://www.keysight.com/us/en/assets/7120-1214/flyers/N1501AE11-67-Balanced-Type-Circular-Disk-Resonator-BCDR.pdf

FPOR

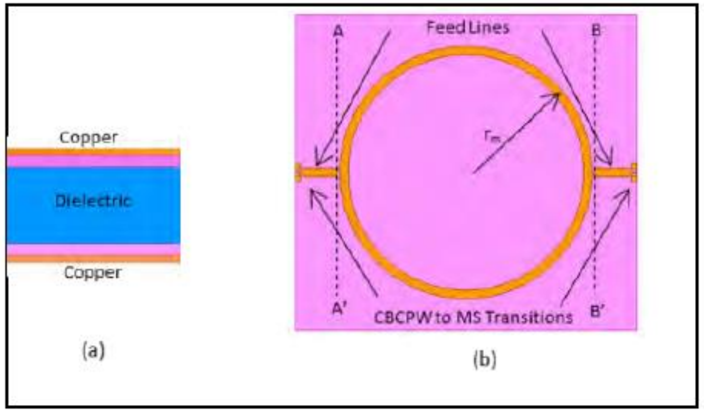
- High measurement precision
- Can be sensitive to user errors
- Uncertainty increases with increasing frequency
- In-plane component of permittivity (typically)
- **JIS R1660-2**
- https://www.qwed.com.pl/resonators.html#ResonatorFPOR
- https://www.keysight.com/main/editorial.jspx?cc=US&lc=eng&ckey=2276755&nid=null&id=2276755

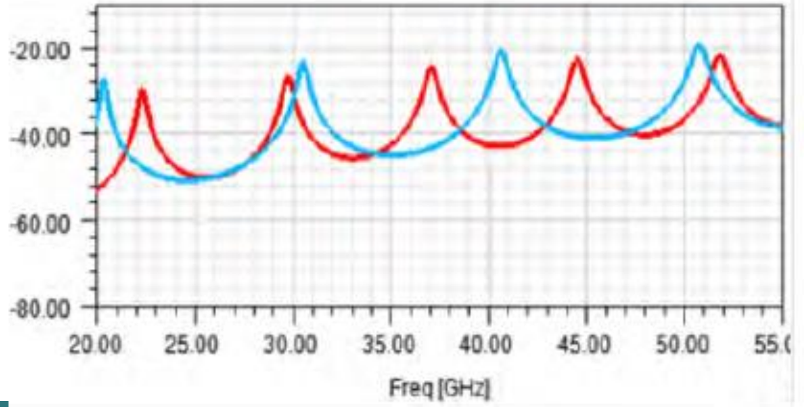
Task 2 Report Nov 2021

Benchmarking EMERGING Measurement Methods

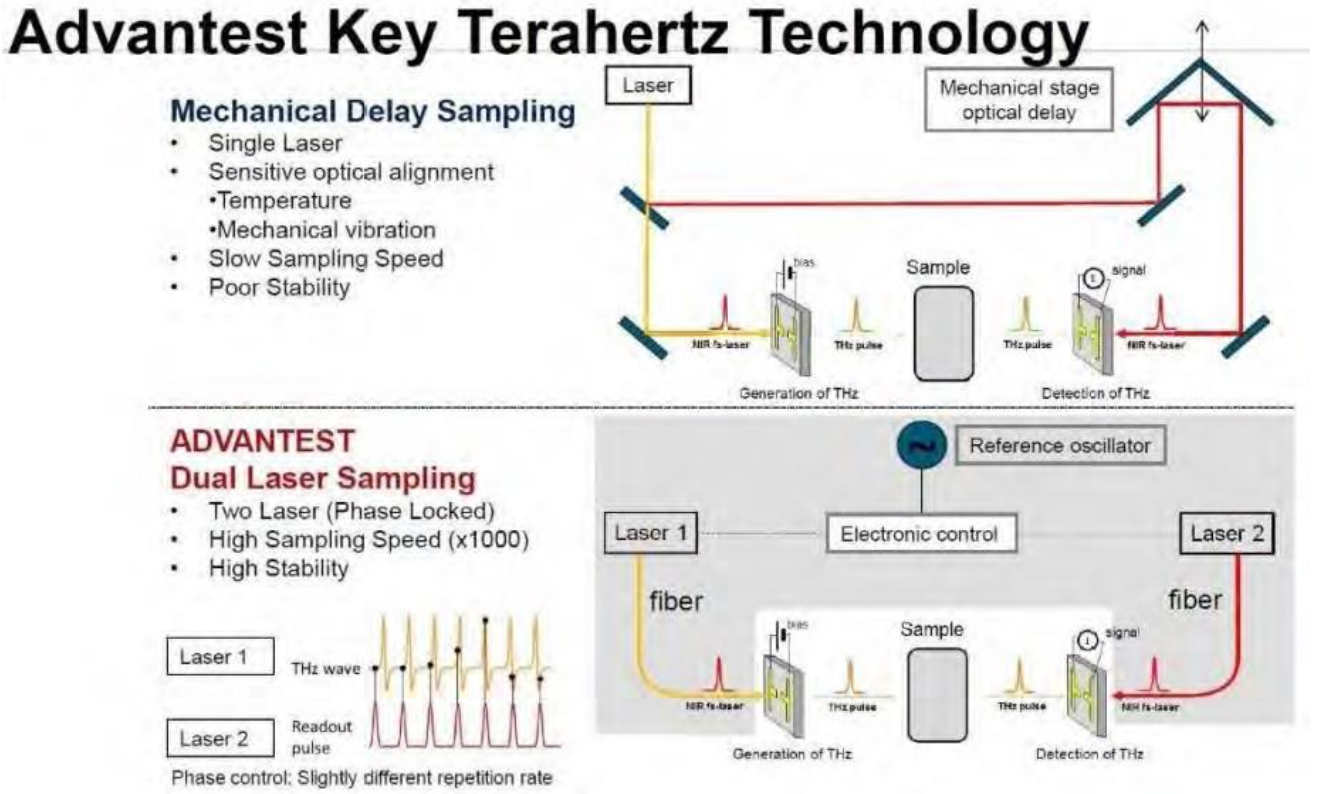
Wafer-Level Measurements and Time Domain Techniques

Microstrip ring resonator (MRR) and coplanar waveguide (CPW) methods





Time domain spectroscopy



Advantest Key Terahertz Technology

Mechanical Delay Sampling

- Single Laser
- Sensitive optical alignment
  - •Temperature
  - •Mechanical vibration
- Slow Sampling Speed
- Poor Stability

ADVANTEST
Dual Laser Sampling

- Two Laser (Phase Locked)
- High Sampling Speed (x1000)
- High Stability

Phase control: Slightly different repetition rate

Task 2 Key Takeaway

- Multiple different resonator-based measurement techniques exist
- Techniques are based on complex physics and require careful sample preparation and attention to “standard operating procedures”, including, but not limited to:
  - Standard reference material
  - Sample Thickness measurement
  - Effect of room temperature and humidity
- Recommendation:
  - Interlaboratory comparison of resonator-based measurement techniques (Round Robin study) – Task 3

Task 3

Global Interlaboratory Comparison

Round Robin Study 1 and 2

Round Robin Overview – Task 3

Sample Material Requirements

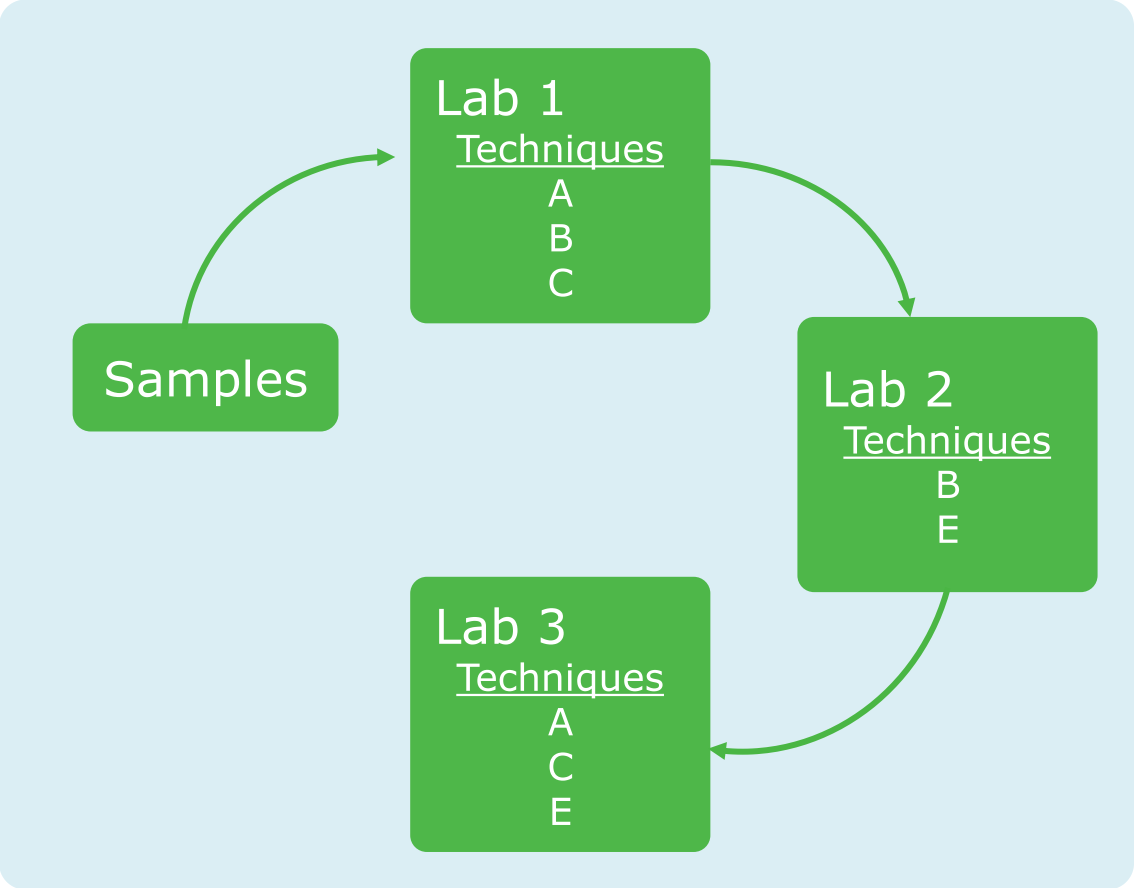
- Stable, Low loss
- Low moisture absorption / temperature dependency
- Isotropic
- Good mechanical & handling properties

Selection for RR1 and 2

- Precision Teflon
- Cyclo Olefin Polymer

Future additions

- Rexolite
- Fused Silica


Samples

Lab 1
Techniques
A
B
C

Lab 2
Techniques
B
E

Lab 3
Techniques
A
C
E

9/10 Laboratories Effort

Reference Sample

Survey of commercial resonators and frequency space resulted in choice of two sample sizes to cover frequency range 10GHz to 100GHz)

Sample	Sample Size	Reference
Teflon 50um	35 mm x 45 mm	DuPont™ Teflon® FEP, Type A
Teflon 125um	35 mm x 45 mm	DuPont™ Teflon® FEP, Type A
Teflon 50um	90 mm x 90 mm	DuPont™ Teflon® FEP, Type A
Teflon 125um	90 mm x 90 mm	DuPont™ Teflon® FEP, Type A
COP 188um	90 mm x 90 mm	Zeonex Cycloolefin Polymer ZF14-188
COP 188um	35 mm x 45 mm	Zeonex Cycloolefin Polymer ZF14-188

Round Robin Overview – Task 3

10 Kits Created

- Sample sizes 35 mm x 45 mm, 90 mm x 90 mm
- 9 International labs participating

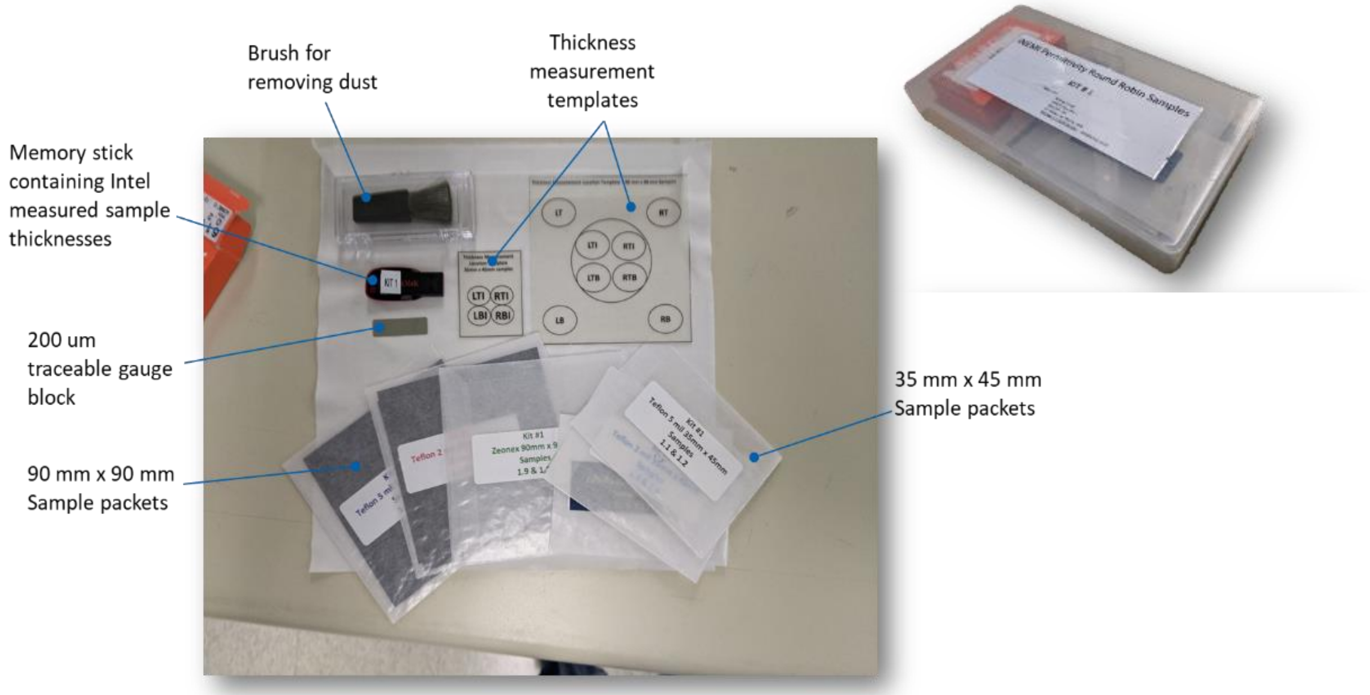
Techniques included

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

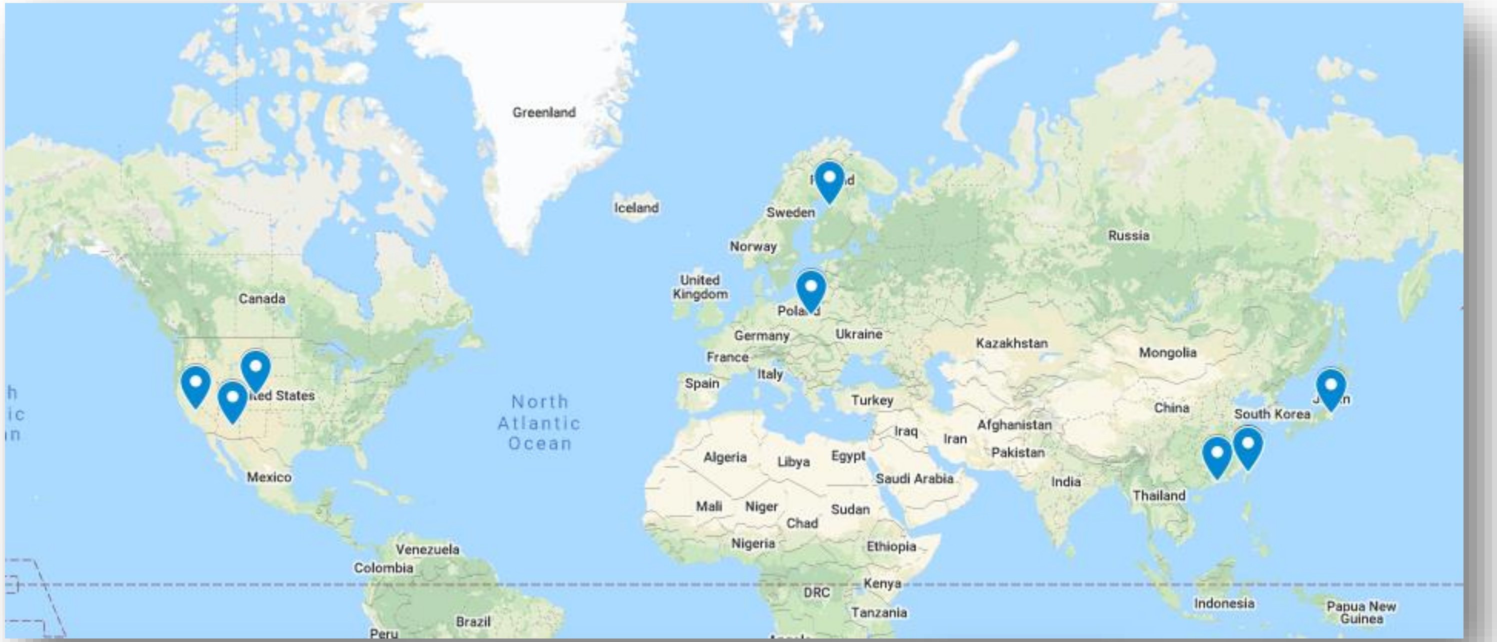
Frequency Span : 10GHz – 100GHz

Goals

1. High level – how much agreement is there in results
2. Thickness – how closely do labs assess thickness
3. Understand sample quality, handling and sizing / compatibility
4. Understand practicality of techniques
5. Look for obvious biases between equipment types
6. Look for frequency dependency at higher frequencies
7. **Do we need traceable standards?**



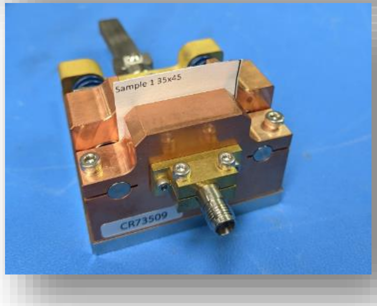
Task 3: Round Robin Experiment



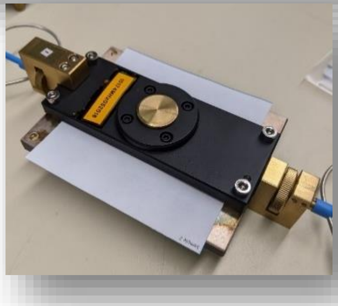
Round Robin Test Labs

3M: USA
Dupont:USA
Intel: USA
ITEQ: Taiwan
ITRI: Taiwan
QWED: Poland

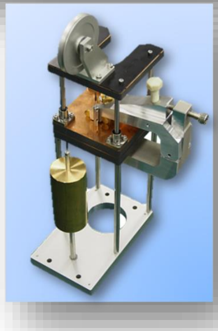
Keysight: USA
Nokia: Finland
NIST: USA
Showa-Denko: Japan
Shengyi Electric: China



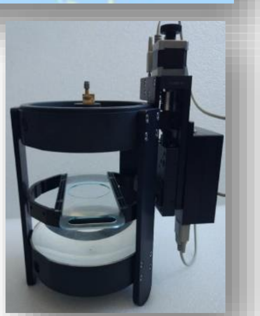
SCR
(Split Cavity Resonator)



SPDR
(Split Post Dielectric Resonator)

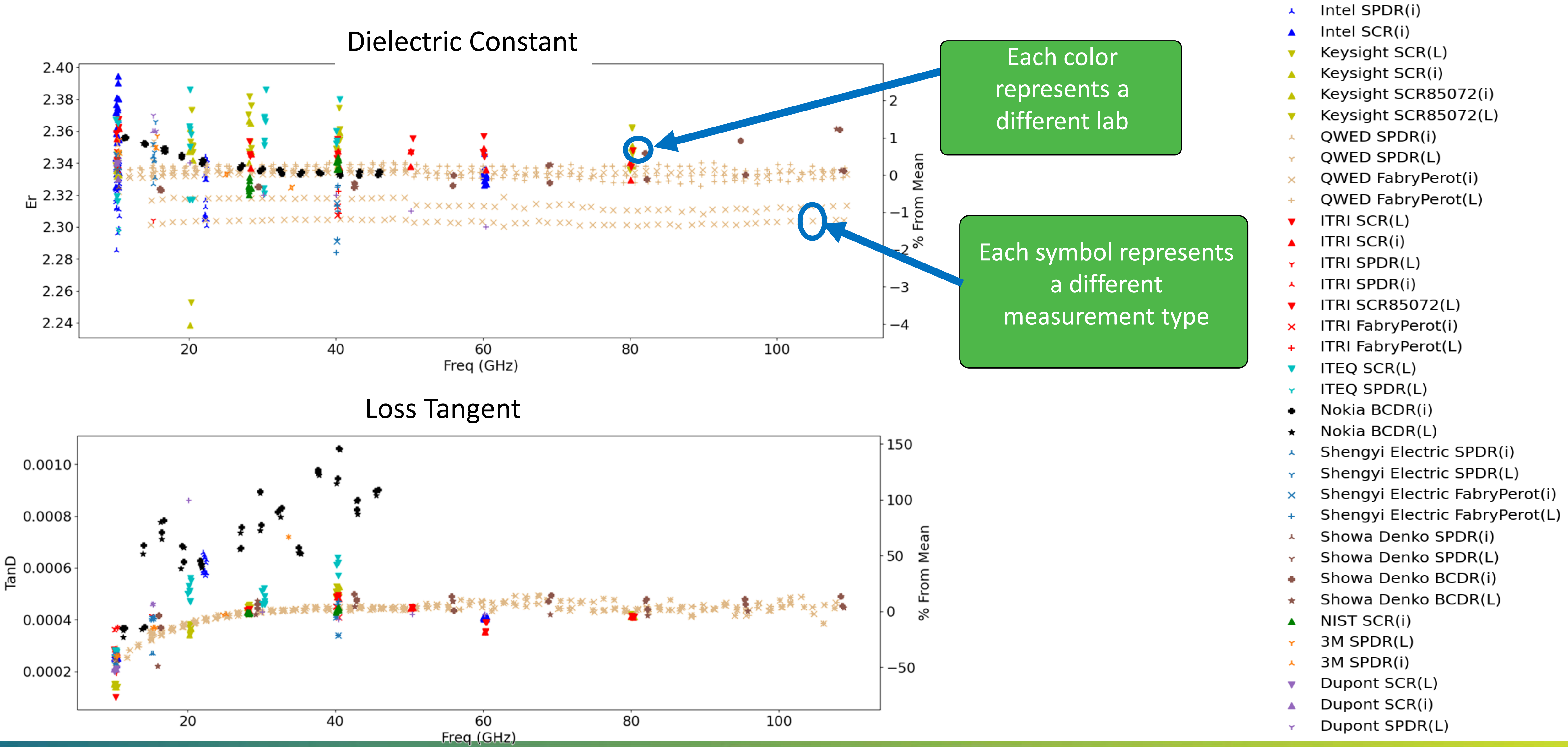


BCDR
(Balanced Circular Disk Resonator)



FPOR
(Fabry-Perot Open Resonator)

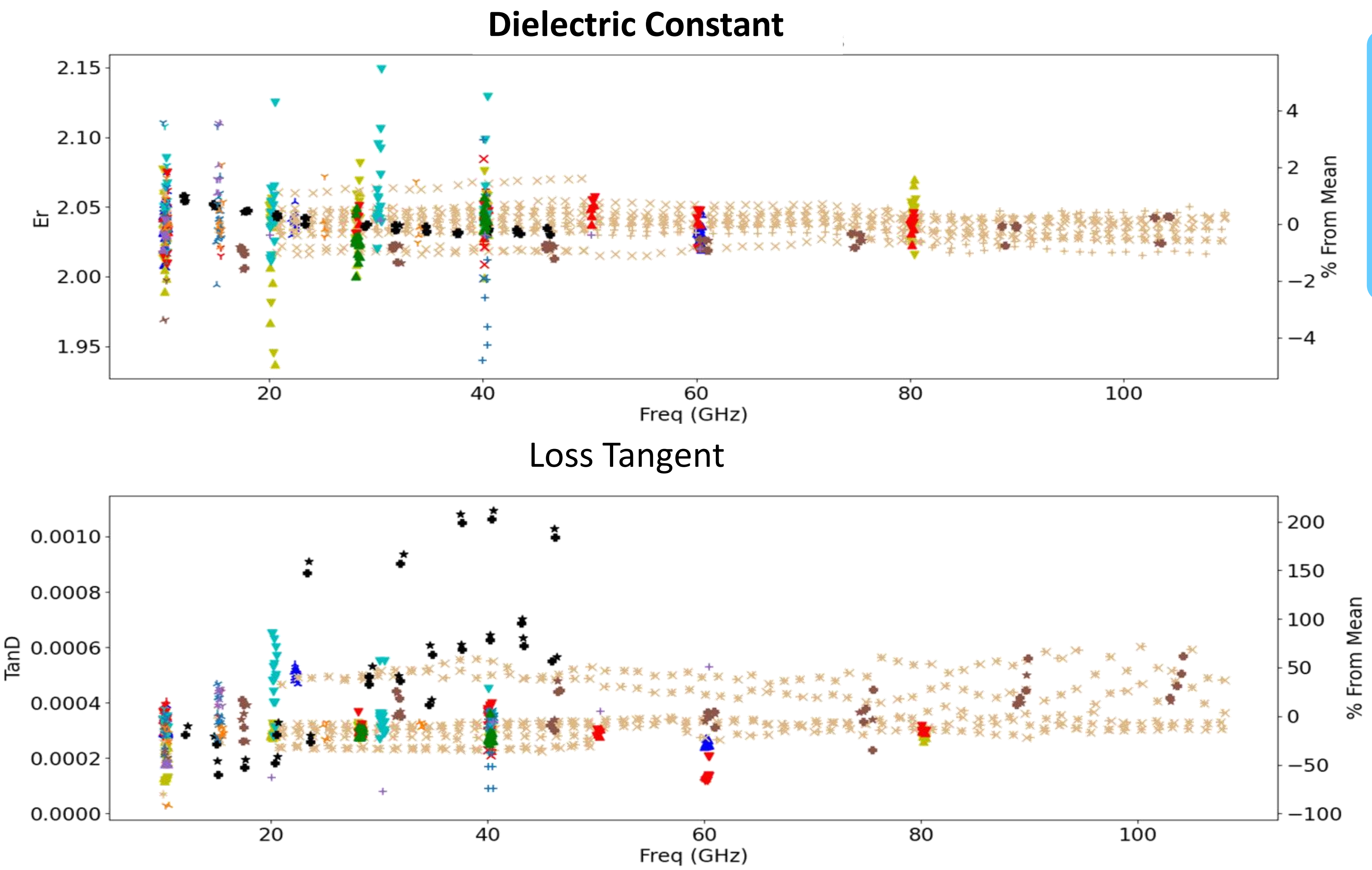
COP Results



Each color represents a different lab

Each symbol represents a different measurement type

Teflon Results



Almost 'ideal' samples:

- ±2% Range for ε_r
- ±0.0002 to ±0.0004 for TanD

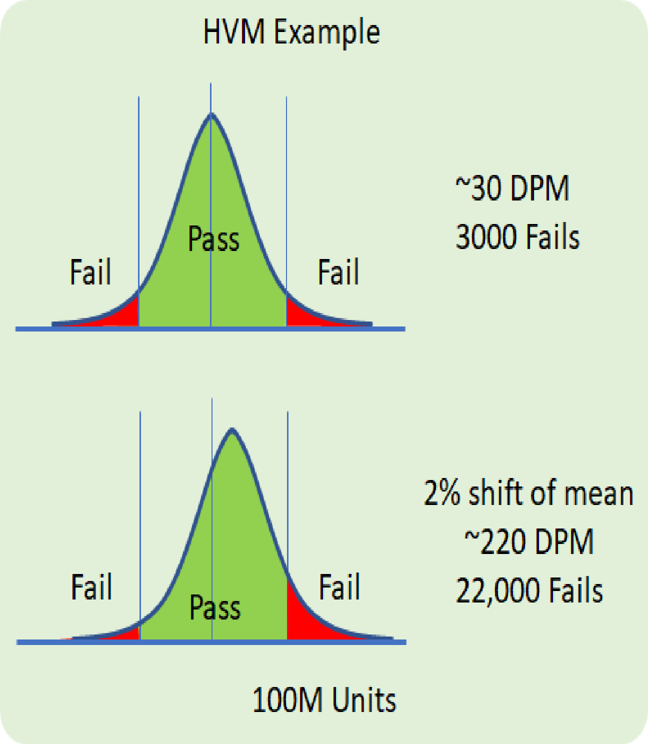
- Unknown accuracy

Is this good?

- Better than many expected
  - Lots of potential lab variations yet results are very good for 'perfect' samples
  - Even within a lab ±2% can be challenging for complicated metrologies

- But – for many applications this is not good enough
  - ±2% error could cause design cycle – customer & supplier could differ by 4%
  - Offset mean values can impact HVM distribution tails & DPMs
  - Intel example – this would cause noticeable miscorrelation with design
  - Real, imperfect samples worse

- Reproducibility does not ensure accuracy
  - Certified standard references still needed
  - Accuracy is very important; we have no way to assess it today



A Year of effort to do this study. If SRM was available, labs would have been able to validate measurement tools independently

Goals – how did we do?

1. High level – how much agreement is there in results?
   Best case samples – don't expect better than ±2%, real samples worse

2. Thickness – how closely do labs assess thickness?
   Labs using similar micrometers and averaging yields ~0.2-0.5% differences in numerical results

3. Understand sample quality, handling and sizing / compatibility
   Sample quality, TTV & flatness is a key limiter, equipment compatibility is challenging

4. Understand practicality of techniques
   Limited experience / skills & speed – SCR & SPDR, benefits of FPOR, BCDR require more experience

5. Look for obvious biases between equipment types
   No obvious biases with given sample sizes, except in industrial materials where anisotropy is visible

6. Look for frequency dependency at higher frequencies
   COP & Teflon appear to be very constant at mmWave frequencies, however, without traceability the confidence in this statement is not clear and we have to rely heavily on BCDR and FPOR results for this claim

7. **Do we need traceable standards?**
   Yes – Further progress in this space is difficult without a high confidence, known reference

Round 2 Kit **Alignment**

- Kit alignment is complicated
  - Sample size compatibility vs method vs lab tools
  - Want good mix of sample – method – lab to get good overlap

Round 1:
Kit 2 NIST 6 samples measured, 1 methods, max 40GHz
Kit 3 Keysight 12 samples measured, 2 methods, max 80 GHz
Kit 4 QWED 12 samples measured, 2 methods (*FP), max 110
Kit 5 ITRI 6 samples measured, 2 methods, max 60GHz
Kit 6 ITEQ 12 samples measured, 2 methods, max 40GHz
Kit 7 Nokia 2 samples measured, 1 methods (*BCDR), max 46GHz (90x90)
Kit 8 Shengyi Electric 12 samples measured, 1 methods, max 15GHz
Kit 9 Showa Denko 6 samples measured, 2 methods (*BCDR), max 110GHz (45x35)

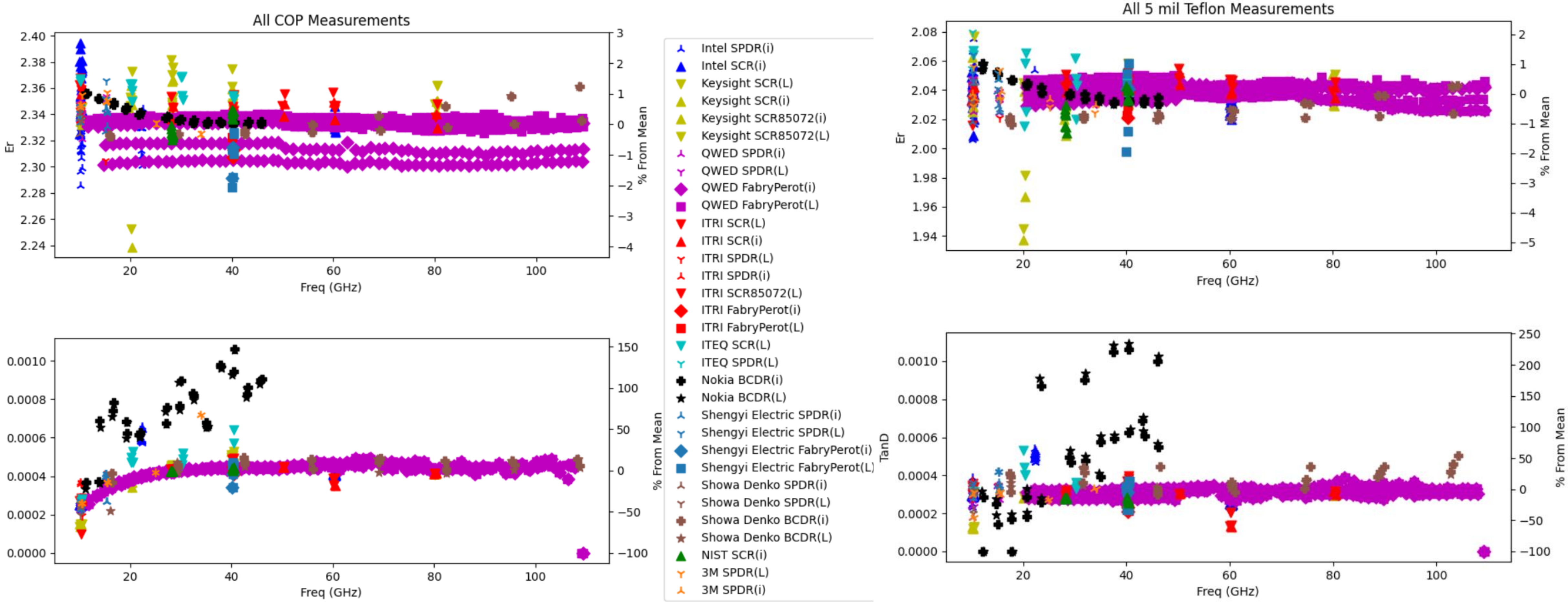
Round 2:
Kit 2->Keysight
Kit 3->NIST
Kit 4->Showa Denko
Kit 5->Nokia
Kit 6->Shengyi Electric
Kit 7->ITRI
Kit 8->ITEQ
Kit 9->QWED

Selection seems to give a reasonable compromise between all the constraints

RR 2 Status

- Qualitative ideas we ultimately want to check:
  - Average thickness assessment matters but may not be totally dominant in variation
  - Lab to lab differences for a specific sample seem less than assuming all samples are the same
  - Do we see frequency dependence in these materials above 10GHz
- “Blind” assessment of material
  - ±2% for ε_r
  - ±0.0002 to ±0.0004 for TanD (for these very low loss samples – may not translate to typical materials)

Current Full Data Set (Both Rounds)



Task 4: “Commercial material testing”

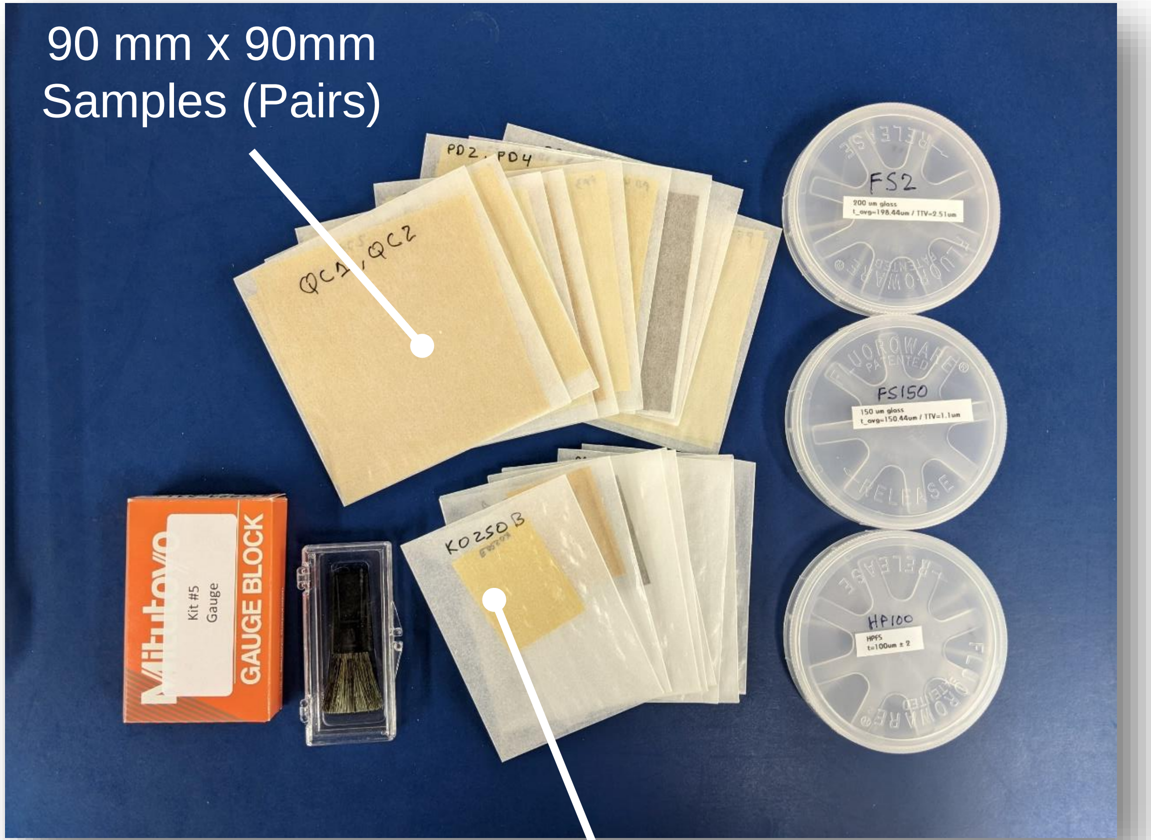
Materials are real, practical substrate materials submitted by industry representatives in the iNEMI group. Also included are Reference samples: Fused Silica and Rexolite

Task 4 Goal:

Seeks to validate the findings of Task 3 by showing that these same measurements are effective on real materials from multiple sectors of industry.

The electronics sample kit looks like

Electronics sample kit: 34 samples from 7 sources



90 mm x 90mm Samples (Pairs)

35 mm x 45 mm samples

Fused Silica samples

- Thicknesses: 60 um – 300 um
- Dielectric constants: 2.2 - 5
- Isotropic and anisotropic samples

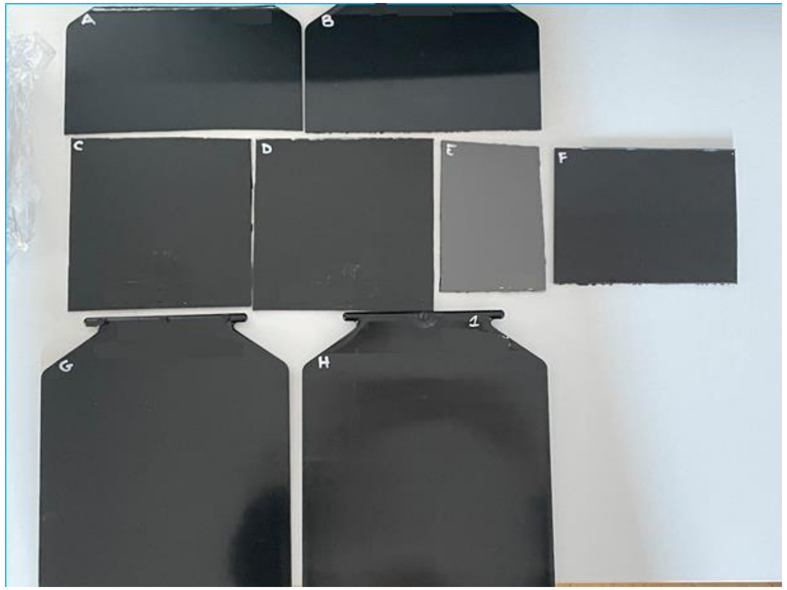
The other kit included some more challenging samples...

The automotive sample kit

- Thicknesses: up to 4 mm
- Composites (thin film on substrate)
- Limited measurement options

Automotive sample kit: 17 samples

Bumper materials



Foils

Limited Number of Test Labs for Efficiency and Schedule

- Keysight
- Intel
- NIST

US Labs

- QWED
- Nokia

EU Labs

Samples submitted by global project members from USA, EU and Asia

Task 4 Key takeaways

- Two sample sizes sufficient to cover all considered test methods (35 mm x 45 mm and 90 mm x 90 mm)
- Accurate **thickness evaluation** and low thickness variation are of high importance
- Results variation of 2% - 5%

- Standard reference materials are of high interest

Disclaimers to the Task 4 results

1. Limited sample size
   - 5 labs total, 3 labs max on one physical sample
   - Compared samples cut from the same material
   - Significant overlap in instrumentation

2. We are all measuring the same kit
   - Sample-to-sample variation is not as well captured

3. We are all using the same thickness measurements*
   - Most direct possible comparison of microwave measurements
   - Removes variation coming from different thickness measurement capabilities between labs

The electronics samples expanded range of Er’ and TanD values

This image cannot currently be displayed.

Real part of permittivity

↕ Task 3 range

This image cannot currently be displayed.

Loss tangent

In just the electronics samples, we cover broad range of frequencies and materials

Summary – Task 4

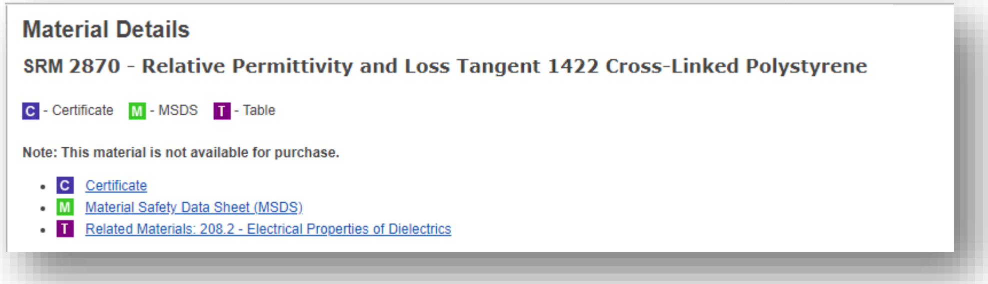
- We are able to measure real materials as well as PTFE & COP
- Results variation across labs is on average +/- 2% for real materials
- Thickness measurement challenges
  - ❖1 um error on 100 um sample leads to 1% change in measured ε
- No unexpected challenges (handling/set up, shelf life) with thickness (60 um – 300 um) or permittivity (2 – 4)
- Only 2 sample geometries needed
- More challenging materials can be measured with specific measurement setups

Limitation – Lack of Standards

- No NIST traceable standards exist
- Previously available standard discontinued

Why not redevelop previous SRM?

SRM 2870
Permittivity & Loss Tangent



Material Details

SRM 2870 - Relative Permittivity and Loss Tangent 1422 Cross-Linked Polystyrene

C - Certificate M - MSDS T - Table

Note: This material is not available for purchase.

- C Certificate
- M Material Safety Data Sheet (MSDS)
- T Related Materials: 208.2 - Electrical Properties of Dielectrics

Currently Available for Purchase!

