Recent developments of resonator measurements for emerging materials and technologies

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Resonator methods for material characterisation

What are resonant methods and why we use them

What resonant methods we know

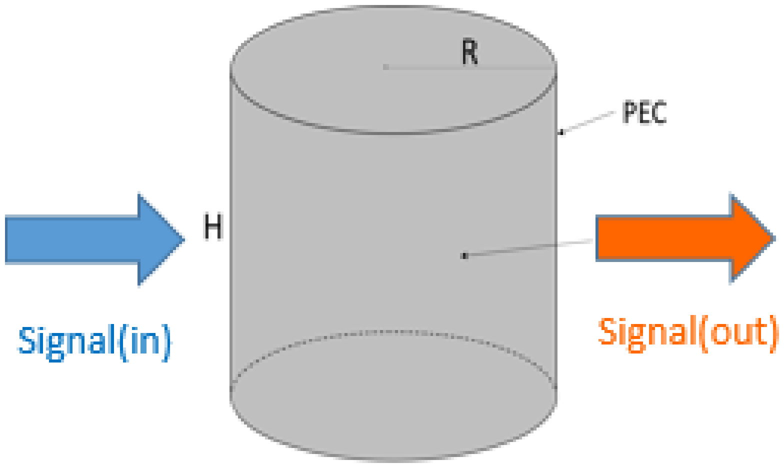
How these resonant methods work

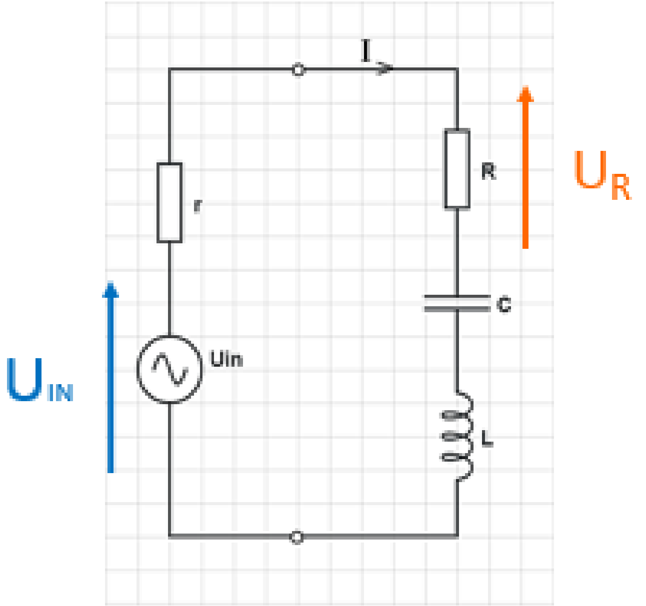
Resonant methods for broadband material characterisation

Presentation will be illustrated with full-wave electromagnetic modeling with QuickWave^{TM} software by

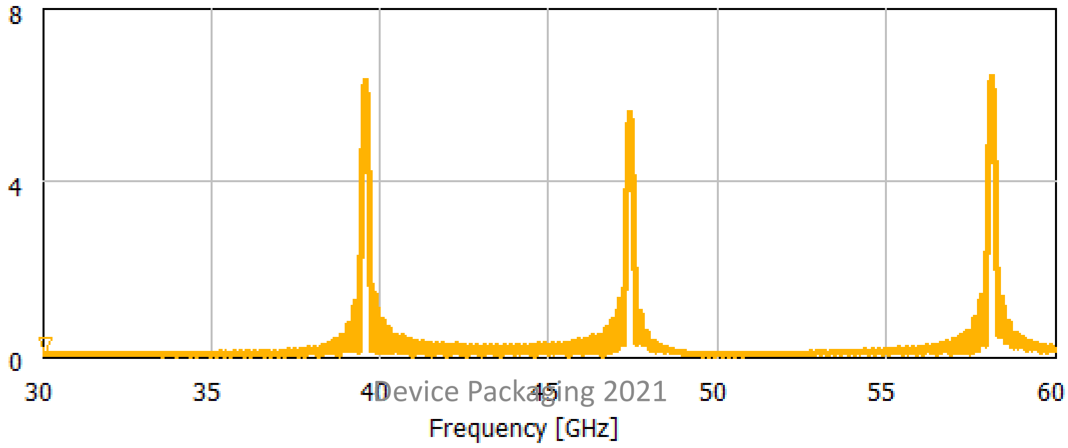
Resonator methods – motivation and background (1)

