5G Electronics: Bridging the measurement challenges with reference material development

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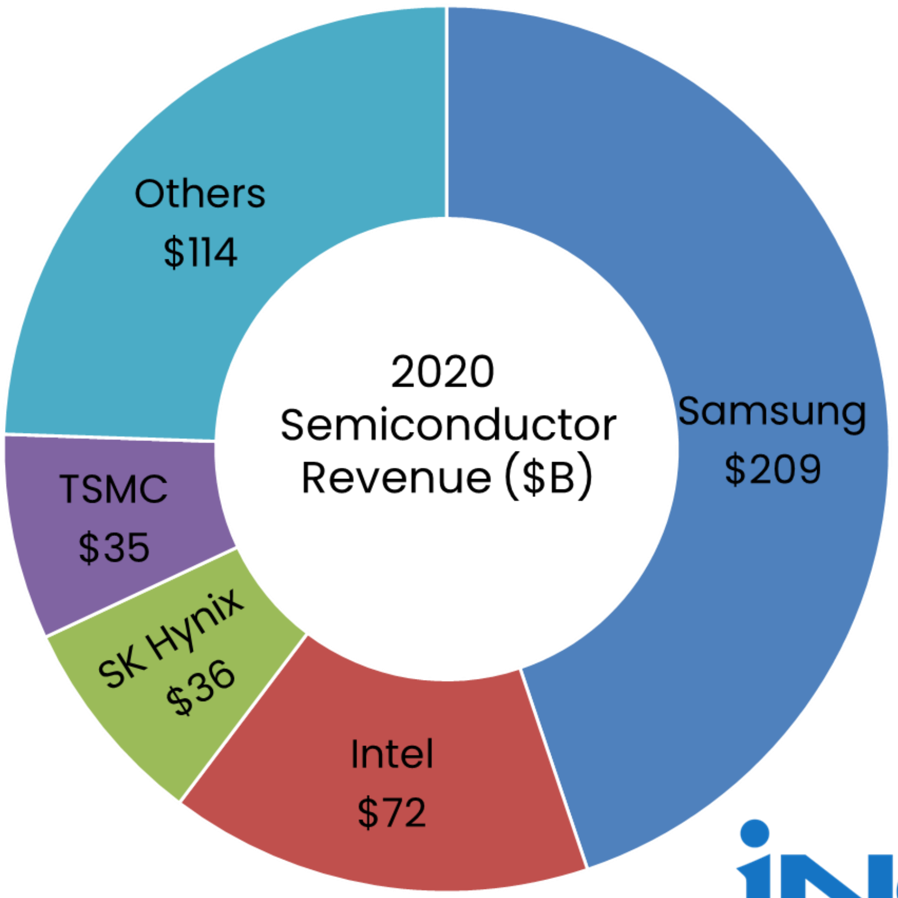
Companies need to understand their materials

Semiconductor Industry Association



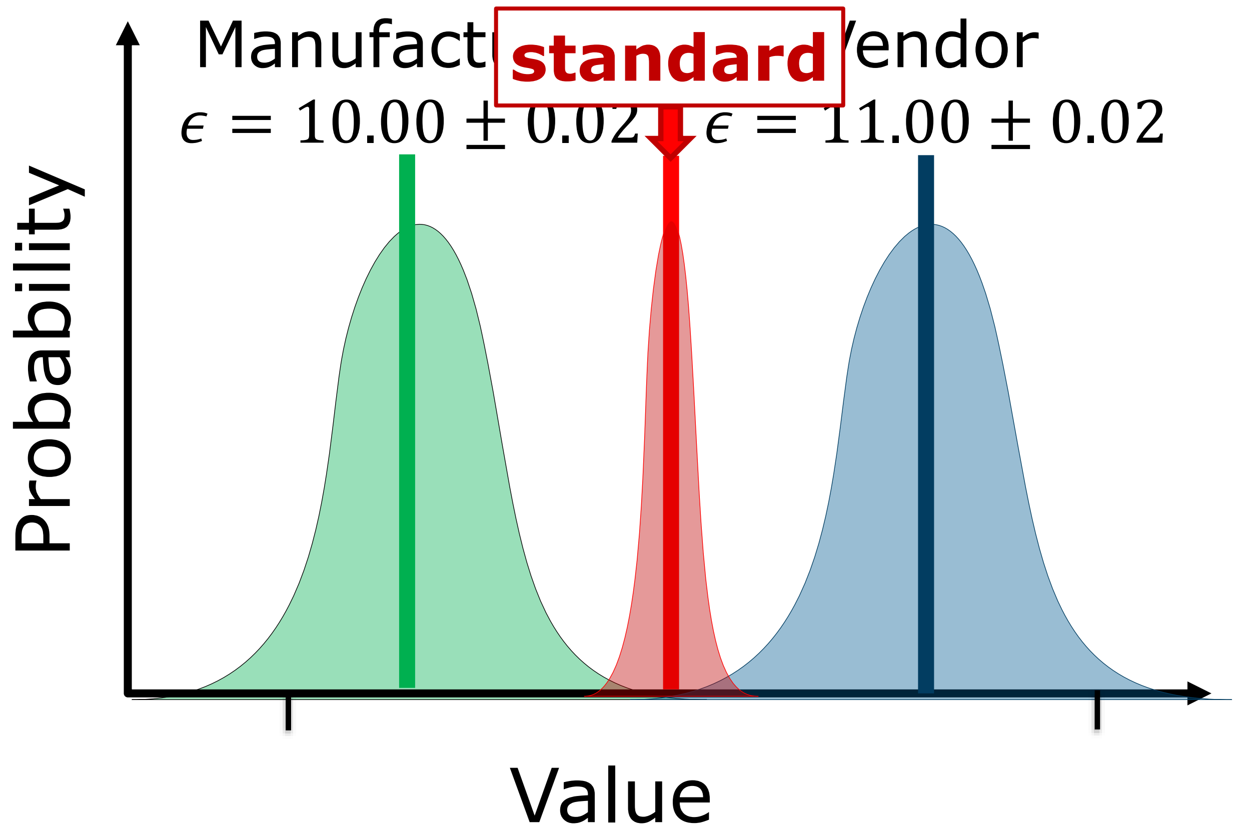
iNEMI 5G Materials Characterization Project Report I:

> "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."

Understanding materials means understanding measurements

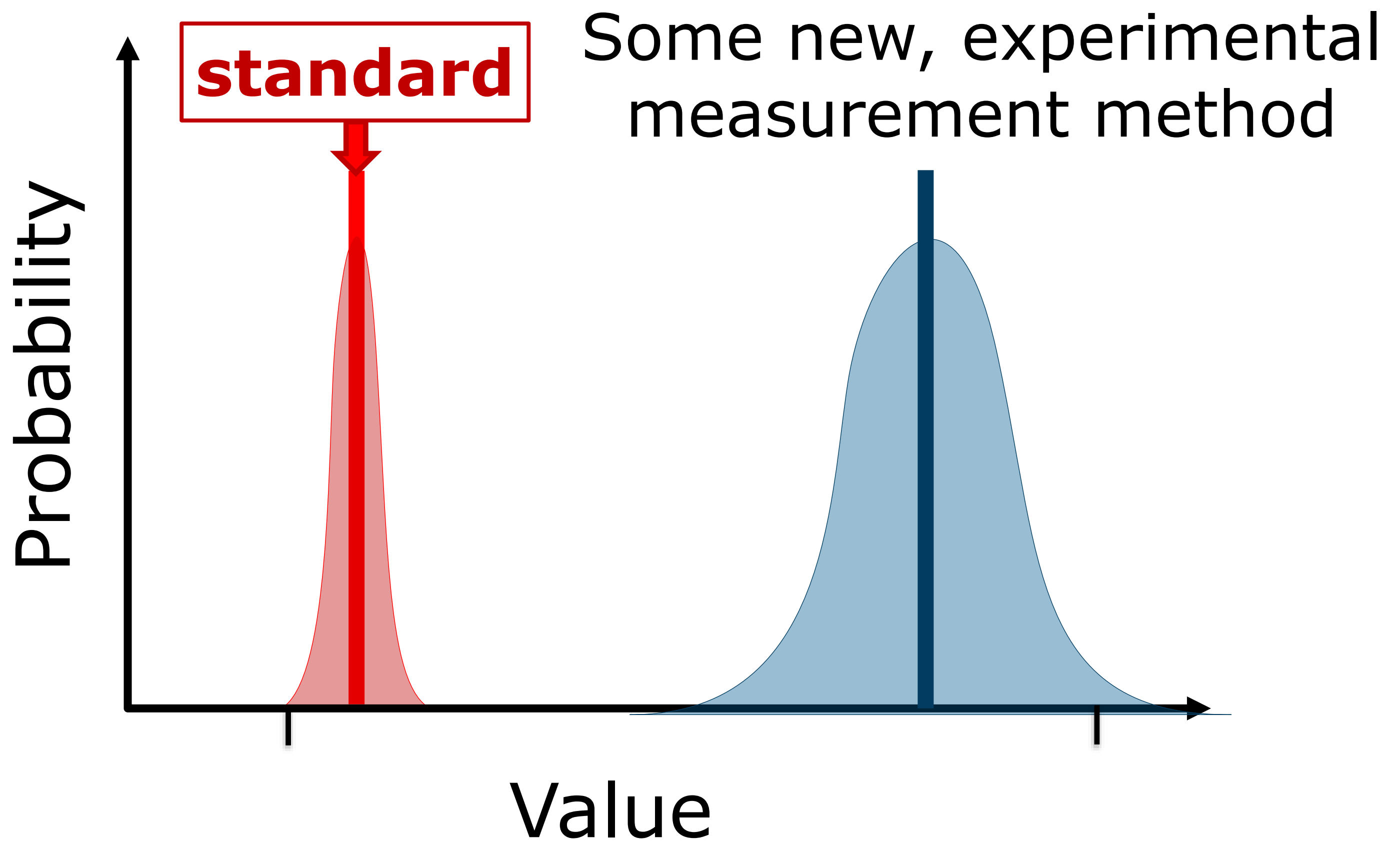
Standards help us understand measurements

Acceptance testing (materials, tools)