SRM 2387
NIST Peanut Butter

SRM 3290
Dry Cat Food

Material Measurement Laboratory
Standard Reference Materials
SRM Online Request System
NIST
National Institute of Standards and Technology

*** Updated SRM Shipping Information 4/3/2020 ***

Login | My Account | View Cart | Checkout

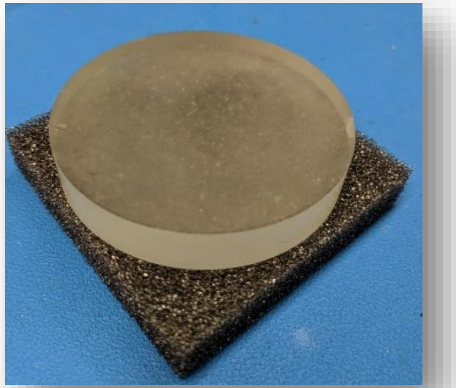
Material Details

SRM 3290 - Dry Cat Food

C - Certificate M - MSDS T - Table

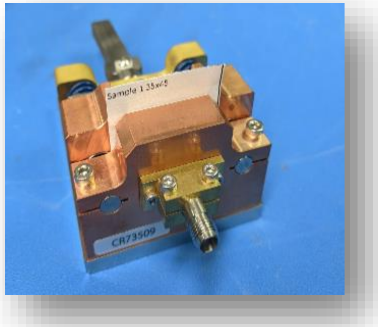
Previous Generation NIST SRM
SRM 2870

- Too thick for low loss mmWave methods shown below
- Required difficult to source machining to thin sample, ruining traceability
- X-Y dimensions of thinned sample still incompatible with most tools
- Certified only at 10 GHz – too low for mmWave / 5&6 G

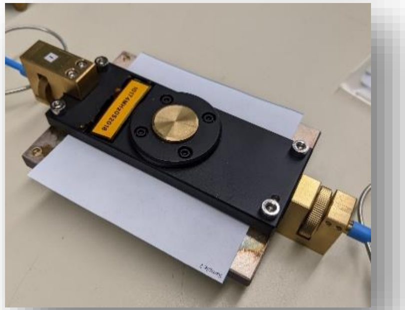


SRM 2870
Permittivity & Loss Tangent

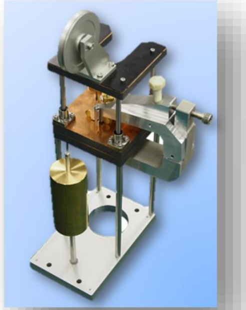
Today, all permittivity tool vendors are operating without traceable standards for validating tool sets



SCR



SPDR

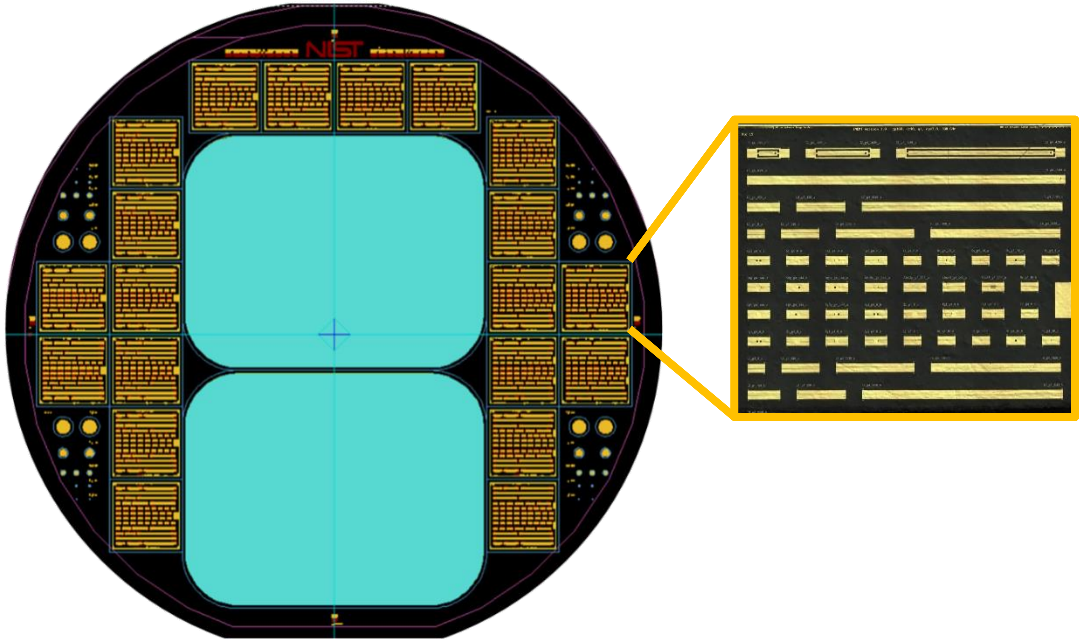


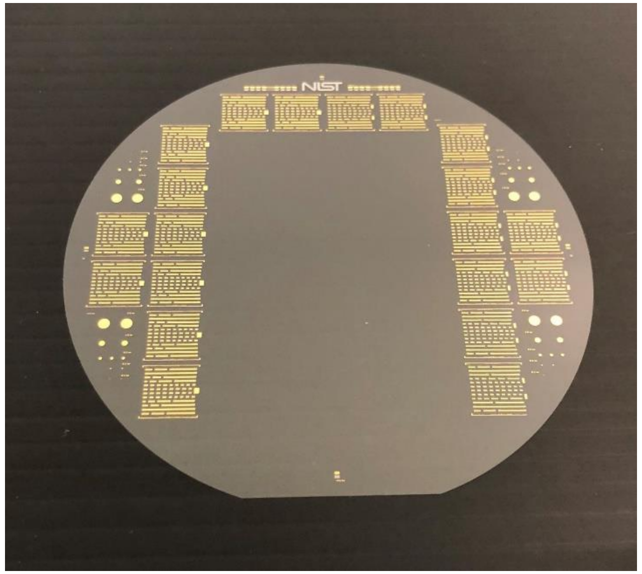
BCDR

FPOR

Where do we go from here?

- New iNEMI project – “5G Reference Material Development”
- Project kick-off Jun 16, 2022
- Contact Urmi Ray for further info) urmi.ray@inemi.org





Thank you for the attention

Review of the efforts on developing traceable permittivity standard reference material

Nate Orloff (NIST)

National Institute of
Standards and Technology
U.S. Department of Commerce

Complex permittivity standard reference materials

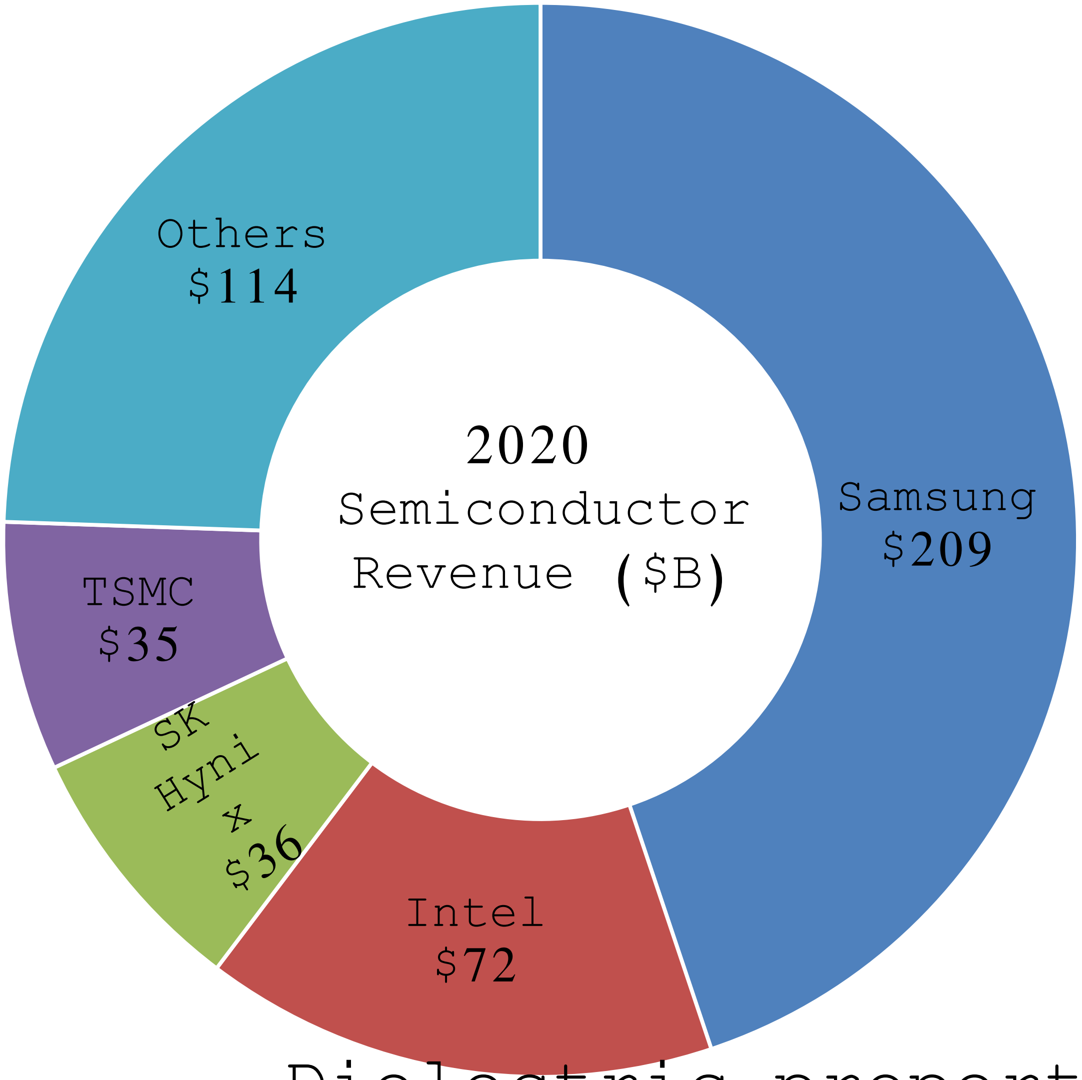
Nate Orloff

Lucas Enright, Nick Jungwirth, Bryan Bosworth, Chris Long, Jim Booth

NIST Semiconductor Series

Semiconductor manufacturer's measurement problem

Semiconductor Industry Association



iNEMI 5G Materials Characterization Project Report I:

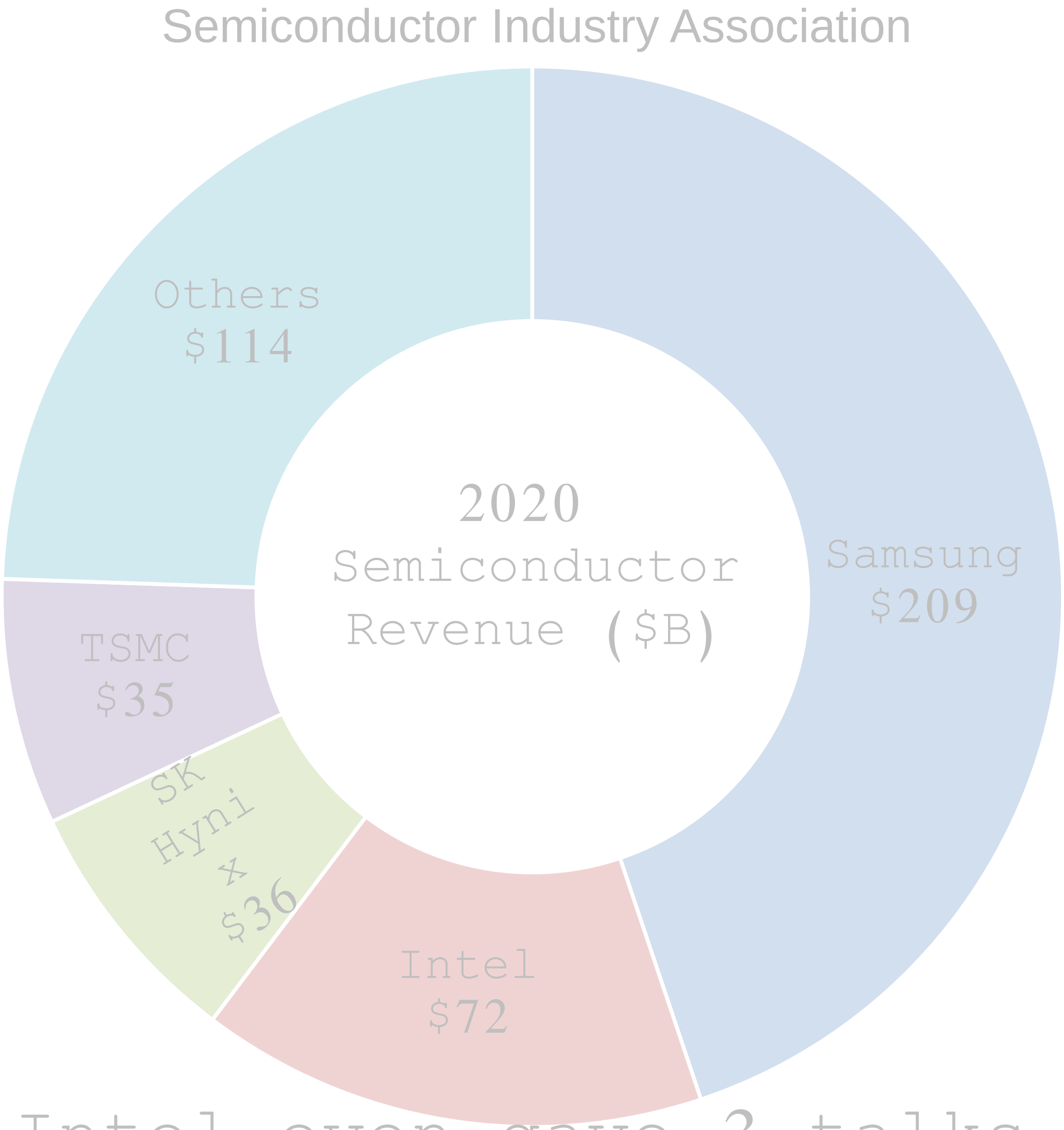
> "The lack of traceable reference material for mmWaves is a very serious problem. This lack makes verification of measurement methods and laboratory techniques impossible in an industry setting."

SRC Research Needs: Packaging

> "Dielectric characterization up to 500 GHz and beyond. Scope includes anisotropic and inhomogeneous materials… High-frequency and high-temperature dielectric characterization of low-loss materials (encapsulants, mold compounds, substrates, etc.)."

Dielectric properties impact all microelectronics manufacturing

Semiconductor manufacturer's measurement problem



iNEMI 5G Materials Characterization Project Report I:

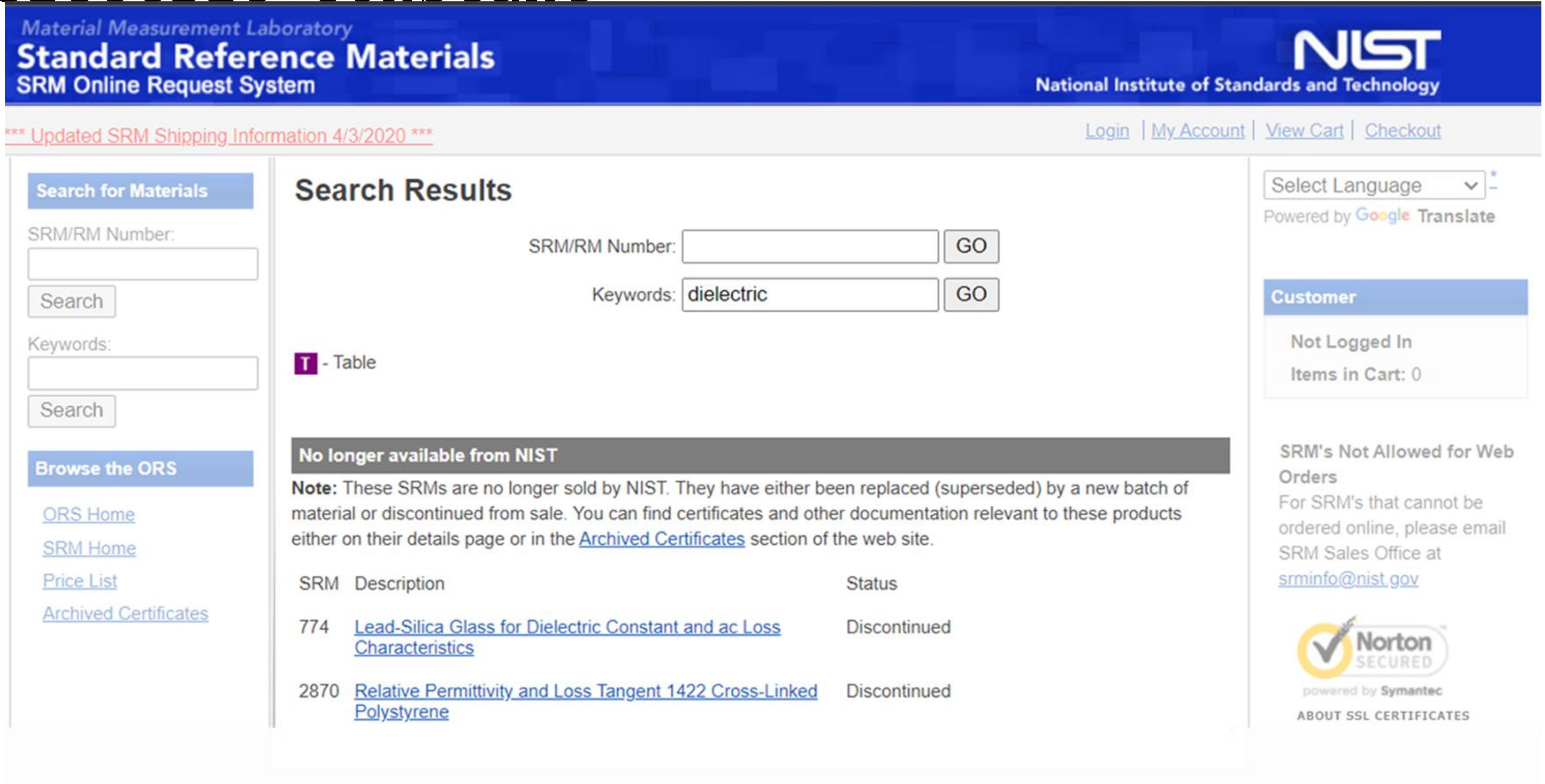
> "The lack of traceable reference material for mmWaves is a very serious problem. This lack makes verification of measurement methods and laboratory techniques impossible in an industry setting."

SRC Research Needs: Packaging

> "Dielectric characterization up to 500 GHz and beyond. Scope includes anisotropic and inhomogeneous materials… High-frequency and high-temperature dielectric characterization of low-loss materials (encapsulants, mold compounds, substrates, etc.)."

Intel even gave 3 talks to NIST about this problem last year

The problem is there's no standard for dielectric constant



Search Results

SRM/RM Number: GO

Keywords: dielectric GO

T - Table

No longer available from NIST

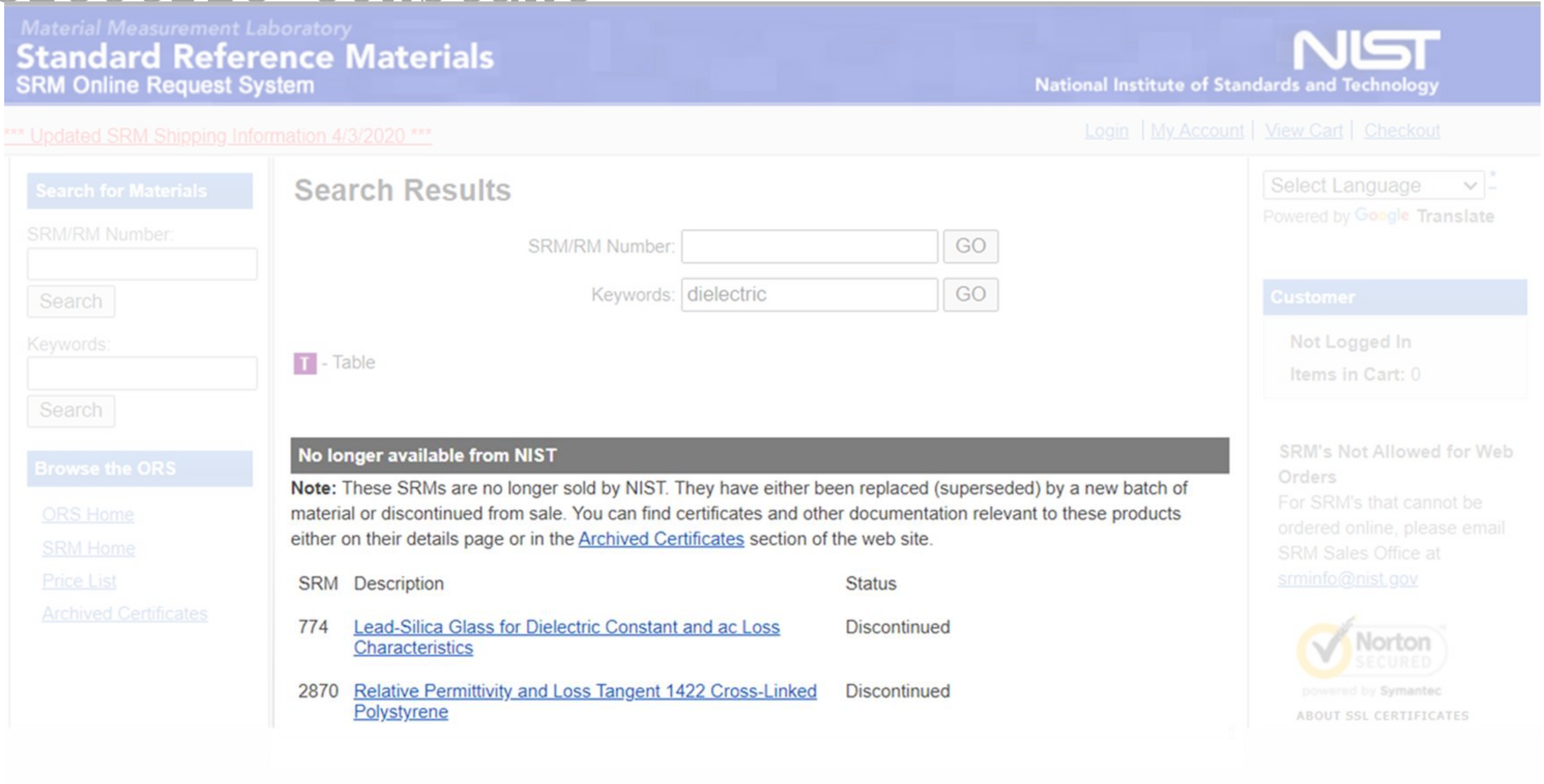
Note: These SRMs are no longer sold by NIST. They have either been replaced (superseded) by a new batch of material or discontinued from sale. You can find certificates and other documentation relevant to these products either on their details page or in the Archived Certificates section of the web site.

SRM	Description	Status
774	Lead-Silica Glass for Dielectric Constant and ac Loss Characteristics	Discontinued
2870	Relative Permittivity and Loss Tangent 1422 Cross-Linked Polystyrene	Discontinued

SRM's Not Allowed for Web Orders

For SRM's that cannot be ordered online, please email SRM Sales Office at srminfo@nist.gov

The problem is there's no standard for dielectric constant



Search Results

SRM/RM Number:

Keywords: dielectric

No longer available from NIST

Note: These SRMs are no longer sold by NIST. They have either been replaced (superseded) by a new batch of material or discontinued from sale. You can find certificates and other documentation relevant to these products either on their details page or in the Archived Certificates section of the web site.

SRM	Description	Status
774	Lead-Silica Glass for Dielectric Constant and ac Loss Characteristics	Discontinued
2870	Relative Permittivity and Loss Tangent 1422 Cross-Linked Polystyrene	Discontinued

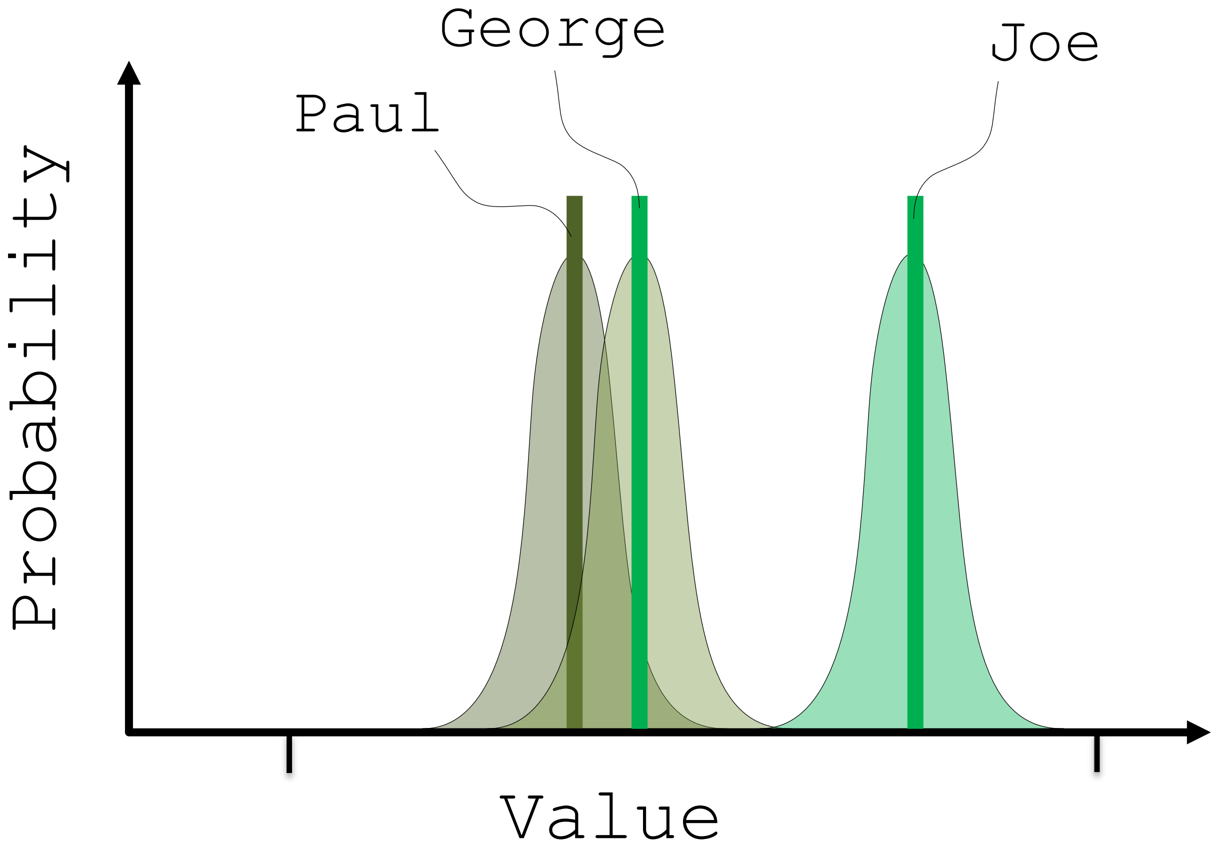
SRM's Not Allowed for Web Orders

For SRM's that cannot be ordered online, please email SRM Sales Office at srminfo@nist.gov

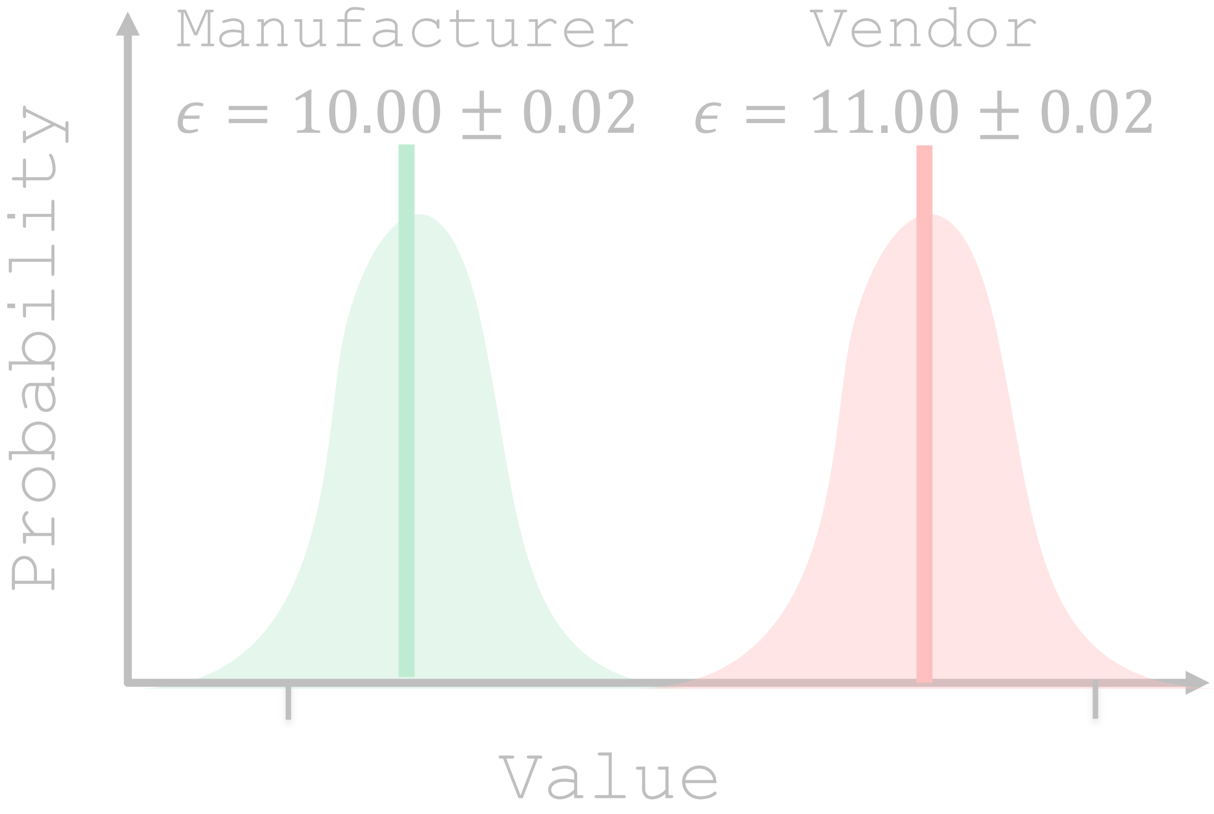
"These SRMs and no longer sold by NIST…"

Why are semiconductor standards so important?

Metrology capability analysis (MCA)



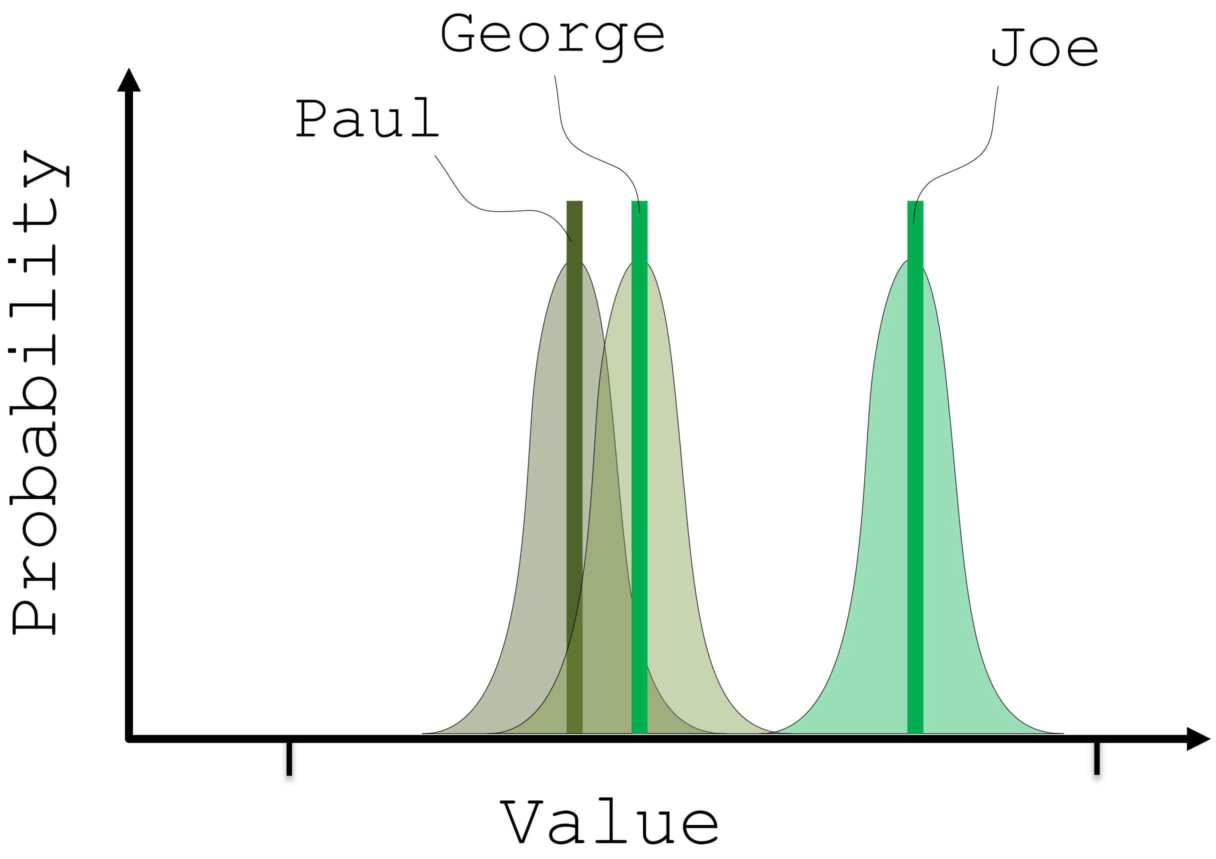
Acceptance testing (materials, tools)



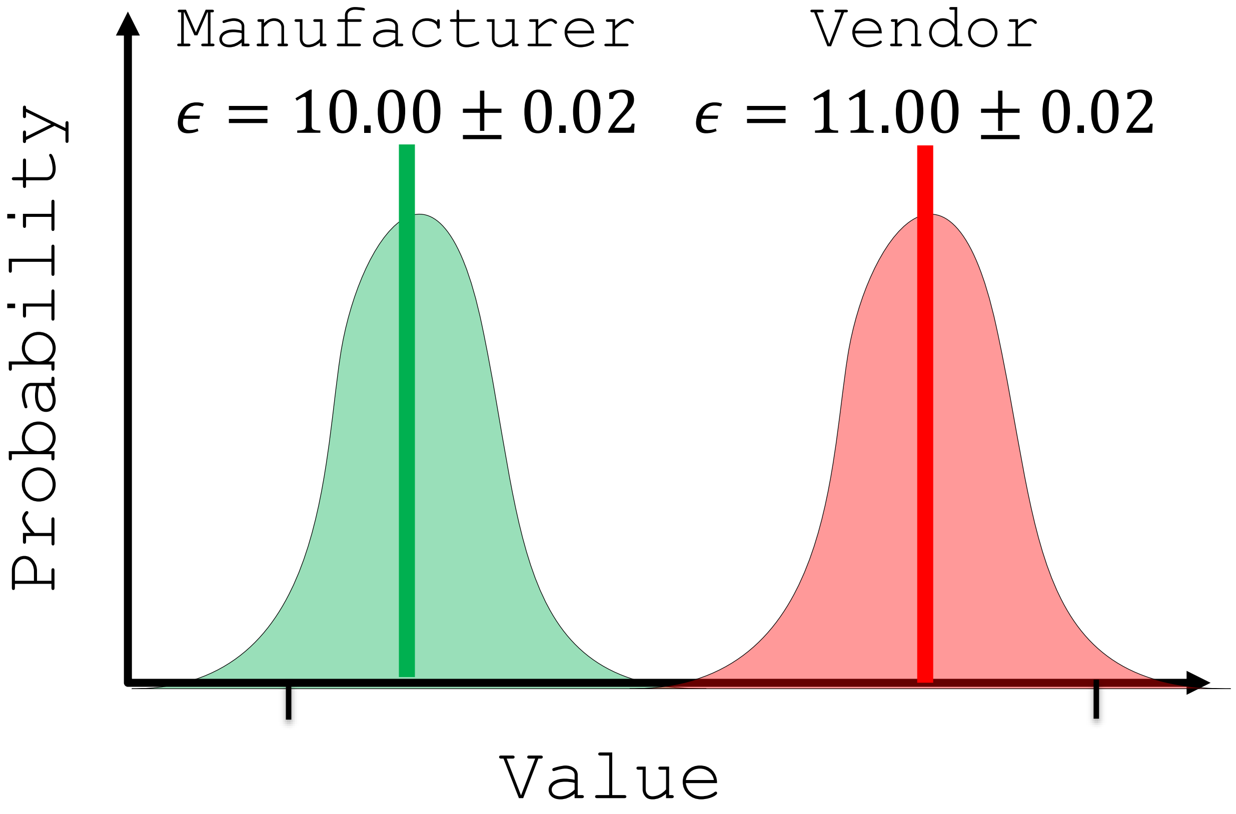
Without a standard industry’s measurements are broken

Why are semiconductor standards so important?

Metrology capability analysis (MCA)



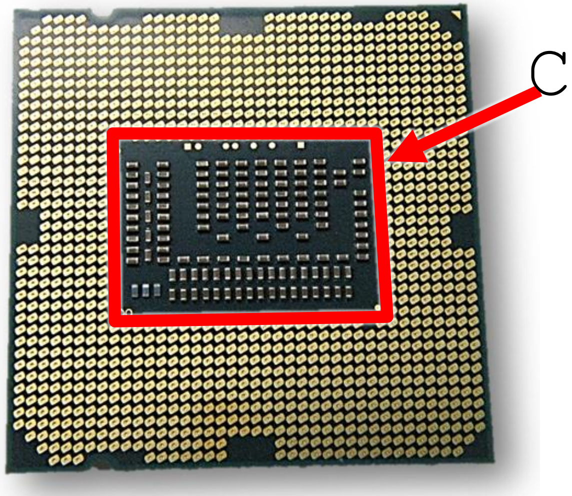
Acceptance testing (materials, tools)



Without a standard industry's measurements are broken

What can happen without a standard…

Top view



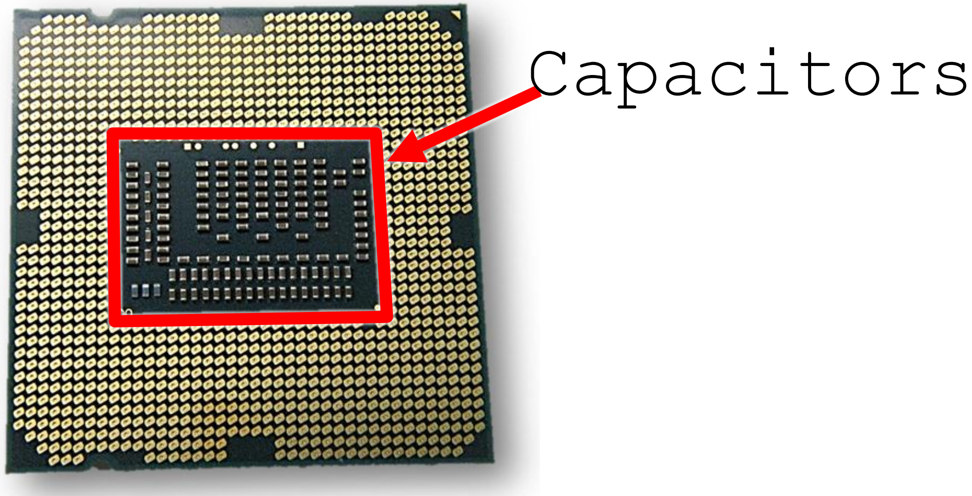
Backside view

10.0 % Error in ϵ_r	
Extra Cost/CPU	$0.34
CPU Volume	100 million units
Additional cost	$34 million

Credit: M. Hill, Intel

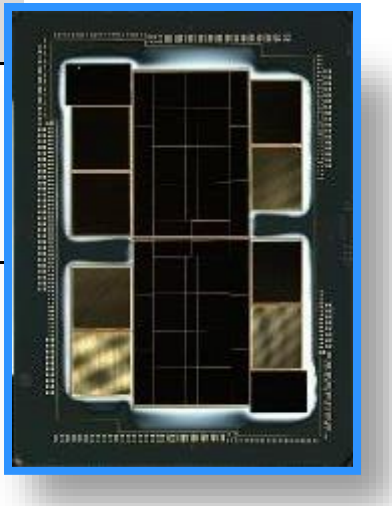
What can happen without a standard…


Top view



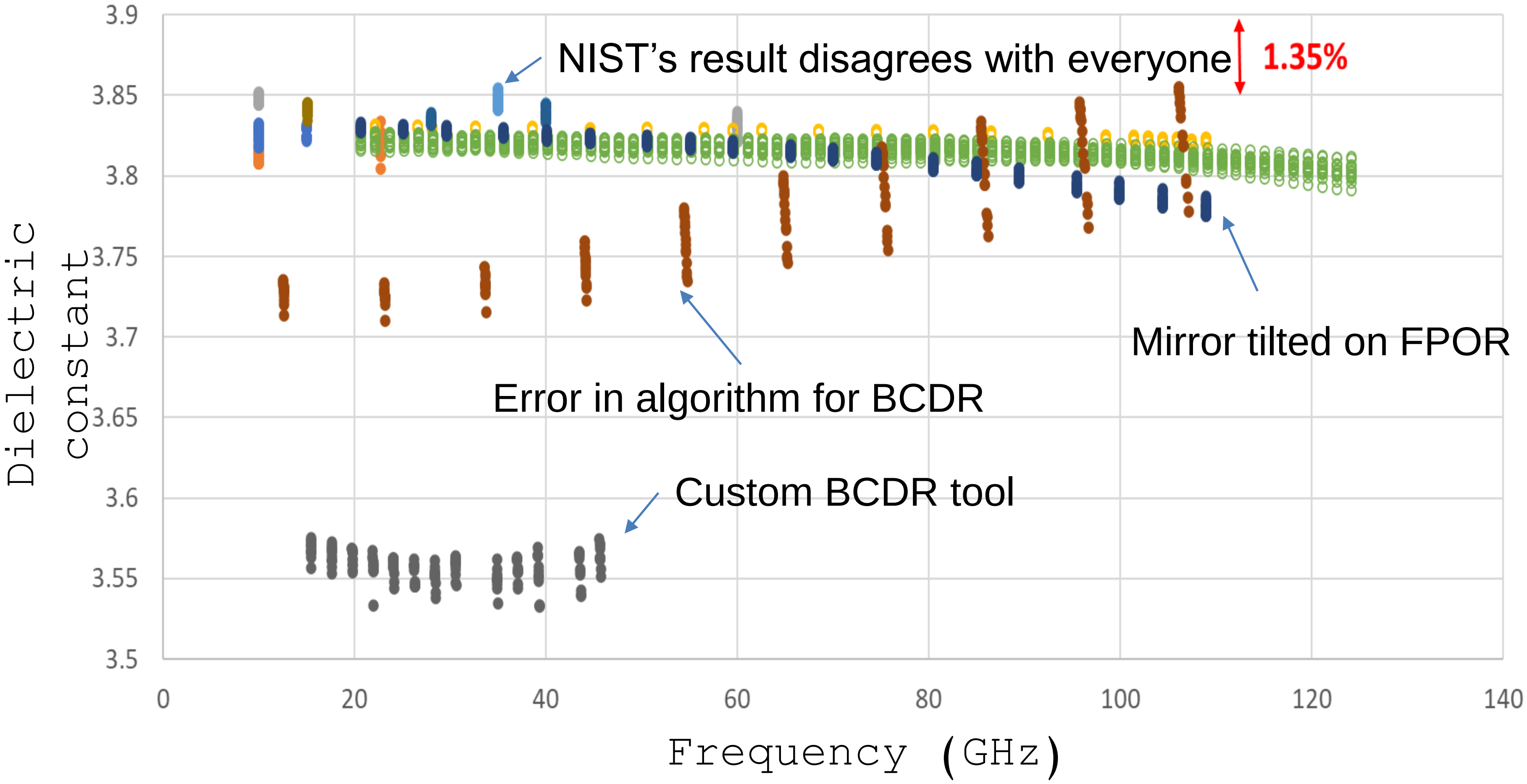
Backside view

10.0 % Error in ϵ_r	
Extra Cost/CPU	\$0.34
CPU Volume	100 million units
Additional cost	\$34 million



Credit: M. Hill, Intel

10% is not crazy



NIST's result disagrees with everyone

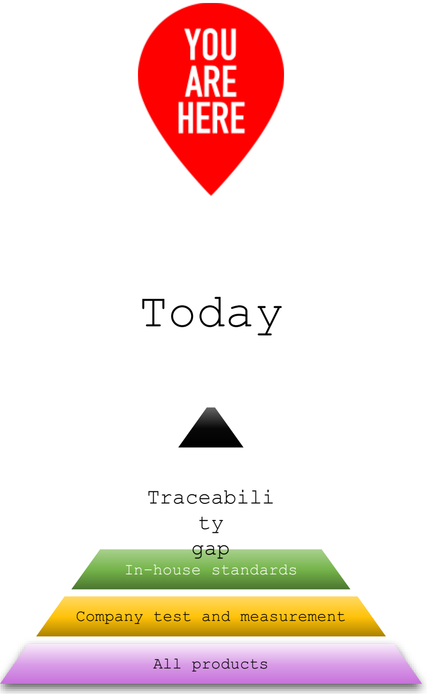
Mirror tilted on FPOR

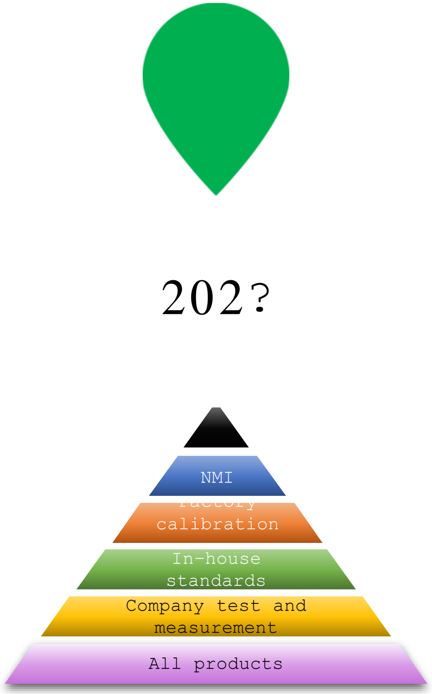
Error in algorithm for BCDR

Custom BCDR tool

Credit: iNEMI round robin

This traceability gap is an opportunity for NIST

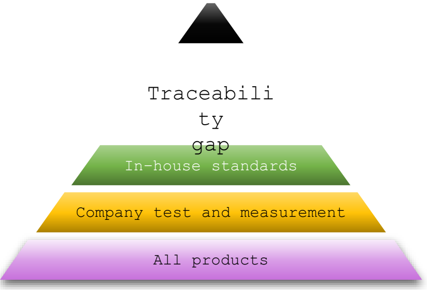




Don't worry we are going to break down all these steps

How can we fill the traceability gap?