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



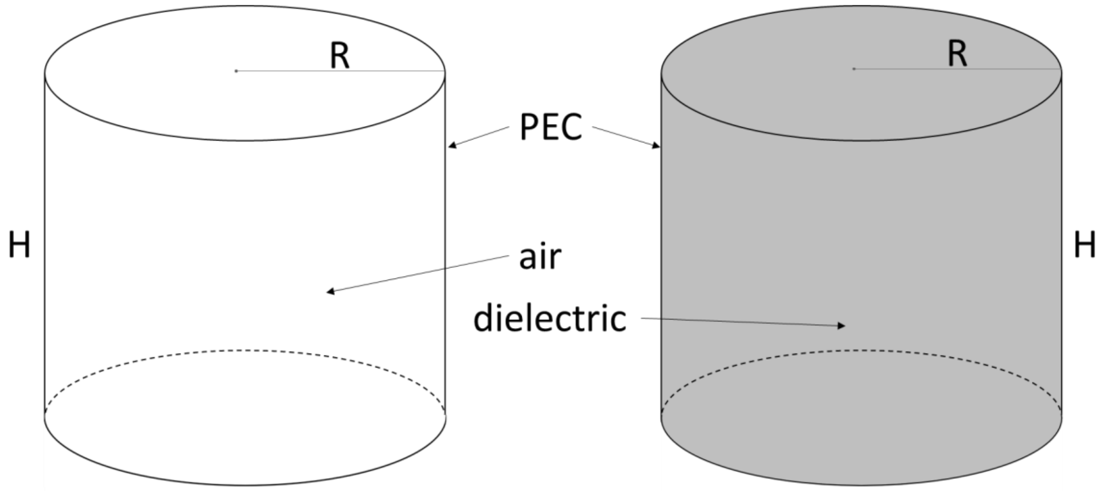


δ(t)



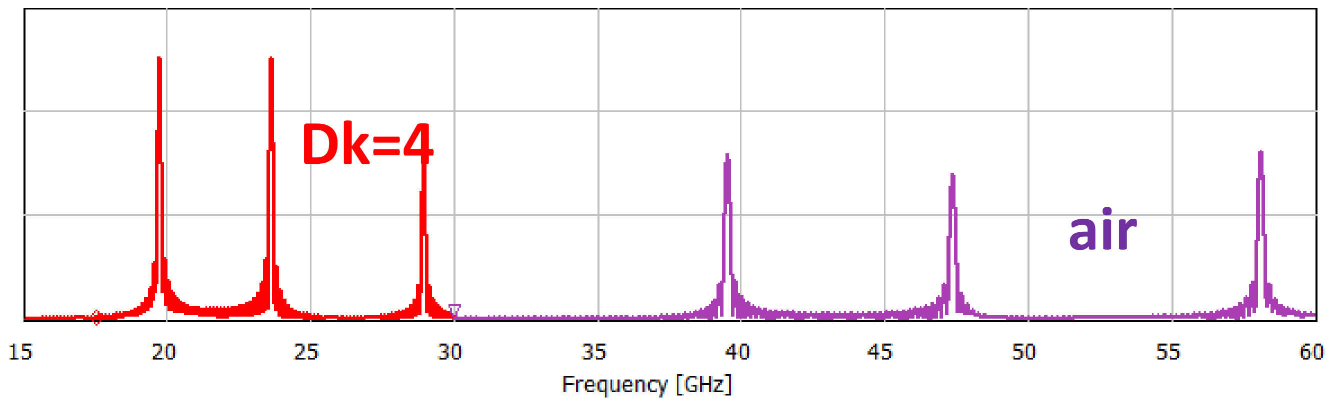
Resonator methods – motivation and background (2)

Resonance in theory: non-zero electromagnetic fields exist in isolated structures (no excitation).
Field properties are well-defined and linked to material properties.
E.g. for cylindrical cavities:

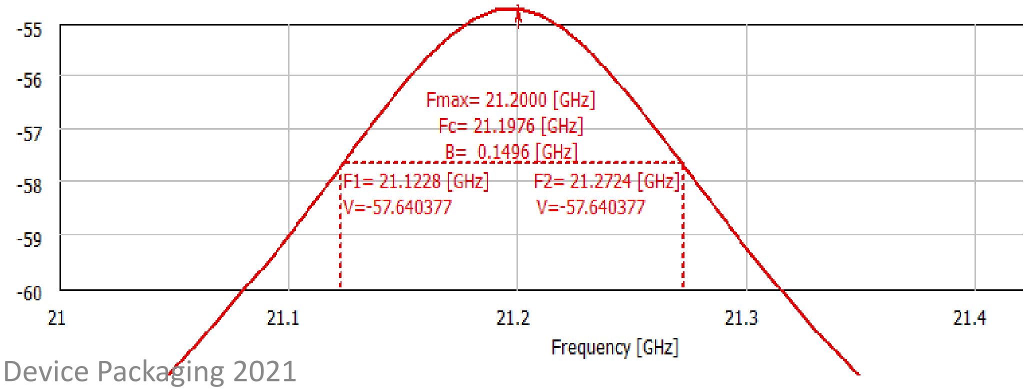


$$f_{r,mnp} = \frac{c}{\sqrt{Dk}} \sqrt{\left(\frac{\kappa_{mn}^{(,)}}{\pi R}\right)^2 + \left(\frac{p}{H}\right)^2}$$

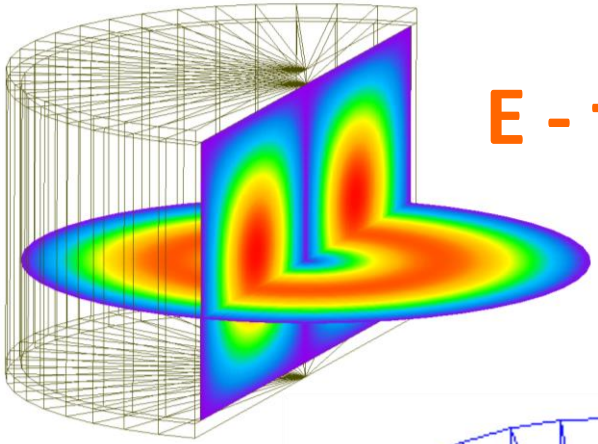
in non-magnetic low-loss dielectrics



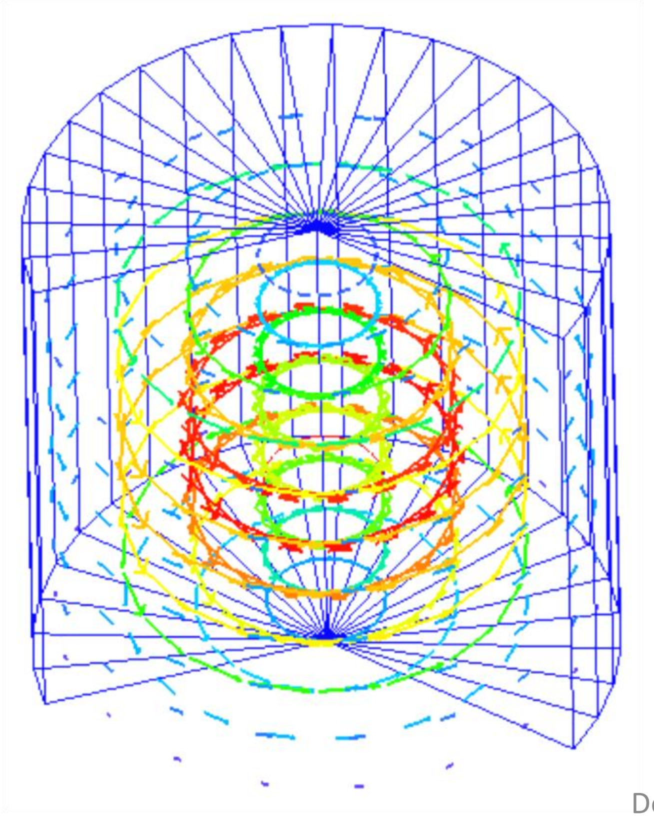
$$Q = 2\pi \frac{\iiint_V \varepsilon \vec{\mathbf{E}} \cdot \vec{\mathbf{E}}^* dv}{T \iiint_V \sigma \vec{\mathbf{E}} \cdot \vec{\mathbf{E}}^* dv} = \frac{\omega\varepsilon}{\sigma} = \frac{1}{Df} \approx \frac{fres}{\Delta f}$$