Using standards, we can find the *right* answer

We can use standards to validate measurement methods

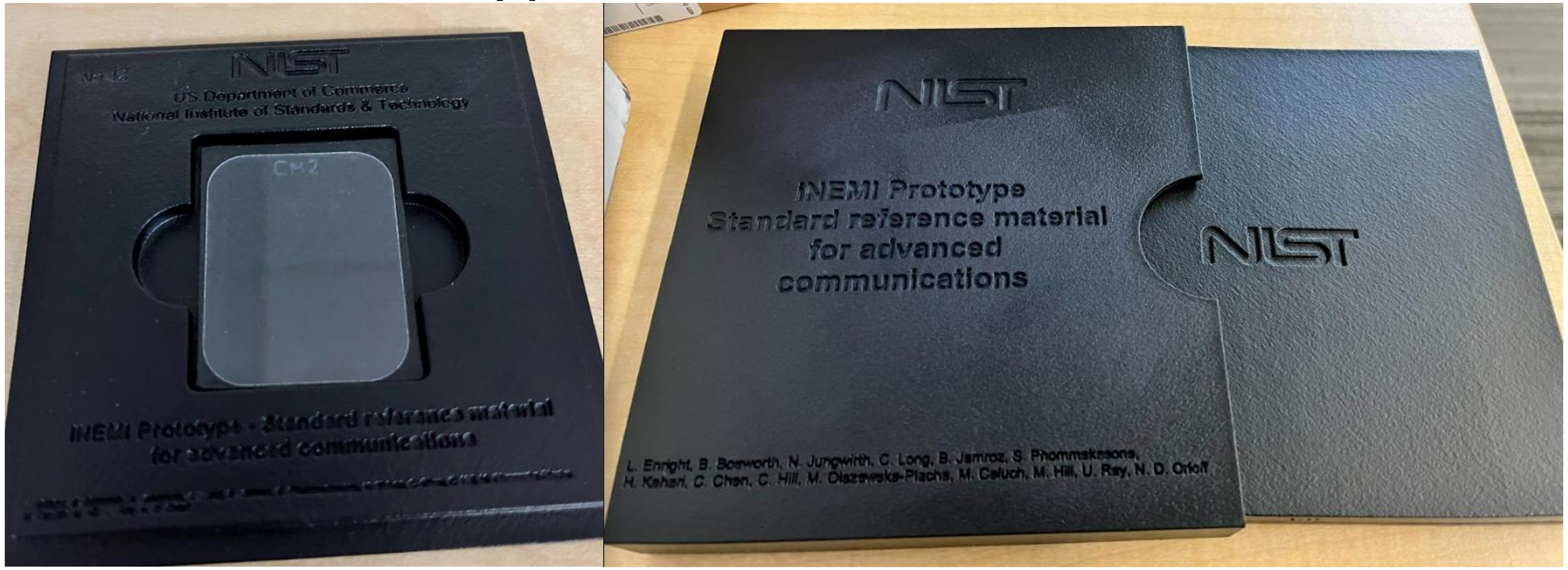


If these two don’t overlap, we know there is a problem

iNEMI orchestrated an industrial round robin

10 labs measuring identical samples with 4 different methods

- Split-cylinder resonators
- Split-post dielectric resonators
- Fabry Perot open resonators
- Balanced-type circular disk resonators



iNEMI International Electronics Manufacturing Initiative

Panasonic, Showa Denko, intel, QWED, Keysight Technologies, 3M, ITRI Industrial Technology Research Institute, NOKIA

The results revealed a serious measurement problem

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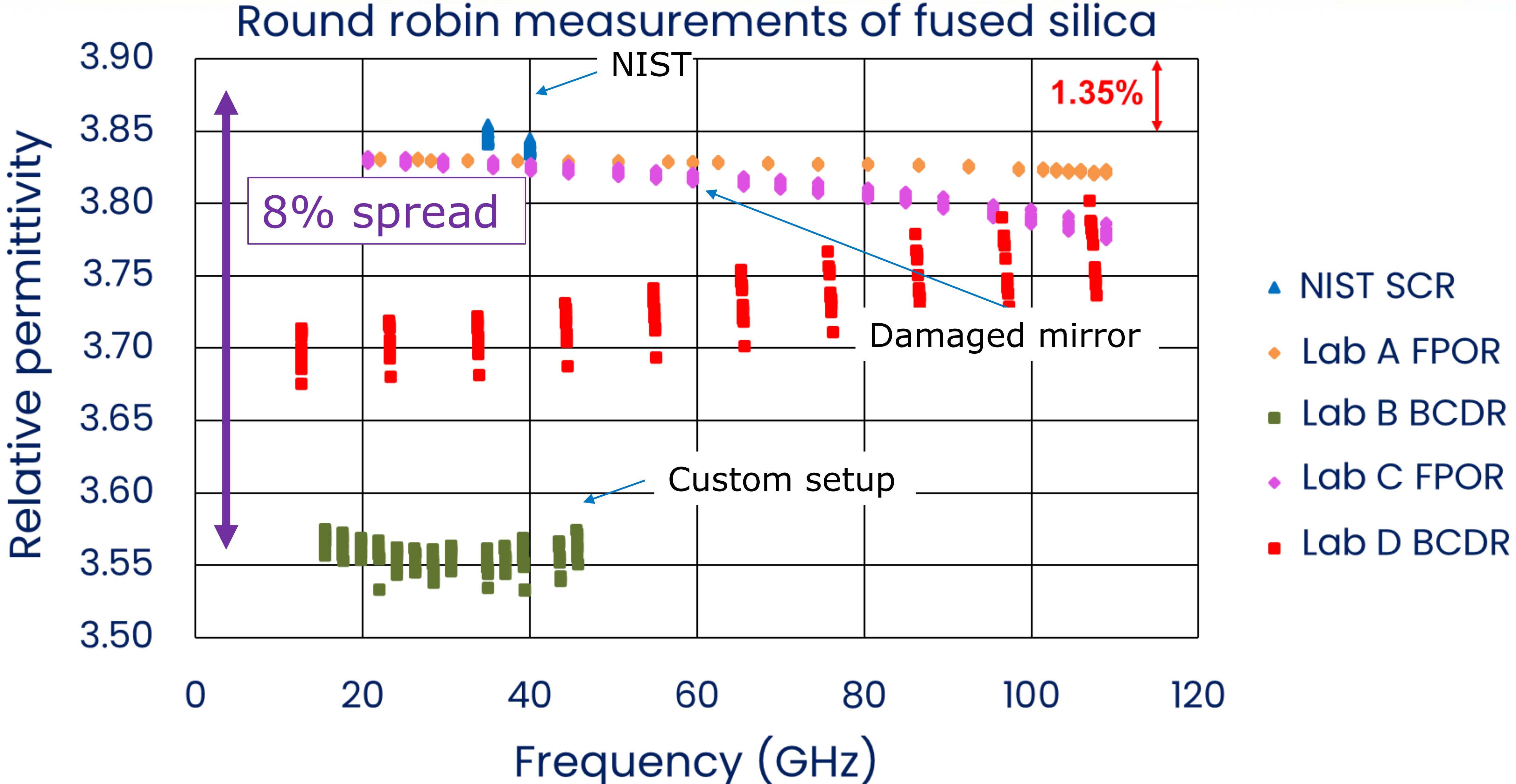
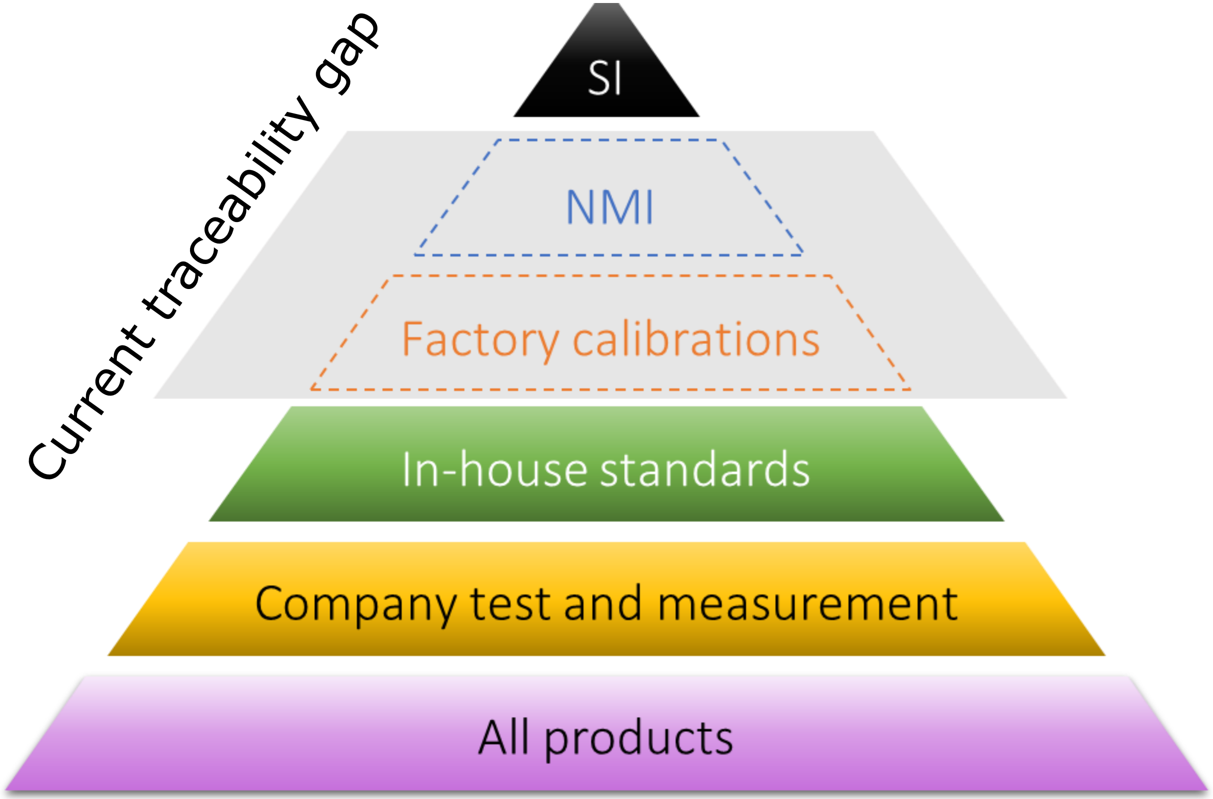
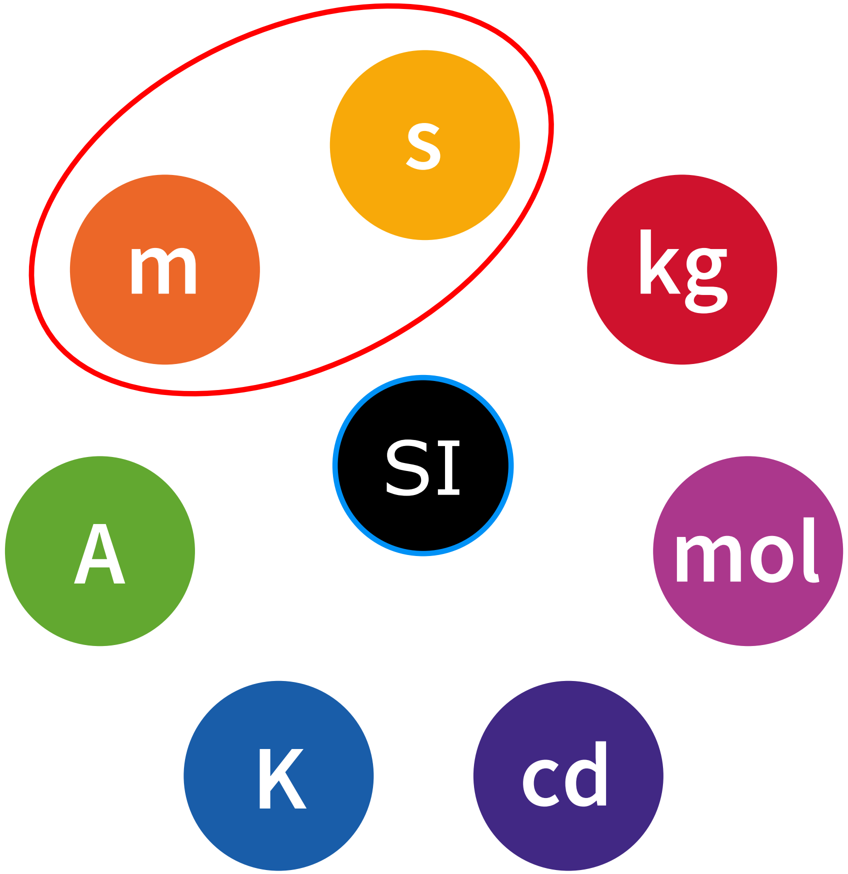
The round robin showed this problem is not hypothetical