Today



Abbreviated for time

1 Chose material

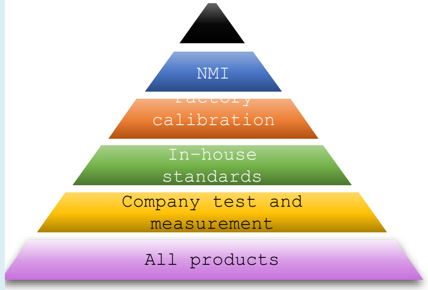
2 Chose method

3 Use theory to map to permittivity

4 Measure Scattering parameters

5 Measure dimensions

202?

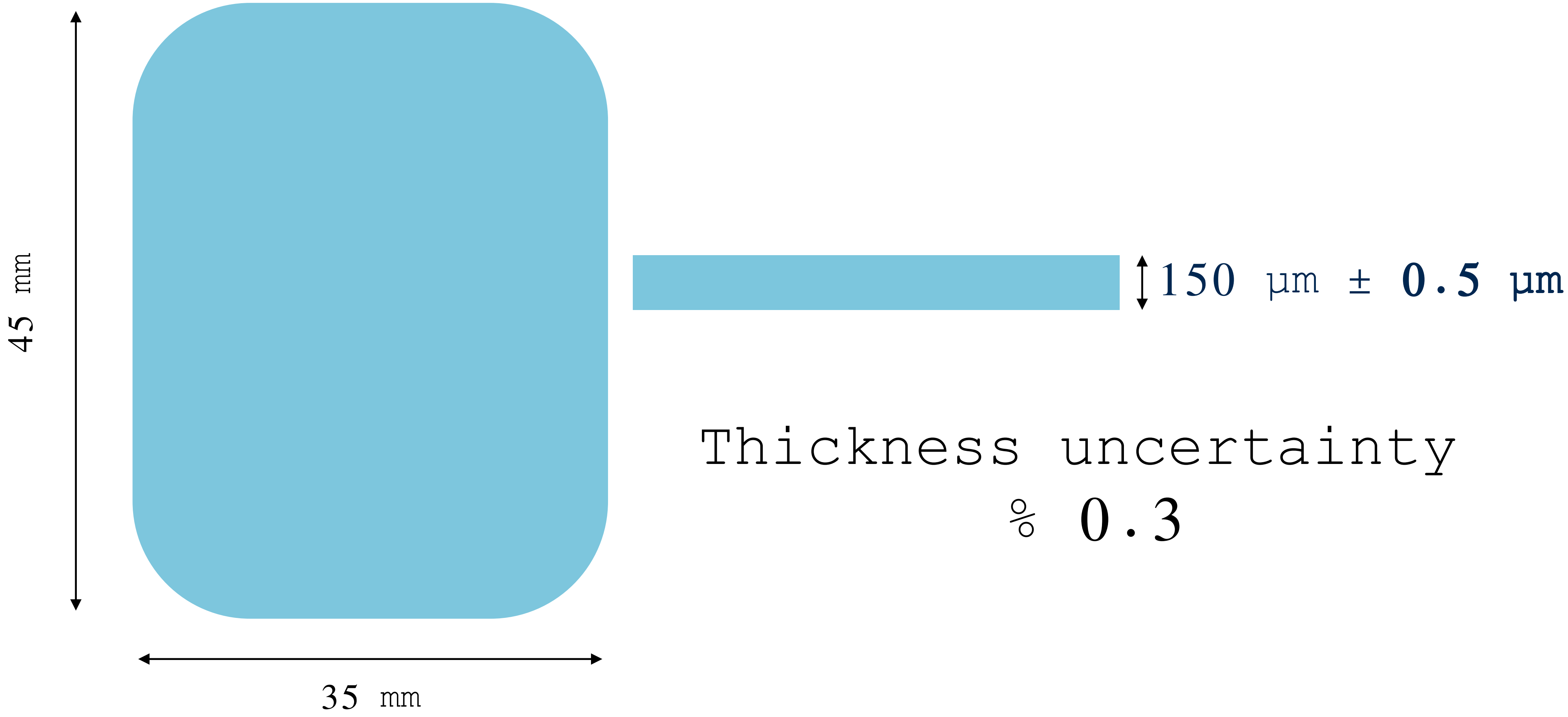


Don’t worry we are going to break down all these steps

iNEMI's special report identified fused silica

1

Chose material



45 mm

35 mm

150 µm ± **0.5 µm**

Thickness uncertainty

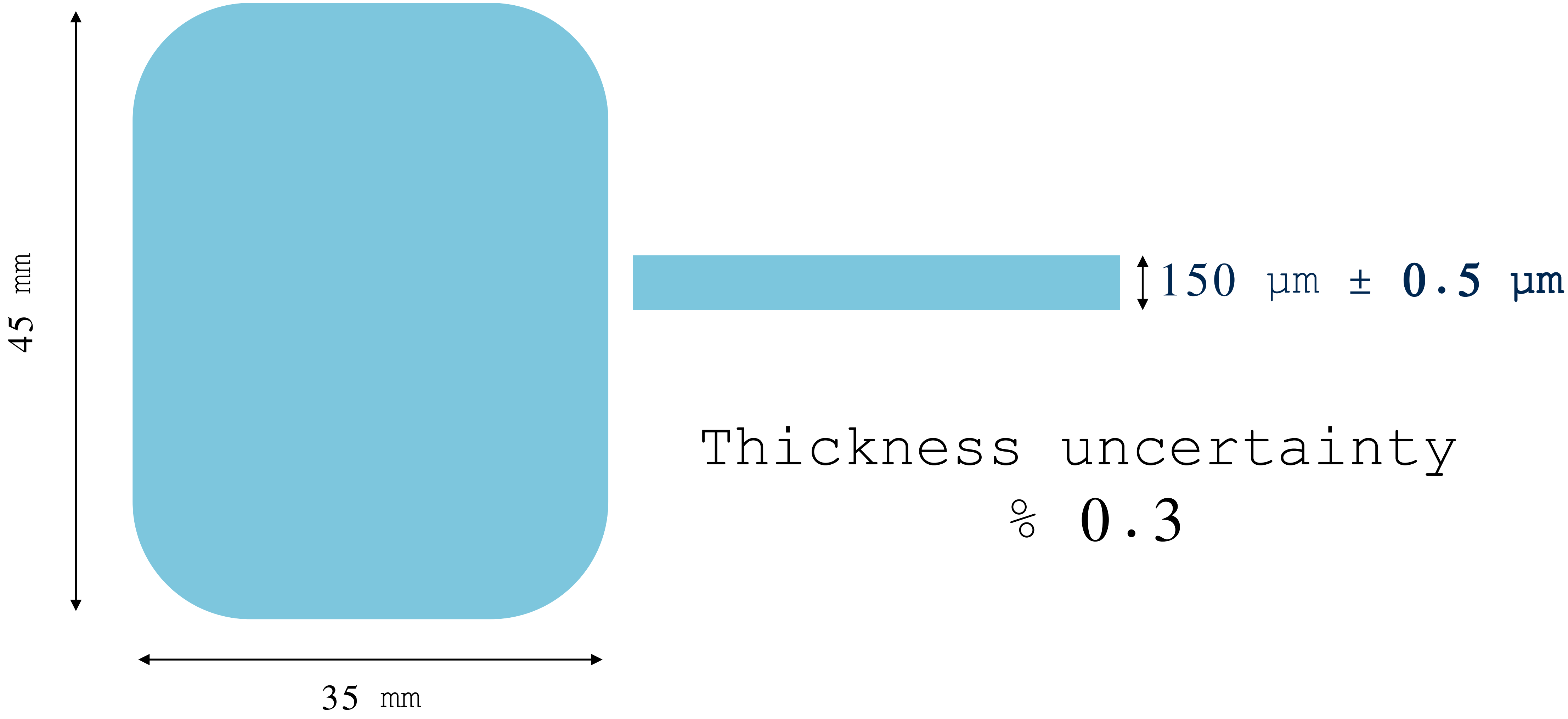
% 0.3

Mosaic developed a special process for Corning's fused silica

iNEMI's special report identified fused silica

1

Chose material



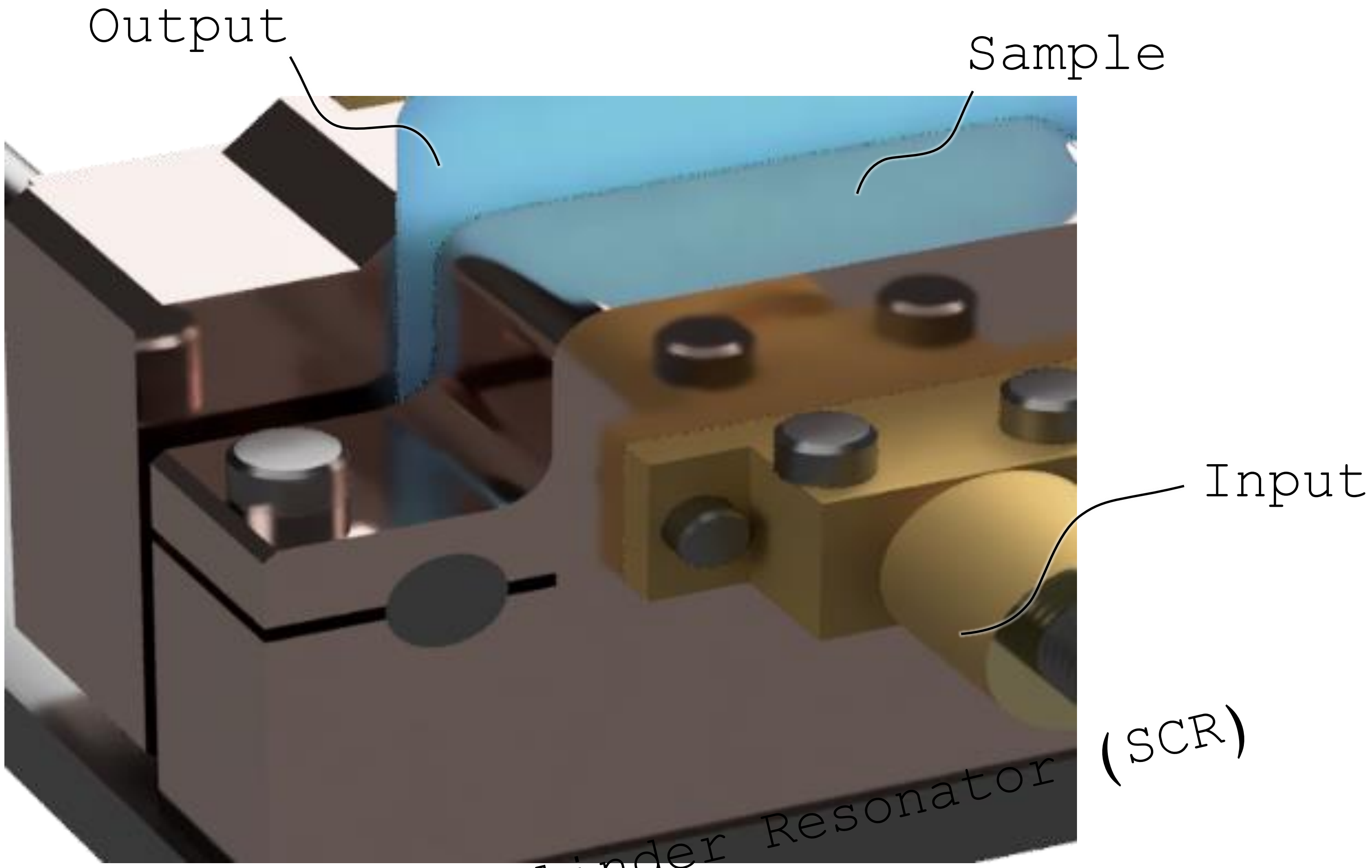
Thickness uncertainty
% 0.3

Mosaic developed a special process for Corning's fused silica

We chose SCR. It has the shortest traceabili
path.

2

Chose method



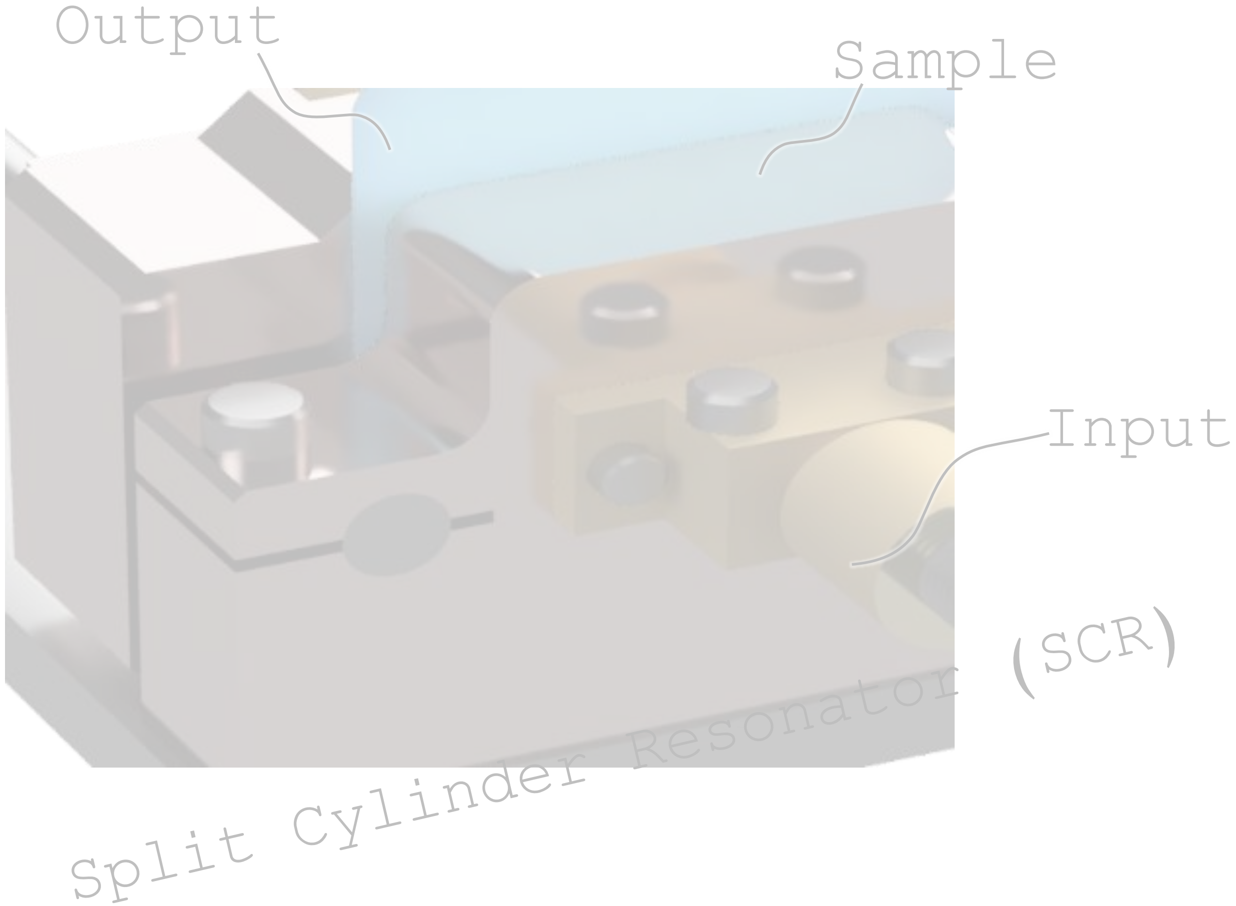
Split Cylinder Resonator (SCR)

The dimensions of the cavity and sample are the critical features

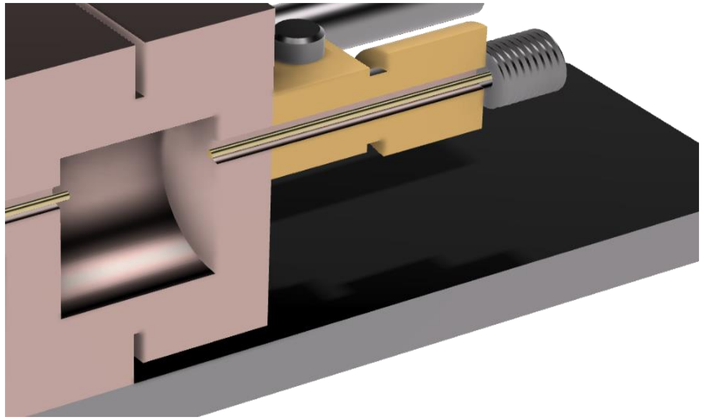
We chose SCR. It has the shortest traceabili
path.

2

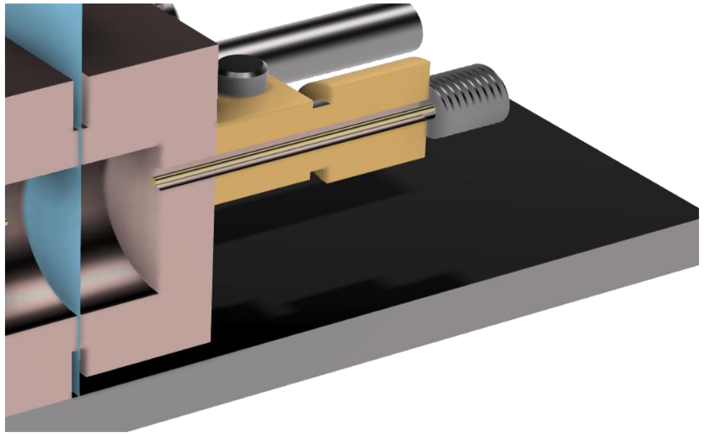
Chose method



no sample



sample



The dimensions of the cavity and sample are the critical features

Theory* relates what we measure to what we want

*this is not exactly the theory we want

3

Use theory to map to permittivity

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

Red = From dimensional metrology and Blue = From fitting S-parameters

Theory* relates what we measure to what we want

*this is not exactly the theory we want

3

Use theory to map to permittivity

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

$$\boxed{\epsilon_{s,r} \approx \frac{1}{2}\left(\frac{V_c}{V_s}\right)\left(\frac{\Delta\omega}{\omega_s}\right) + 1}$$

$$\boxed{\epsilon_{s,i} \approx \frac{1}{4}\left(\frac{V_c}{V_s}\right)\left(\frac{Q_c - Q_s}{Q_c Q_s}\right)}$$

Red = From dimensional metrology and Blue = From fitting S-parameters

Theory* relates what we measure to what we want

*this is not exactly the theory we want

3

Use theory to map to permittivity

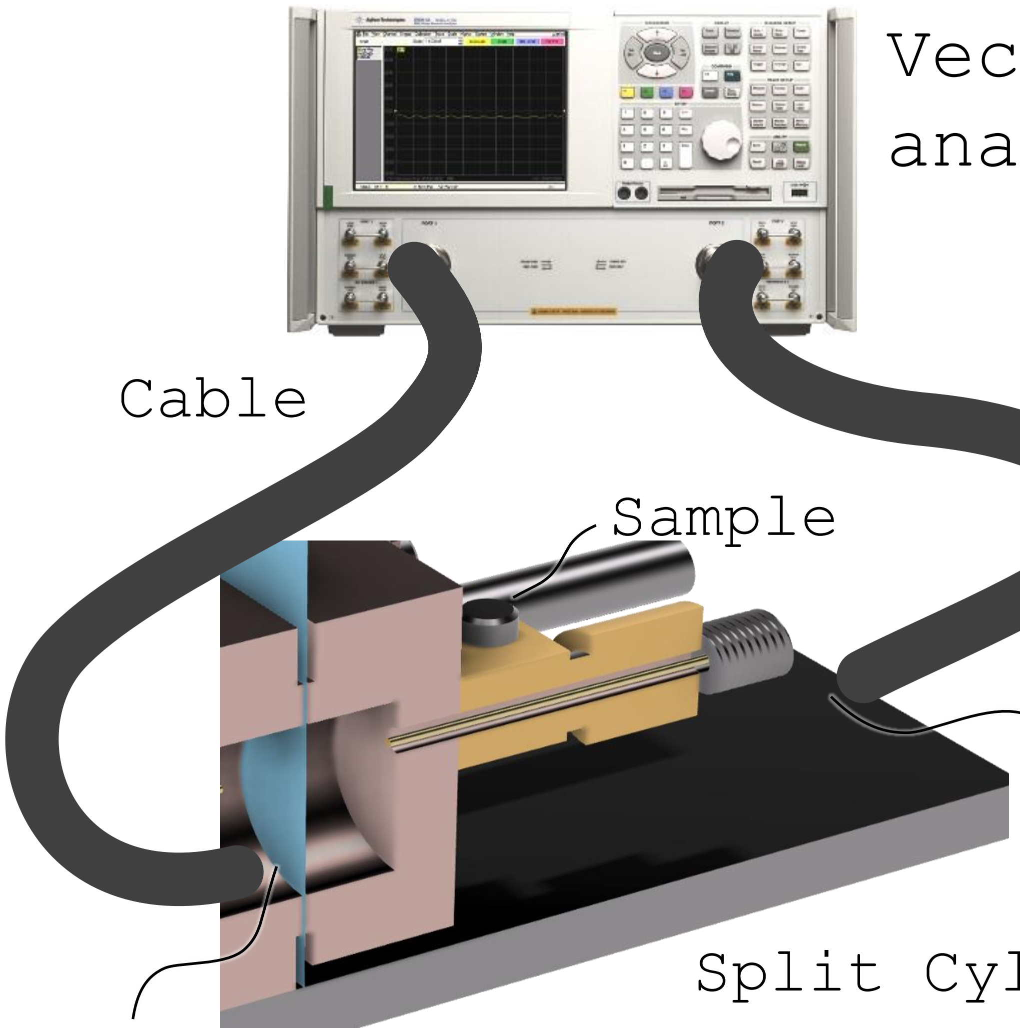
$$\frac{\widetilde{\omega}_c - \widetilde{\omega}_{cs}}{\widetilde{\omega}_c} = \frac{\int_{V_s} [(\bar{E}_c \cdot \bar{D}_s - \bar{E}_s \cdot \bar{D}_c) - (\bar{H}_c \cdot \bar{B}_s - \bar{H}_s \cdot \bar{B}_c)] dV}{\int_{V_c} (\bar{E}_c \cdot \bar{D}_c - \bar{H}_c \cdot \bar{B}_c) dV}$$

$$\epsilon_{s,r} \approx \frac{1}{2}\left(\frac{V_c}{V_s}\right)\left(\frac{\Delta\omega}{\omega_s}\right) + 1$$

$$\epsilon_{s,i} \approx \frac{1}{4}\left(\frac{V_c}{V_s}\right)\left(\frac{Q_c - Q_s}{Q_c Q_s}\right)$$

Red = From dimensional metrology and Blue = From fitting S-parameters

We use a network analyzer to measure the data



Vector network analyzer

Cable

Sample

Cable

Input

Split Cylinder Resonator (SCR)