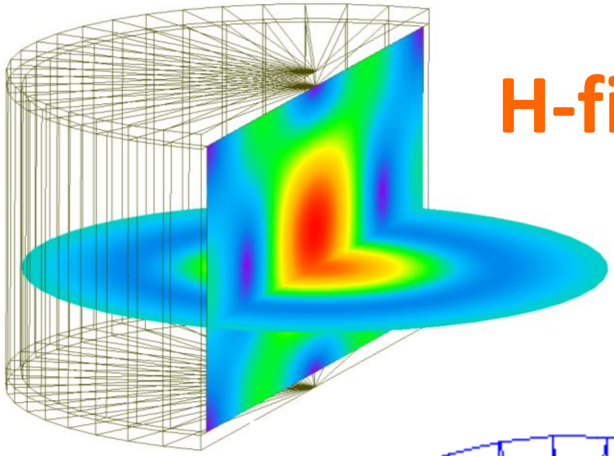


Cylindrical resonator: TE011 mode

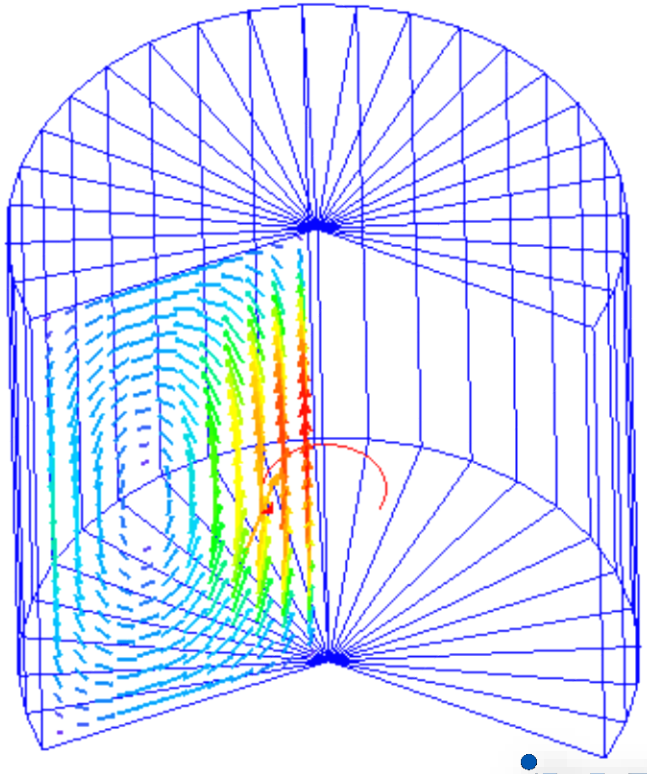


E - field

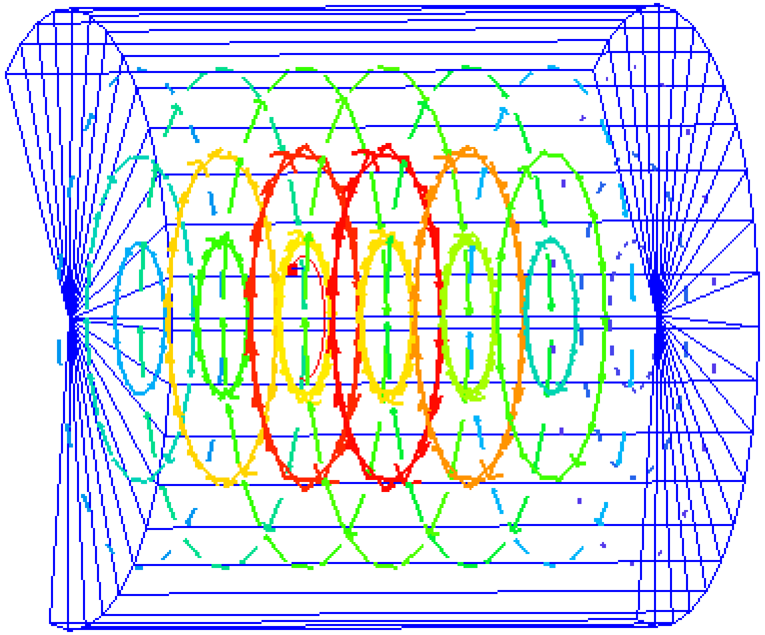




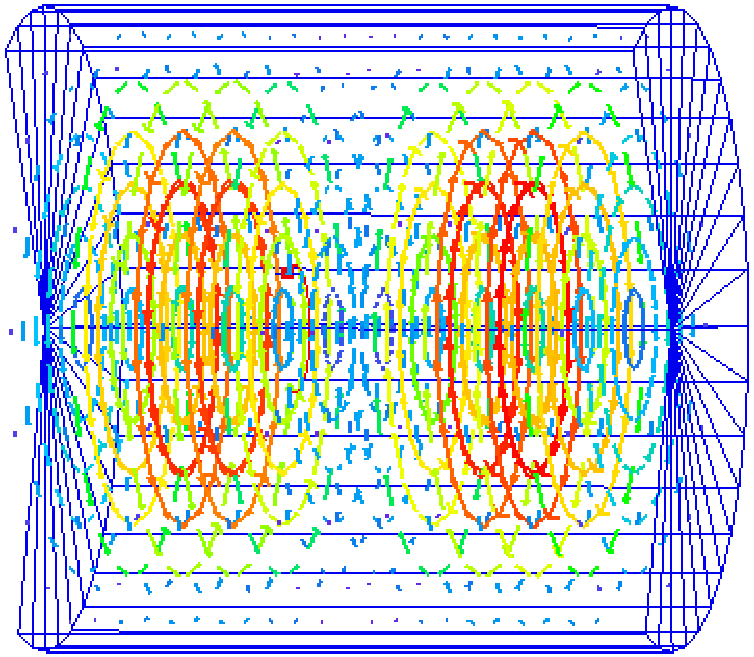
H-field



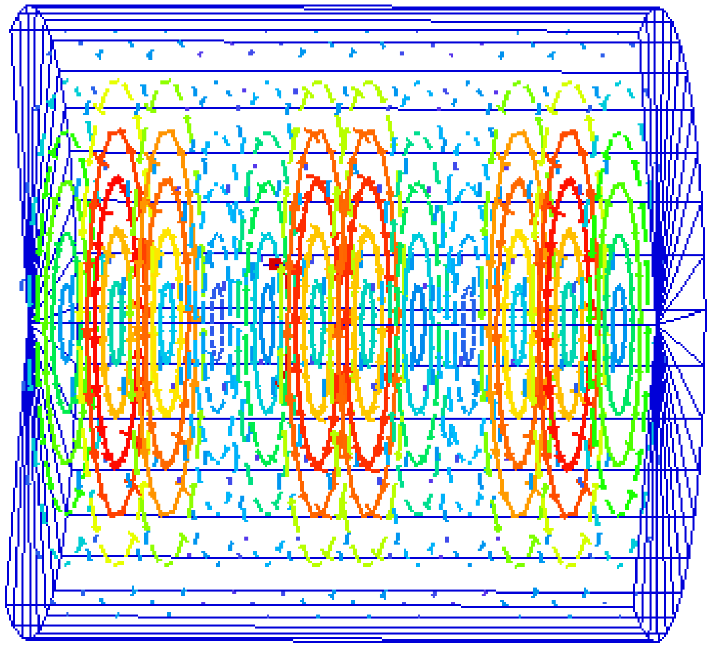
Cylindrical resonator: single-mode versus multi-mode operation



TE011 @ 29.43 GHz



TE012 @ 47.25 GHz



TE013 @ 57.95 GHz

Resonators are multimode devices.

Hence formally, material measurement can be performed at many frequencies in the same resonator.

However, some modes provide highest accuracy of material characterization. Some are difficult to excite.