We need a traceable standard to know which answer is 'right'

Currently, there is no traceable standard





"Traceability" is an unbroken chain of measurements that end at the SI

We need to fill the traceability gap

Already done

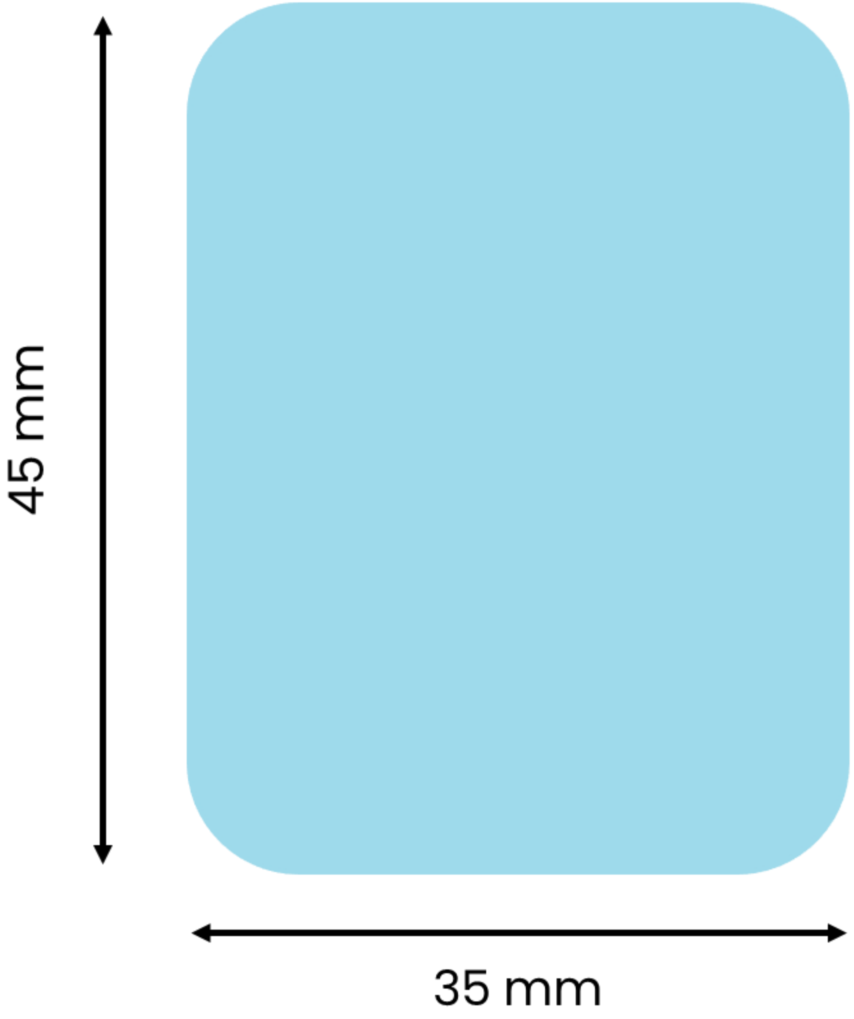
In progress

0	1	2	3	4	5
Incorporate industry feedback	Choose material	Choose method	Use theory to map to permittivity	Measure Scattering parameters	Measure dimensions