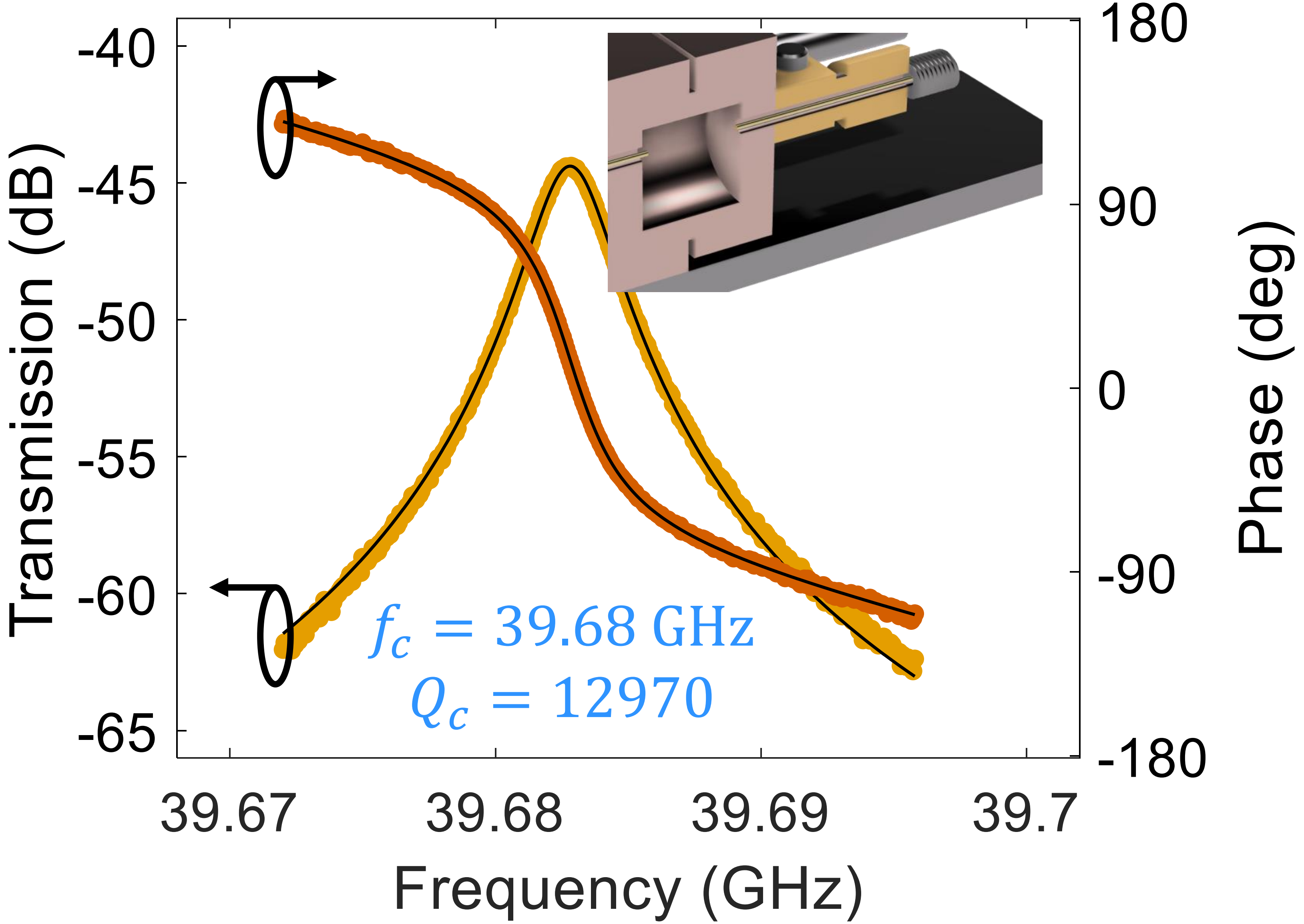
Output

We plan on using the SCR to start because it is the simplest

Here is what the cavity looks like with no sample

4

Measure Scattering parameters

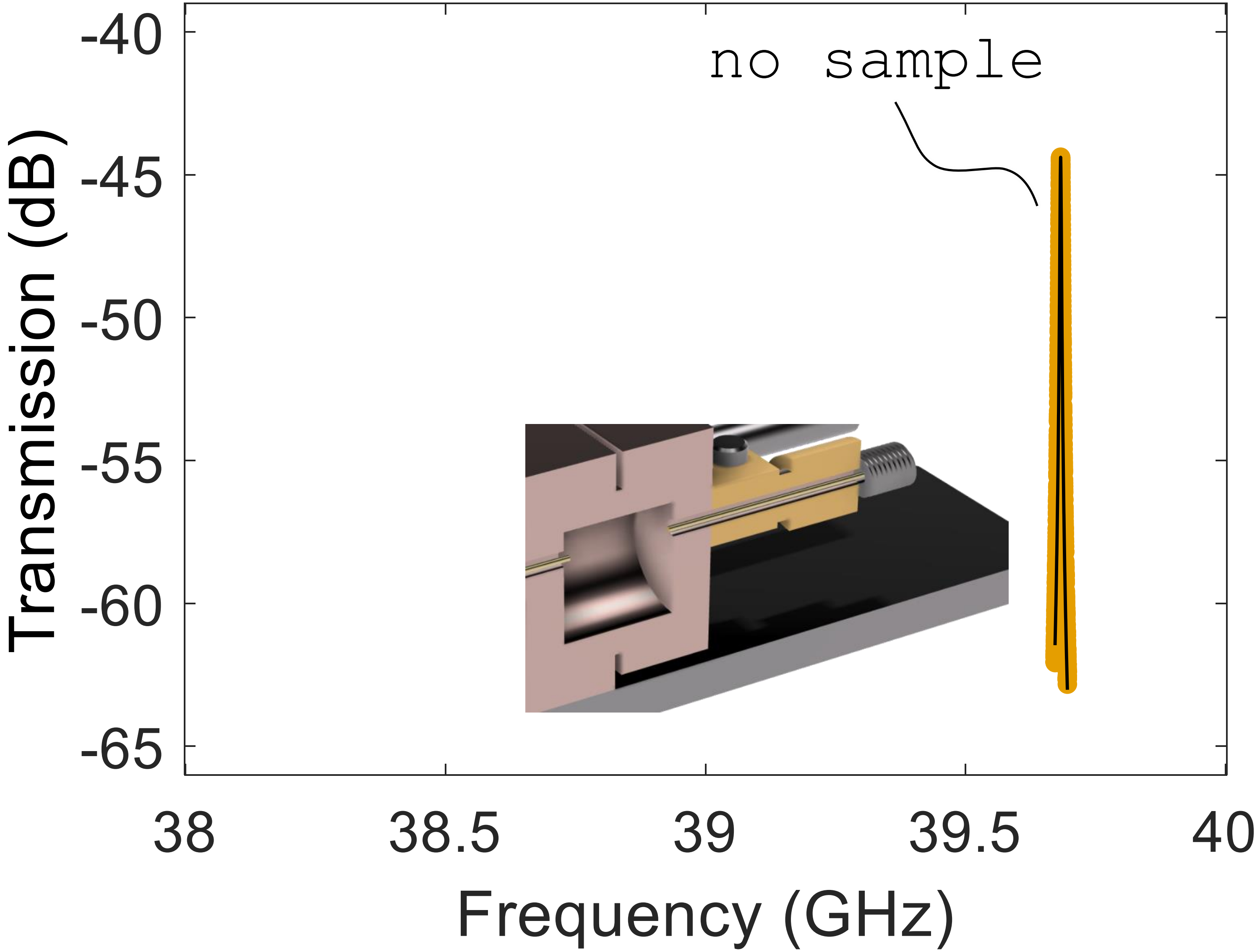


Q_c and ω_c describe the cavity without the sample

The sample moves the peak to the left and down

4

Measure Scattering parameters

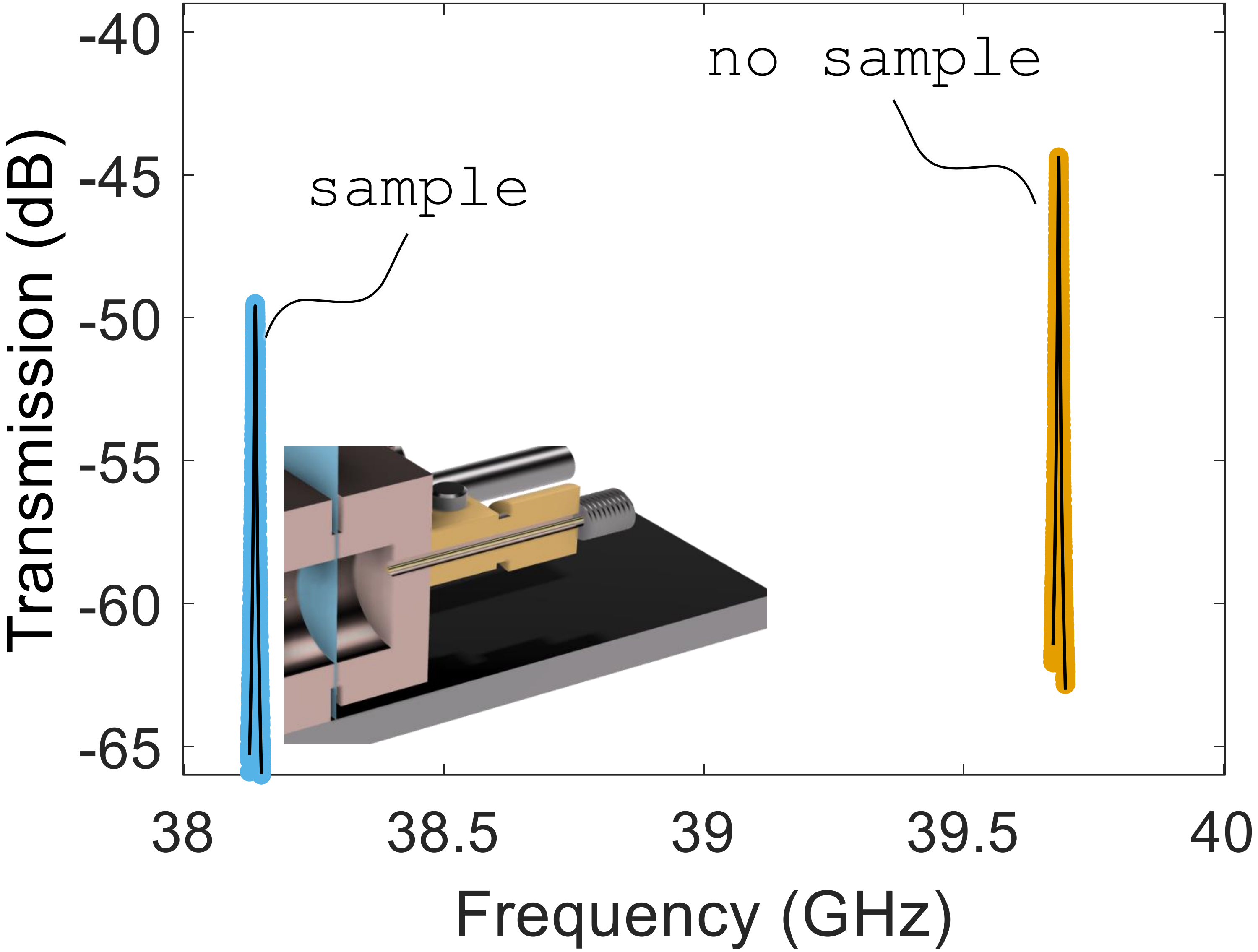


Next, we stick the sample in

The sample moves the peak to the left and down

4

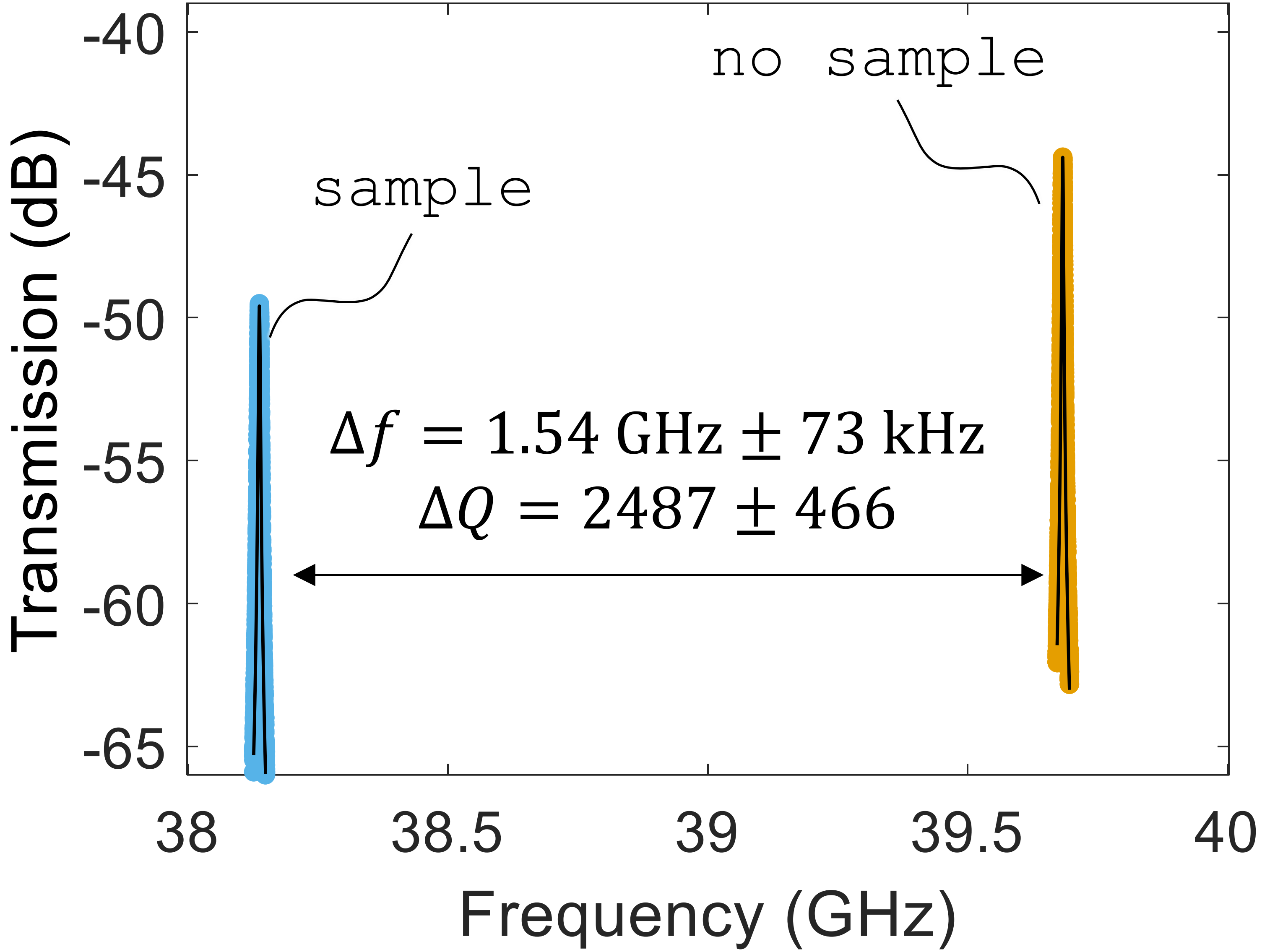
Measure Scattering parameters



The sample moves the peak to the left and down

4

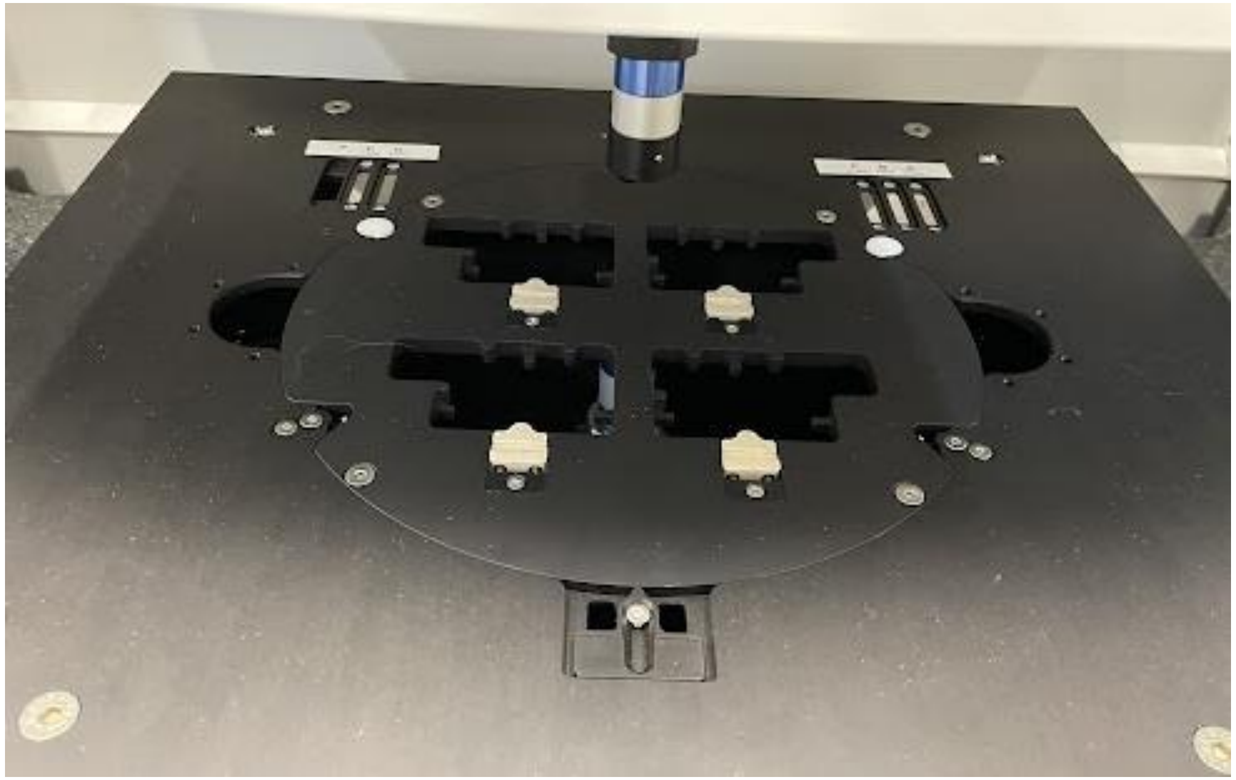
Measure Scattering parameters



We think* a white chromatic light sensor is best

5

Measure dimensions

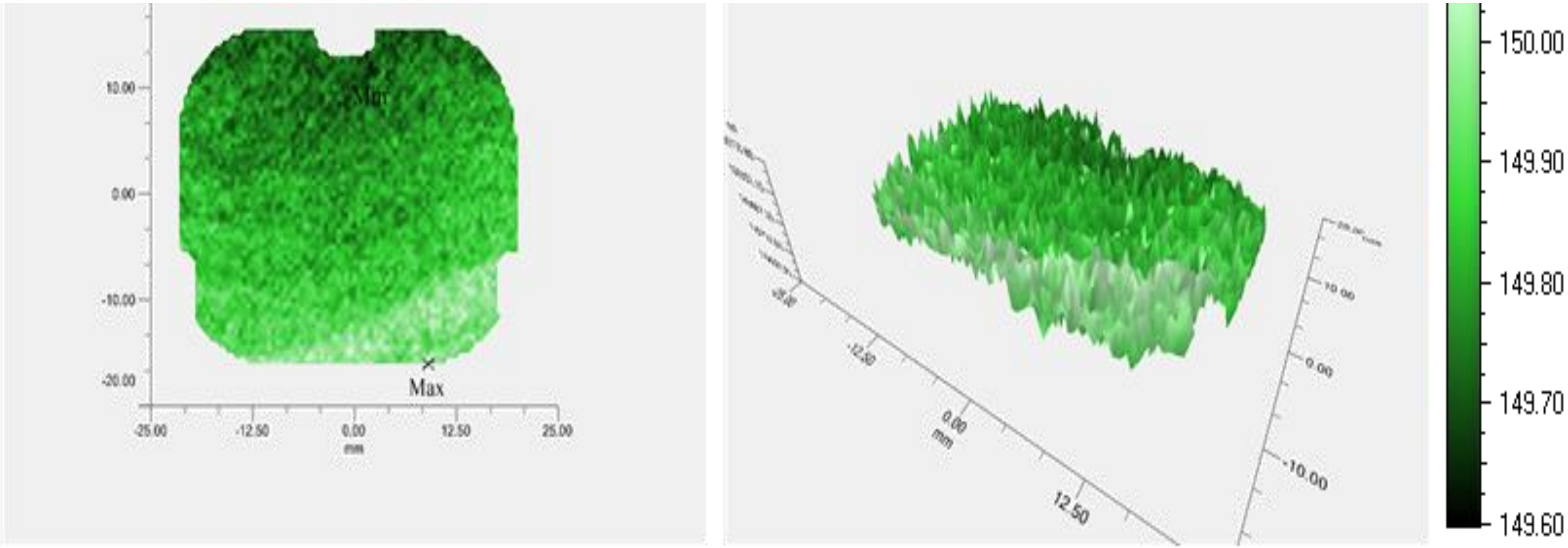


We can’t assume the index and must measure from both sides

We think* the best way is red-light interferometer

5

Measure dimensions

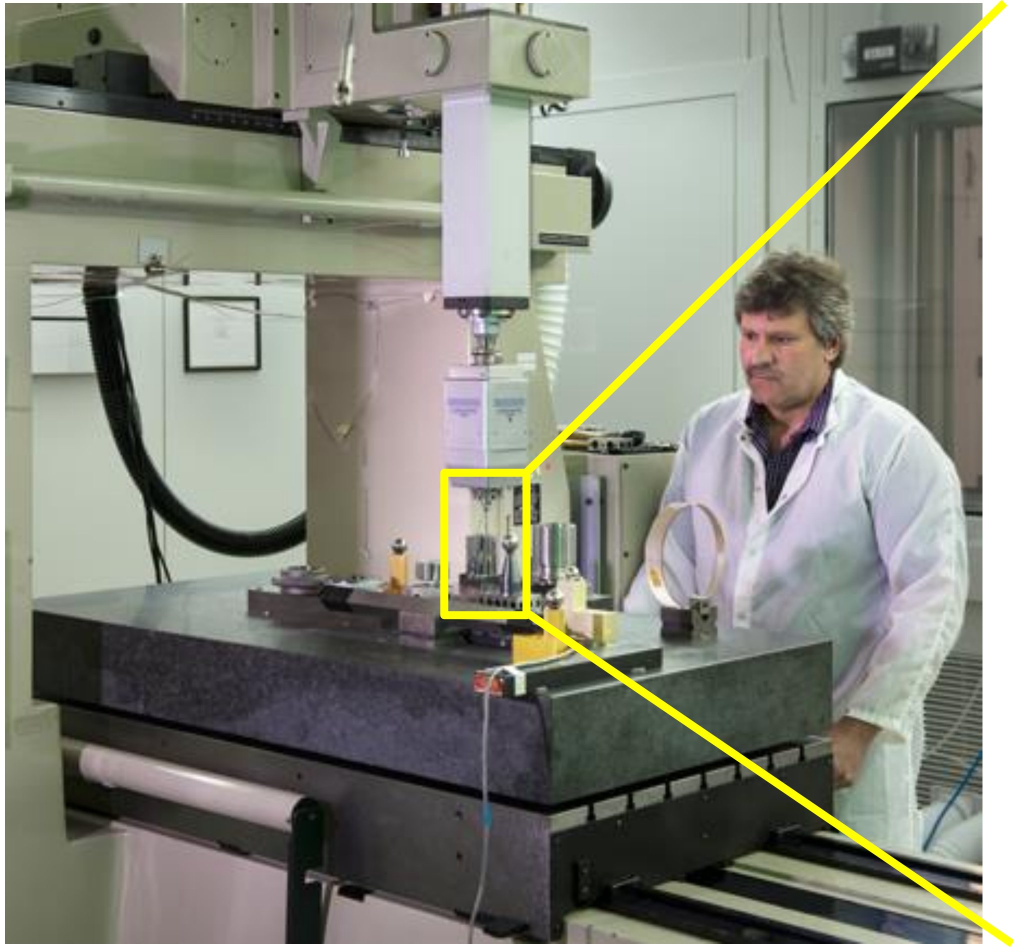


We can’t assume the index and must measure from both sides

We think* that a CMM is best for the cavities

5

Measure dimensions

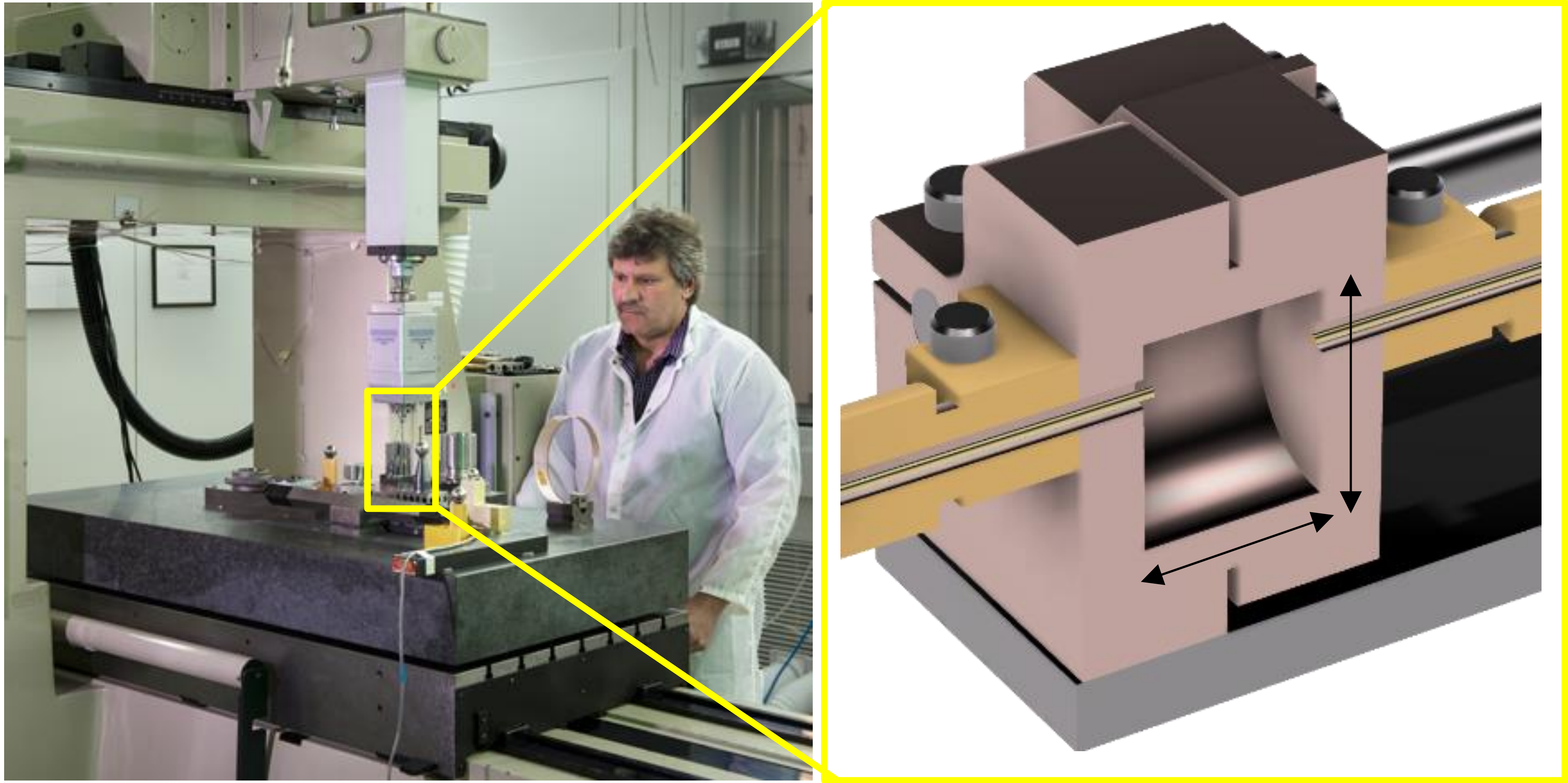


We need the dimensions of the cavity to about 1 μm at a few points

We think* that a CMM is best for the cavities

5

Measure dimensions

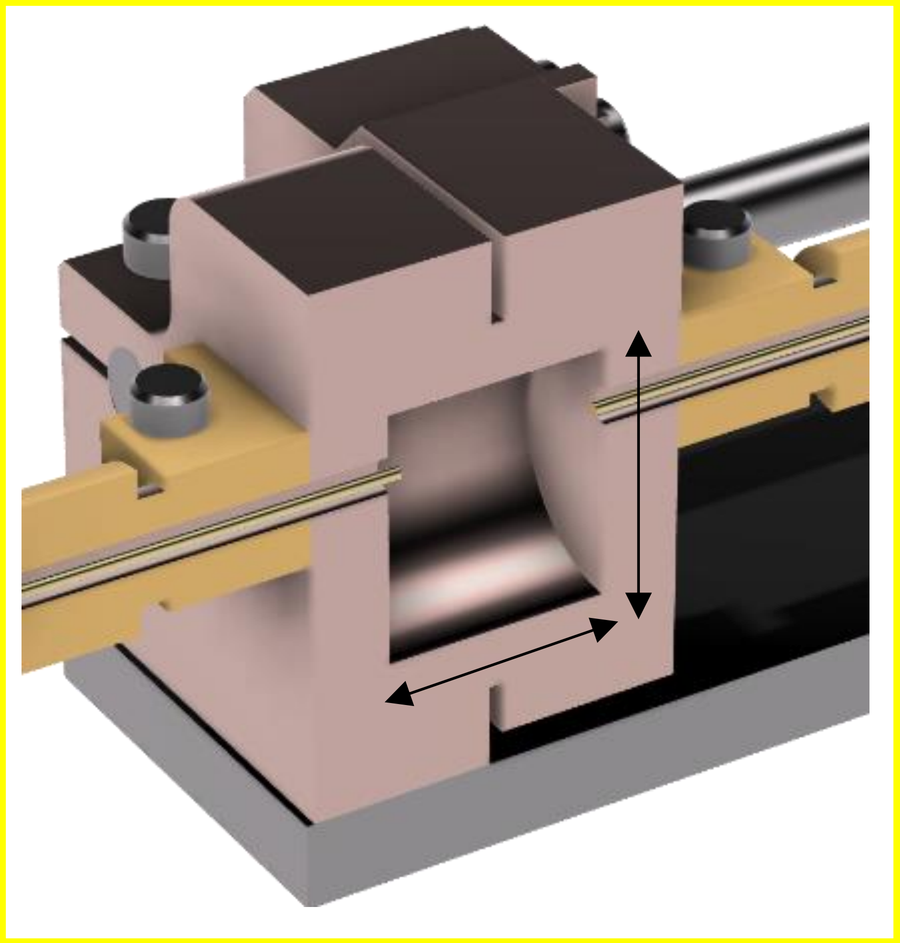


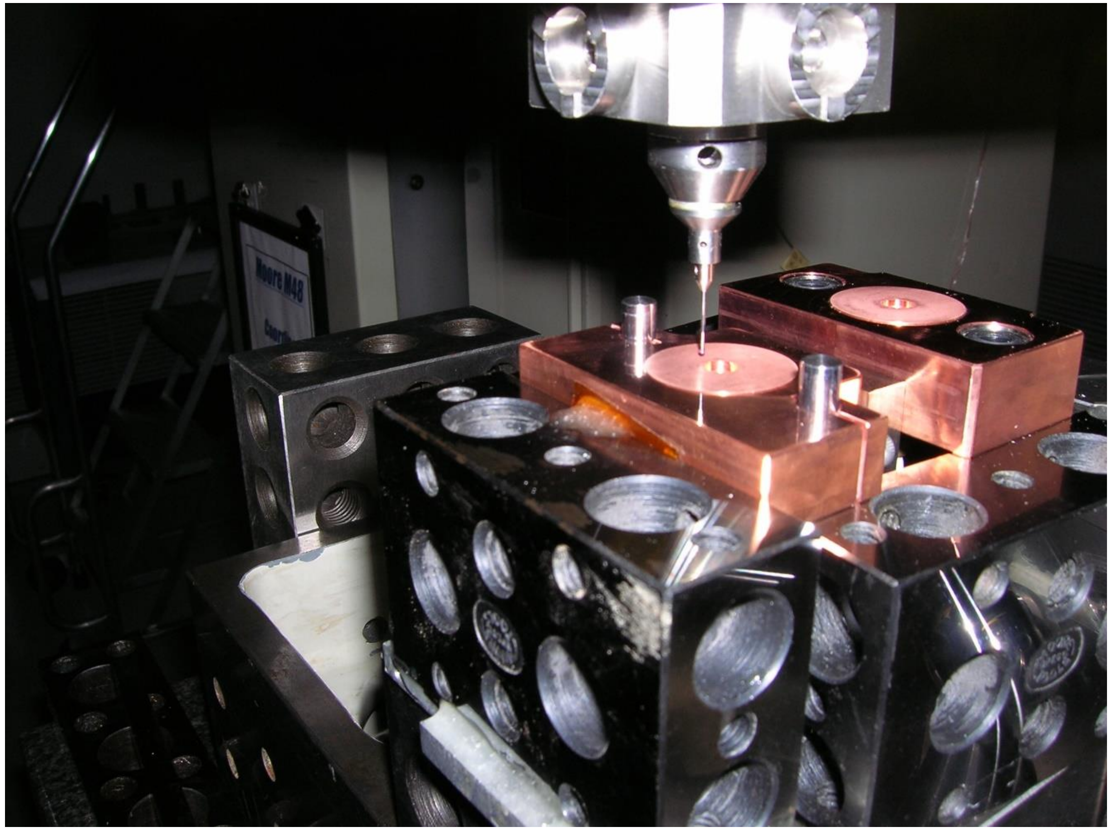
We need the dimensions of the cavity to about 1 µm at a few points

We think* that a CMM is best for the cavities

5

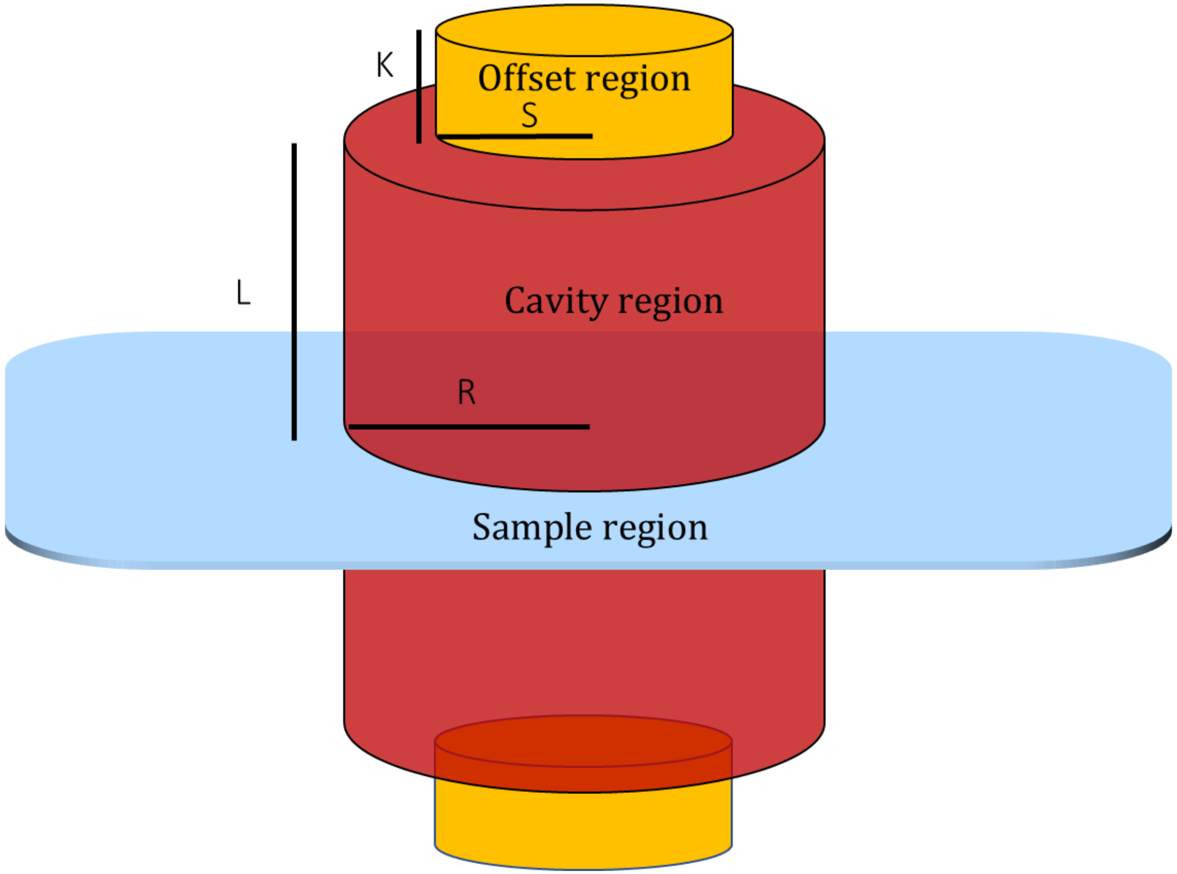
Measure dimensions





We need the dimensions of the cavity to about 1 μm at a few points

Here are the dimensions for our 28 GHz cavity



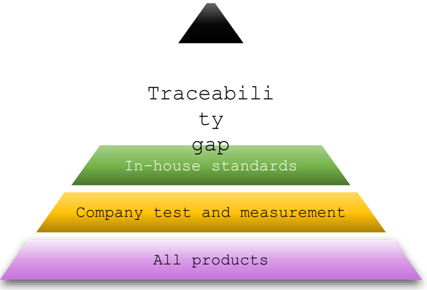
K	0.71100 ± 0.001 mm
S	6.89650 ± 0.001 mm
L	4.69874 ± 0.001 mm
R	7.60784 ± 0.0002 mm

We are getting about the 27.771 GHz for the empty cavity

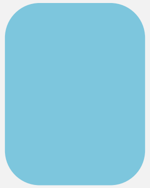
This path is not as far off as you might imagine

YOU ARE HERE

Today



1



Chose material

2

Chose method

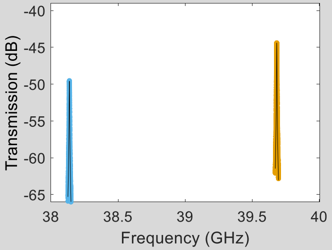
3

$$\epsilon_{s,r} \approx \frac{1}{2}\left(\frac{V_c}{V_s}\right)\left(\frac{\Delta\omega}{\omega_c}\right)+1$$

$$\epsilon_{s,i} \approx \frac{1}{4}\left(\frac{V_c}{V_s}\right)\left(\frac{Q_c - Q_s}{Q_c Q_s}\right)$$

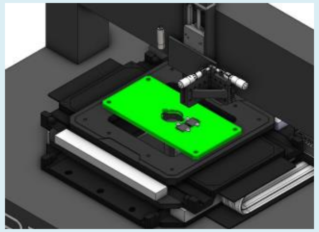
Use theory to map to permittivity

4



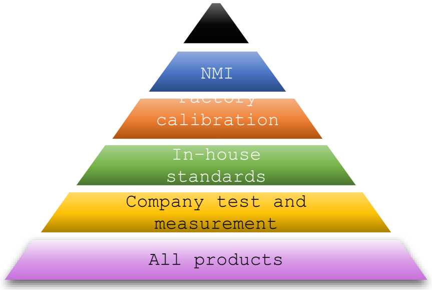
Measure Scattering parameters

5



Measure dimensions

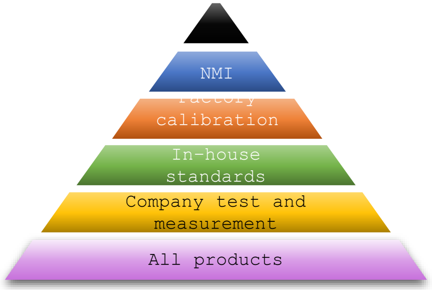
202?



We made 7 prototypes already…

What specifications do we have to hit?

202?

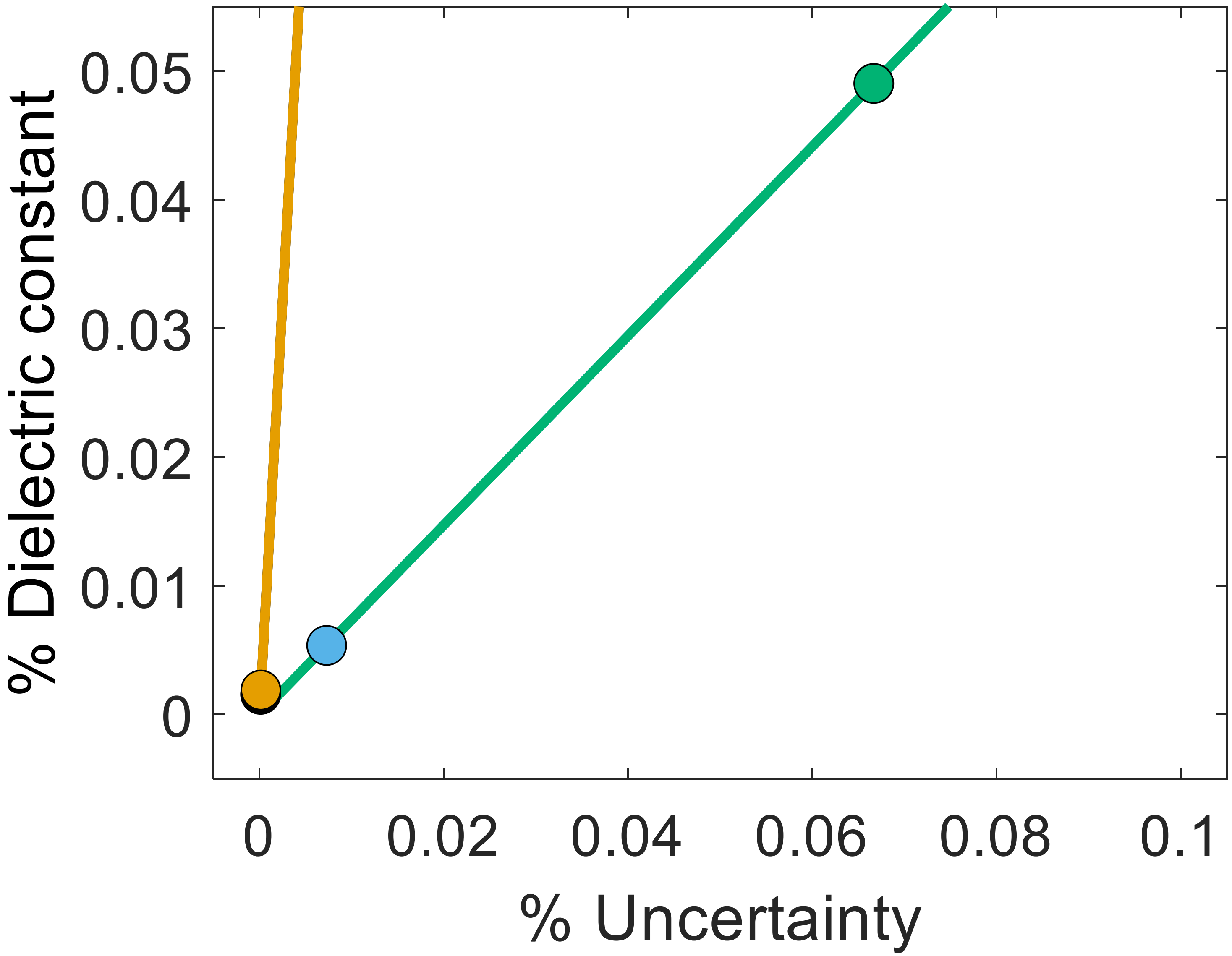

NMI

Factory calibration

In-house standards

Company test and measurement

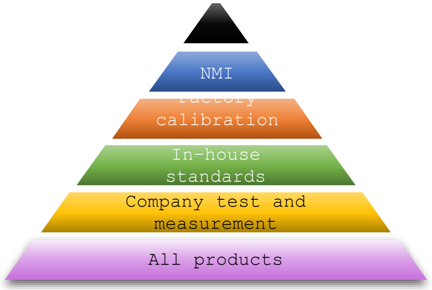
All products



This plot is a rough estimate

What specifications do we have to hit?

202?



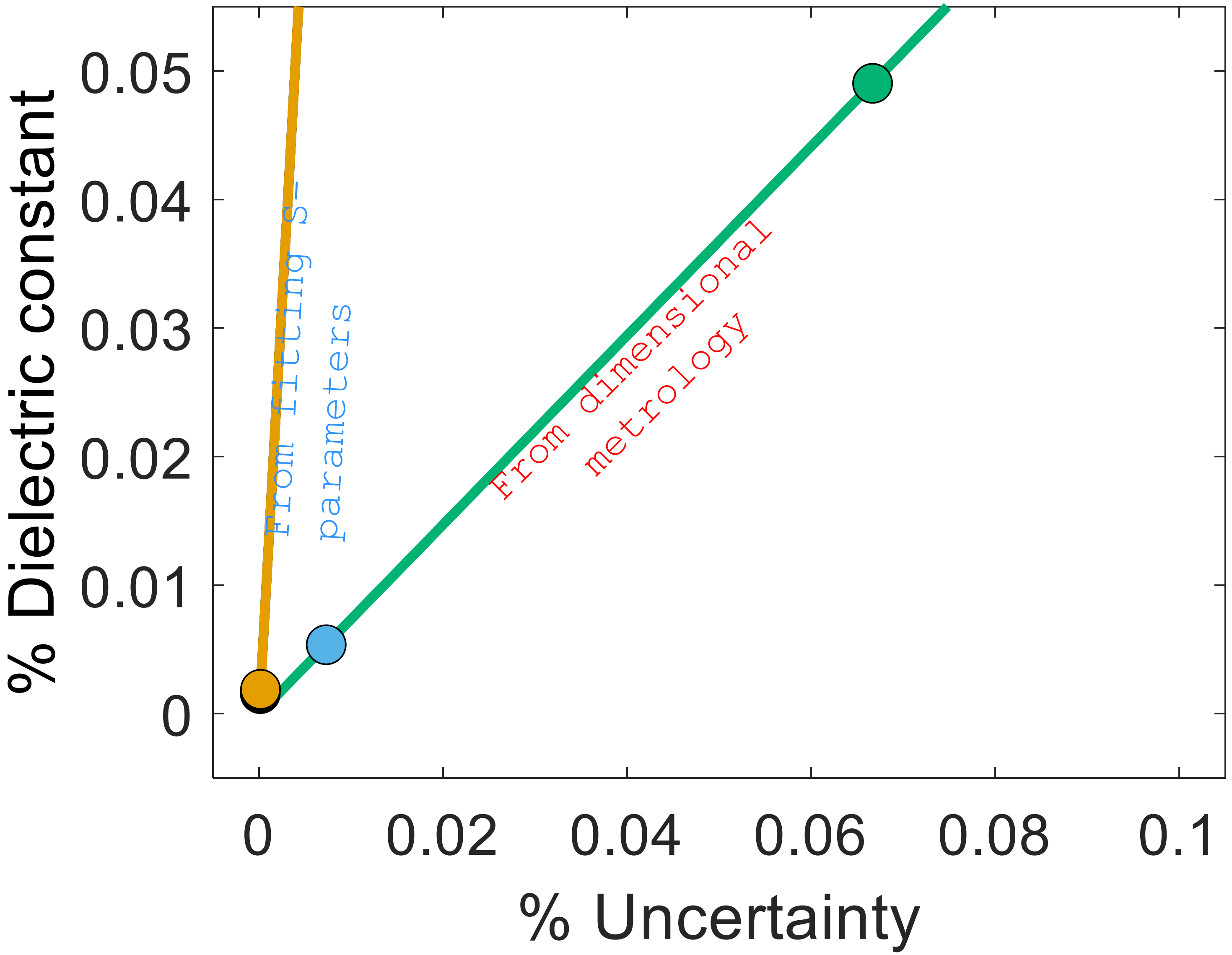
NMI

Factory calibration

In-house standards

Company test and measurement

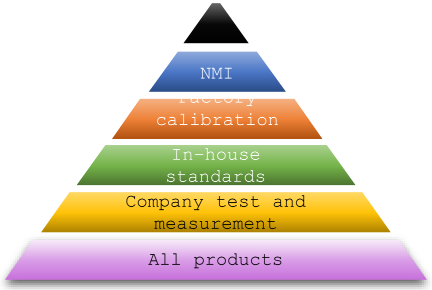
All products



This plot is a rough estimate

What specifications do we have to hit?

202?