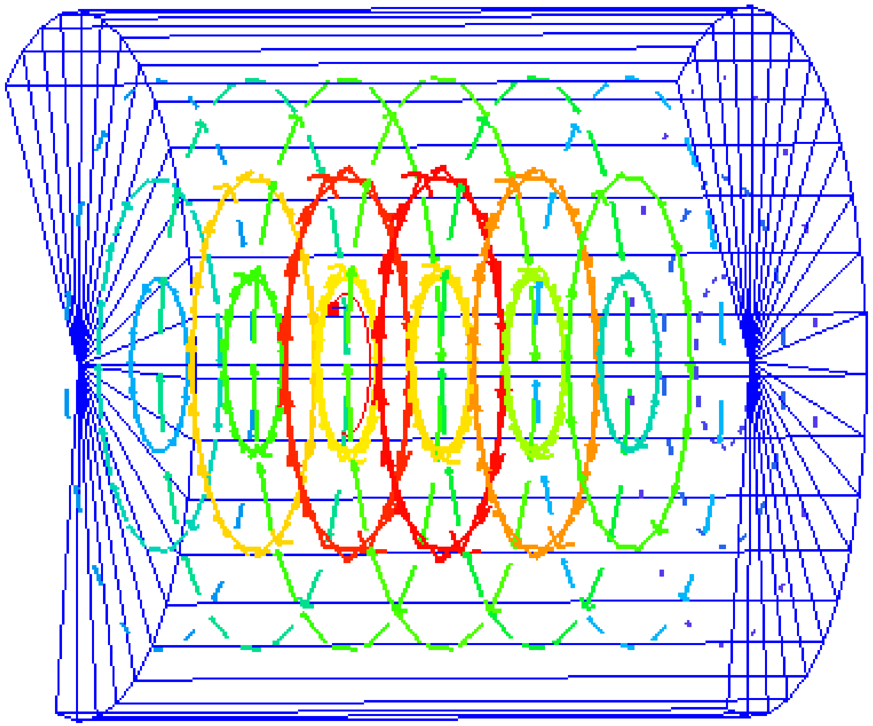
Software provided with the resonator in compatible only with modes pre-selected by the vendor.

Software provided with the resonator in compatible only with modes pre-selected by the vendor.

Among the popularly available resonators, BCDR and FPOR work as multi-modal.

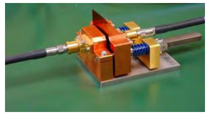
Resonator methods – motivation and background (3)