We built a fused silica prototype to meet industry needs

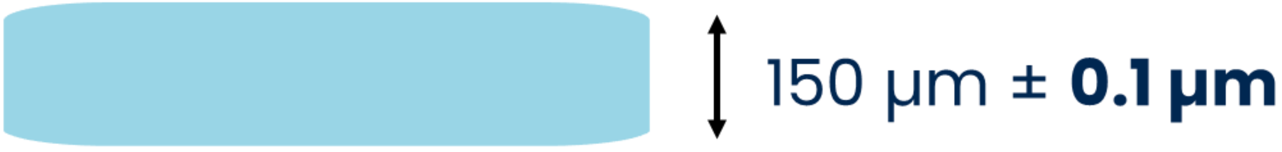
1

Choose material



$\epsilon' \approx 3.8$

$\tan\delta < 1e{-3}$



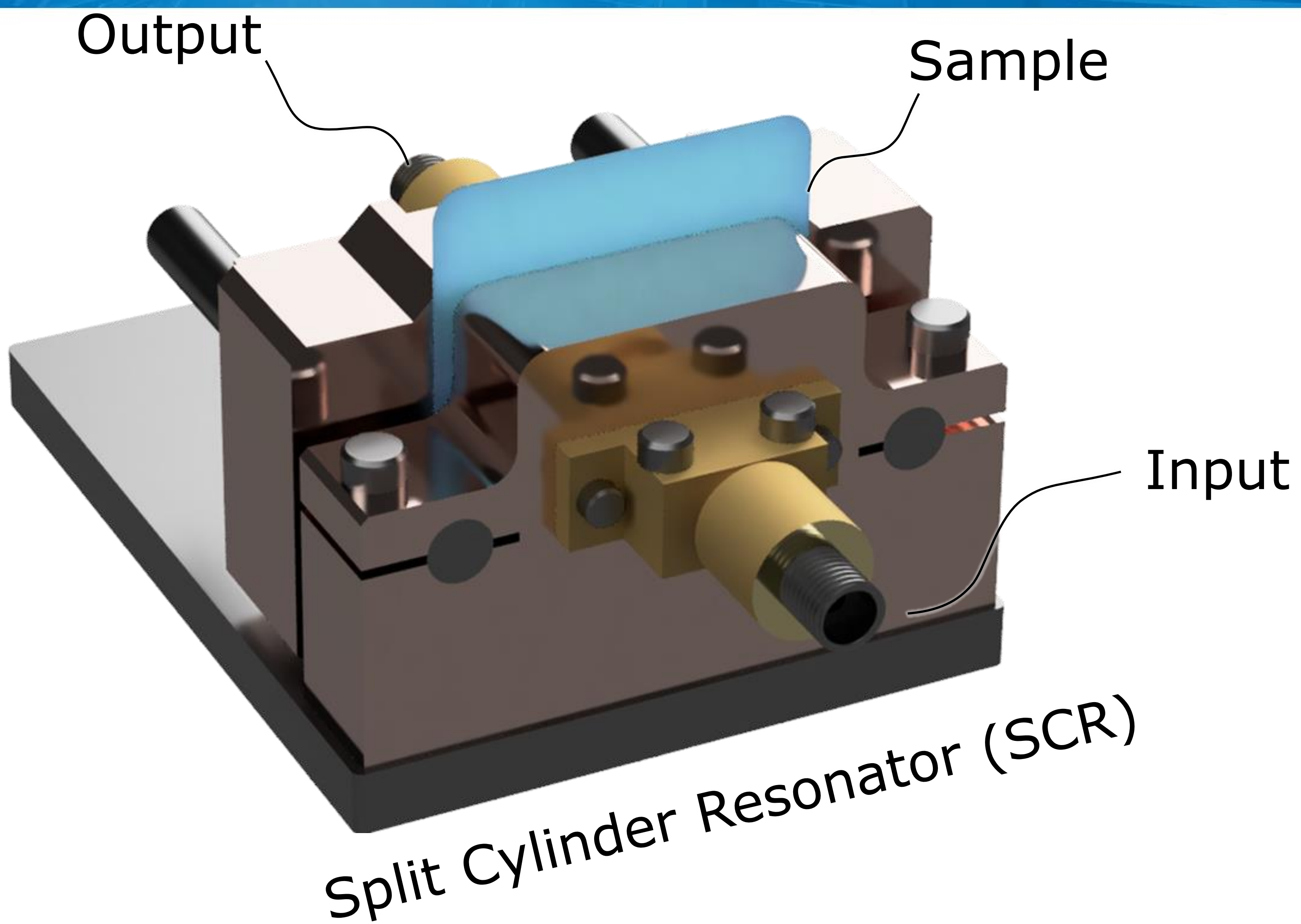
0.06% thickness variation

Thin + low ϵ' = compatible with commercially available resonators

Split-cylinder resonators offer a path to traceability

2

Choose method

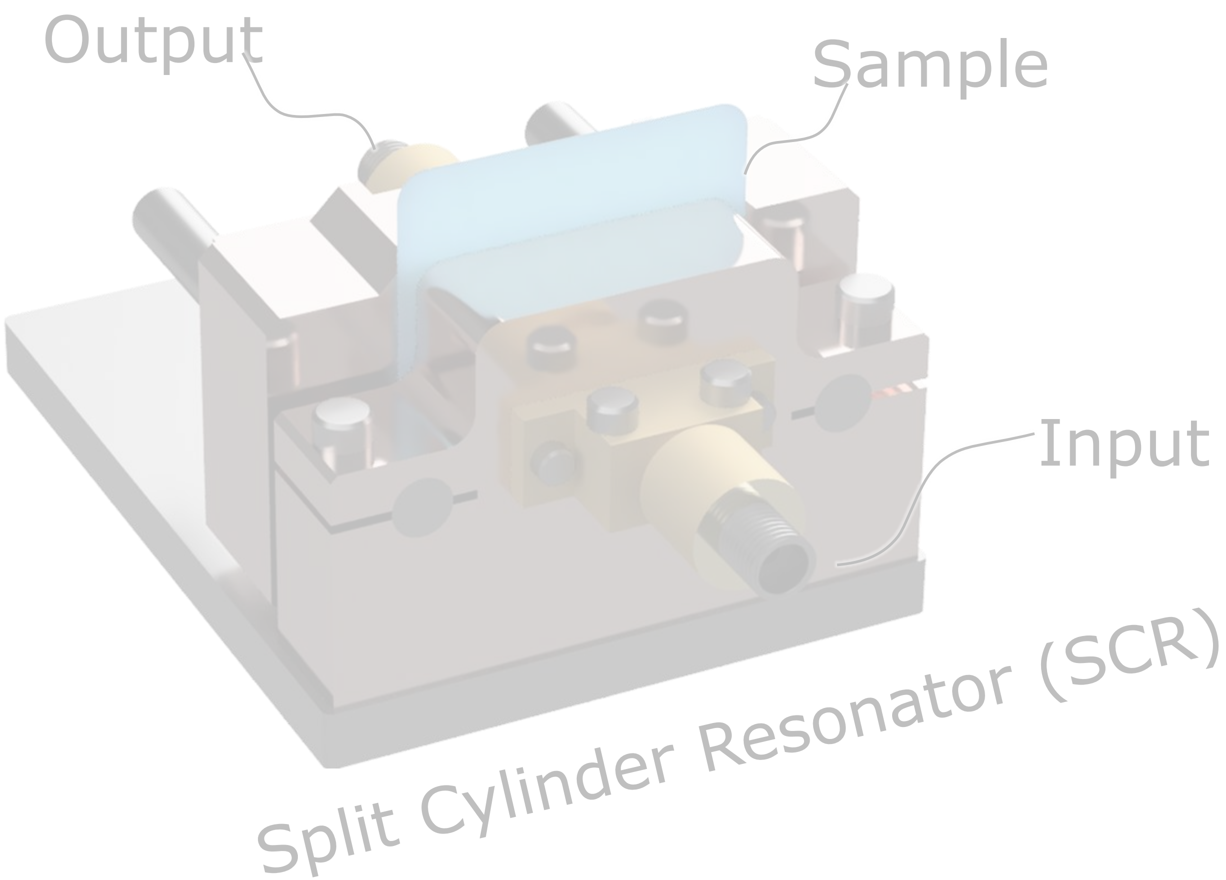


The dimensions of the cavity and sample are the critical features

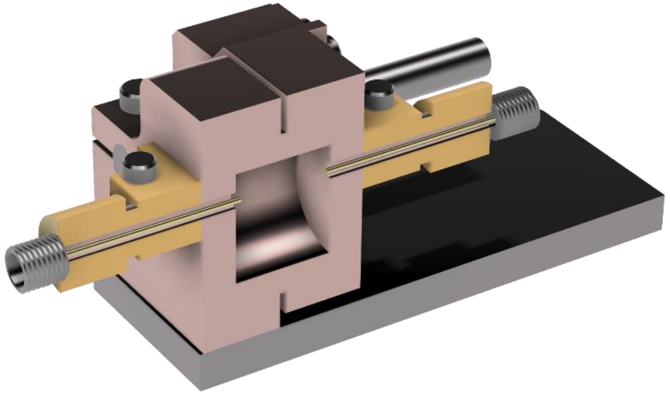
Split-cylinder resonators offer a path to traceability

2

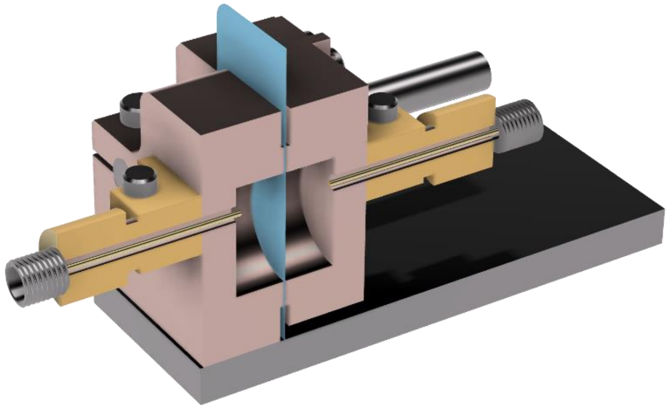
Choose method



no sample



sample

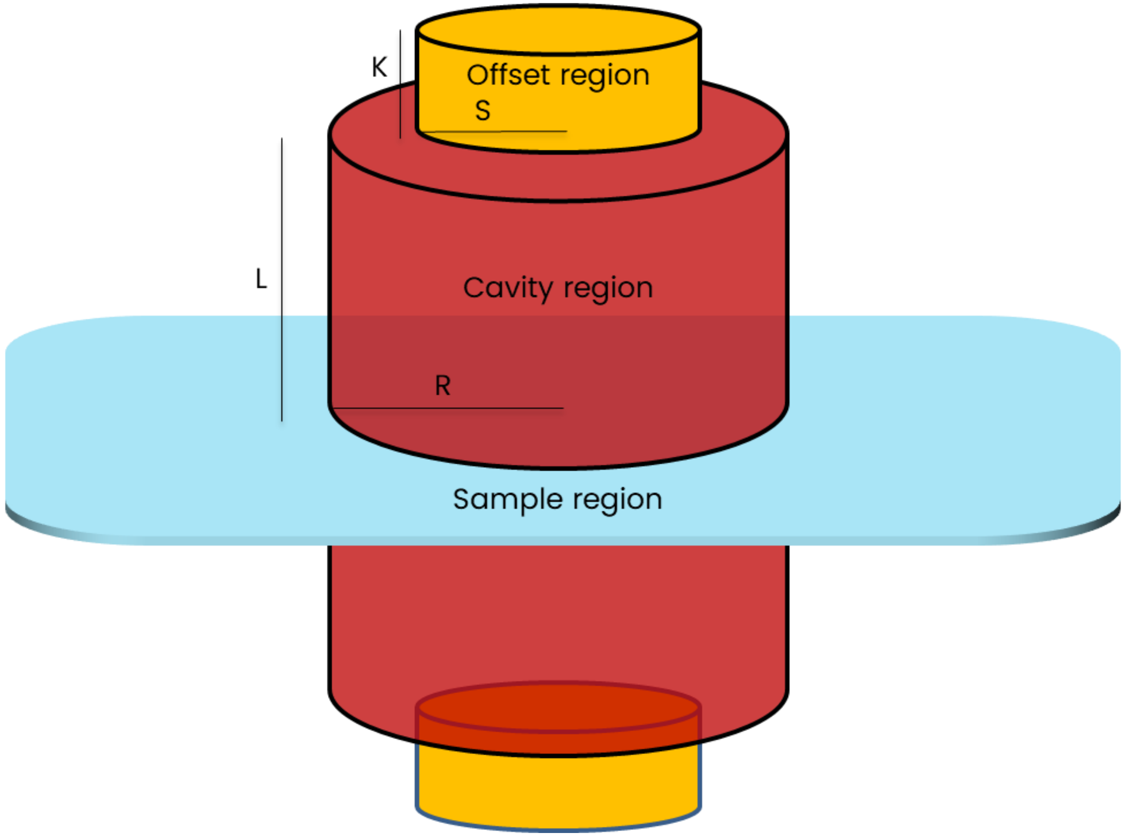


The dimensions of the cavity and sample are the critical features

We use mode-matching to extract permittivity

3

Use theory to map to permittivity



Traceable dimensions
+ Traceable resonance frequency
= Traceable permittivity

We assume every surface is a perfect conductor and $\vec{E}$ & $\vec{H}$ are continuous at each interface