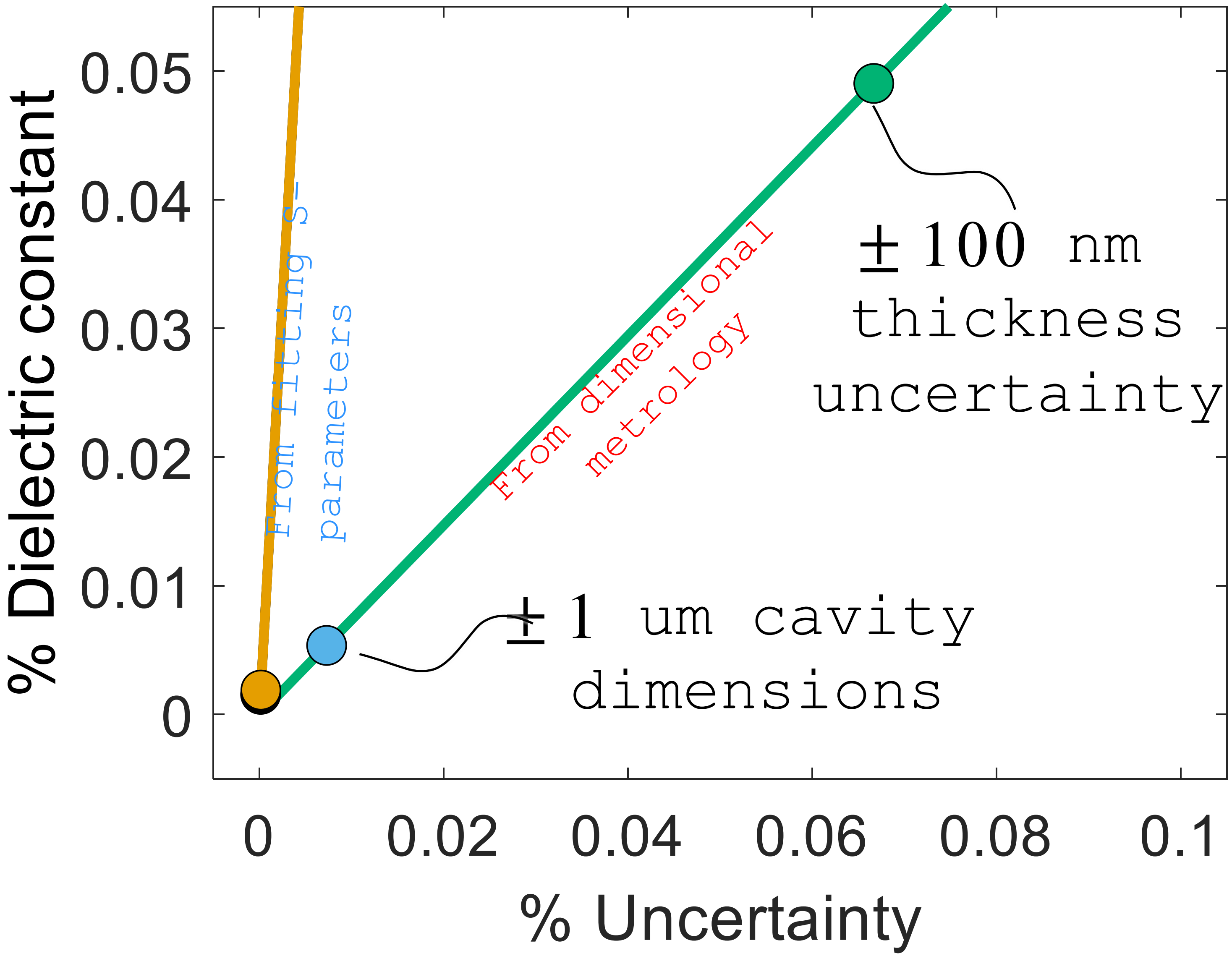
NMI

Factory calibration

In-house standards

Company test and measurement

All products

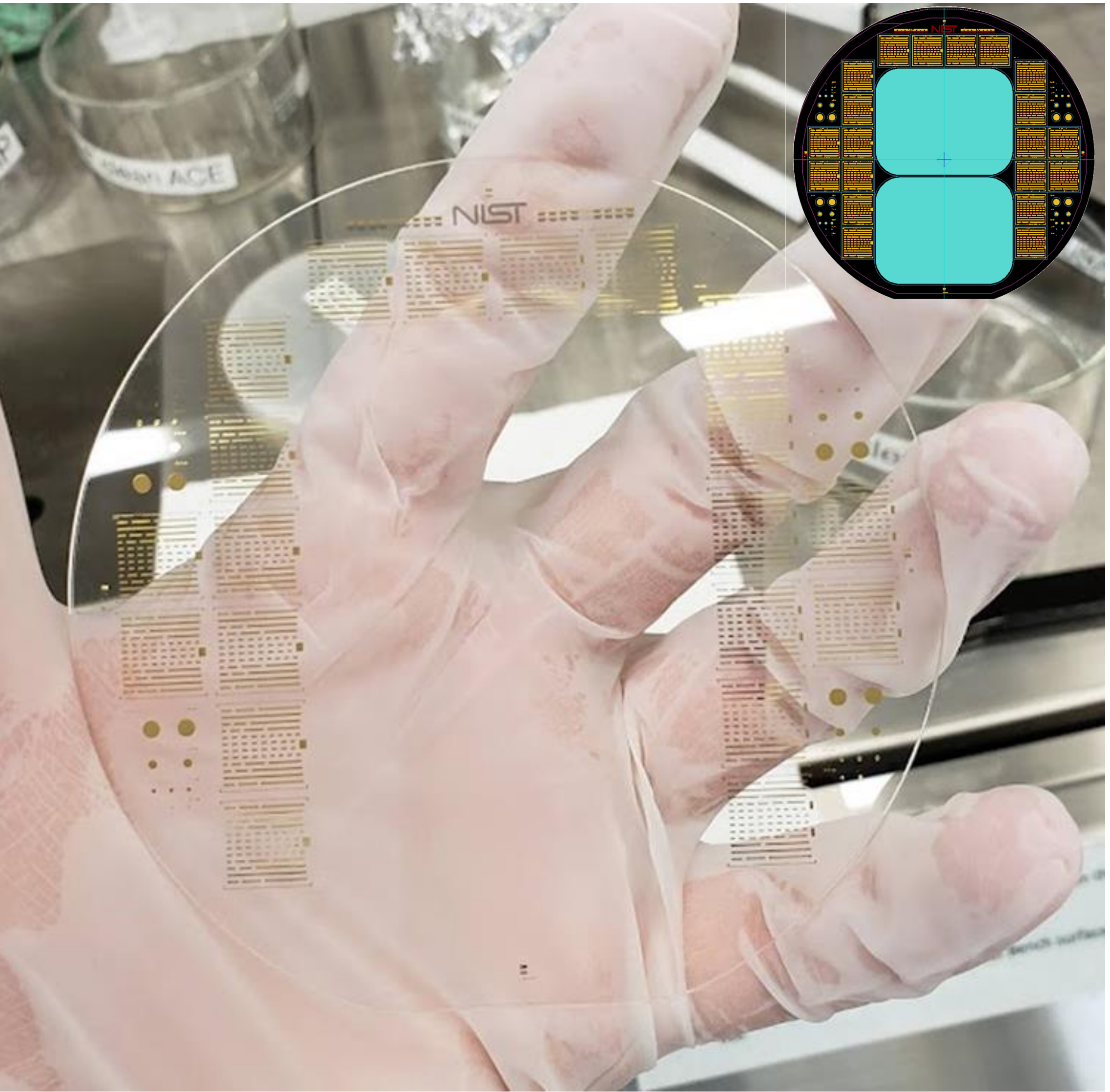


This plot is a rough estimate

Here is the first prototype SRM 42

#2 of 7 actual prototypes

Lucas Enright

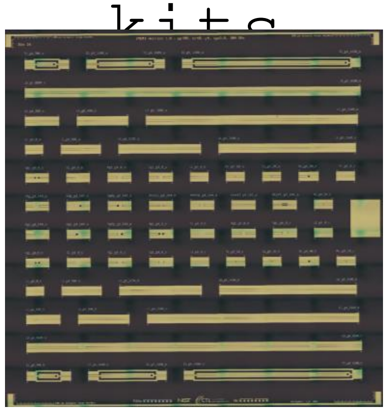


Photographs of the prototype SRM

Coupon

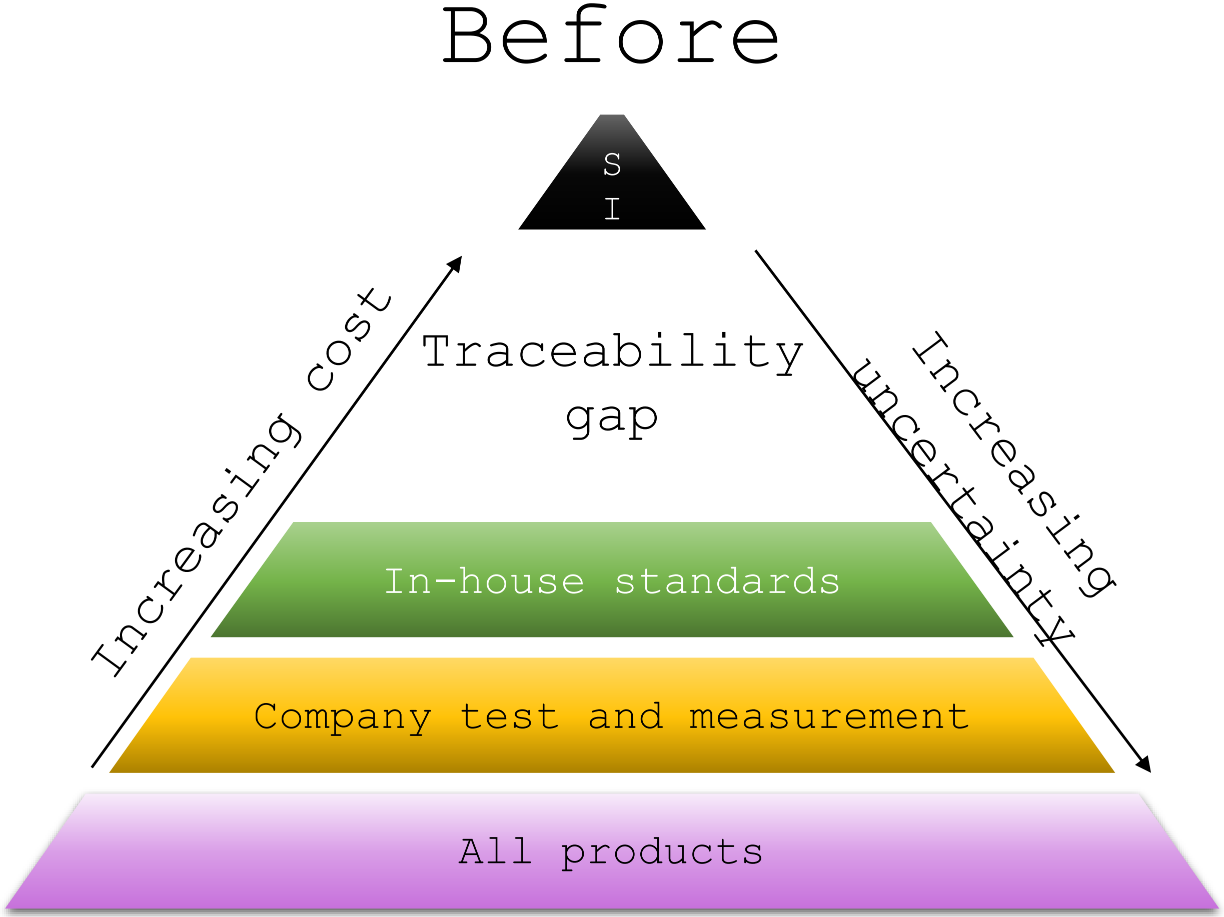
100 mm

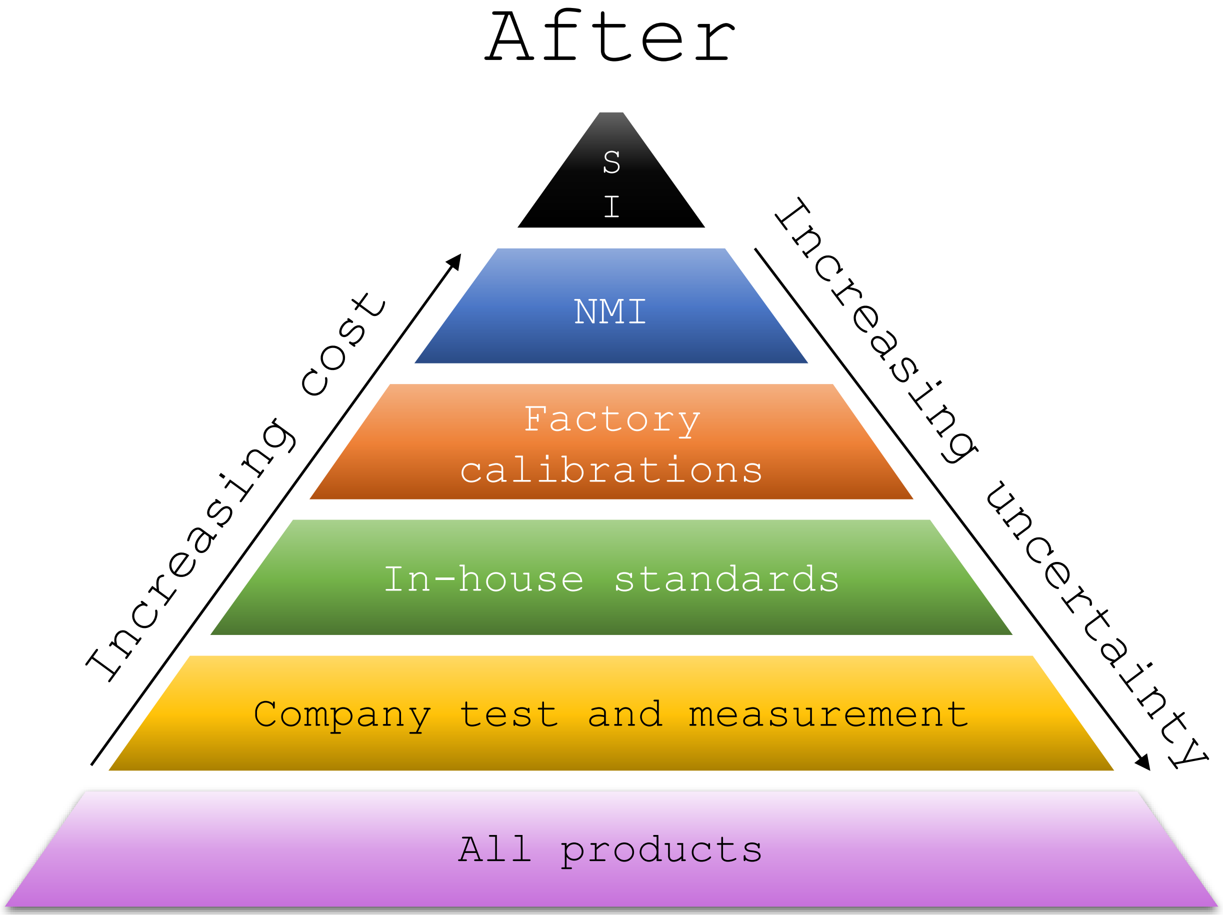
“300 GHz” kits



1 cm

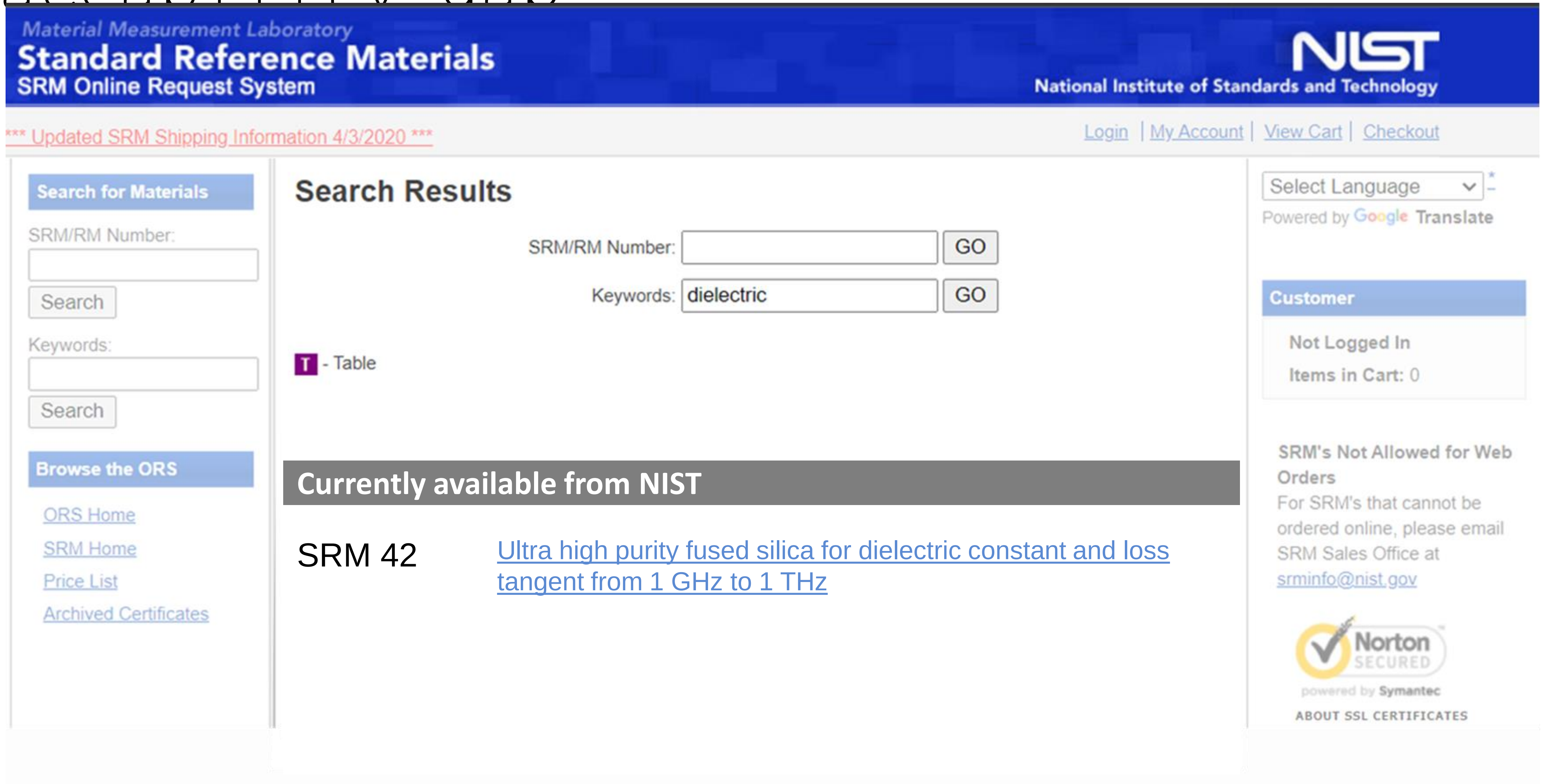
What other traceability chains can use this?





S-parameters, RF power, Antennas, Liquids, and more?

Only NIST can fill the dielectric traceability gap



*** Updated SRM Shipping Information 4/3/2020 ***

SRM/RM Number:

Keywords:

Search Results

SRM/RM Number:

Keywords: dielectric

T - Table

Not Logged In

Items in Cart: 0

SRM's Not Allowed for Web Orders

For SRM's that cannot be ordered online, please email SRM Sales Office at srminfo@nist.gov

Currently available from NIST

SRM 42	Ultra high purity fused silica for dielectric constant and loss tangent from 1 GHz to 1 THz

Summarizing this talk…

Objective: Develop a standard for dielectric constant and loss

State-of- New split cylinder cavities for dielectric

Key idea: New high purity fused silica with ultra low TTV

Impact: Enables metrology capability analysis and acceptance

Risks: Dimensional uncertainties are too high; samples are

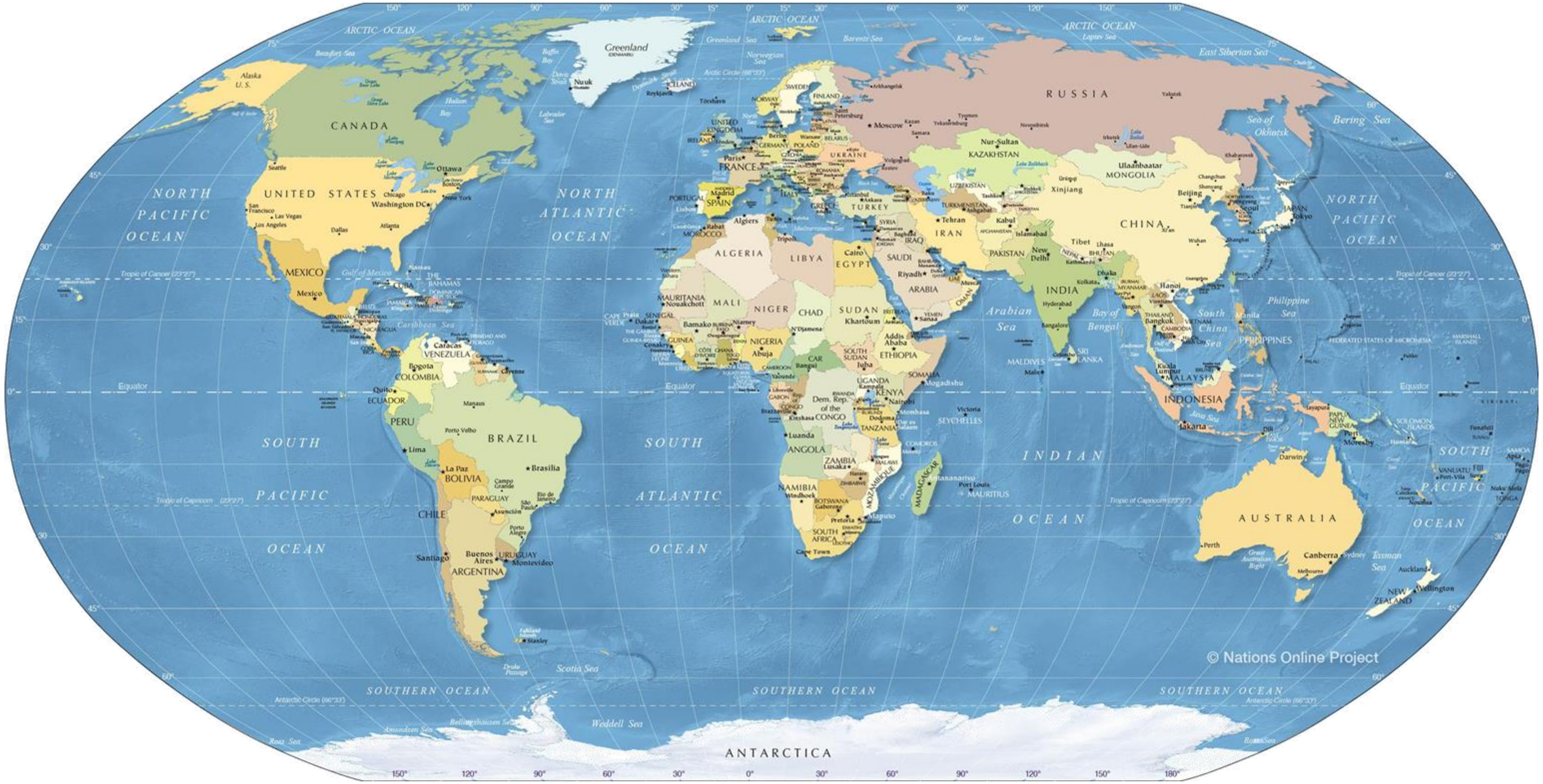
Metrics: Dielectric constant and loss tangent to better than

Thanks

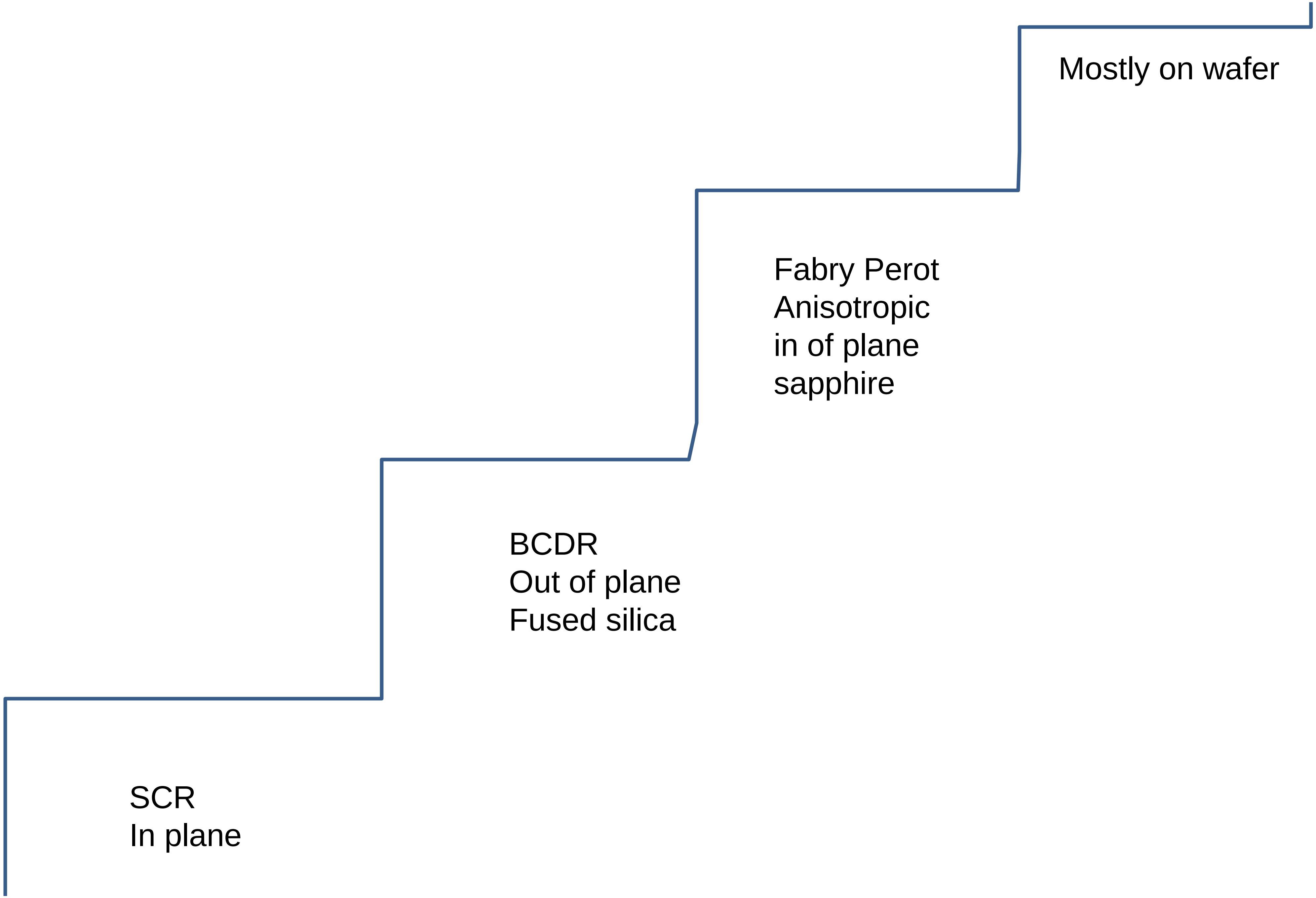
And thanks to iNEMI
Urmi, Mike (s), Say, Malgorzata, Marzena,
Chiawen, Lucas, Bryan, and the whole team!

Do dielectric materials matter to you?

Lucas Enright



You can participate in the new iNEMI project making a 5G SRM



SCR
In plane

BCDR
Out of plane
Fused silica

Fabry Perot
Anisotropic
in of plane
sapphire

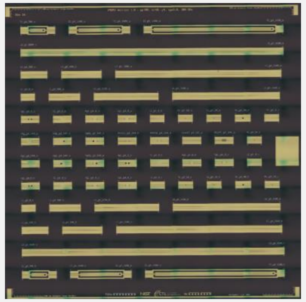
Mostly on wafer

What is the research staircase?

①

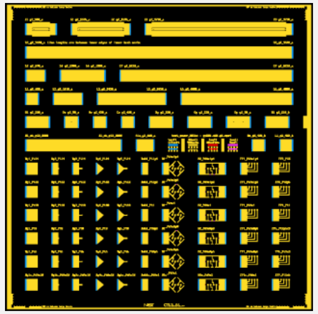
SRM

②



S-parameters

③



Power

④

Phase

⑤

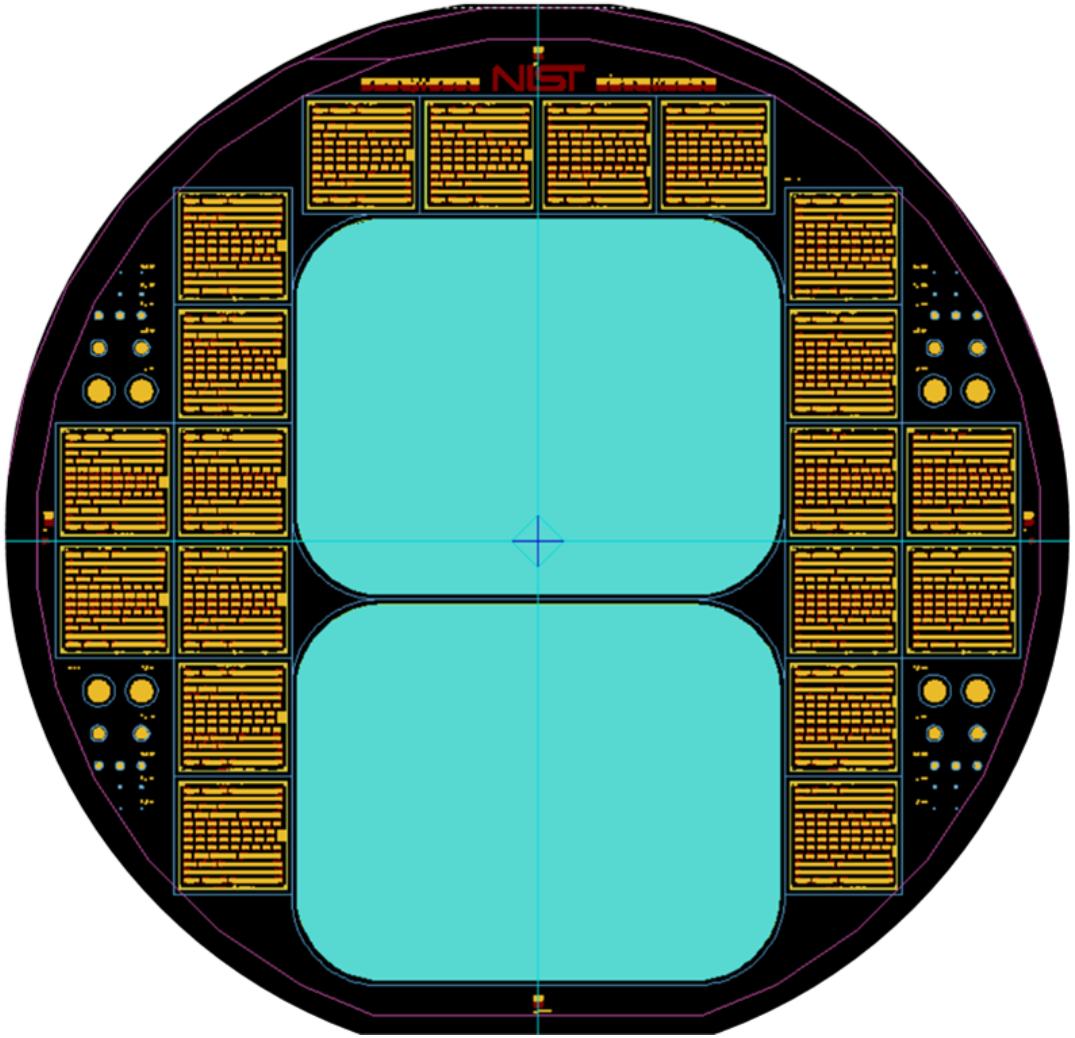
Antennas

S-parameters, RF power, Antennas, Liquids, and more?

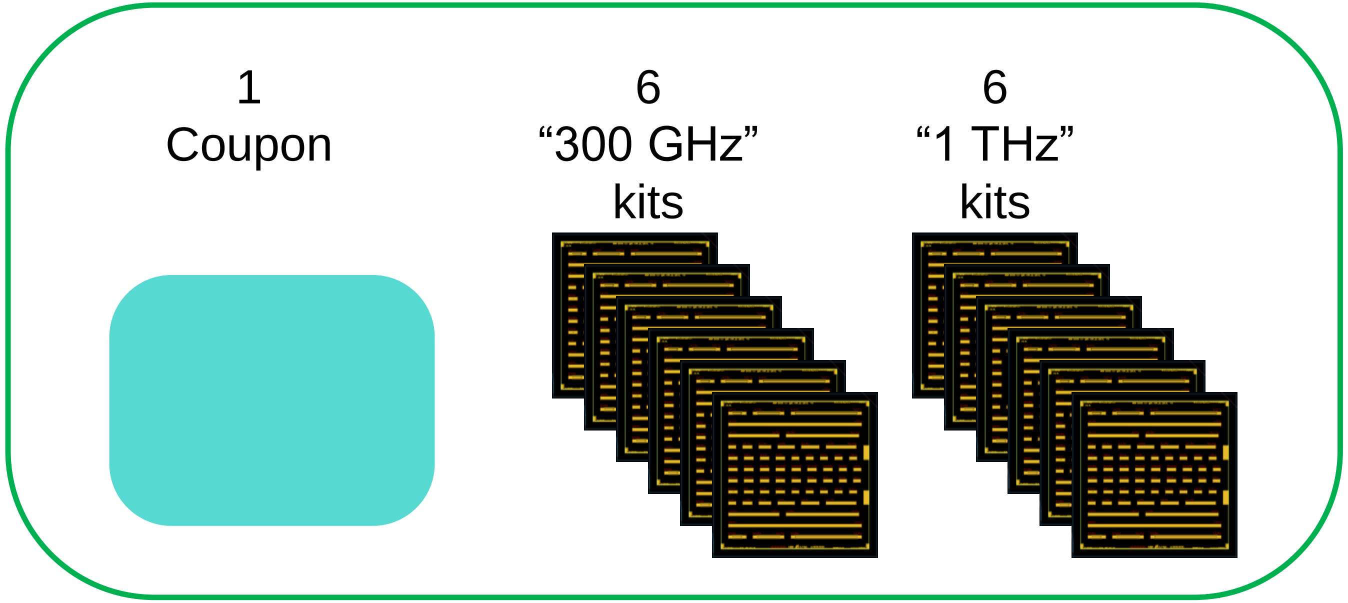
Here is the first prototype SRM 4242


Lucas Enright

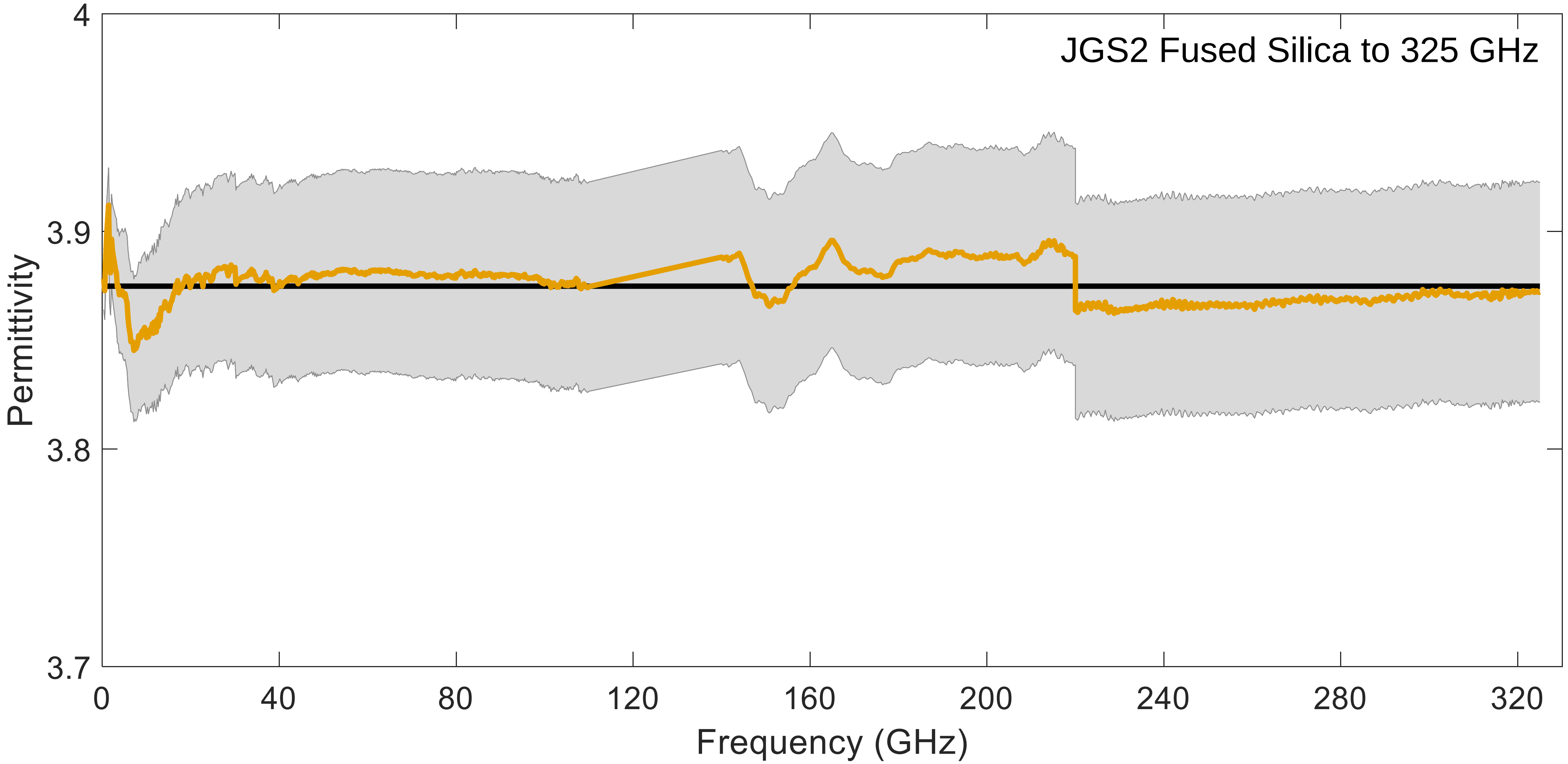
This is a 4” FS wafer



Proposed “5g mmWave” SRM 4242

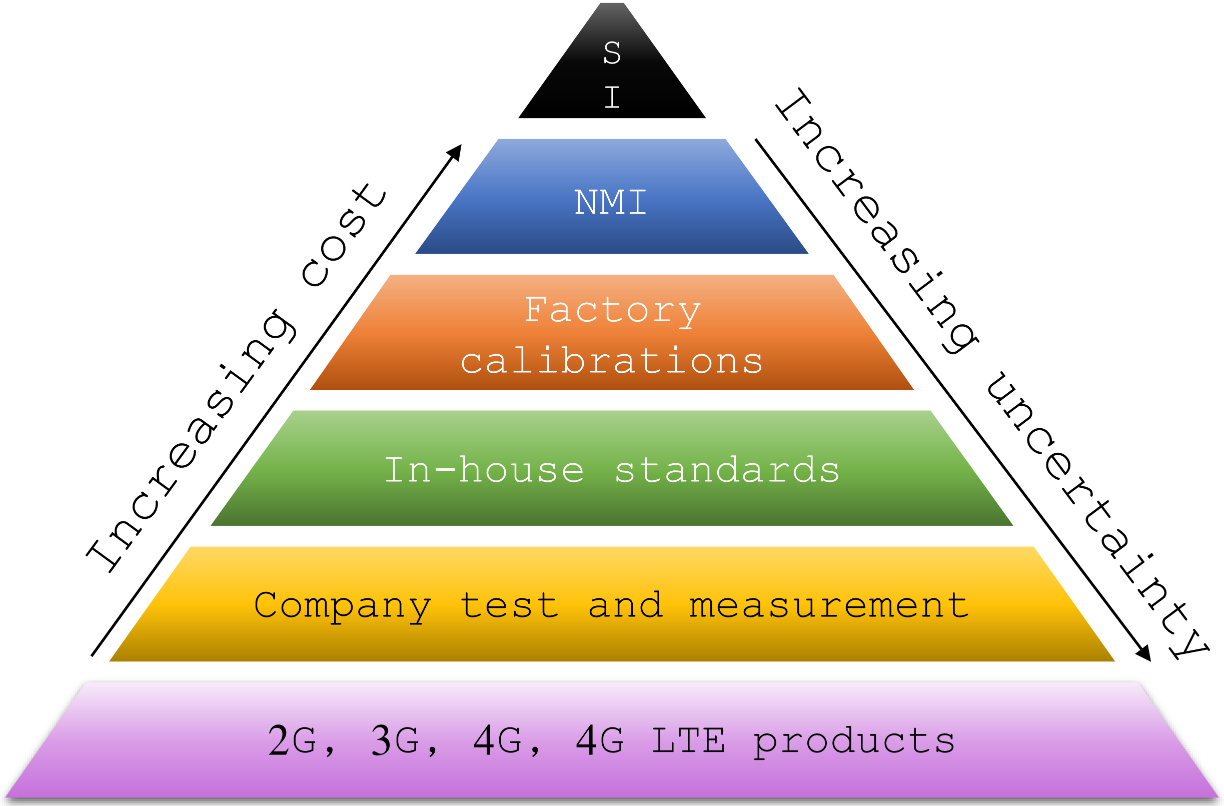


On-wafer lets us extend these ideas above 100 GHz



A semiconductor SRM can fill this traceability gap

Before 2017



SI

NMI

Factory calibrations

In-house standards

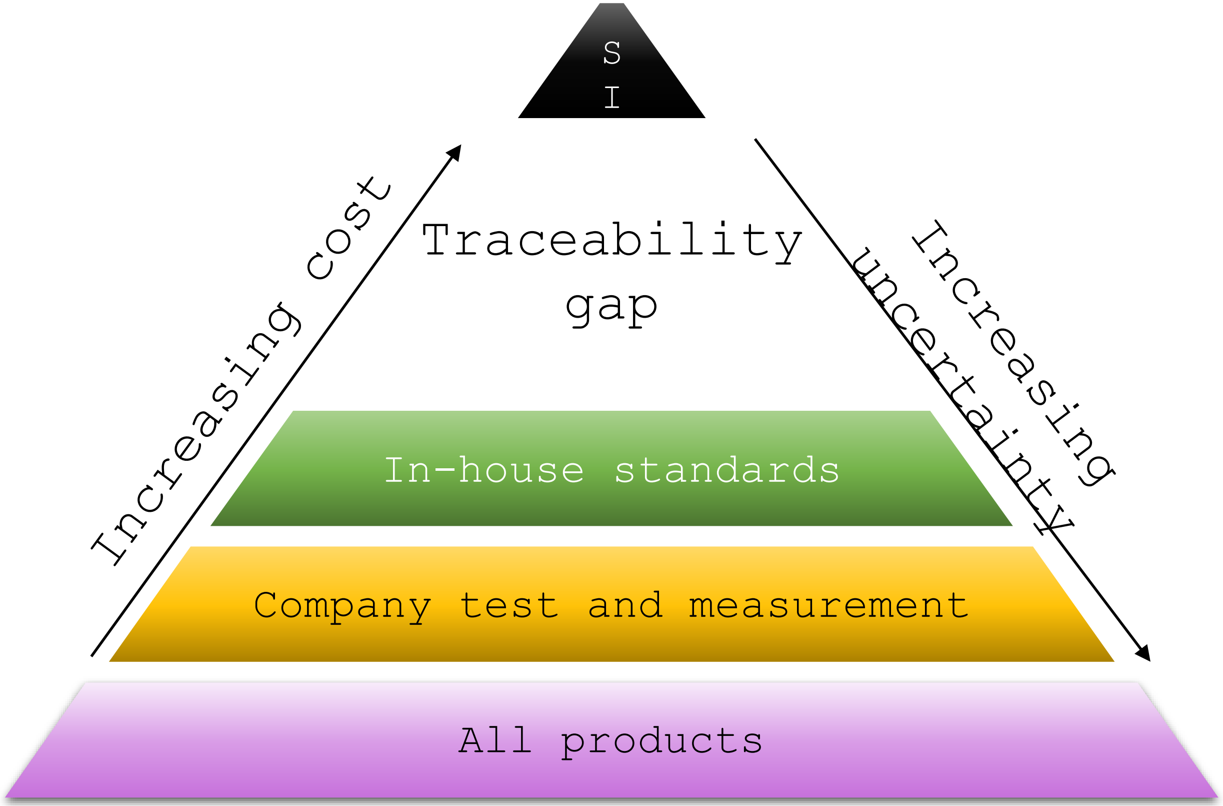
Company test and measurement

2G, 3G, 4G, 4G LTE products

Increasing cost

Increasing uncertainty

After 2017



SI

Traceability gap

In-house standards

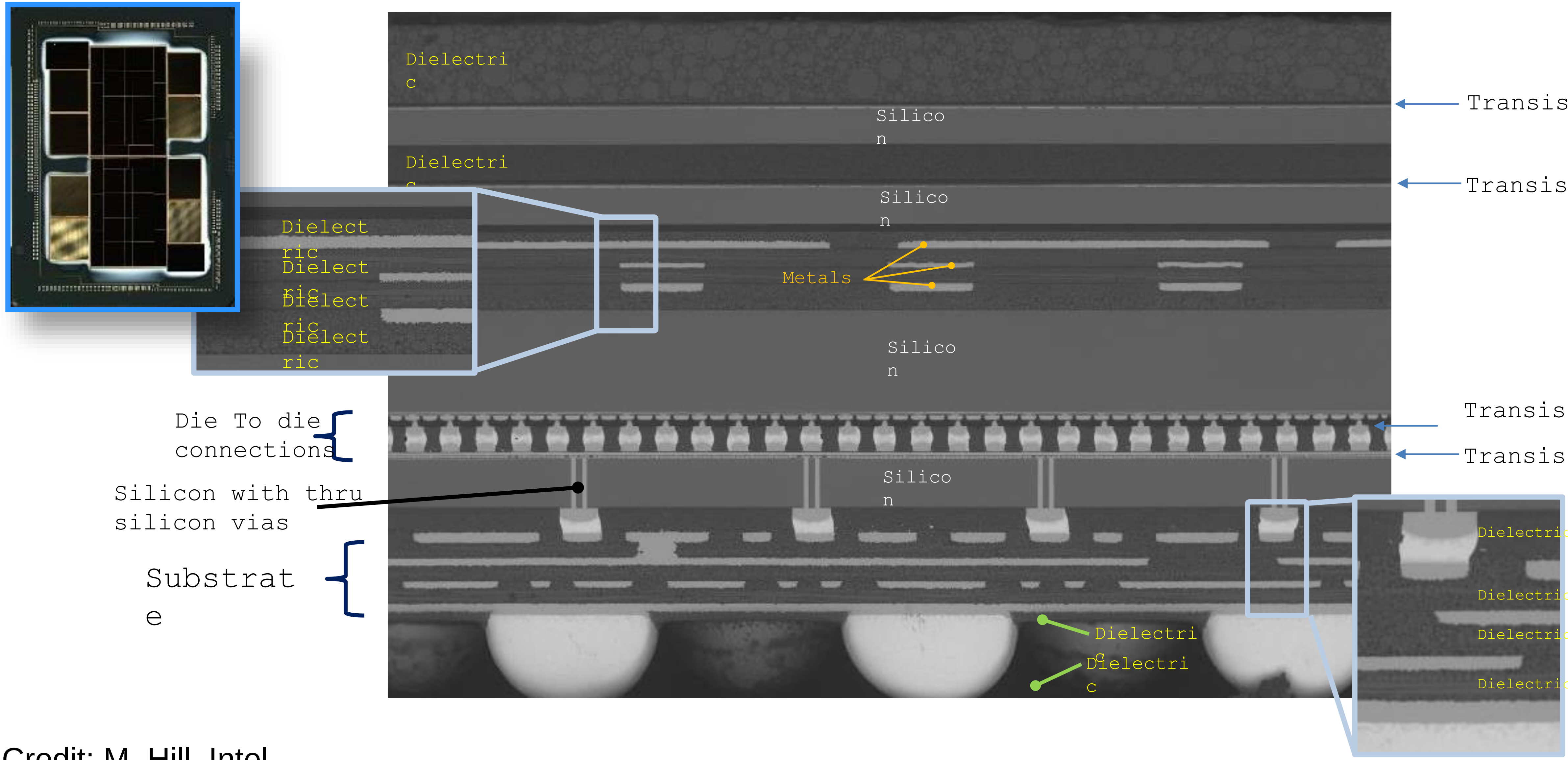
Company test and measurement

All products

Increasing cost

Increasing uncertainty

Intel's problem scales with the # of dielectrics



Credit: M. Hill, Intel

Propagating the uncertainty through the theory

3

Use theory to map to permittivity

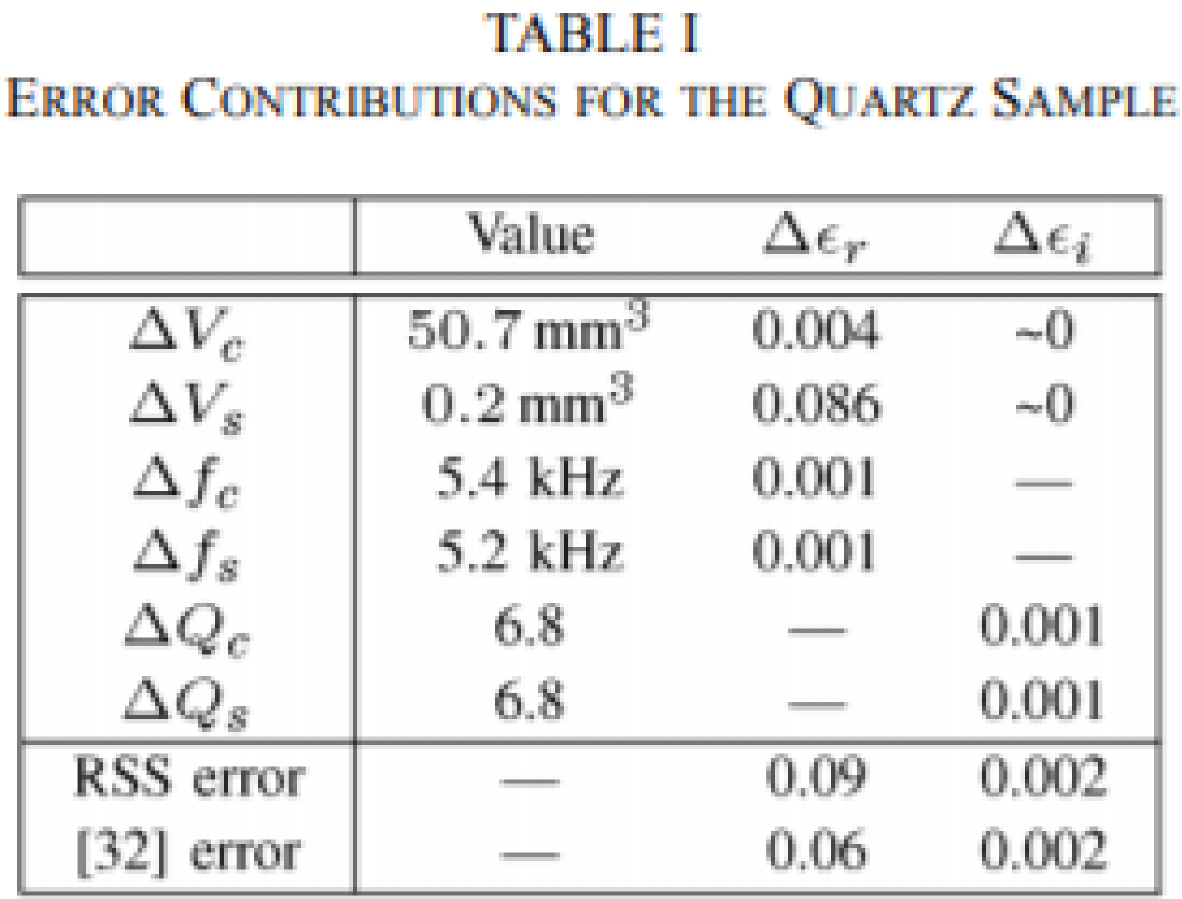


TABLE I

ERROR CONTRIBUTIONS FOR THE QUARTZ SAMPLE

	Value	$\Delta\epsilon_r$	$\Delta\epsilon_i$
ΔV_c	50.7 mm^3	0.004	~0
ΔV_s	0.2 mm^3	0.086	~0
Δf_c	5.4 kHz	0.001	—
Δf_s	5.2 kHz	0.001	—
ΔQ_c	6.8	—	0.001
ΔQ_s	6.8	—	0.001
RSS error	—	0.09	0.002
[32] error	—	0.06	0.002