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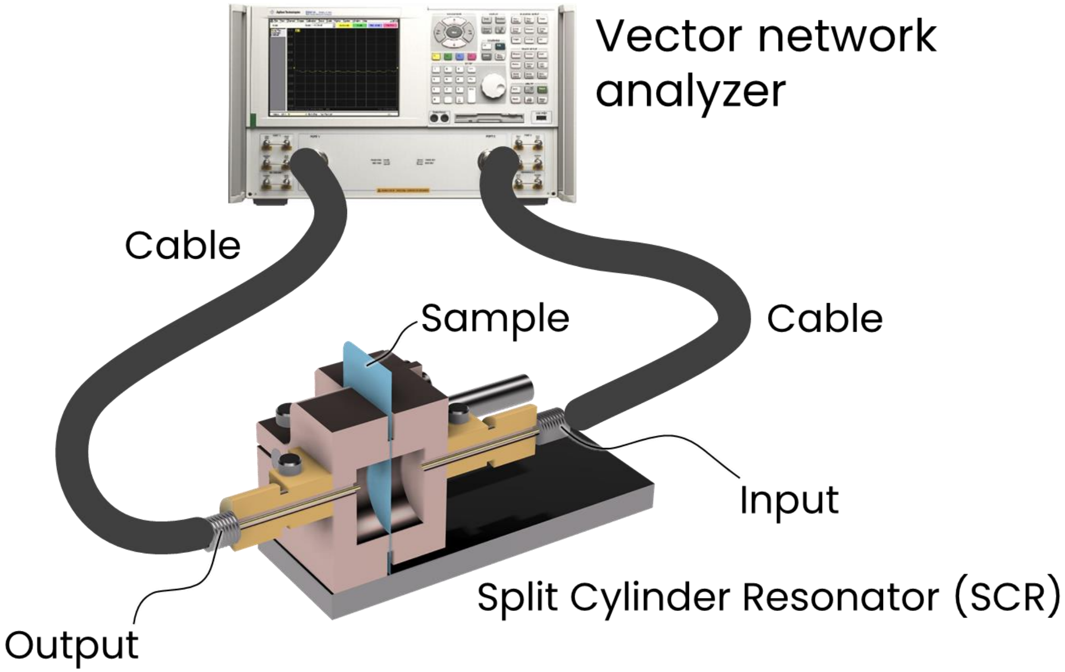
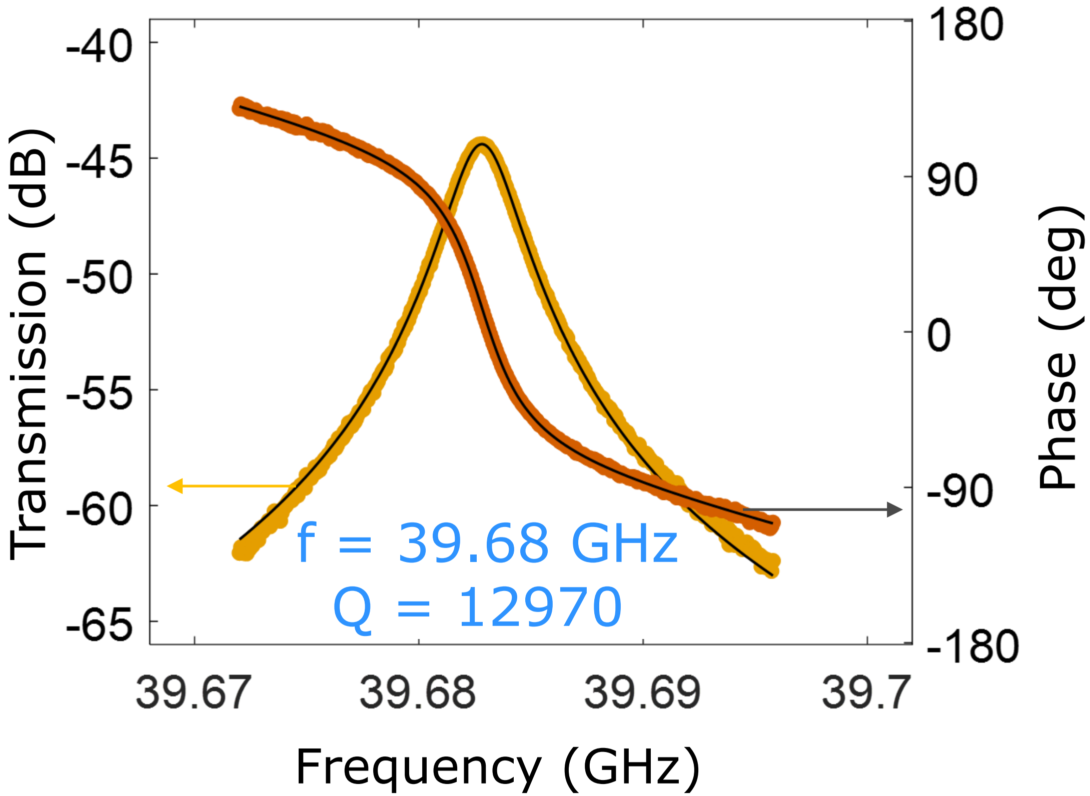
We use a vector network analyzer (VNA) to measure f_{res} & Q

4

Measure Scattering parameters

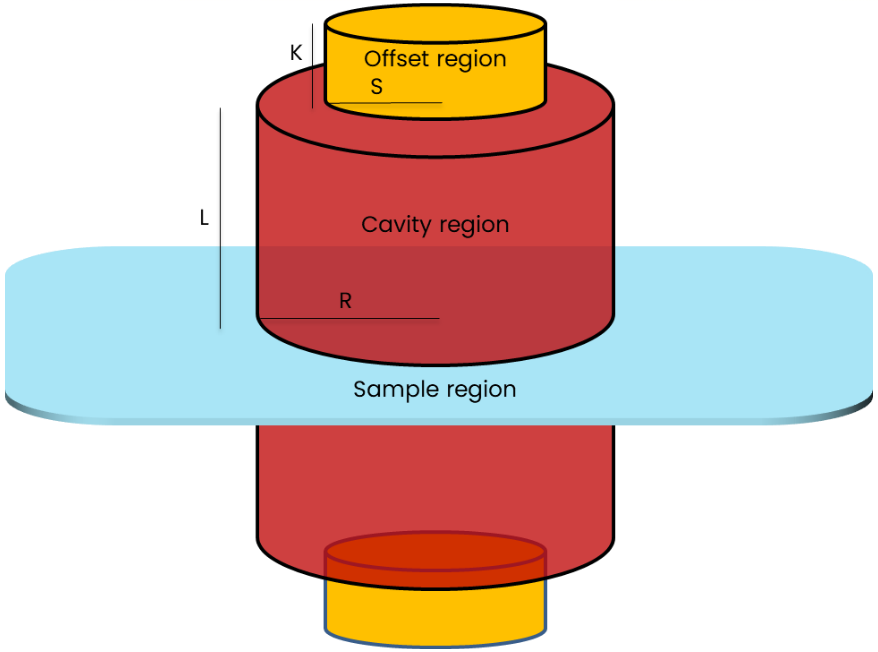




NIST collaborators are dimensioning the cavities

5

Measure dimensions



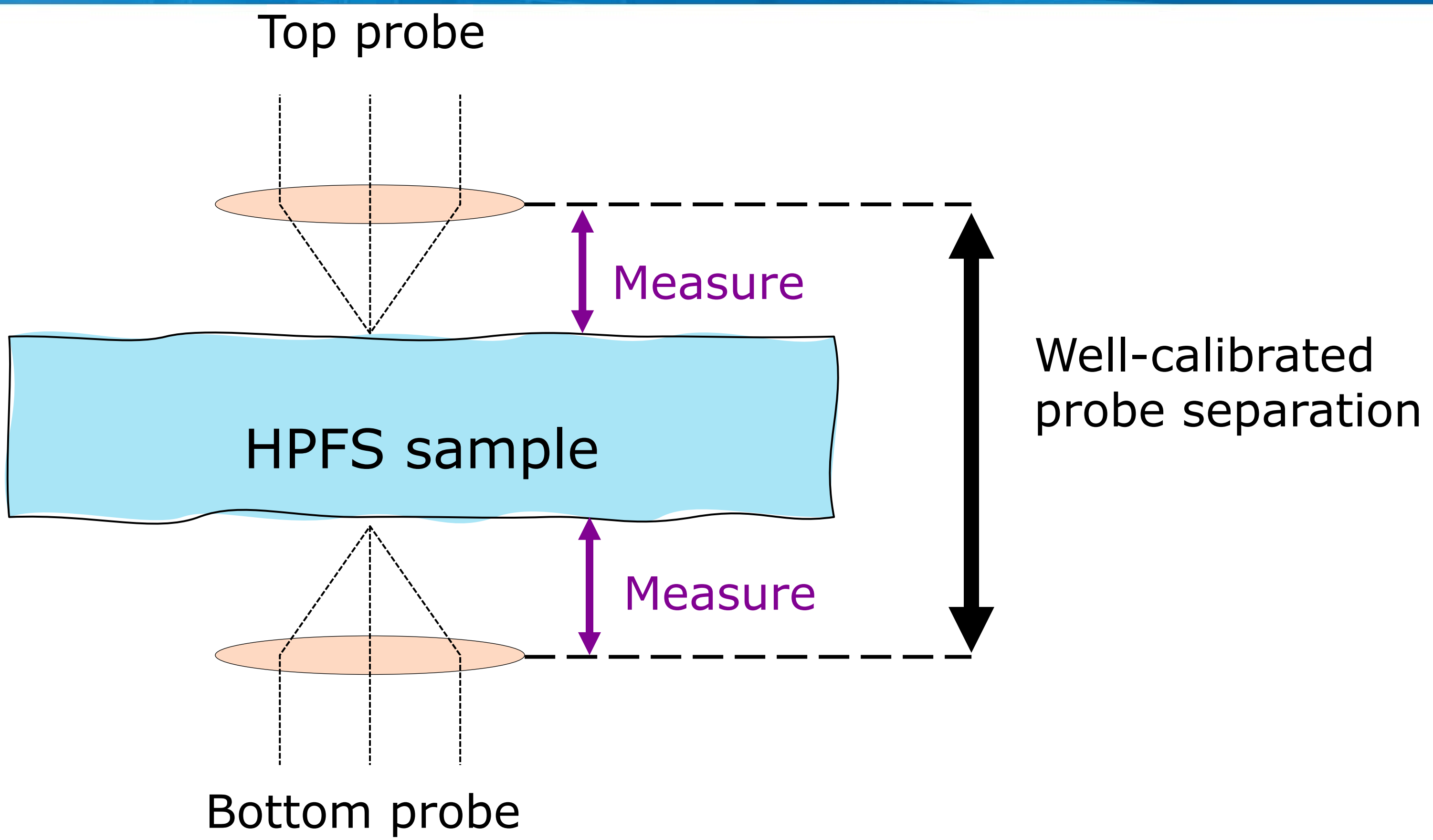
K	0.71100 ± 0.001 mm
S	6.89650 ± 0.001 mm
L	4.69874 ± 0.001 mm
R	7.60784 ± 0.0002 mm

Measurement uncertainties (≤ 1 micron) << our mean values

The sample dimensions are more difficult

5

Measure dimensions

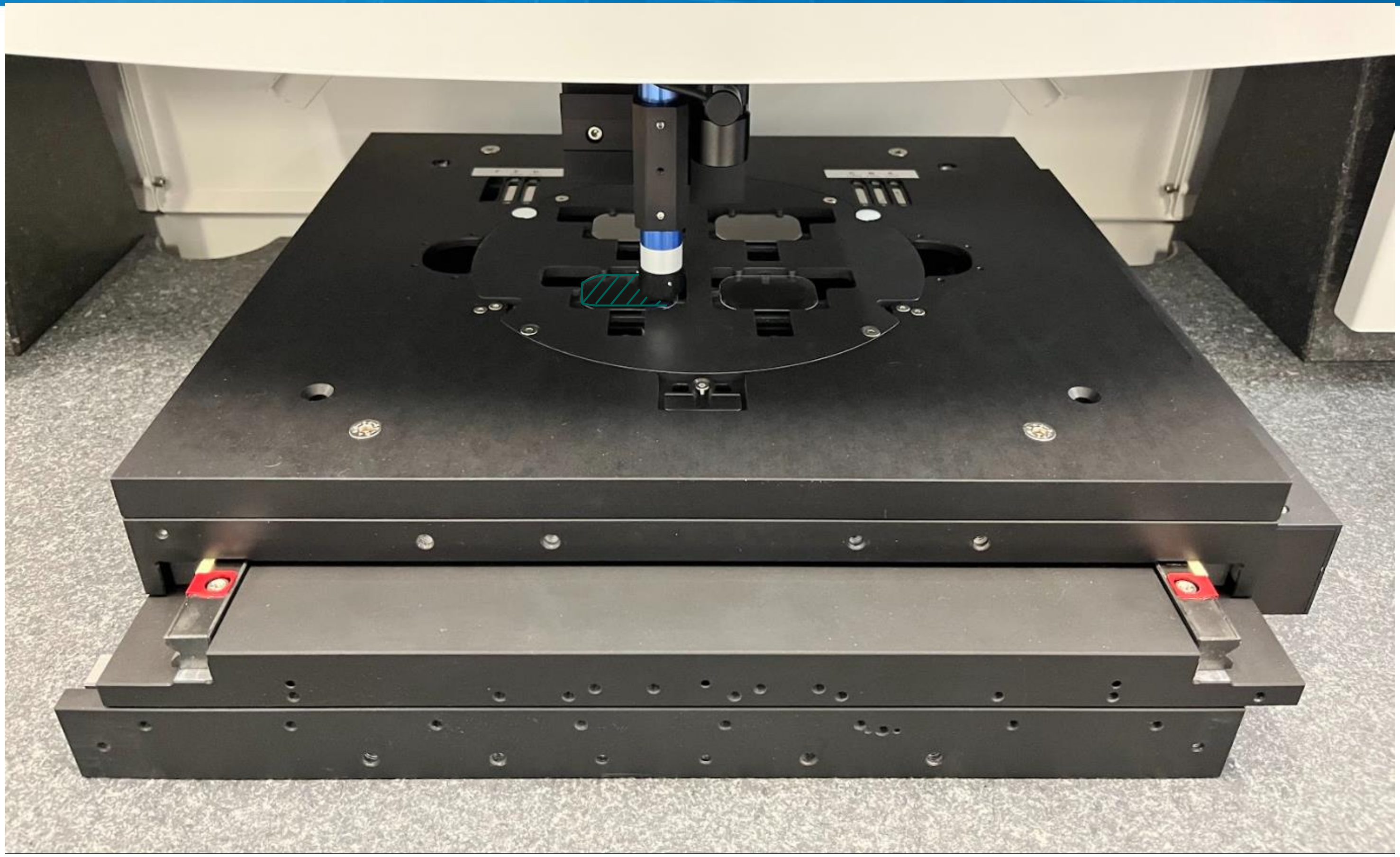


Chromatic white light sensors let us find both sample surfaces without assuming refractive index

The sample dimensions are more difficult

5

Measure dimensions



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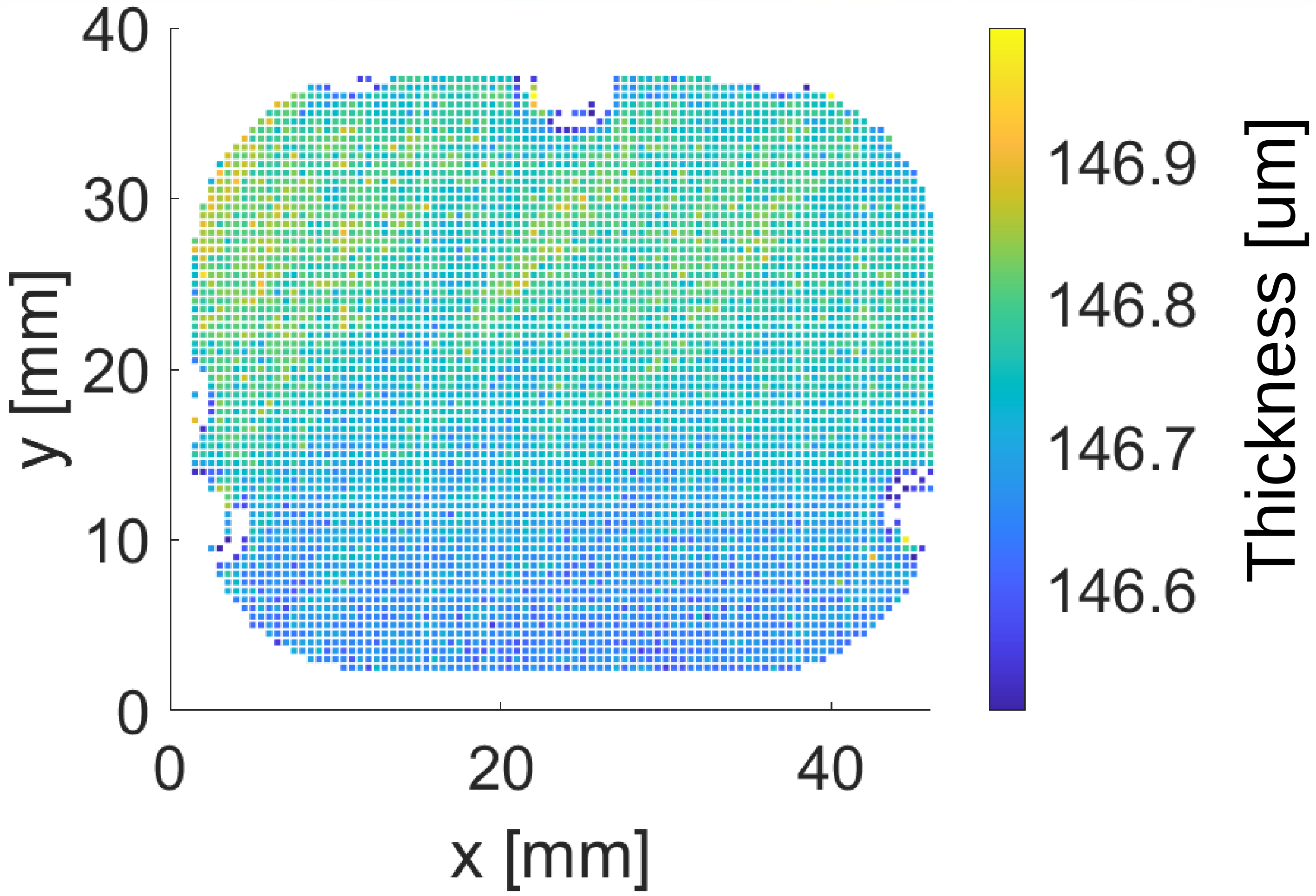
Measure dimensions



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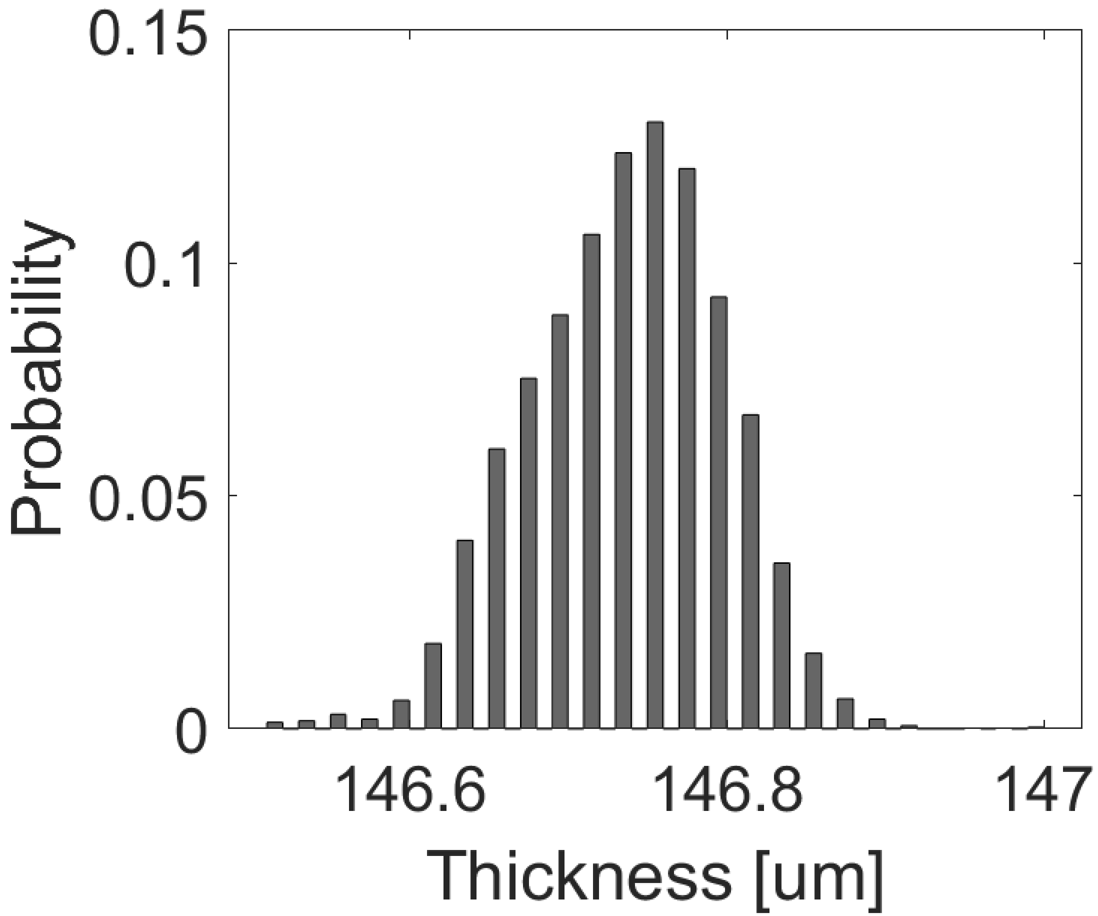
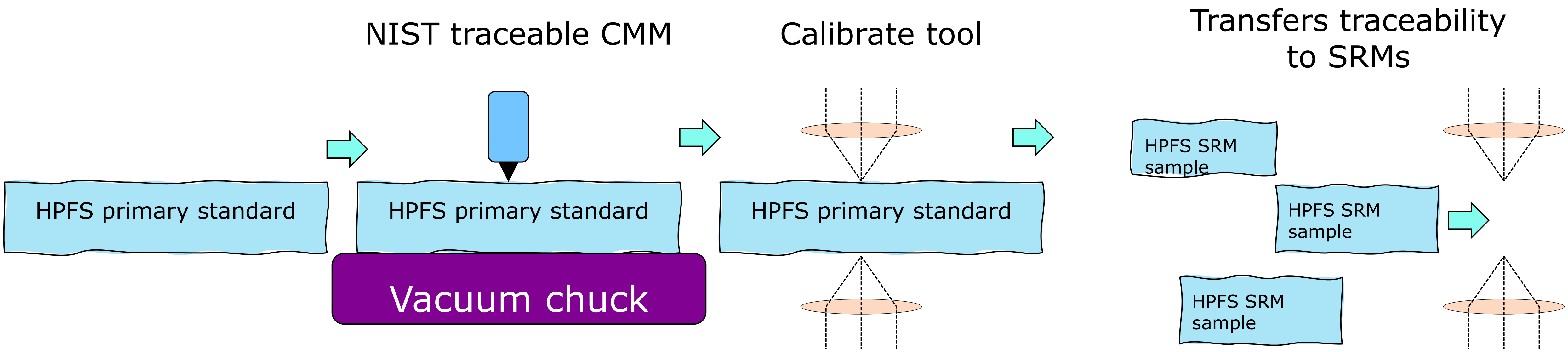