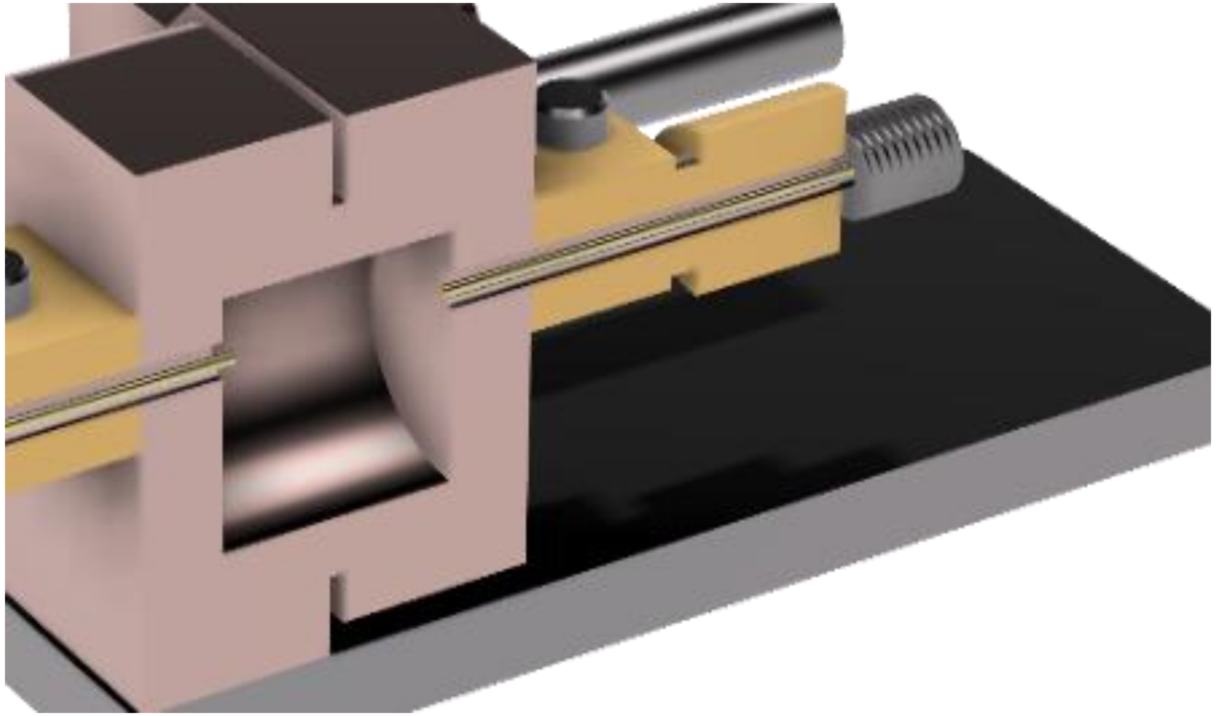
Dimensional Uncertainty

Fit uncertainty

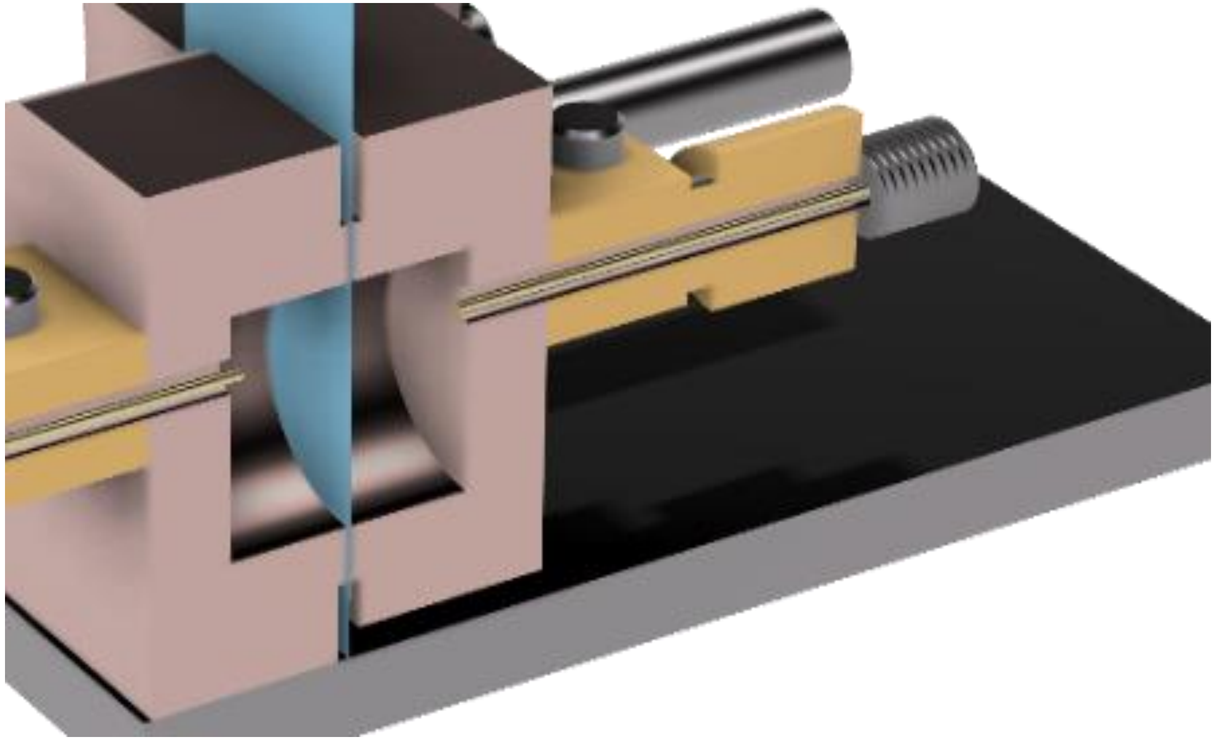
*This is specific to this cavity and not general

And that's it we have traceability…

Measuring a sample is easy (Side view)



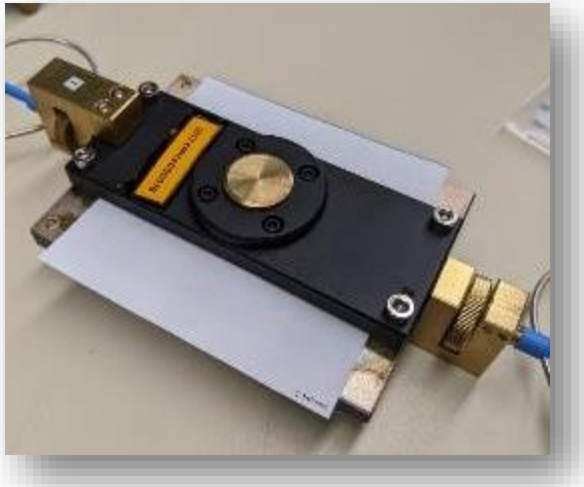
no sample



sample

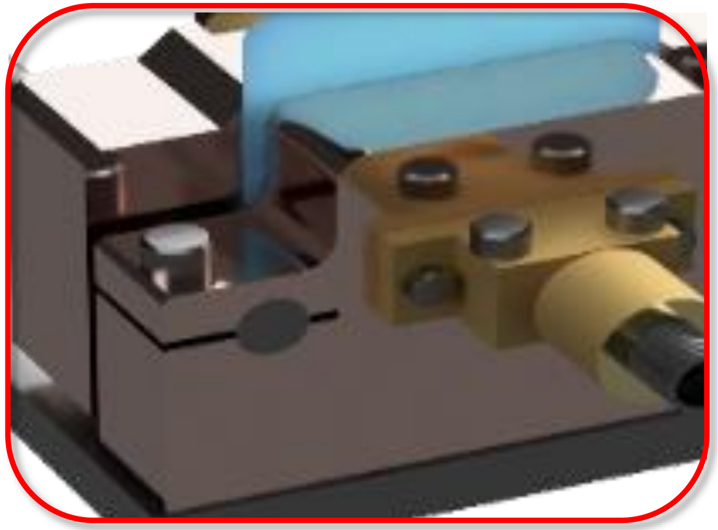
We plan on using the SCR to start because it is the simplest

There are many different types of cavity resonators



SPDR

(Split Post Dielectric Resonator)

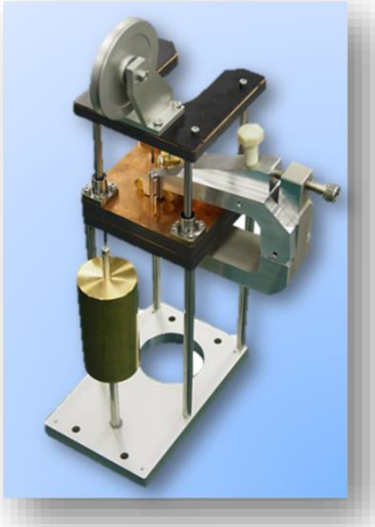


SCR

(Split Cavity Resonator)

FPOR

(Fabry-Perot Open Cavity Resonator)



BCDR

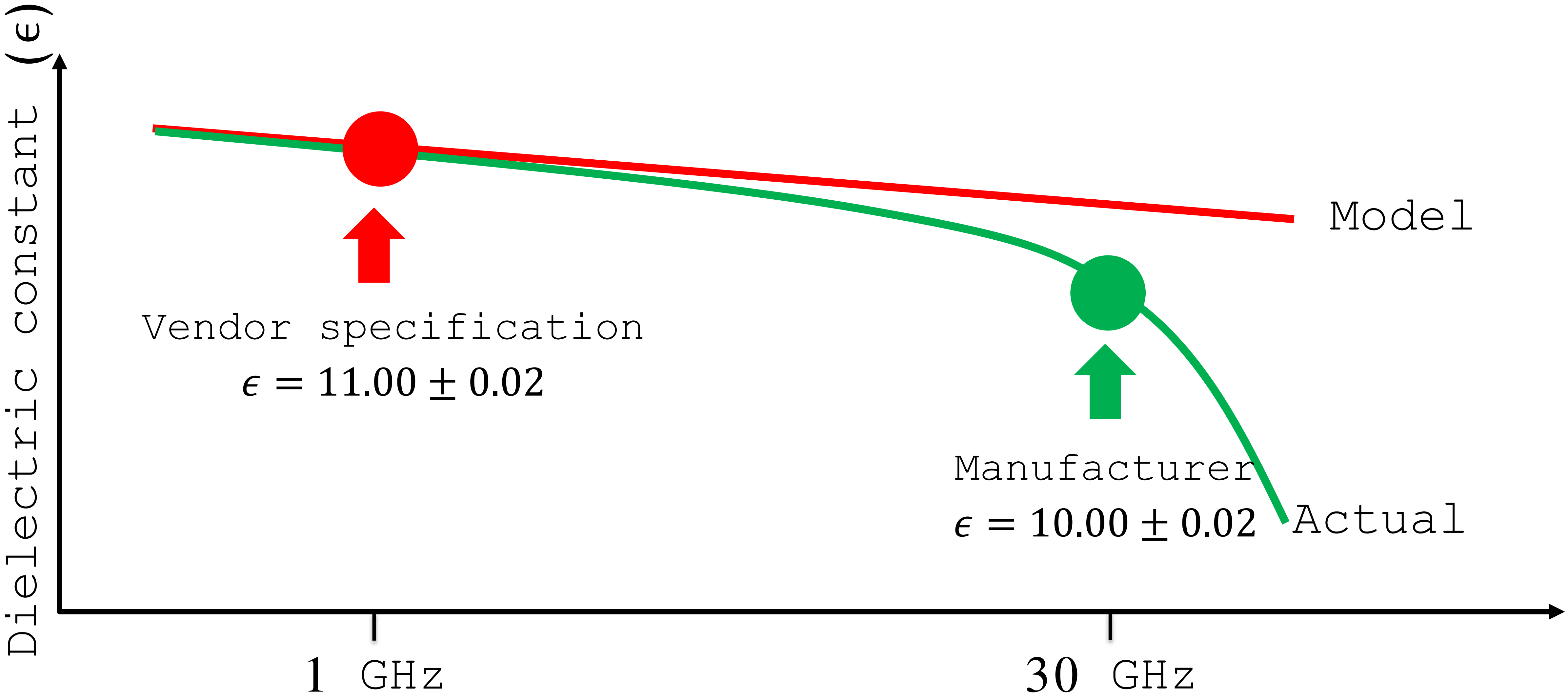
(Balanced Circular Disk Resonator)

We chose SCR because it has the shortest traceability path

We can't bring SRM 2870 back…

1. It is too thick
2. It is too small
3. We cannot fabricate on it

One frequency is not enough…



The y-axis can also be wrong

Review of the iNEMI round-robin SRM candidate material characterisation results and challenges

Marzena Olszewska-Placha (QWED)

Benchmarking project

- Benchmarking existing dielectric materials characterization methods
- Associating standardization institutes, electronic industry, equipment vendors, etc.
- Investigating repeatability and reproducibility
- Known and industrial materials

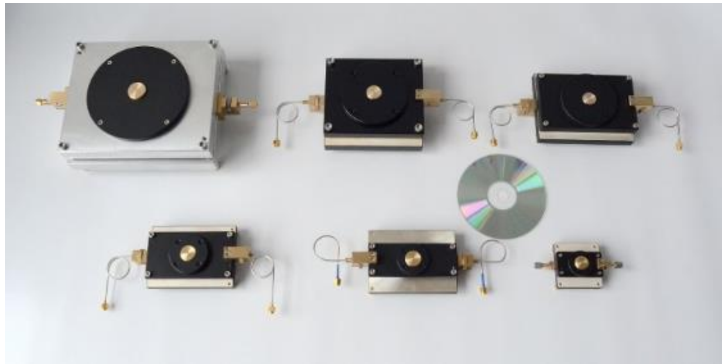
- Characterization techniques: SPDR, SCR, BCDR, FPOR

Benchmarking project (2)

- Four resonant methods:
  - SPDR, SCR, BCDR, FPOR
- 3 material types
- 12 samples (6 in each of two sizes)

- 10 samples kits
- 11 labs
- Following common thickness acquisition procedure

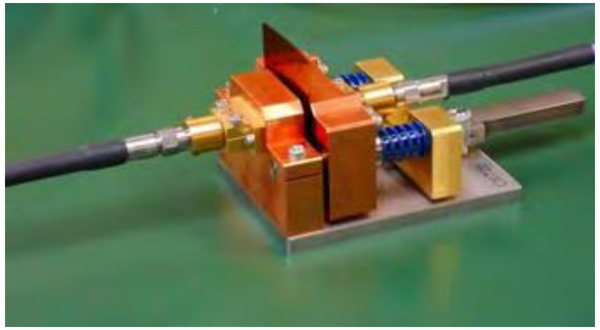
SPDRs



FPOR

BCDR

SCR

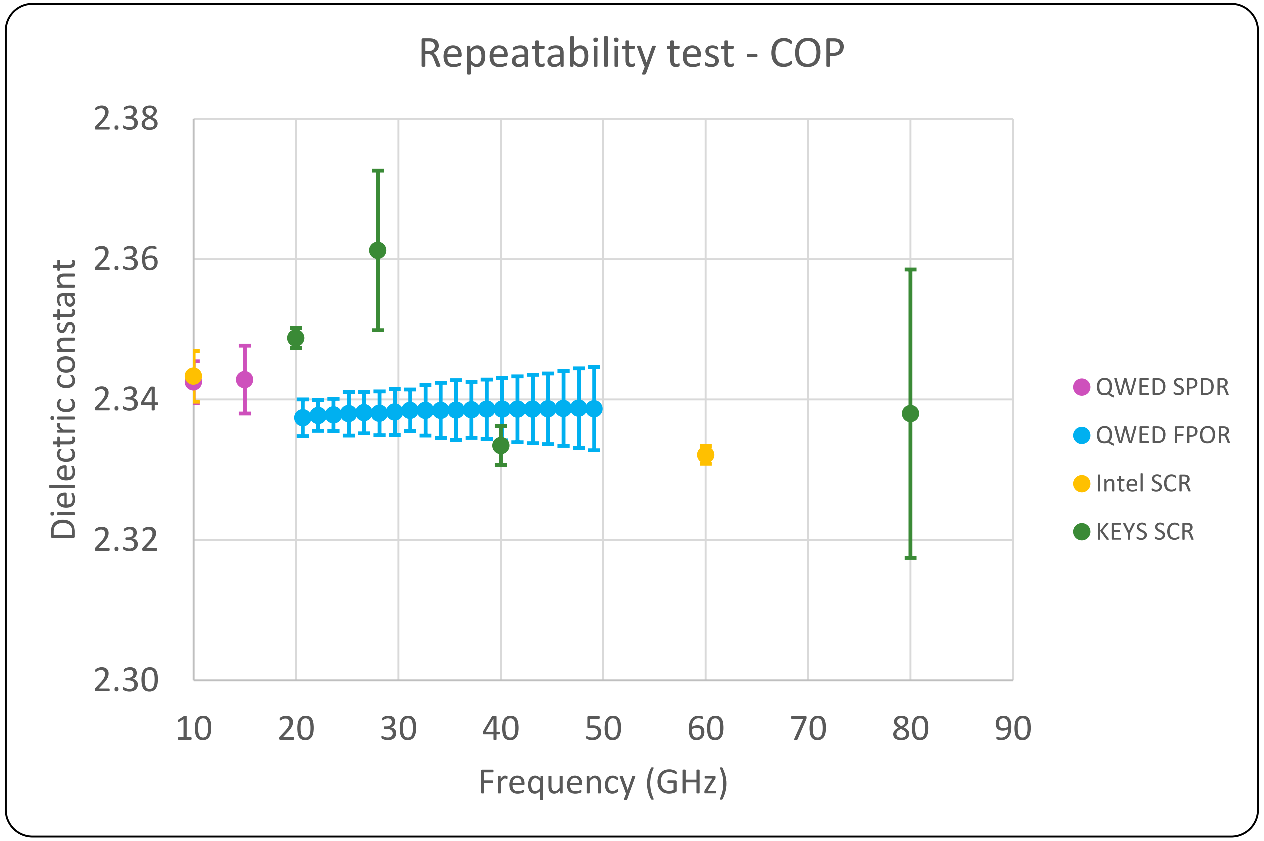


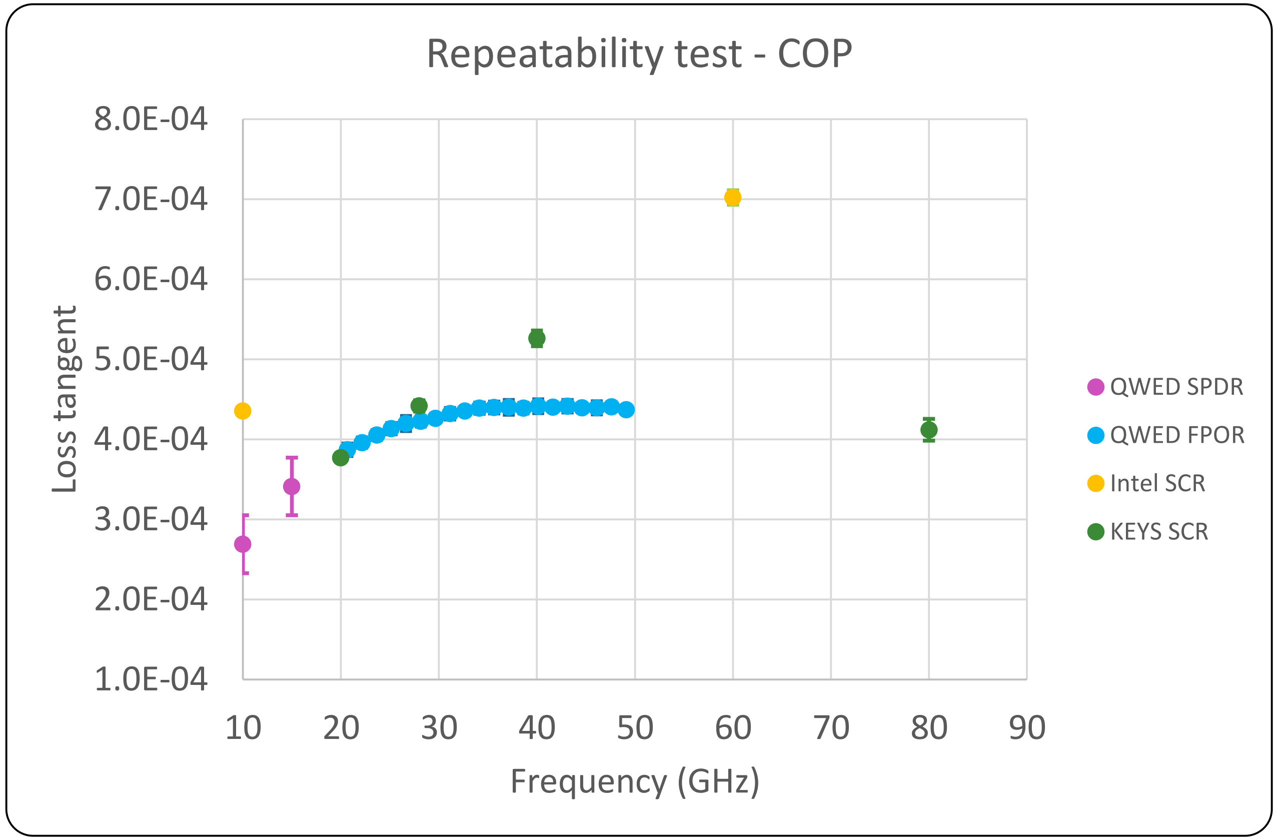
Benchmarking results (1)

Repeatability studies

Each measurement repeated 16 times

Repeatability bounds: ±3σ





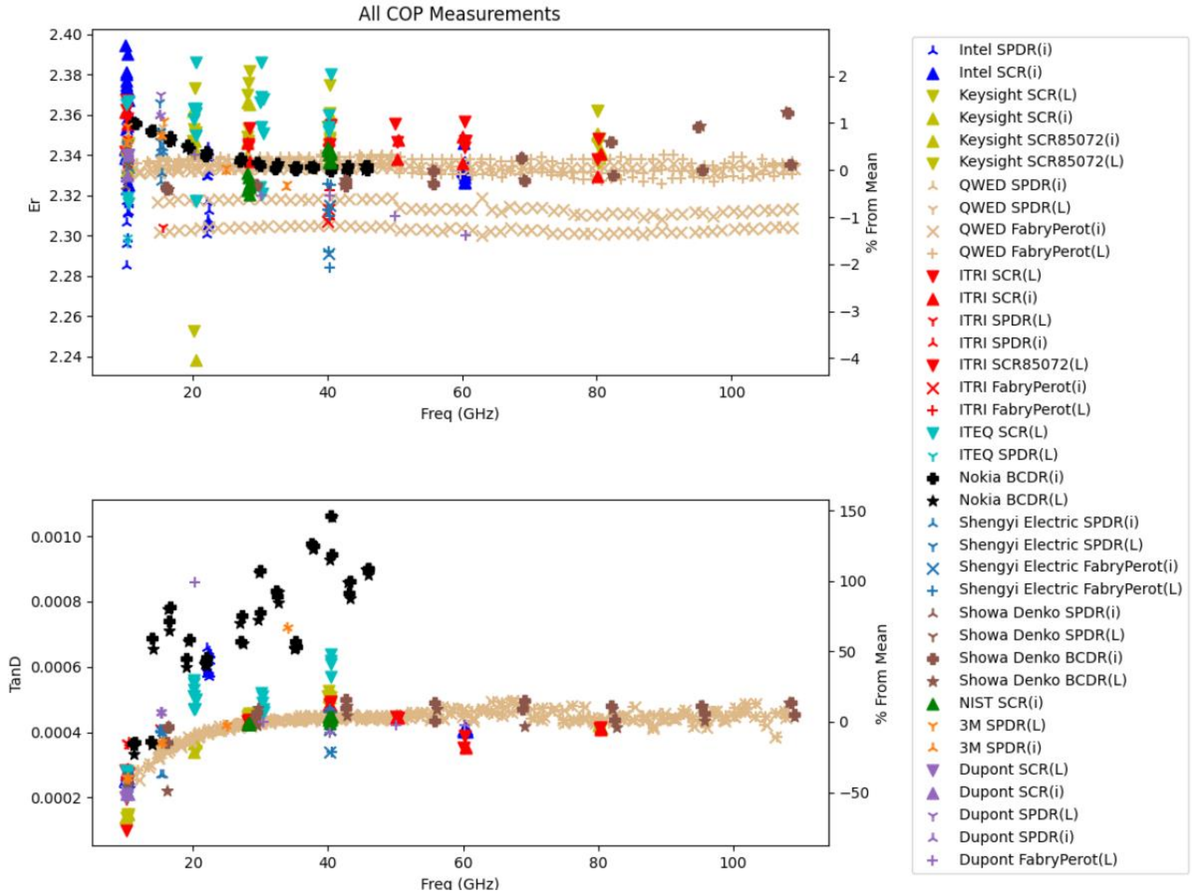
M. Celuch, M.J. Hill, T. Karpisz, M. Olszewska-Placha, S. Phommakesone, U. Ray, B. Salski, "Benchmarking of GHz resonator techniques for the characterisation of 5G/mmWave materials", 51st European Microwave Conference April 2021, pp. 568-571.

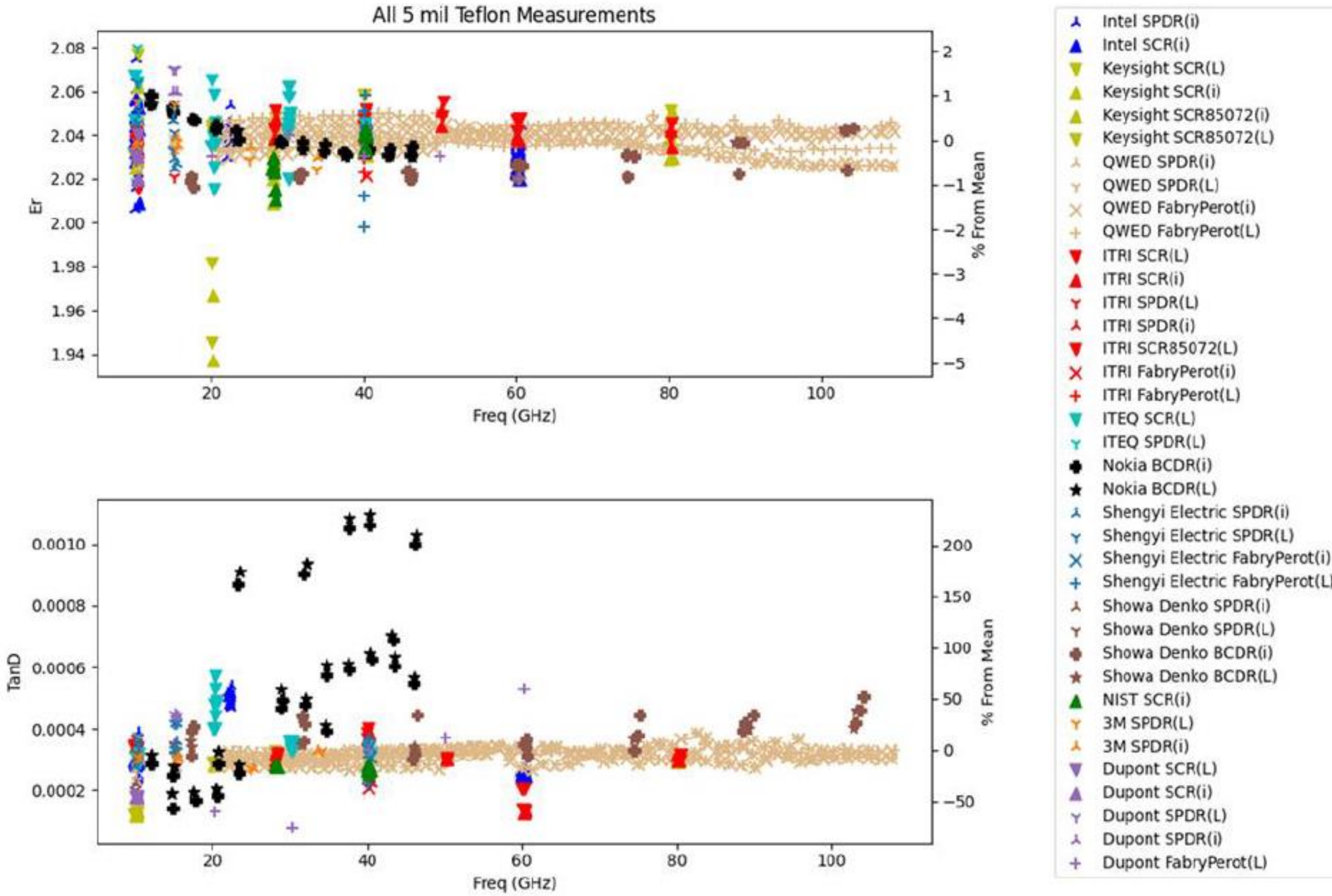
Benchmarking results (2)

INEMI *5G/mmWave Materials Assessment and Characterization* project results

Over 1000 measurement points in total

Round 1

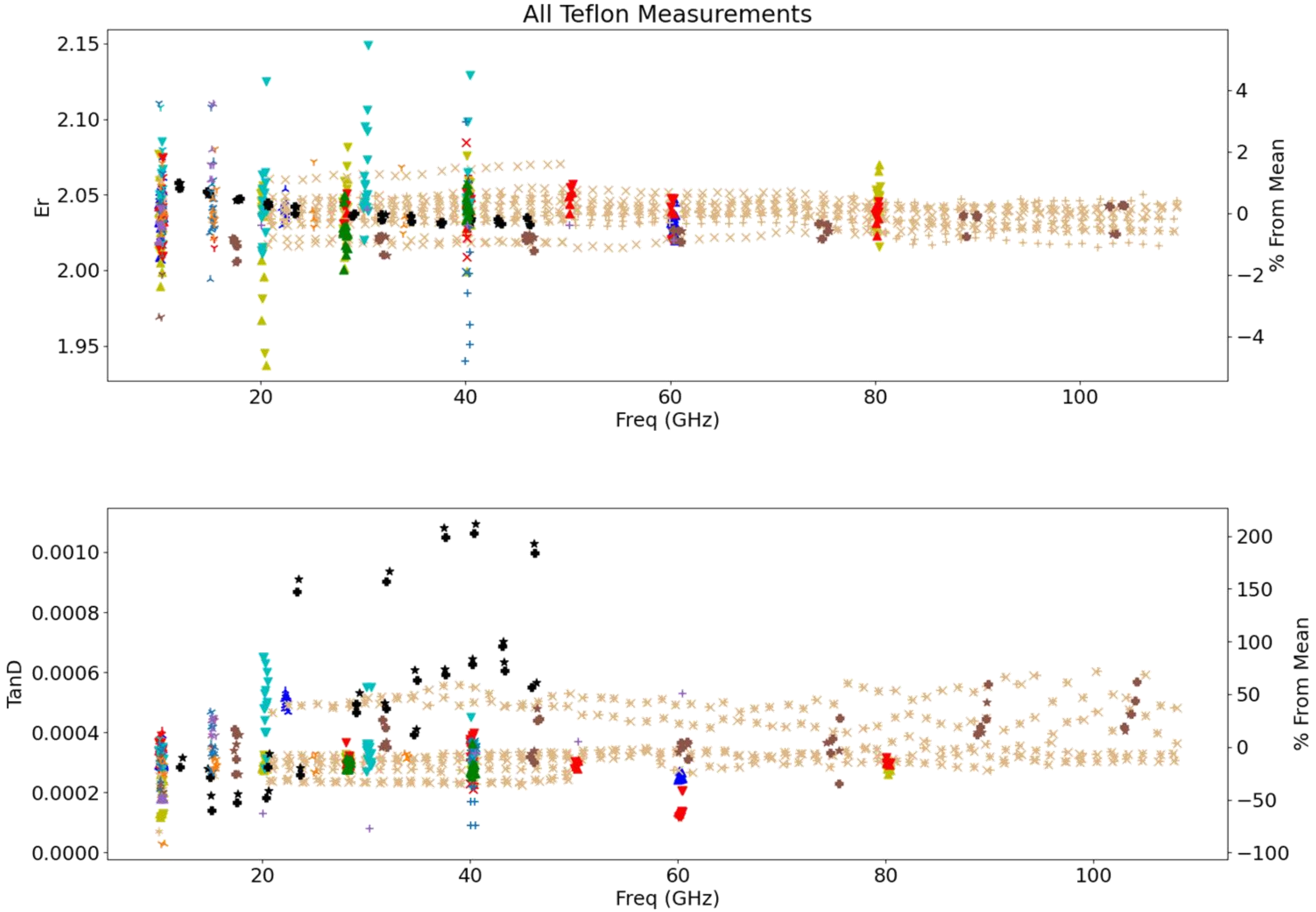




Spread of Dk: ±2%

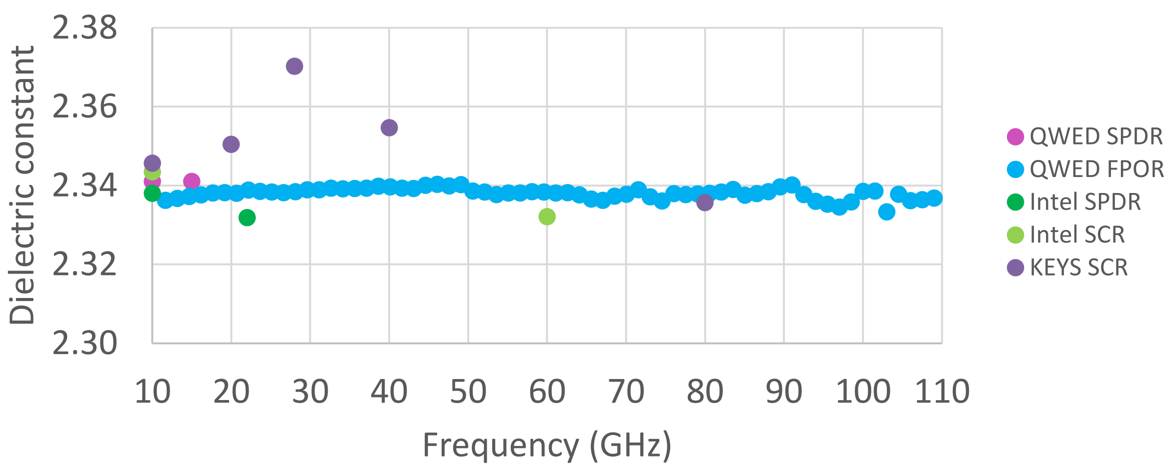
Benchmarking results (3)

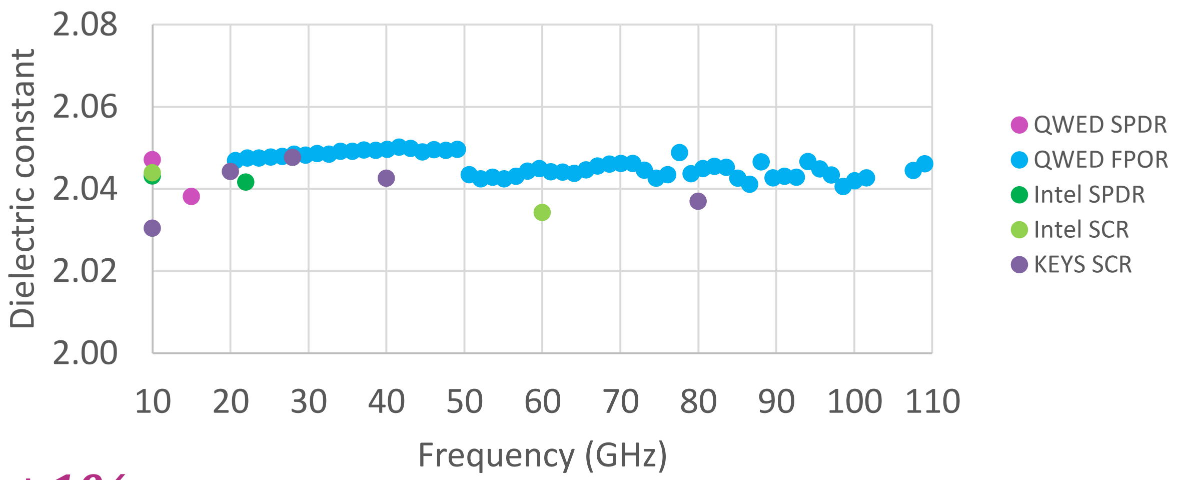
INEMI *5G/mmWave Materials Assessment and Characterization* project results



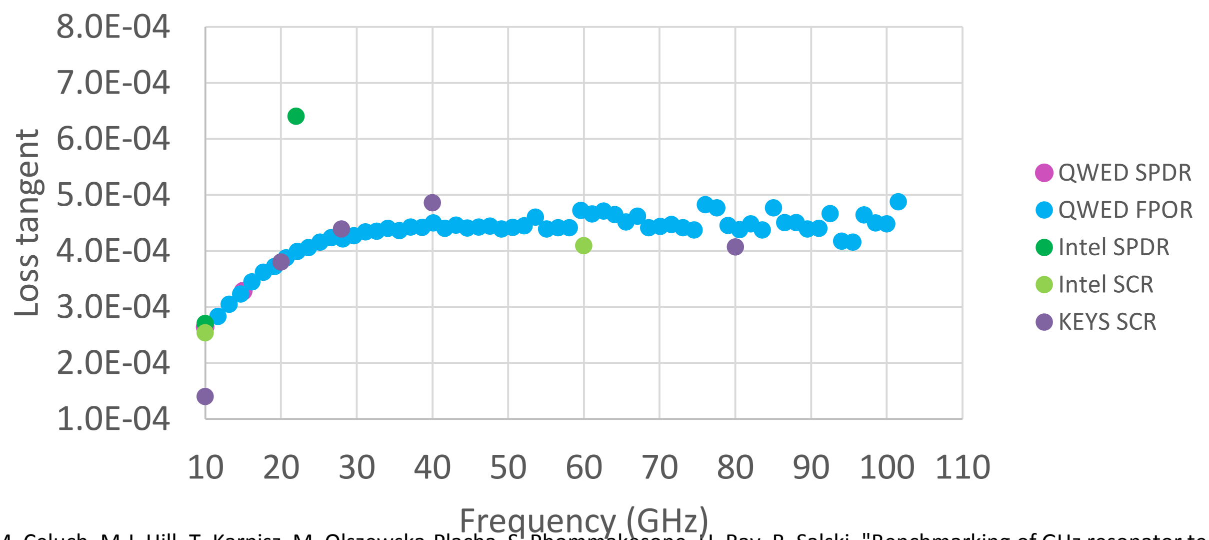
Spread of Dk: ±4%

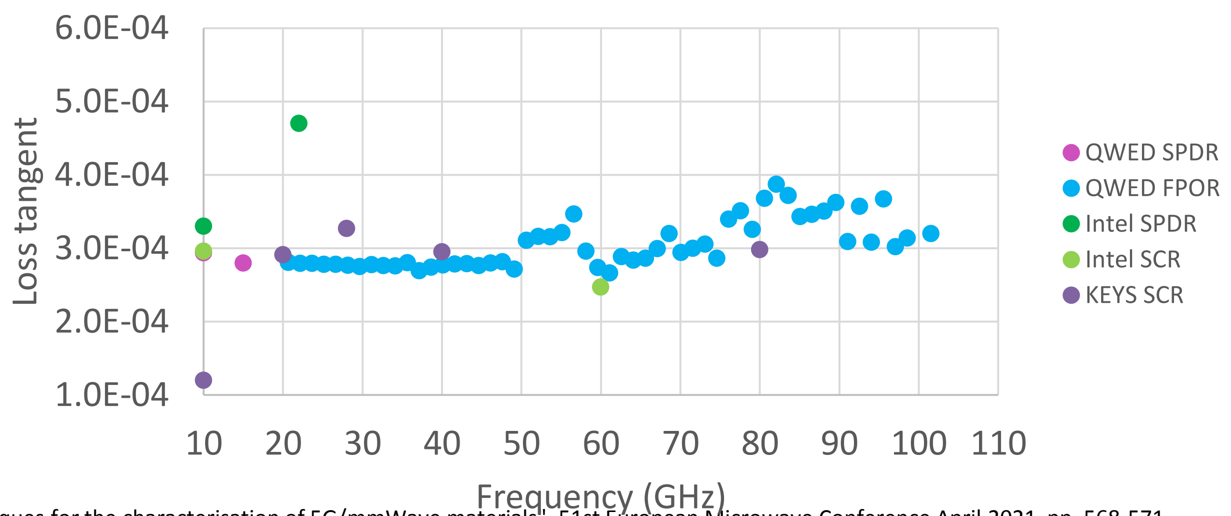
Benchmarking results (4)


COP 186µm


Teflon 5mils

Spread of Dk: ±1%

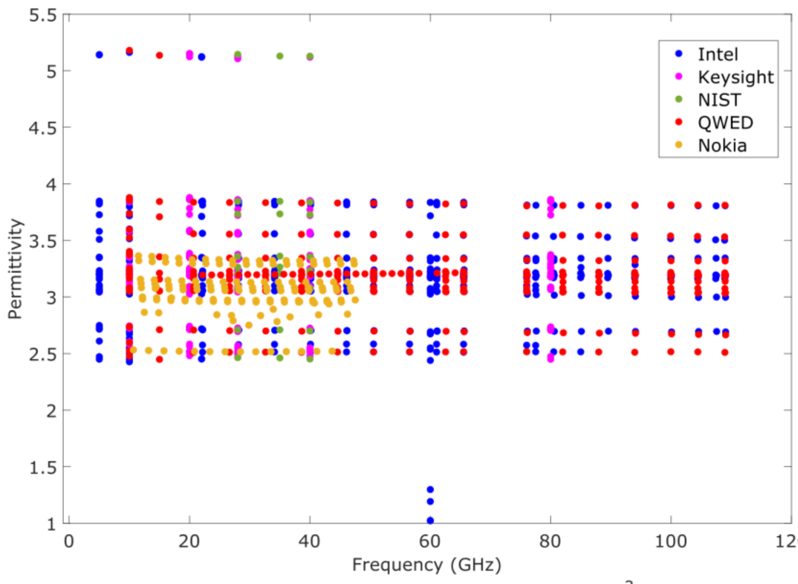

COP 186µm

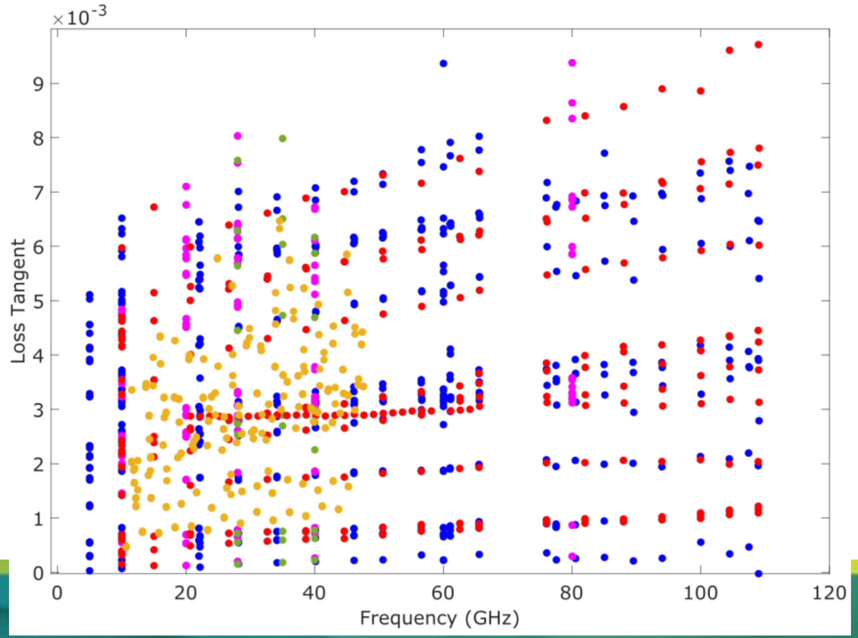

Telfon 5mils

M. Celuch, M.J. Hill, T. Karpisz, M. Olszewska-Placha, S. Phommakesone, U. Ray, B. Salski, "Benchmarking of GHz resonator techniques for the characterisation of 5G/mmWave materials", 51st European Microwave Conference April 2021, pp. 568-571.