Chromatic white light sensors let us find both sample surfaces without assuming refractive index

We use the mechanical measurements to validate



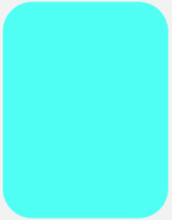
Our uncertainties are on the order of 100 nm (0.067%)

We need to fill the traceability gap

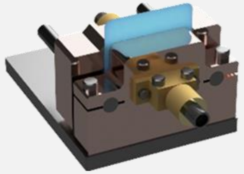
Already done

0 Incorporate industry feedback

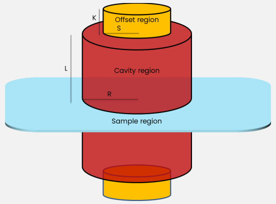
1 Choose material



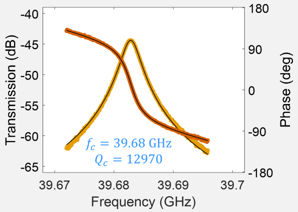
2 Choose method



3 Use theory to map to permittivity

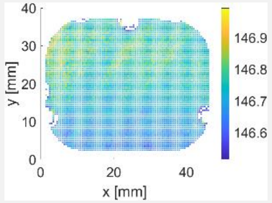


4 Measure Scattering parameters



In progress

5 Measure dimensions



The project overall and the progress we have made

Objective:	Develop a standard for relative permittivity and loss tangent
State-of-art:	Resonant cavities for low-loss dielectric measurement
Key idea:	High purity fused silica with ultra low TTV Mode-matching theory including complete cavity geometry
Impact:	Establishing a known ‘right’ answer for permittivity Material acceptance testing and evaluating metrology

This standard is just the beginning

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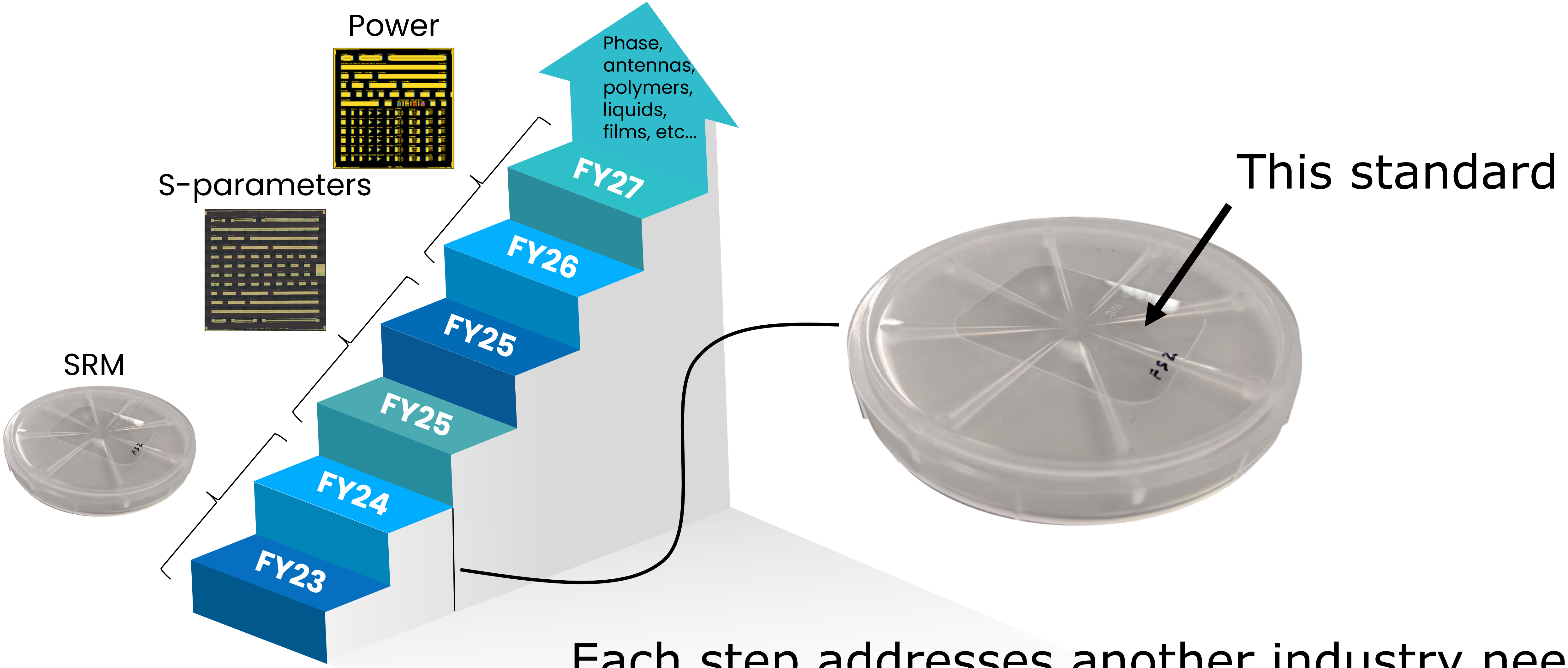
A staircase of future standards



Each step addresses another industry need

Thank you!

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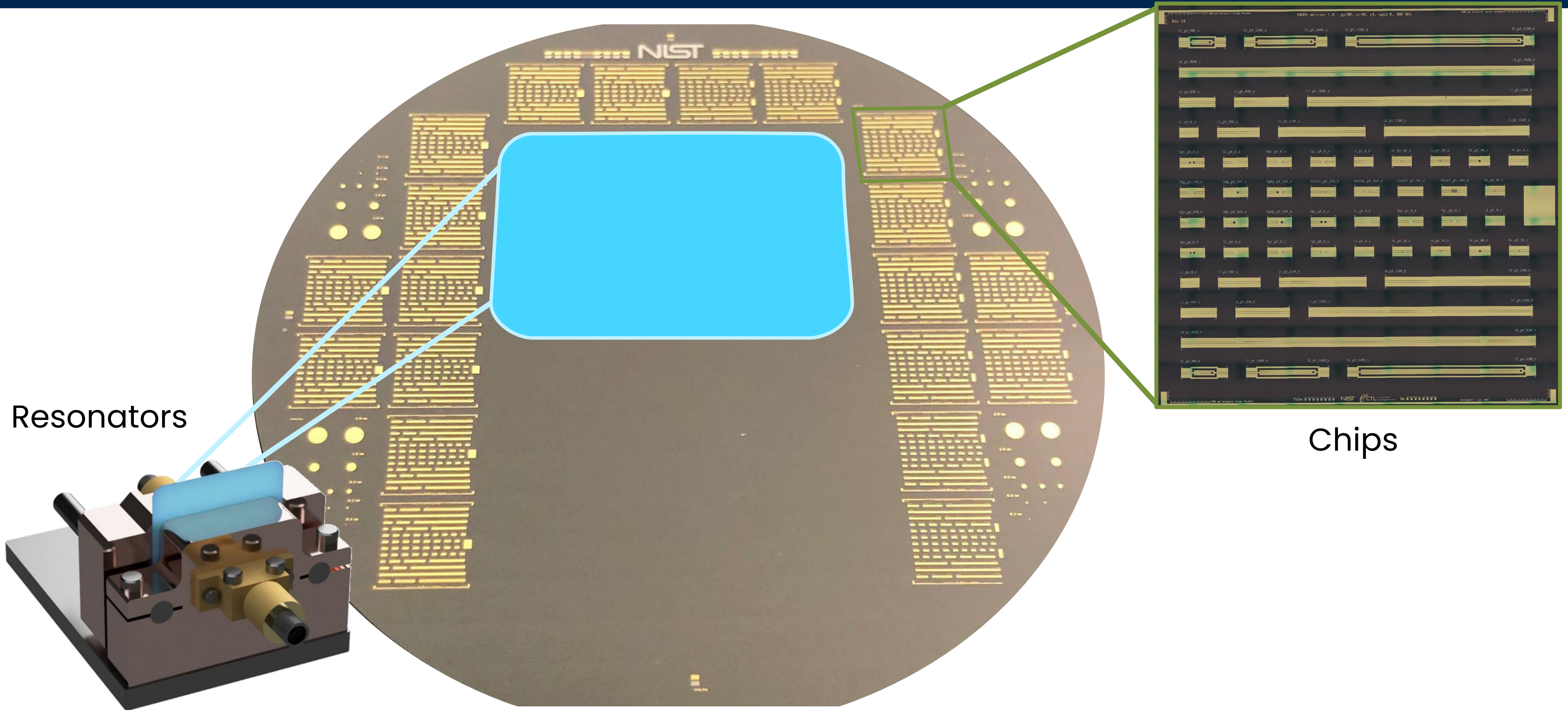
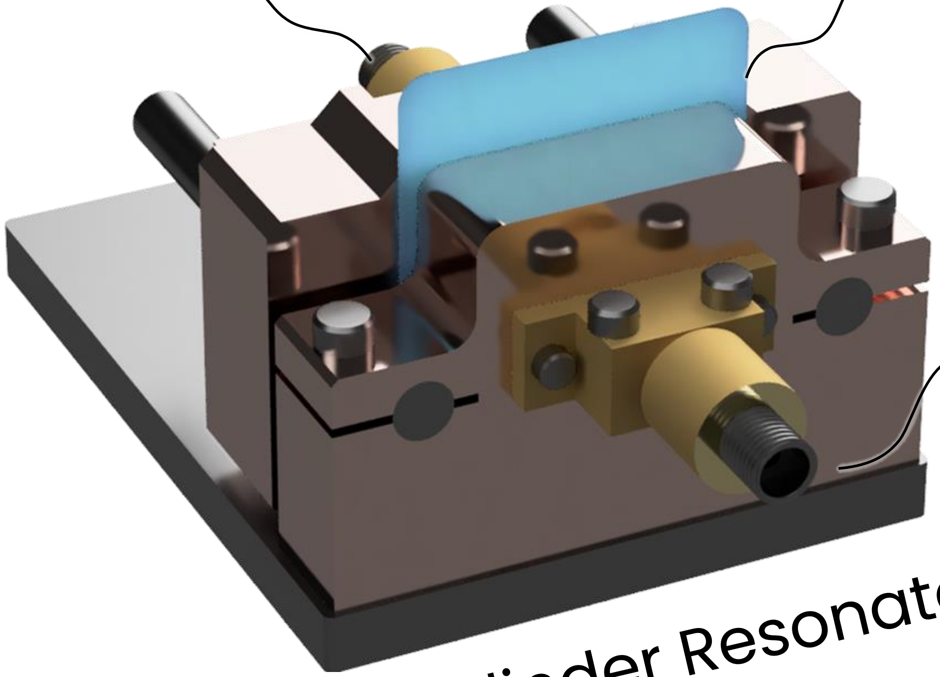
We measured the same wafer two ways