Characterisation of „real” materials

- ☐ Industry samples provided by the members of Project Consortium
- ☐ 2 types of material samples: electronic and automotive
- ☐ Over 50 samples in total
- ☐ 5 labs
- ☐ 4 measurement techniques (SPDR, SCR, FPOR, and BCDR)

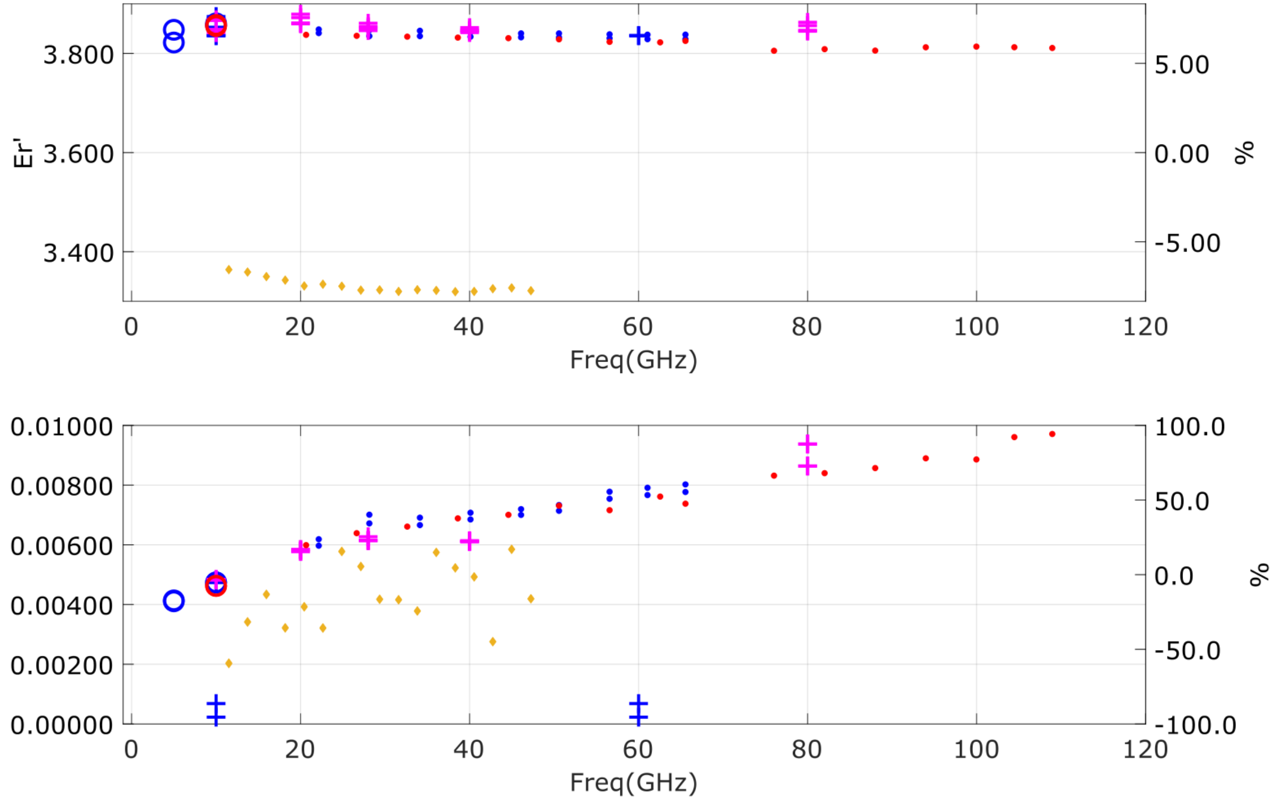




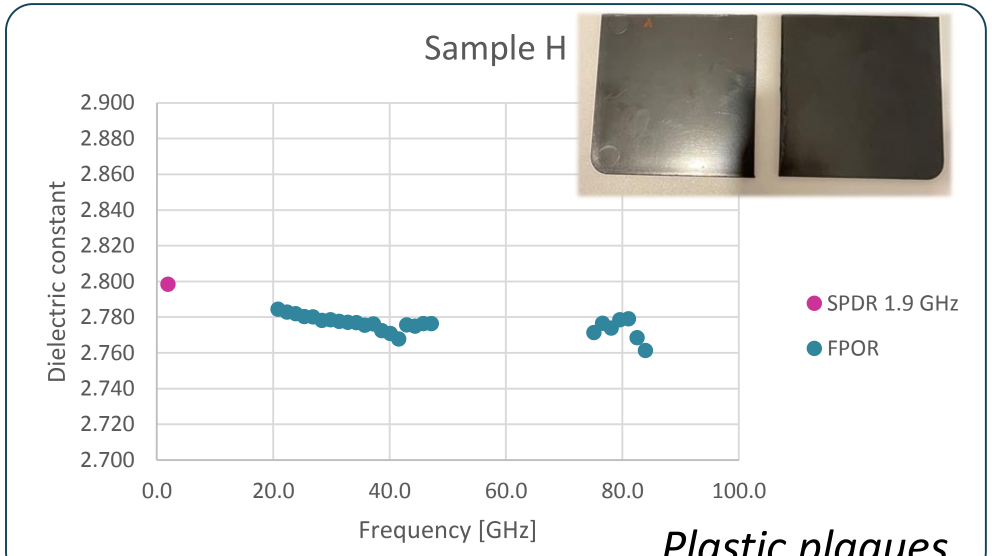
Characterisation of „real” materials (2)

Electronic materials

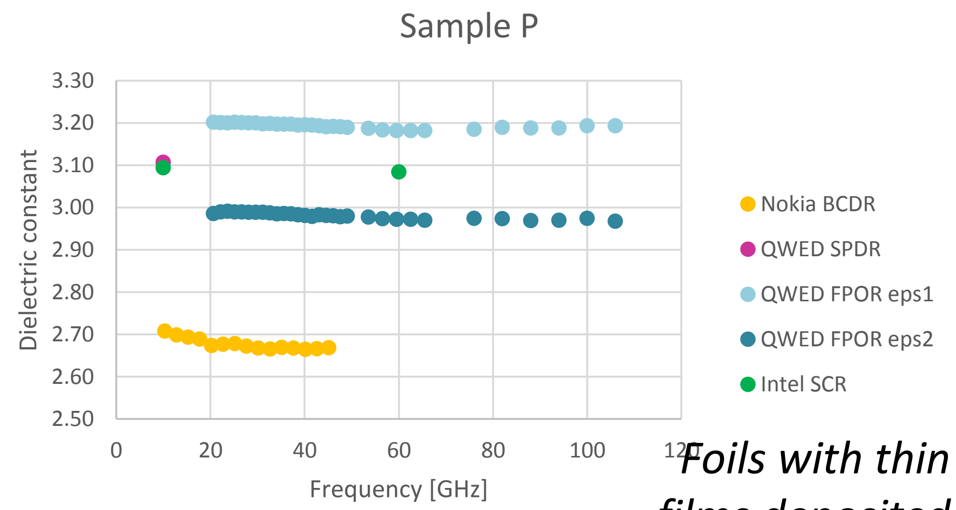
Highest measured permittivity material



Automotive materials



Plastic plaques



Foils with thin films deposited

Observations and conclusions

- Two sample size sufficient to cover all considered test methods
- Accurate thickness evaluation is of high importance
- Thickness variation and sample flatness determine uncertainty of Dk extraction
- Results variation across the labs of ±2%

- *Standard reference materials are of high interest*

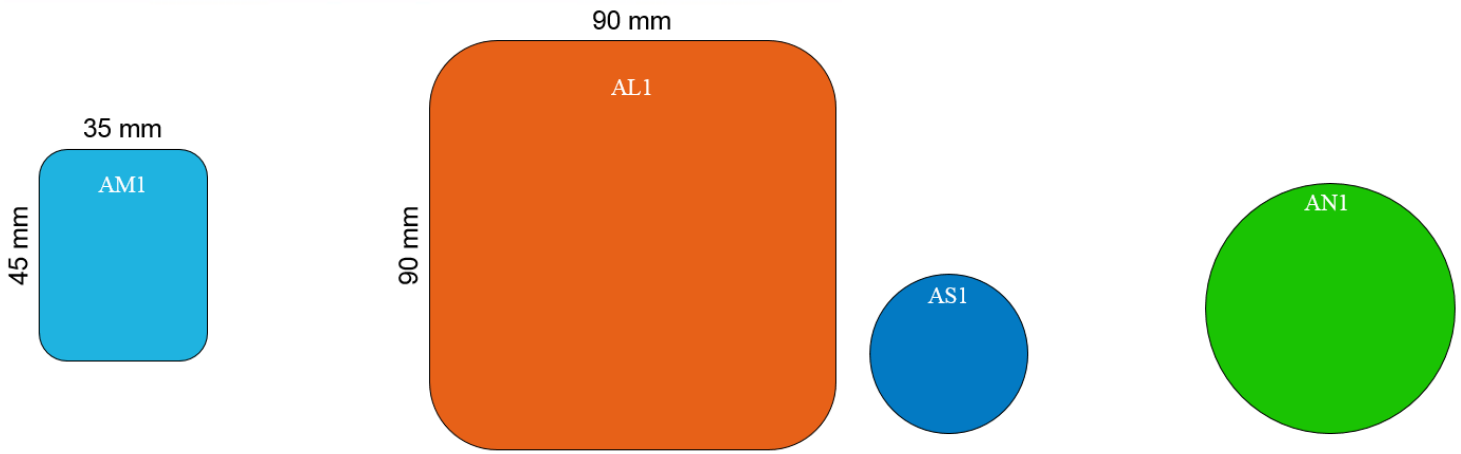
Standard reference material

- A strong need for standard reference material
- Traceable standard – dielectric parameters certified by NIST
- Calibration of 5G & 6G material characterization fixtures

- Targeting 0.2% uncertainty in SRM in round robin results
- 9 labs in round robin testing

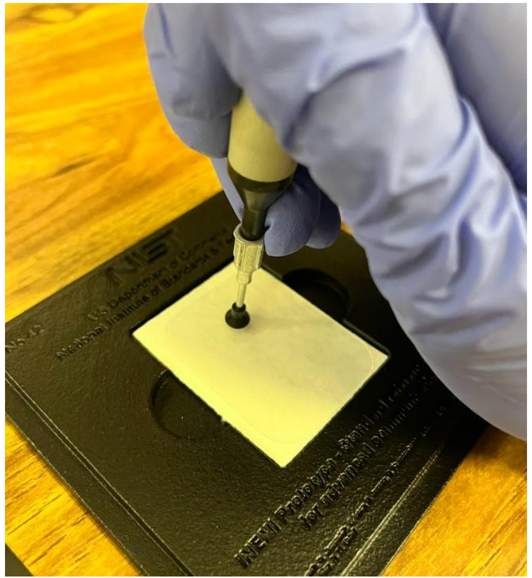
Round Robin 1

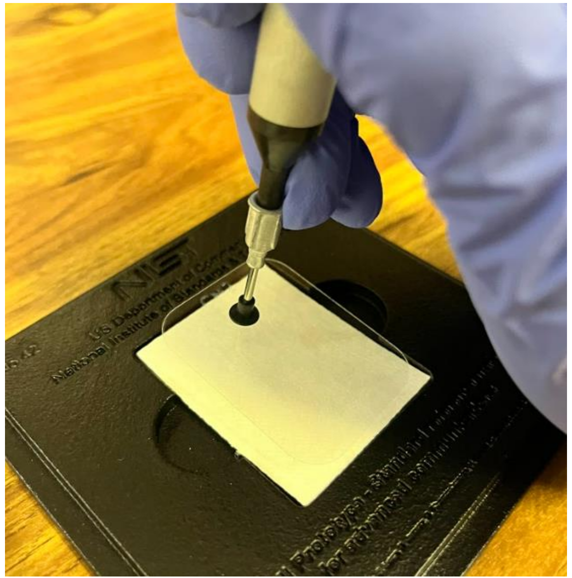
- SRM candidate material – fused silica
- 137um – thick sample
- Four characterization methods: SCR, SPDR, FPOR, BCDR
- Three sample sizes:
  - – 90 x 90 mm
  - – 35 x 45 mm
  - – Dia 30 mm & dia 49 mm

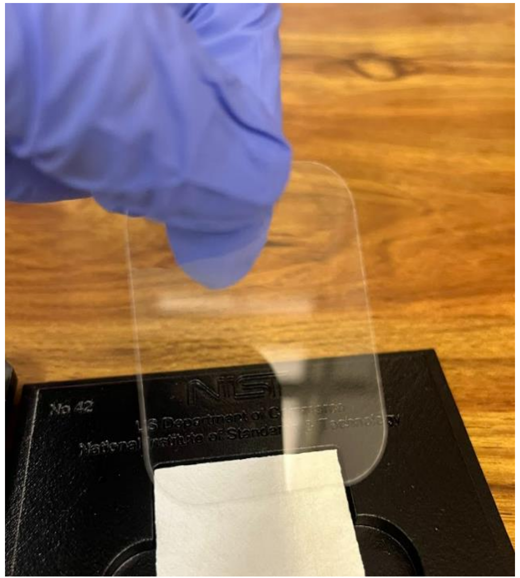


- 9 labs involved
- Testing in-plane (FPOR) and out-of-plane (BCDR) anisotropy

SRM candidate

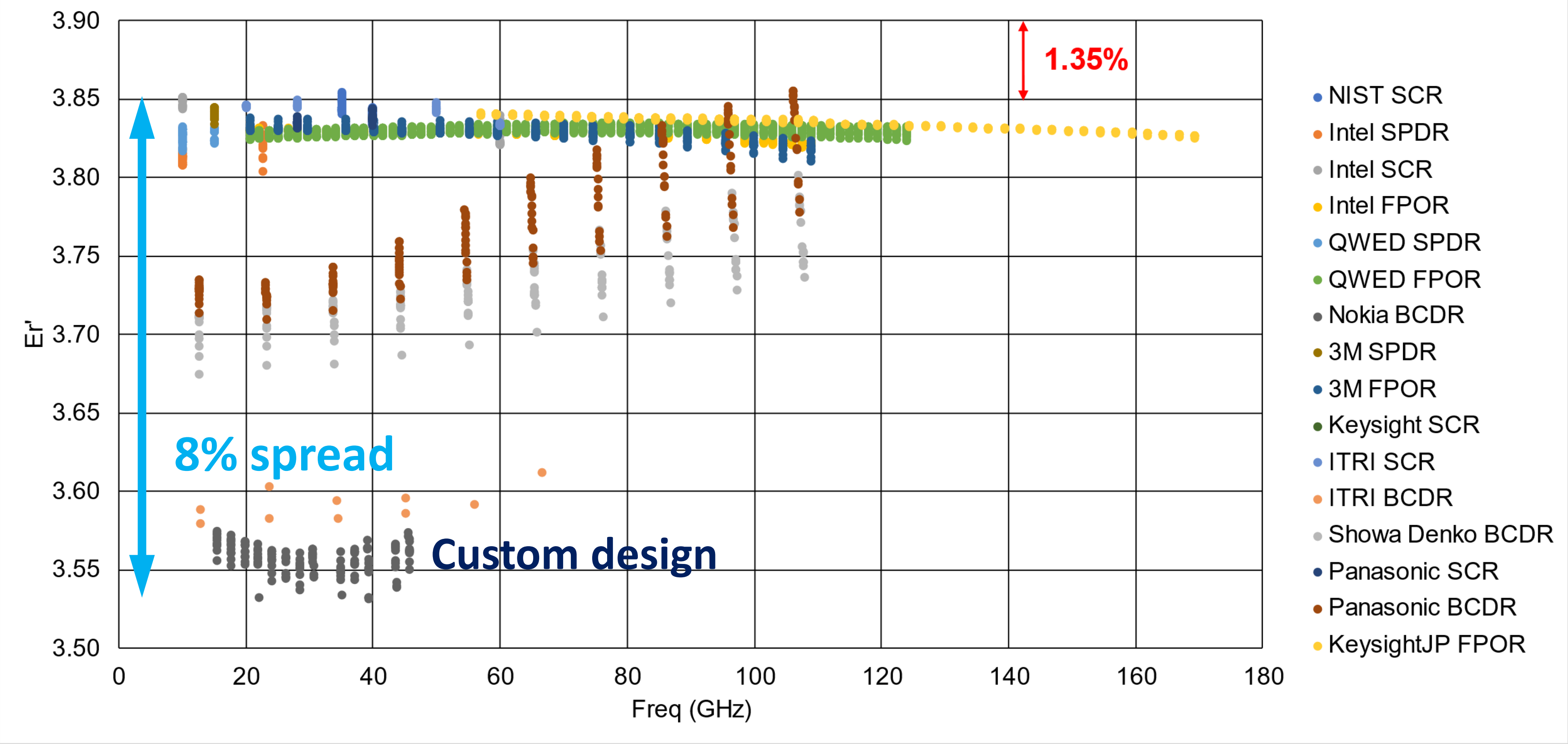






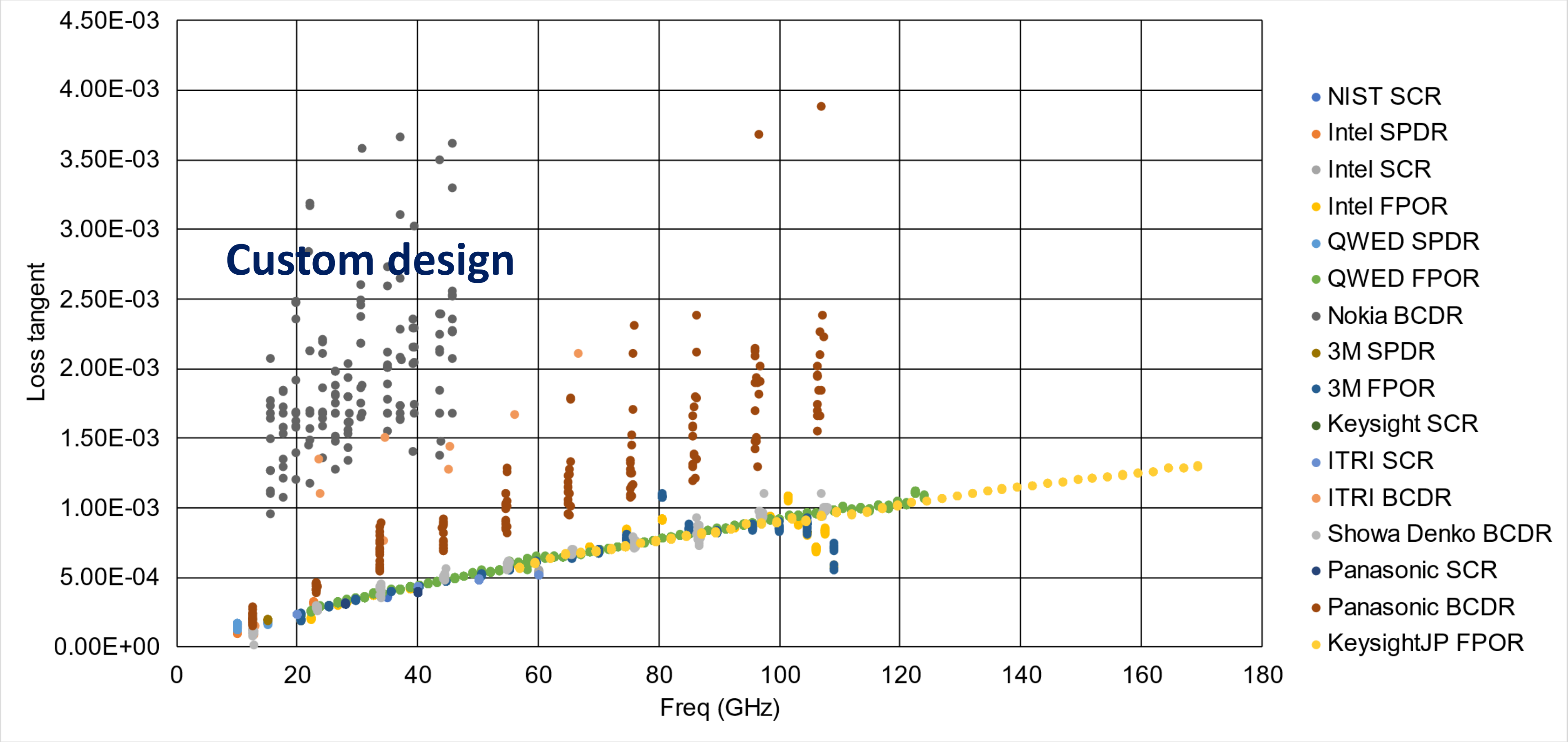
Round Robin 1 results (1)

Total of 2991 measurement points



Round Robin 1 results (2)

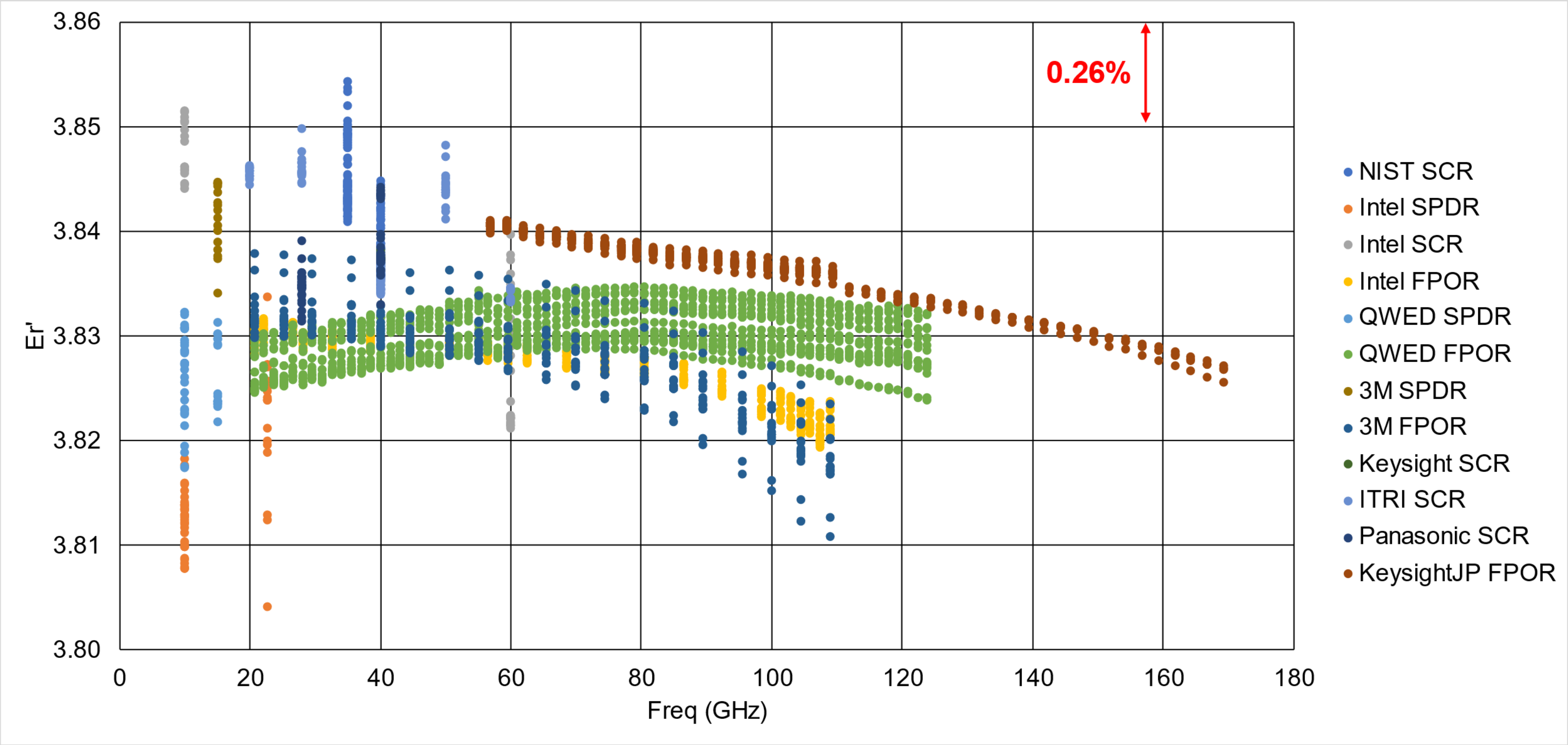
Total of 2991 measurement points



Round Robin 1 results (3)

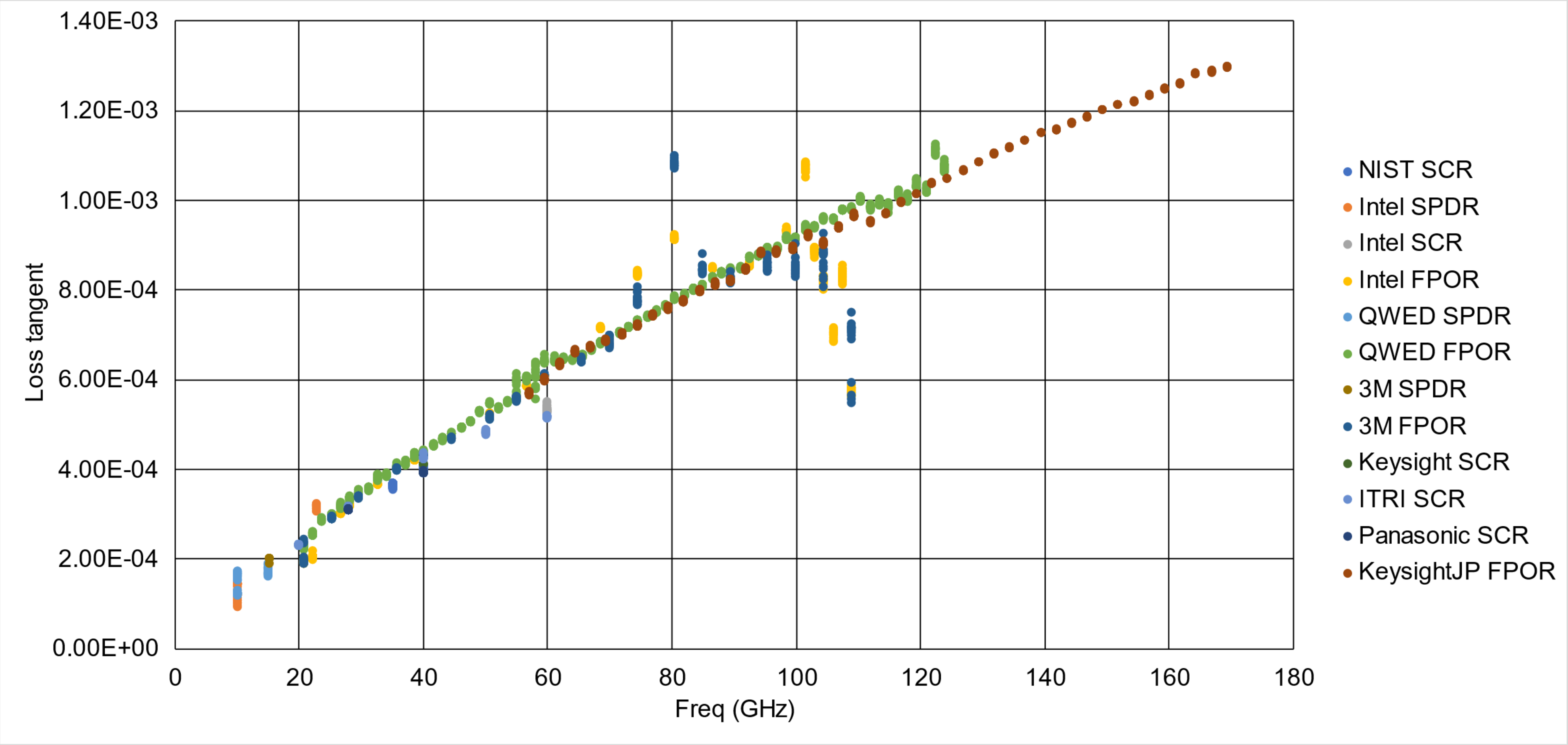
In-plane measurements

Agreement within 1.6%

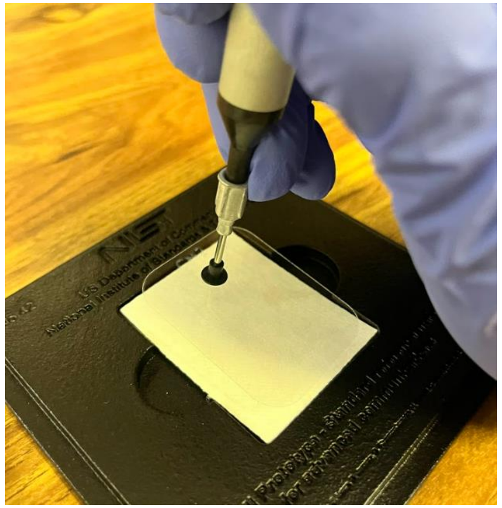


Round Robin 1 results (4)

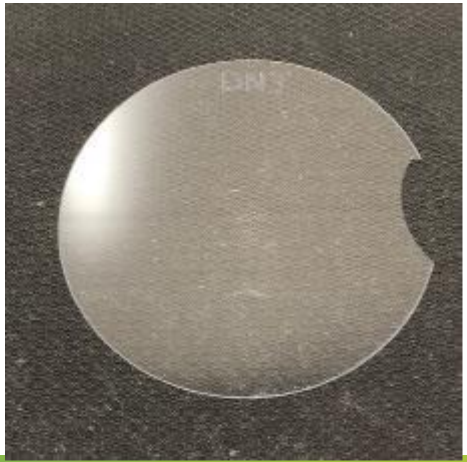
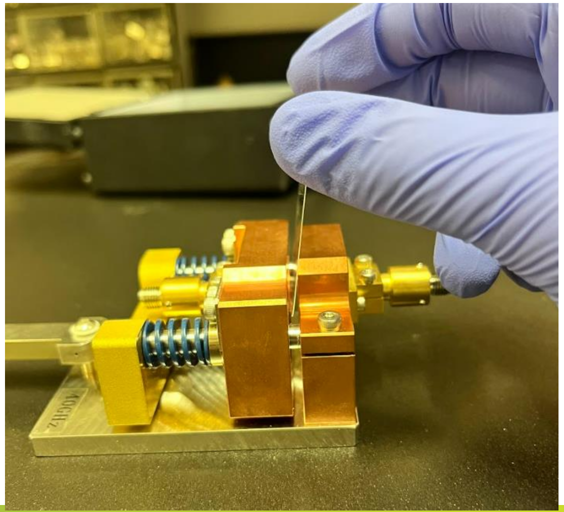
In-plane measurements



Challenges




- 137 um SRM candidates tested
- Handling issues - samples breakage:
  - Samples clamping
  - Thickness measurements
  - In between measurements
- Thickness uncertainty → potential source of Dk spread

- Round Robin 2:
  - Improving handling – 150um thick sample
  - Expected ‘strength’ to increase ~th^3
  - Thickness measurements insight

Thank you for the attention

5G/6G mmWave Materials and Electrical Test Technology Roadmap

Urmi Ray (iNEMI)

6G and sub-THz Materials and Test Requirement Roadmap

5G/6G mmWave Materials and Electrical Test Technology (5G/6G MAESTRO) – NIST Advanced Mfg Roadmap

Urmi Ray, iNEMI
urmi.ray@inemi.org

Presented to: IMS 2023 Industry Workshop
www.inemi.org

Advancing manufacturing technology

- Intro to iNEMI
- 5G/6G Communications Overview
- NIST Maestro Roadmap
  - Key Findings
  - Roadmap Table
- Summary and Conclusions

Intro to iNEMI

Advancing manufacturing technology

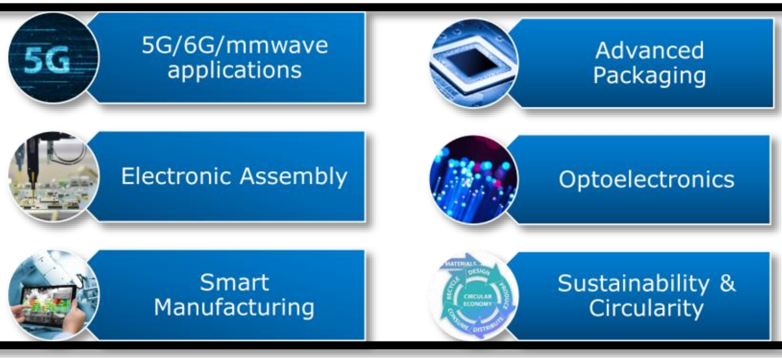
iNEMI – Premier Industry-led Global Consortium for Electronics Manufacturing

Forecast and accelerate improvements in the electronics manufacturing industry

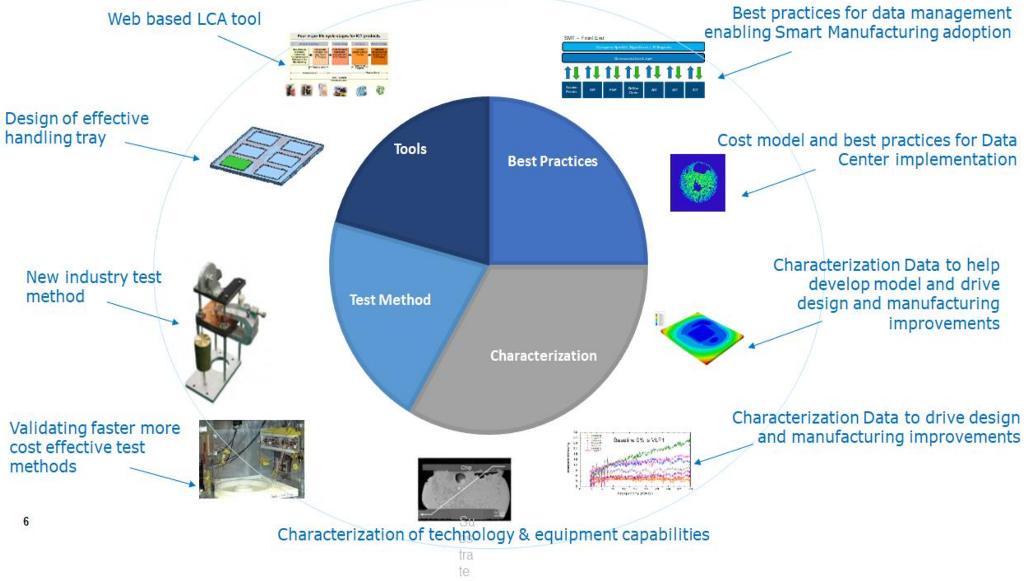
Accelerate Innovation

Think Strategically, Collaborate Wisely, Solve Creatively

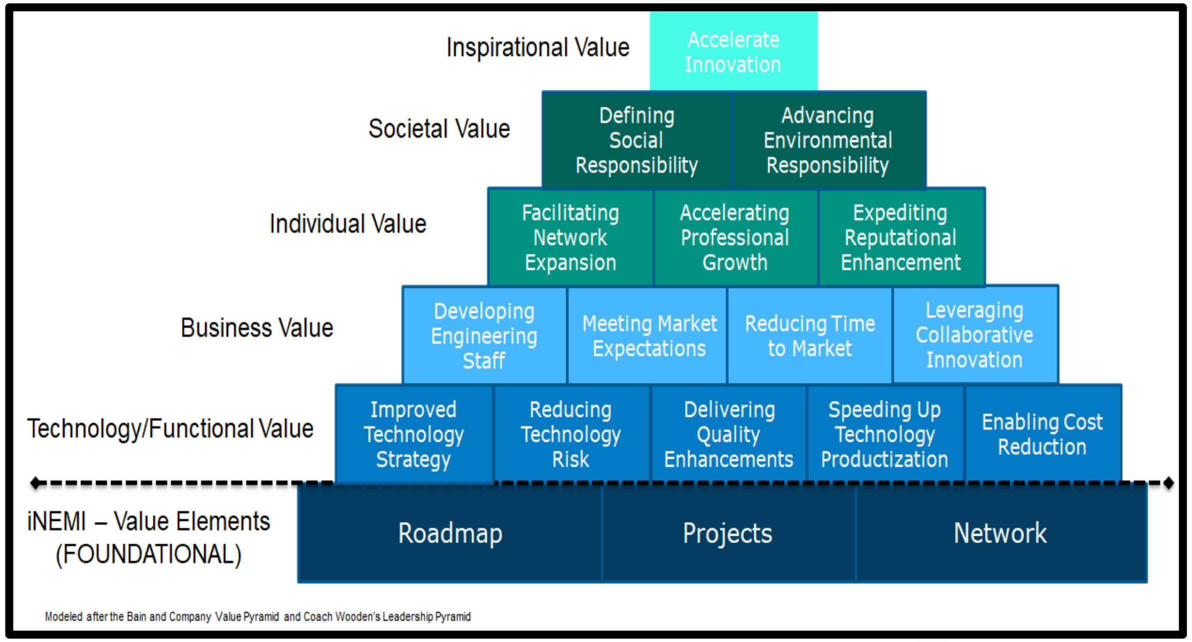
88 Members	40+ Projects	14 Roadmaps Since 1996	87% Member Engagement



Outcomes & Impact



iNEMI Member Value Pyramid



Inspirational Value	Accelerate Innovation				
Societal Value	Defining Social Responsibility	Advancing Environmental Responsibility			
Individual Value	Facilitating Network Expansion	Accelerating Professional Growth	Expediting Reputational Enhancement		
Business Value	Developing Engineering Staff	Meeting Market Expectations	Reducing Time to Market	Leveraging Collaborative Innovation	
Technology/Functional Value	Improved Technology Strategy	Reducing Technology Risk	Delivering Quality Enhancements	Speeding Up Technology Productization	Enabling Cost Reduction
iNEMI – Value Elements (FOUNDATIONAL)	Roadmap	Projects	Network		

Modeled after the Bain and Company Value Pyramid and Coach Wooden's Leadership Pyramid

International Electronic Manufacturing Initiative

Industry-led Global Consortium for Electronics Manufacturing

IBM
intel
GE
Microsoft
JABIL
NOKIA
Celestica
Georgia Institute of Technology
calce
AMED

hp
APPLIED MATERIALS make possible
MED-EL
DELL
imi
KEYSIGHT TECHNOLOGIES
PLEXUS
NIST National Institute of Standards and Technology
IEEC Integrated Electronics Engineering Center

Amphenol
FIT
Universal Instruments
ASMPT enabling the digital world
Heraeus
JOHN DEERE
MIT Massachusetts Institute of Technology
PURDUE UNIVERSITY

AGC
SHINKO
INSIDIX
MacDermid Alpha ELECTRONICS SOLUTIONS
SAFRAN Sagem
SLB
CBA Group
Fraunhofer IZM
RIT Rochester Institute of Technology

akrometrix
Kulicke & Soffa Technology . Innovation . Solutions
DELO
INTERFLUX ELECTRONICS
3M
Nordson ELECTRONICS SOLUTIONS
cimetrix by PDF/SOLUTIONS

picosun AN APPLIED MATERIALS COMPANY
LOTES
TPCA 台灣電路板協會 Taiwan Printed Circuit Association

IBIDEN
DUPONT
AT&S
Besi
SEKISUI
Superior NIHON SUPERIOR
MYCRONIC
Ansys
Moldex3D MOLDING INNOVATION
1867 THAYER SCHOOL OF ENGINEERING AT DARTMOUTH
semi

isola
ITEQ INNOVATION · TEAMWORK · EXCELLENCE · QUALITY
Panasonic INDUSTRY
INDIUM CORPORATION
unow 優諾 材料科技
سابك sabic
IPC ASSOCIATION CONNECTING ELECTRONICS INDUSTRIES
U.S. DEPARTMENT OF DEFENSE
CRF CENTRO RICERCHE FIAT

Tyndall National Institute Institiúid Náisiúnta
ZESTRON High Precision Cleaning
ViTrox
SMIC Senju Comtek Corp.
USCONEC
Avishtech
SMTA Surface Mount Technology Association
PSMA

DELTON TECHNOLOGY
HOVER-DAVIS
RESONAC
Celanese
Unimicron
ITRI Industrial Technology Research Institute
ecia Electronic Components Industry Association
University at Buffalo The State University of New York

生益科技 SHENGYI TECHNOLOGY
SENKO Advanced Components
FORESITE
MOSAIC microsystems
OPTICA Formerly OSA
FiberQA

KAIST

Present Member List

iNEMI

Next Generation mmWave Communication

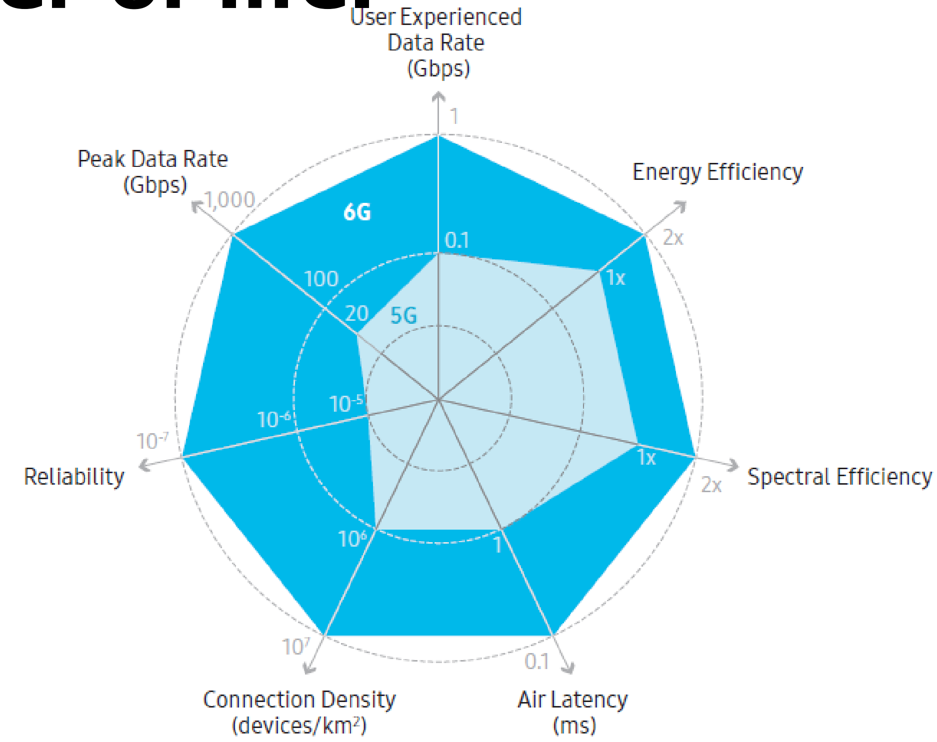
5G: Disruptions Enabling next level of communication

- 5G is expected to enable **$12.3 trillion of global economic output** (almost as much as total US consumer spending in 2016).
- The global 5G value chain will generate **$3.5 trillion in output** and support **22M jobs** in 2035.
- The 5G value chain will invest an average of **$200 billion annually** in infrastructure (about half of the total US gov't spending on transportation infrastructure in 2014).

CTIA 2018

Samsung’s 6G Vision

Bring the next hyper-connected experience to every corner of life.



- THz Technology
- Novel Antenna Materials
- Metamaterial antenna to avoid need for phase shifters
- Comprehensive AI
- Split Computing
- Setting up of specifications in 2028, possible rollout in 2028

5G/THZ mmWave- Critical Industry Initiatives Needed

5G Semiconductor Challenges Summary

Challenge	Attractive Approaches
Need for Antenna in Package (AiP)	• Laminate-based solutions • eWLB (FO-WLP) solutions
High speed/ Ultra Low Loss materials	• Cost-effective materials at mmWave frequencies • Materials characterization and test methods
Heterogeneous Integration (SiP)	• Increases in # of components → Miniaturization • Advanced molding technologies • Shielding
Test	• Contact vs OTA testing → still TBD • More sensitivities to process variations

5G solutions require complex packaging approaches and requires close collaboration.

Source: Heterogeneous Integration
Roadmap: 2019

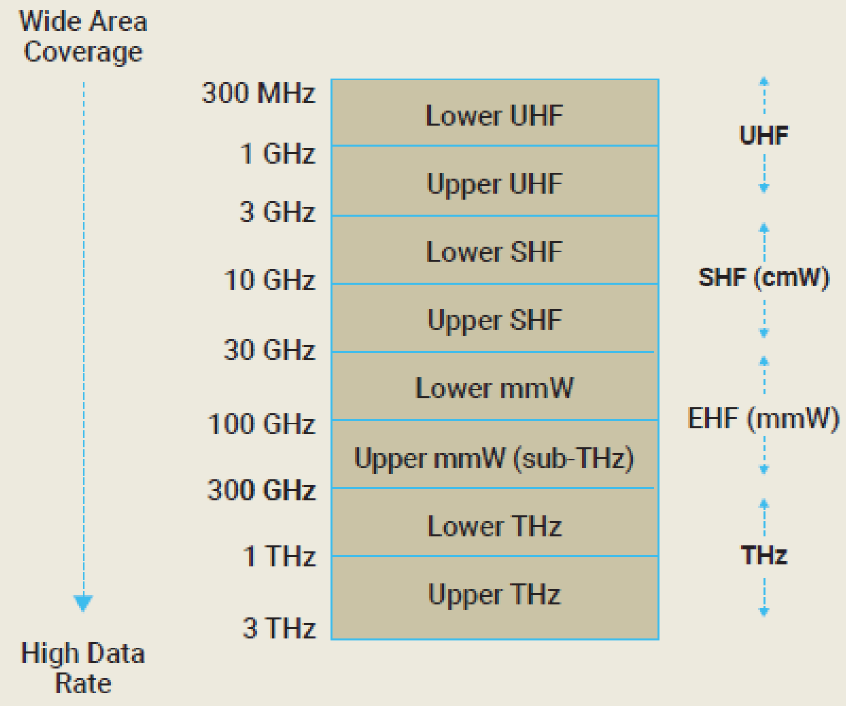
NIST MAESTRO Roadmap Activities

Project Leader: Dr. Urmi Ray, iNEMI

Supported by: National Institute of Standards and Technology (NIST) Office of Advanced Manufacturing

FEDERAL AWARD ID NUMBER: 70NANB22H050

https://www.inemi.org/maestro



Wide Area Coverage

High Data Rate

300 MHz
Lower UHF
1 GHz
Upper UHF
3 GHz
Lower SHF
10 GHz
Upper SHF
30 GHz
Lower mmW
100 GHz
Upper mmW (sub-THz)
300 GHz
Lower THz
1 THz
Upper THz
3 THz

UHF
SHF (cmW)
EHF (mmW)
THz

(a): Potential 6G Spectrum

iNEMI
Advancing manufacturing technology

iNEMI 5G/6G MAESTRO: Partners

Roadmap contributors are leaders in this field
from industry, universities and research institutes

3dGS
3M
AMD
APPLIED MATERIALS
BINGHAMTON UNIVERSITY
STATE UNIVERSITY OF NEW YORK
DELL
DOW

DUPONT
FIU FLORIDA INTERNATIONAL UNIVERSITY
ASU Arizona State University
PennState
Georgia Institute of Technology
IBM
intel

ITRI Industrial Technology Research Institute
KEYSIGHT TECHNOLOGIES
liloTree
MOSAIC microsystems
NANTERO
NIST RF Technology Center

NOKIA
PennState
qorvo
TechSearch INTERNATIONAL

For further information and to get involved, please contact Dr. Urmi Ray (urmi.ray@inemi.org)

iNEMI: 5G/6G MAESTRO – Project Objective

Create a technology roadmap

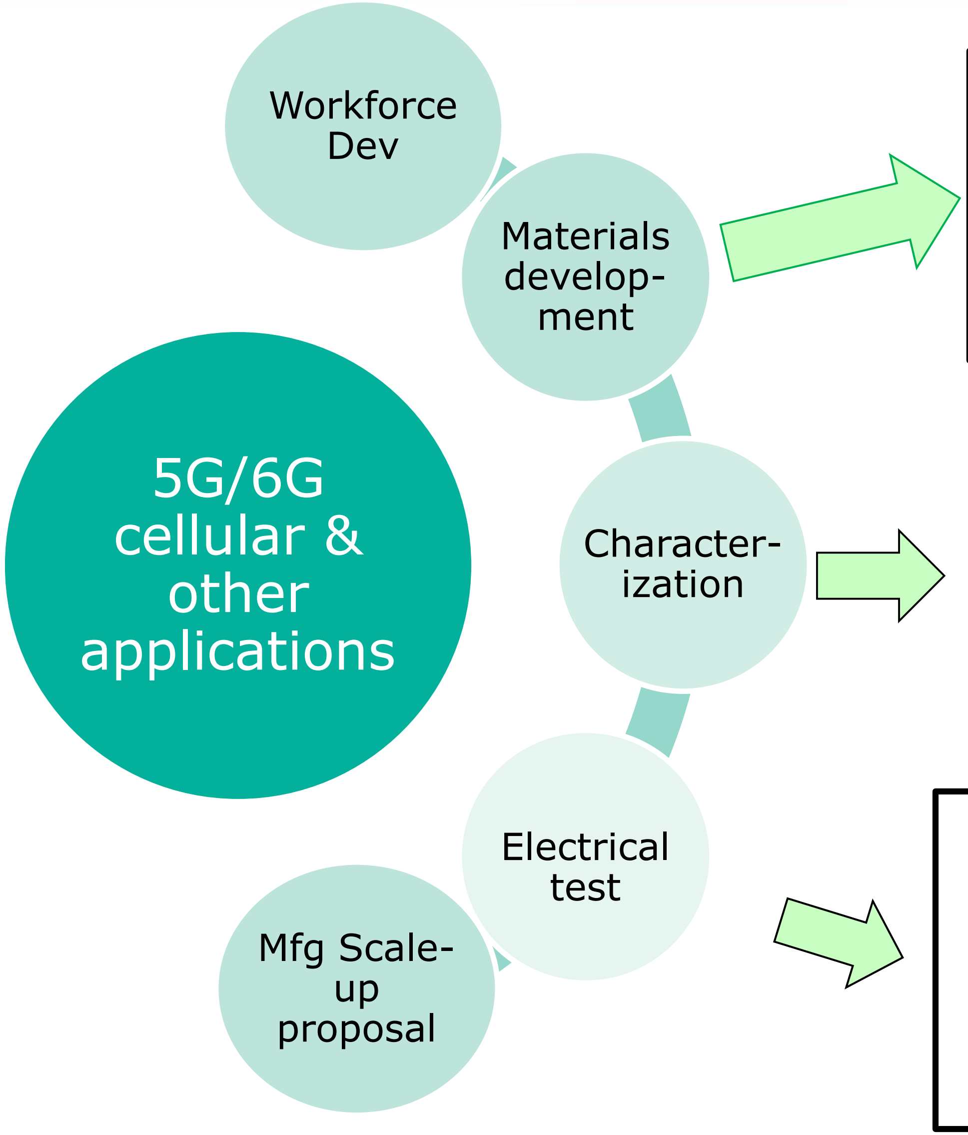
- Develop a comprehensive 10-year hardware roadmap for mmWave materials development & electrical characterization and testing.

Develop a U.S.-focused implementation strategy

- Recommend a U.S.-centric, cross-supply-chain consortium to execute the vision of the roadmap, the foundations for a strong U.S. manufacturing ecosystem in RF materials and testing.
- Promote the growth of a strong and diverse U.S. workforce in RF communication technologies, by proposing a plan of university curricula development and training.

5G/6G MAESTRO: Technology Scope

110GHz-170GHz (D-Band), 220-350GHz (G Band)



5G/6G cellular & other applications

Workforce Dev

Materials develop-ment

Character-ization

Electrical test

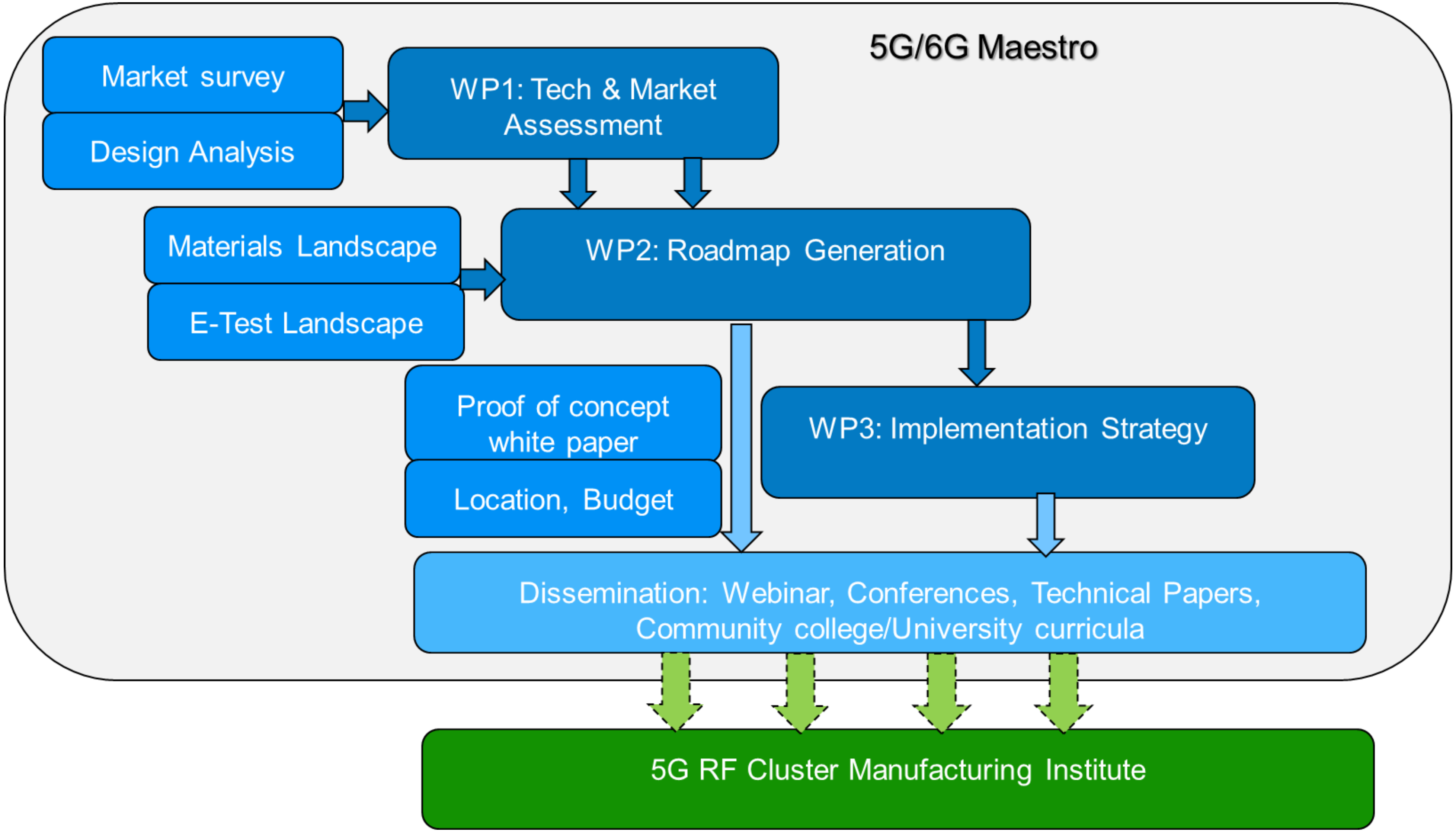
Mfg Scale-up proposal

- mmWave frequency bands
- Roadmap materials to meet functional requirements on the loss tangent and dielectric constant
- Mechanical and thermal properties in scope
- Constraint: right cost-point & manufacturability at scale

- Identify techniques for repeatable fast low-loss material characterization
- Address lack of standard reference materials (SRM)
- Propose cross-industry approaches, enabling cross-supplier comparisons

- Transition from contact testing to over-the-air testing, particularly with pervasive use of massive MIMO at mmWave frequencies
- Consider changes in RF front-end packaging, including emergence of antenna-in-package technology
- Scaling up from lab-level testing to high-volume manufacturing environments

iNEMI 5G/6G MAESTRO: Project Flow



5G/6G Maestro

Market survey

Design Analysis

WP1: Tech & Market Assessment

Materials Landscape

E-Test Landscape

WP2: Roadmap Generation

Proof of concept white paper

Location, Budget

WP3: Implementation Strategy

Dissemination: Webinar, Conferences, Technical Papers, Community college/University curricula

5G RF Cluster Manufacturing Institute

NIST MAESTRO Key Findings

iNEMI®

Advancing manufacturing technology

Market Survey Key Findings

Material Needs: Mobile

- RF front end
  - Si CMOS or BEOL CNT-FET CMOS device projected to be used through 2032
  - Laminate substrates, embedded trace substrate (ETS), molded interconnect substrate (MIS), buildup film and wafer level packages (WLP); increased use of WLP projected for 2030-2032
  - PCB layer counts increasing from 8-12 layers, up to 16 layers 2023-24, 16-20 layers 2026-2028, >20 layers in 2030-2032 (however, layer count adds thickness and cost)
- Power amplifier
  - CMOS and GaAs (2023), plus GaN (2024-2032)
  - Laminate substrates and WLP
  - PCB with 4-8 layers (2022-2028), >8 layers (2030-2032)
- Increased use of antenna-in-package (AIP) modules

Based on Survey and 1:1 interviews with industry

Market Survey Key Findings

Infrastructure

- 5G mmWave capable handsets introduced ahead of infrastructure
- US 5G mmWave infrastructure expected to roll out in 2024 (2X current levels) with peak in 2027 (for U.S., Japan, South Korea, Australia, and Thailand mainly)
  - Slower because of CAPEX and OPEX
- C-band delayed 5G mmWave deployment in US
- 6G expected to roll out 10 years from now
- 6G at concept phase with massive technological foundation that is not fully laid out (a work in progress)

Based on Survey and 1:1 interviews with industry

Market Survey Key Findings

Material Needs: Base Stations, Automotive, Defense

- Deployment of infrastructure for 5G and future wireless technologies requires a diverse range of materials and packaging technologies to meet performance, cost, and reliability requirements
- GaAs and GaN are the primary materials used in base stations, with the possibility of SiGe for lower power applications
- Laminate substrates are widely used, but the use of system-in-package (SiP) is anticipated to increase; glass and glass core substrates expected to mature
- More use of antenna-in-package (AiP) with unique designs and IC functionality integration without an embedded air cavity
- Automotive radar modules for 79-81 GHz mmWave use FC-CSP laminate substrates and FO-WLP,. FO-WLP also provides smooth conductor, high-speed material sets, controlled impedance, excellent RF isolation, and reliable performance in harsh conditions. The industry is anticipating mmWave modules for 94-100 GHz in the future.
- The defense industry uses Si, SiGe, GaAs, and GaN devices, with Si CMOS being an important choice for 6G. InP HBT transferred to AlN is also being considered for better thermal capability. The integration of InP and Si is a challenge for package materials, and advanced thermal management techniques are needed. Diamond substrates and micro-fluidic cooling channels are being investigated, and sintered silver die attach processes have been developed. LTCC provides higher reliability due to CTE matching and better thermal dissipation. PCBs will require higher frequency materials, embedded antennas and filters, and improved thermal capability. Defense final test needs require extremely low defect rates with much higher test coverage than commercial needs.

Market Survey Key Findings

Electrical Testing and Metrology Needs

- Testing at multiple levels is required to detect and prevent the small deviations that can cause performance issues
- Major challenges to overcome overall cost
- While over-the-air (OTA) testing is considered best for development, it is often undesirable in high-volume manufacturing due to cost concerns. The use of wafer-level test and self-test, along with increased use of AI, is expected in the future. Some companies plan to test antennas separately at higher frequencies. Designs are typically centered on 28 GHz, and BIST features are used for electrical testing with some limited OTA.
- To address data concerns, non-destructive metrology tools are needed, such as 3D x-ray coupled with AI/ML to analyze components (e.g., small cells, base stations, and mobile devices) each of which has its own replacement cycles

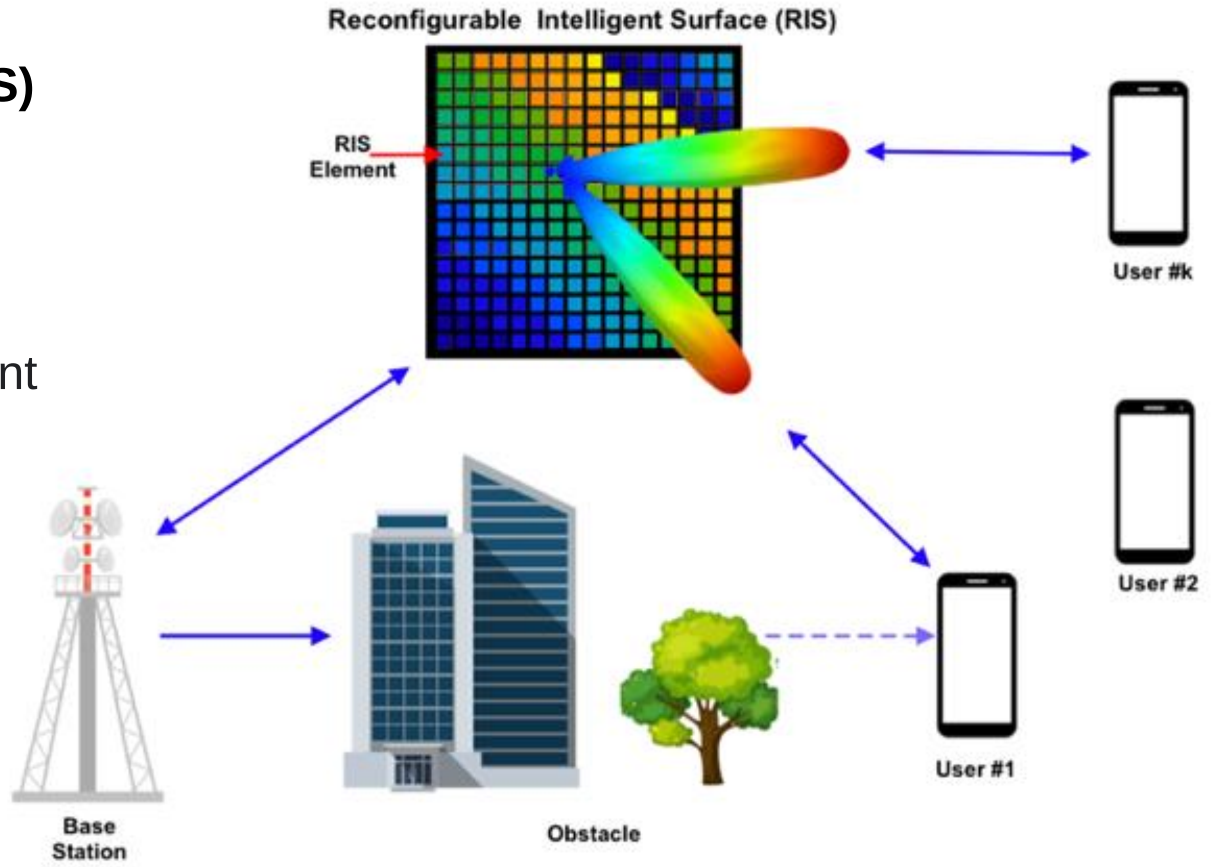
Based on Survey and 1:1 interviews with industry

Reconfigurable Intelligent Surfaces – Assisted Joint Beamforming

Small wavelengths at 5G/6G mm-Wave frequencies are subject to path losses and multipath scattering leading to beam blockage

Reconfigurable Intelligent Surfaces (RIS) supersede relay performance using large apertures with simple circuitry.

- ✓ Spectrally more efficient
- ✓ RIS reduce hardware complexity.



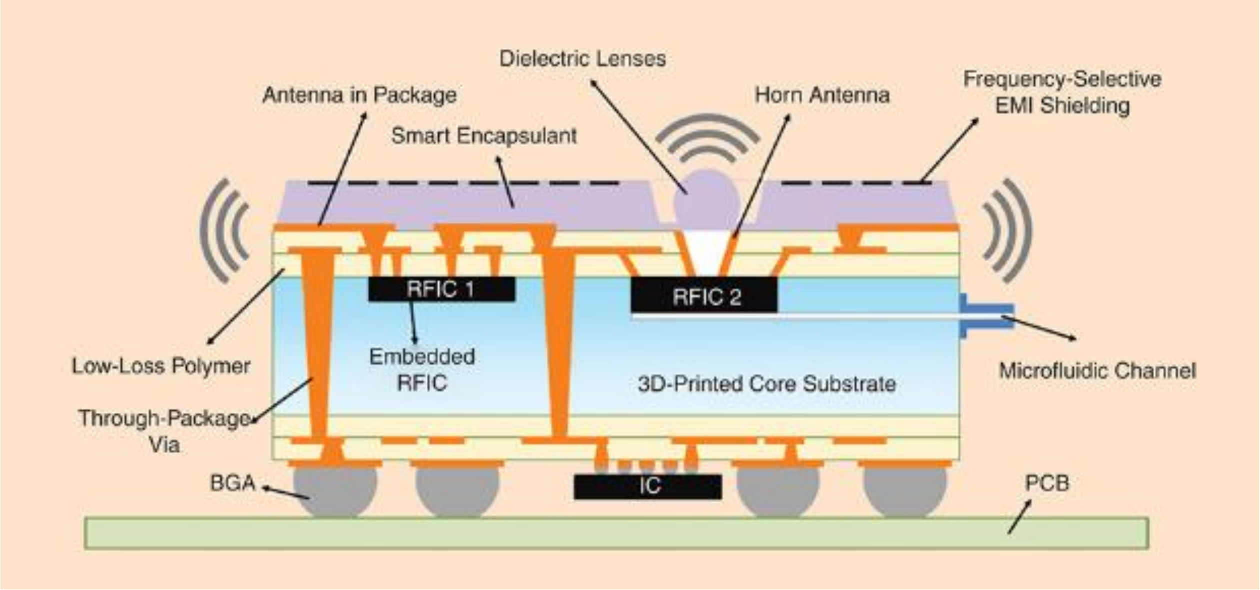
Alternative Technology: Relays

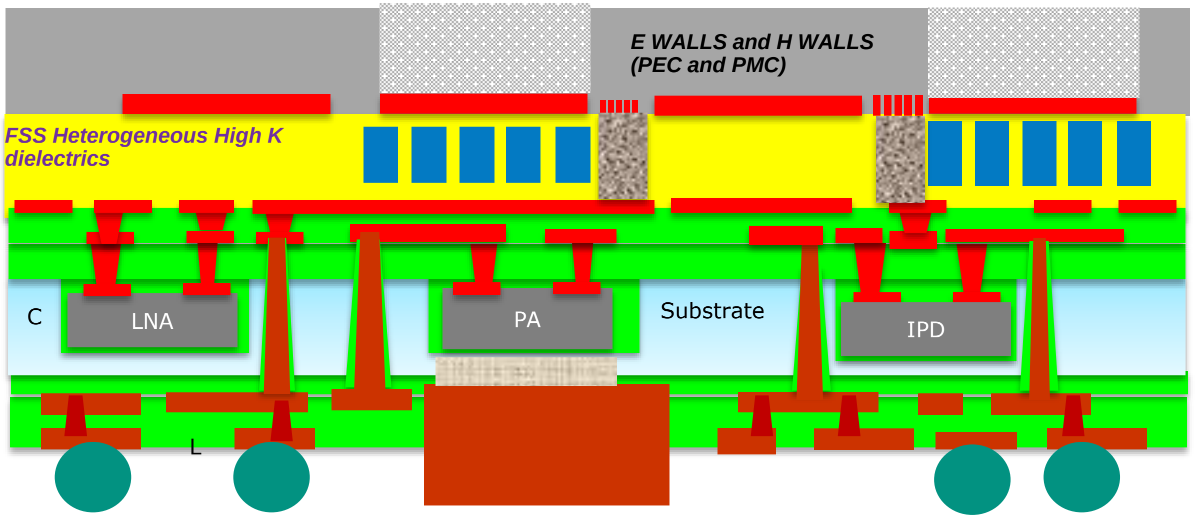
- × A dedicated power source per relay
- × Reception and re-transmission circuitry
- × Signal processing complexities.

Use of Meta Materials

Goal: Beamforming and adaptive nulling using RIS via a very simple circuitry

Advanced Packaging Needs: 5G/mmWave Package Integration





- High-density and low-loss transmission lines:
- Ultra-fine vias and TPVs for seamless 3D interconnects
- Precision circuitry for impedance matching
- Smooth surface for low losses

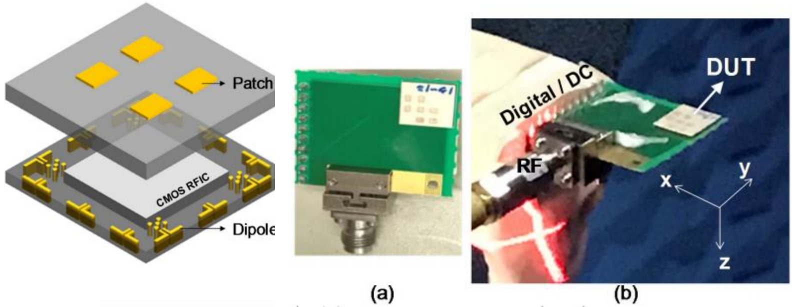
- RF and digital in the same package
- Advanced antenna array for wideband and gain
- Embedded FSS for improved performance
  - Heterogeneous high-K superstrates as lenses, E walls, H walls, AMCs

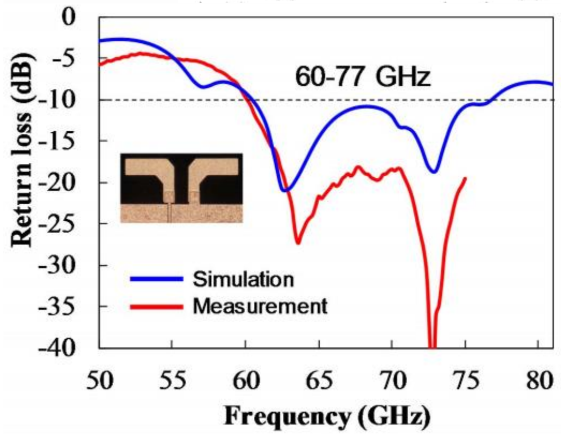
- Package- and board-level reliability
- Large-area panel processing

He, Bahr, Tentzeris, IEEE Microwave Magazine, August 2022

High-Density Packaging: Chip-first mm-wave packages using Fan out Technologies

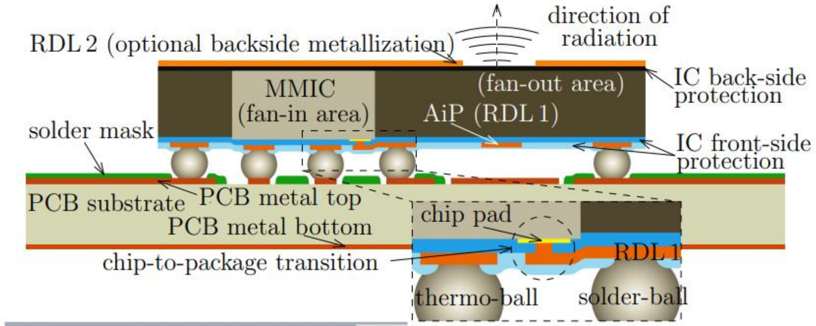
InFO-AiP (TSMC)

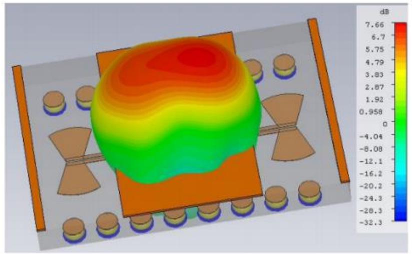


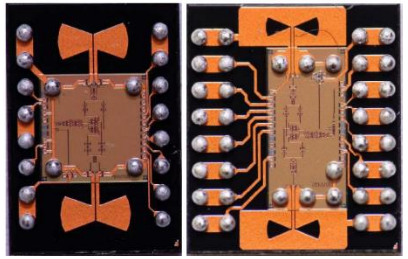


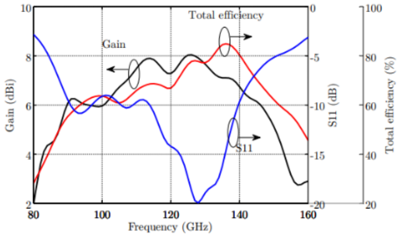
- ✓ Thickness reduction
- ✓ Low signal loss from Chip to Antenna
- × Unbalanced stack-up – Warpage
- × Patterning precision on molding compound

eWLB (Infineon)



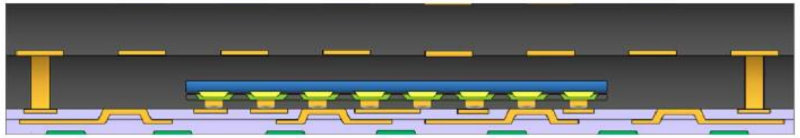






- ✓ Thickness reduction
- × Distance variation from Gnd to Patch
- × Patterning precision on molding compound

Fan-out AiP (ASE)



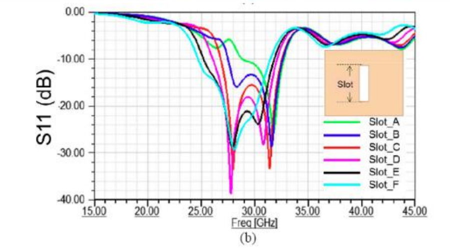


Fig. 11. Simulation result of various return loss by adjusting the dimension of notching slot structure.

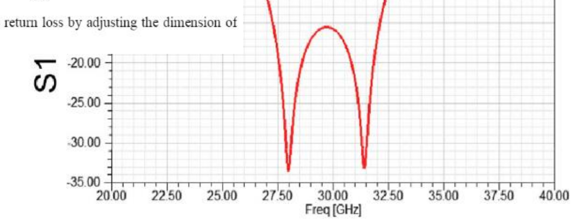


Fig. 12. Simulation result of stacking patch antenna

- ✓ Thickness reduction
- × High signal loss in through-mold vias
- × Mold-on-mold causes thickness variations

5G Challenges – Material, Substrate

- Novel Material –better electrical, microwave and thermal properties at a low cost
- Low loss materials, characterization/metrology

Material properties of glass provide attractive solutions

🟢	Good
🟡	Fair
🔴	Poor

✓ Low loss

✓ CTE match

✓ Smooth

✓ Thin

✓ Cost-effective

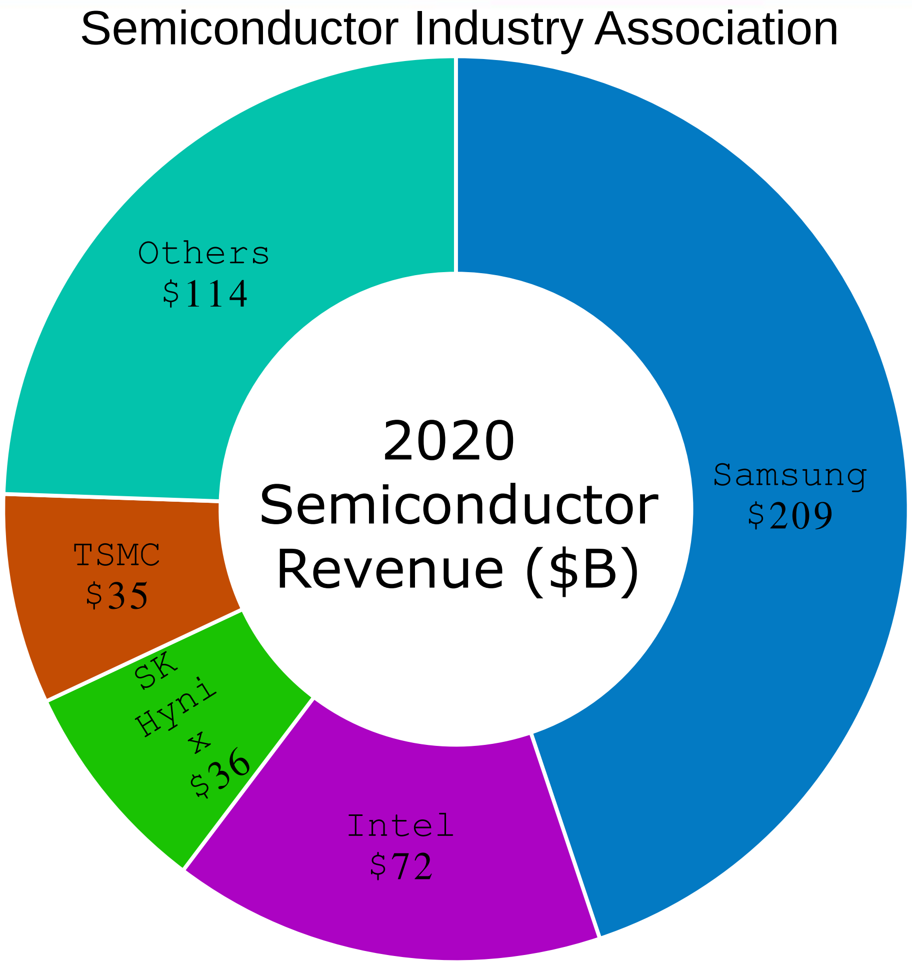
✓ Scalable

Characteristic	**Ideal property**	**Materials**			
		Glass	Si	Organic	Ceramic
Electrical	• High resistivity • Loss loss, low k	🟢	🔴	🟢	🟢
Physical	• Smooth surface • Large area scalability • Ultra thin	🟢	🟡	🟡	🟡
Thermal	• High conductivity	🟡	🟢	🔴	🟡
Mechanical	• High strength, modulus • Low warpage	🟡	🟡	🔴	🟡
Chemical	• Resistance to process chemistry	🟢	🟡	🟡	🟡
Via and RDL cost	• Low cost for both	🟡	🔴	🟡	🔴
Reliability	• CTE match to Si and PWB	🟢	🟢	🟡	🟡
Cost/mm^2	• @25 um I/O pitch	🟢	🔴	🔴	🔴

PRC

Source: Georgia Tech, HIR Roadmap

Metrology needs: Semiconductor manufacturer's measurement problem



iNEMI 5G Materials Characterization Project Report I:

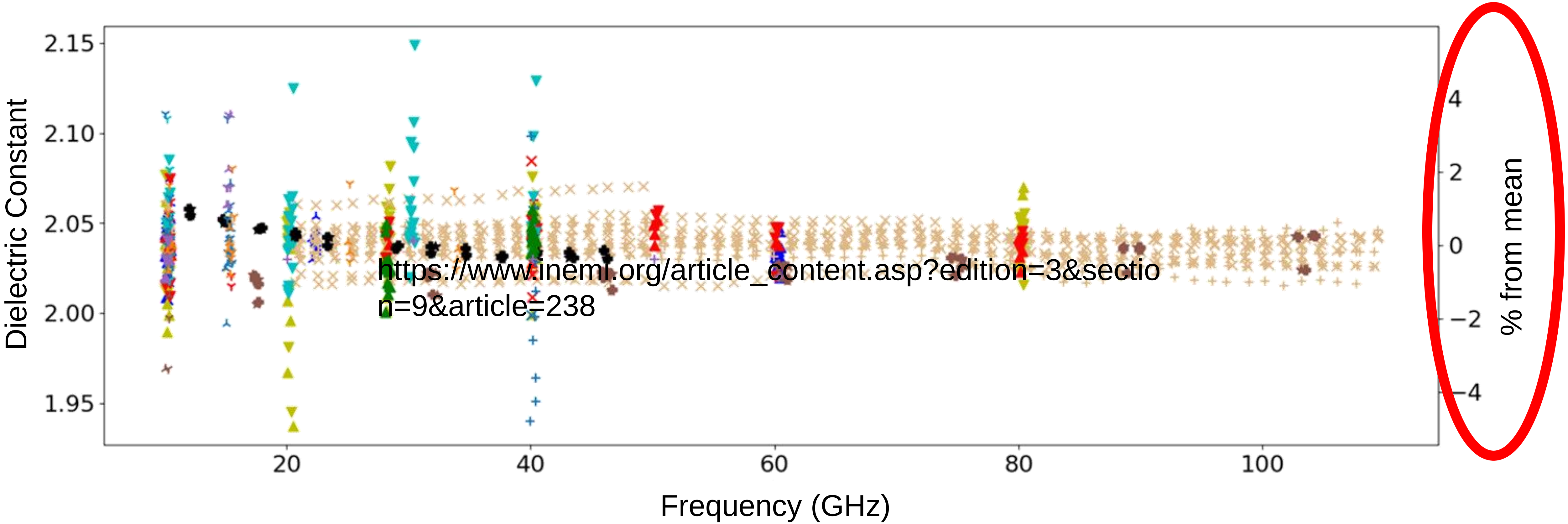
> "The lack of traceable reference material for mmWaves is a very serious problem. This lack makes verification of measurement methods and laboratory techniques impossible in an industry setting."

SRC Research Needs: Packaging

> "Dielectric characterization up to 500 GHz and beyond. Scope includes anisotropic and inhomogeneous materials… High-frequency and high-temperature dielectric characterization of low-loss materials (encapsulants, mold compounds, substrates, etc.)."

Dielectric properties impact all microelectronics manufacturing

Metrology Needs: Accurate, Repeatable Measurements



https://www.inemi.org/article_content.asp?edition=3&section=9&article=238

Need for Standard Reference Materials

https://www.inemi.org/article_content.asp?edition=3&section=9&article=238

MAESTRO Roadmap Example: Gaps

Table 5G-3 Materials Characterization Needs, Gaps, and Today's Technology Status with Respect to Current and Future Needs

	ROADMAP TIMEFRAME			
TECHNOLOGY ISSUE	**TODAY (2023)**	**3 YEARS (2026)**	**5 YEARS (2028)**	**10 YEARS (2033)**
	Frequency Range= 28-110 GHz	**Frequency Range= 110-170 GHz (D-Band)**	**Frequency Range= 220-350 GHz (G Band)**	**Frequency Range= >500 GHz**
CHARACTERIZATION FREQUENCY RANGE				
NEED	Tools needed at 5G frequencies (28-39 GHz)	Tools needed at D-band (110-170 GHz)	Tools needed G-band (220-350 GHz)	Tools needed for >500 GHz
CURRENT TECHNOLOGY STATUS	**Solutions deployed or known**	**Solutions need optimization**	**Solutions not known**	
GAP	(NO GAP?)	Few tool options	Robustness and availability	
CHALLENGE	Limited tool availability for high frequencies	Supporting equipment is expensive (i.e., 100 GHz VNA)	Expensive supporting equipment	
CHALLENGE	High frequencies place burden on mechanical precision of equipment	Methods still in academic space		
CHALLENGE	High equipment cost			

In-table color + label key	Description of Technology Status
Solutions not known	Solutions not known at this time
Solutions need optimization	Current solutions need optimization
Solutions deployed or known	Solutions deployed or known today
Not determined	TBD

MAESTRO Roadmap Example: Potential Solutions

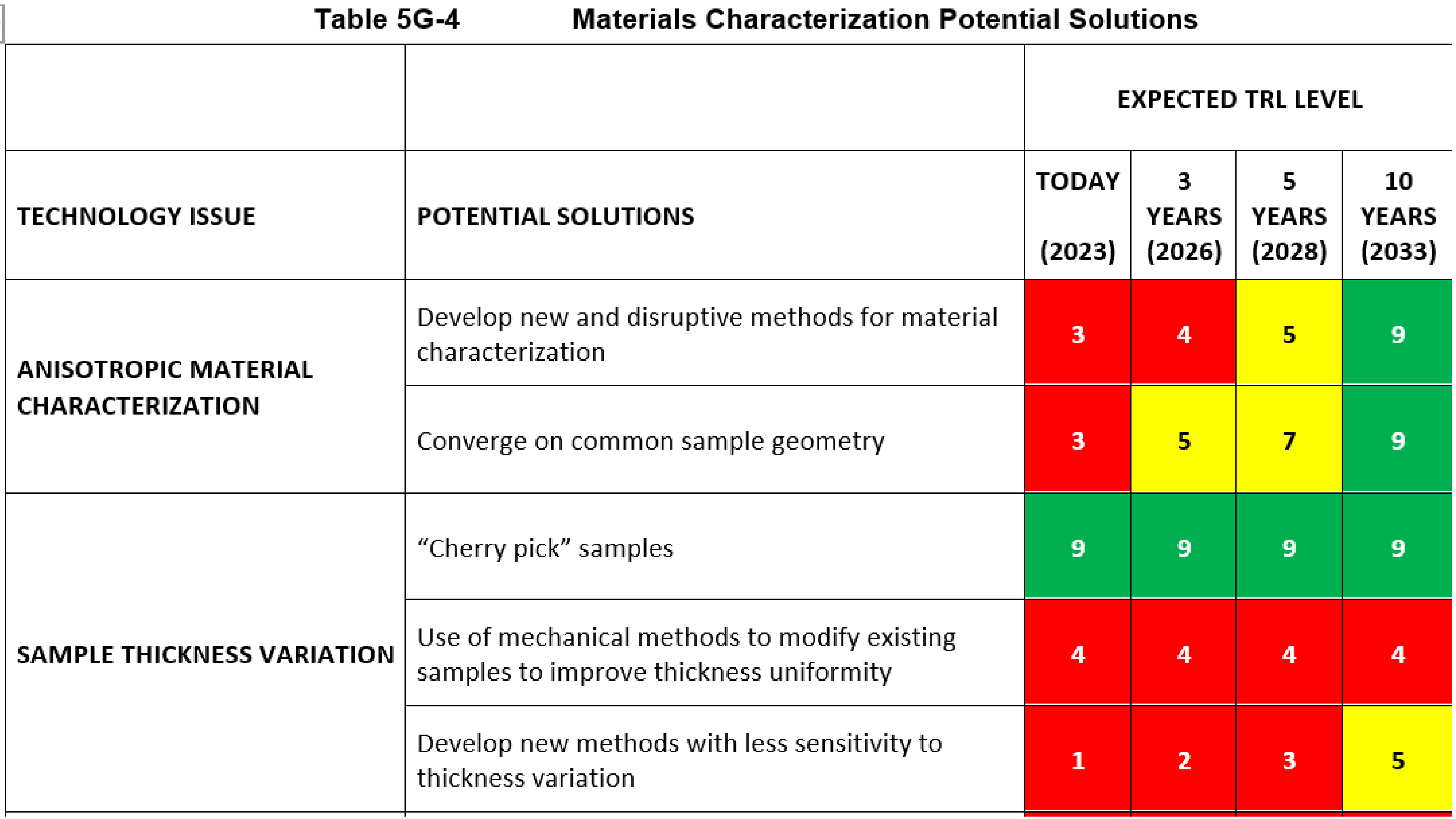


Table 5G-4 Materials Characterization Potential Solutions

		EXPECTED TRL LEVEL			
TECHNOLOGY ISSUE	**POTENTIAL SOLUTIONS**	**TODAY (2023)**	**3 YEARS (2026)**	**5 YEARS (2028)**	**10 YEARS (2033)**
ANISOTROPIC MATERIAL CHARACTERIZATION	Develop new and disruptive methods for material characterization	3	4	5	9
	Converge on common sample geometry	3	5	7	9
SAMPLE THICKNESS VARIATION	"Cherry pick" samples	9	9	9	9
	Use of mechanical methods to modify existing samples to improve thickness uniformity	4	4	4	4
	Develop new methods with less sensitivity to thickness variation	1	2	3	5

Color and Range of Technology Readiness Levels (TRL)	Description
🟥 TRL: 1 to 4	Levels involving **research**
🟨 TRL: 5 to 7	Levels involving **development**
🟩 TRL: 8 to 9	Levels involving **deployment**

https://www.inemi.org/maestro

Summary and Conclusions

Advancing manufacturing technology

5G/THZ mmWave- Need for Collaborative Approaches

5G Semiconductor And Package Integration Challenges Summary

- New Materials, Packaging and Testing Needs
- Complexity of challenges including architecture to overcome losses (including hybrid beamforming)
- Collaborative pre-competitive approaches are needed
- Many new areas of research are emerging – opportunities for ground breaking research and development

Acknowledgement

MAESTRO Team

NIST Office of Advanced Manufacturing

https://www.inemi.org/maestro

iNEMI®
Advancing manufacturing technology