Each method has its own pros and cons

Method 1: We measured coupons in resonators



We measure **resonance frequency**, **quality factor**, and **sample thickness** to get ϵ_r' and ϵ_r''

Pros:

- Repeatability
- We can make it *traceable*

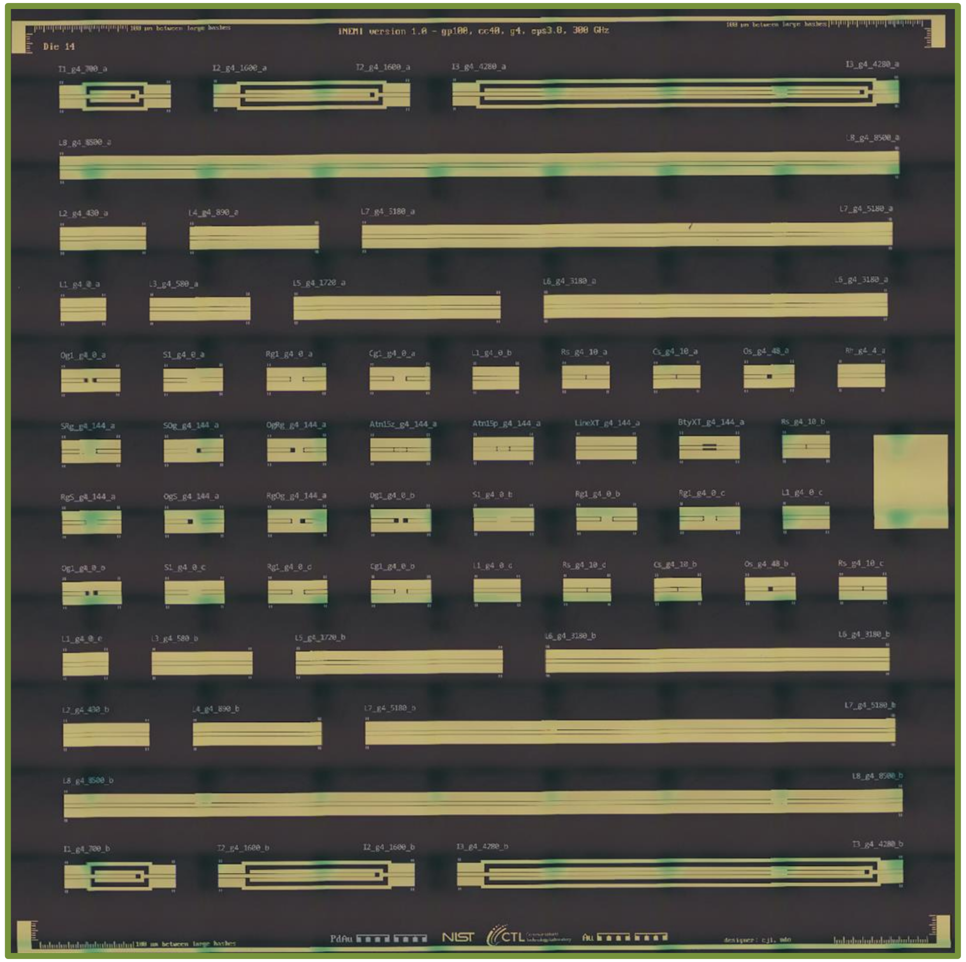
Cons:

- Single frequency
- Requires thin, low ϵ_r' materials

Our resonators have small, *traceable* uncertainties

Method 2: We measured chips on a probe station

We measure **propagation constant** and **impedance** to get ϵ_r' and ϵ_r''



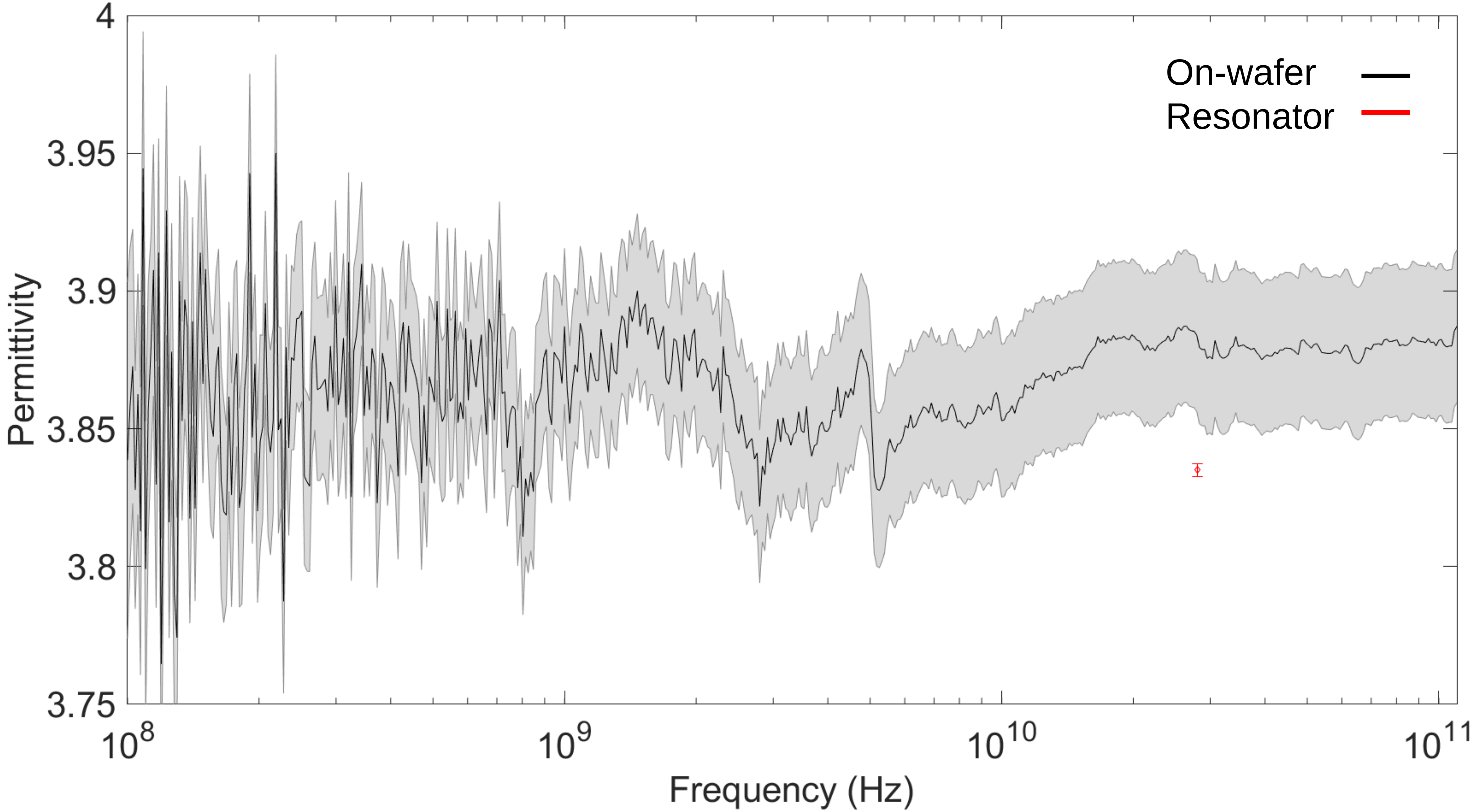
Pros:
- Broadband
- Insensitive to sample thickness

Cons:
- Larger uncertainties
- Requires microfabrication

*Detailed method description here:
Drisko, Jasper A., et al. "Optimal series resistors for on-wafer calibrations." *IEEE Transactions on Microwave Theory and Techniques* 68.1 (2019)

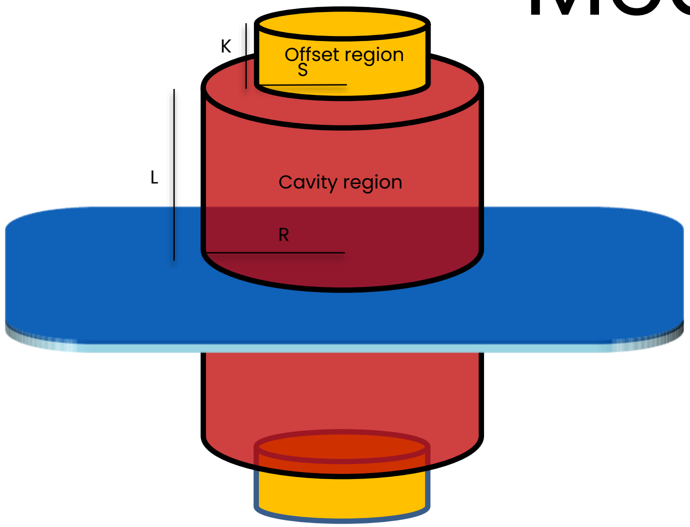
These broadband measurements have larger uncertainties

We compared on-wafer to traceable resonators



Traceable measurements would give us the *right* answer

Measuring isotropic thin-films



Film region (known thickness and **unknown permittivity**)

Substrate region (known thickness and permittivity)

Dimensioned cavity
+
Dimensioned substrate
+
Measured S-parameters
=
Substrate permittivity

→ Then, dep a film on the substrate

Substrate permittivity
+
Film thickness
=
Film permittivity

Our uncertainty is dominated by sample thickness