TE010

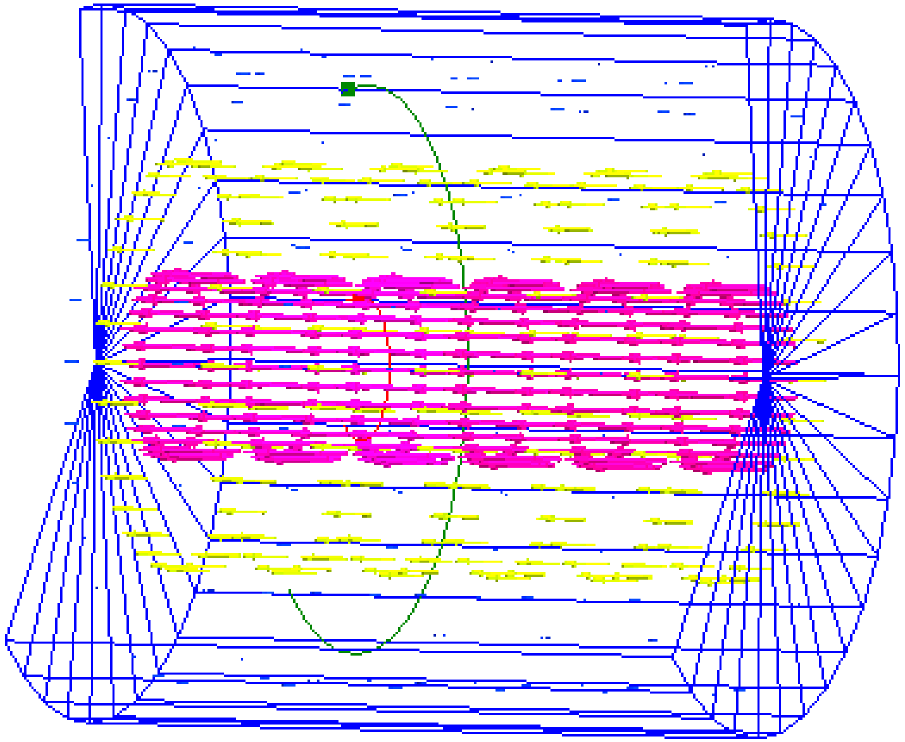


TE modes to measure
in-plane component of Dk, Df

SCR, SPDR, FPOR

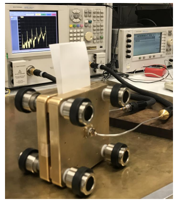


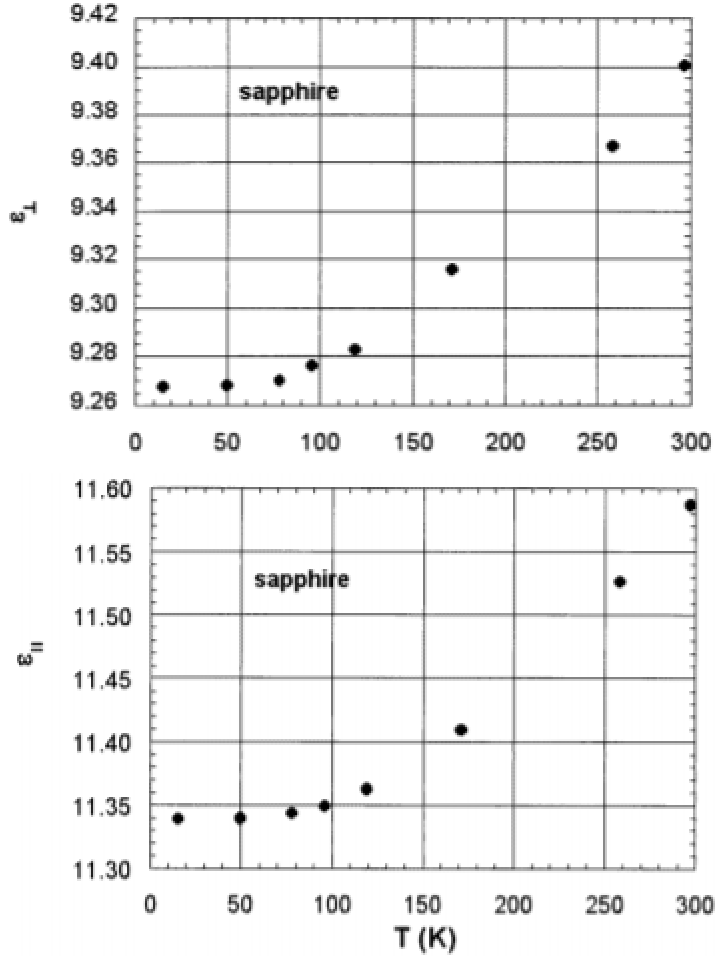
TM010



TM modes to measure
out-of-plane component of Dk, Df

BCDR

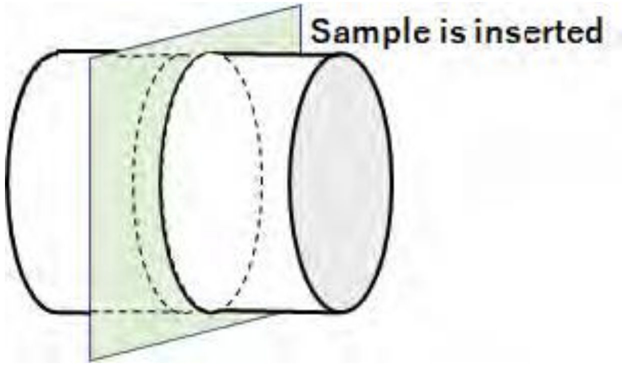


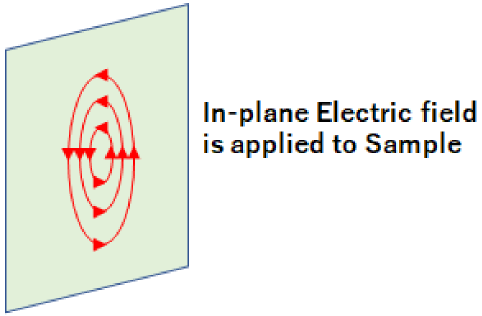


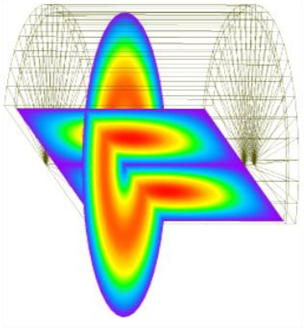
J.Krupka et al., "Complex permittivity of some ultralow loss dielectric crystals..", Meas. Sci. Technol. 10 (1999).

Full characterisation of anisotropic materials (like crystals) requires both measurements.

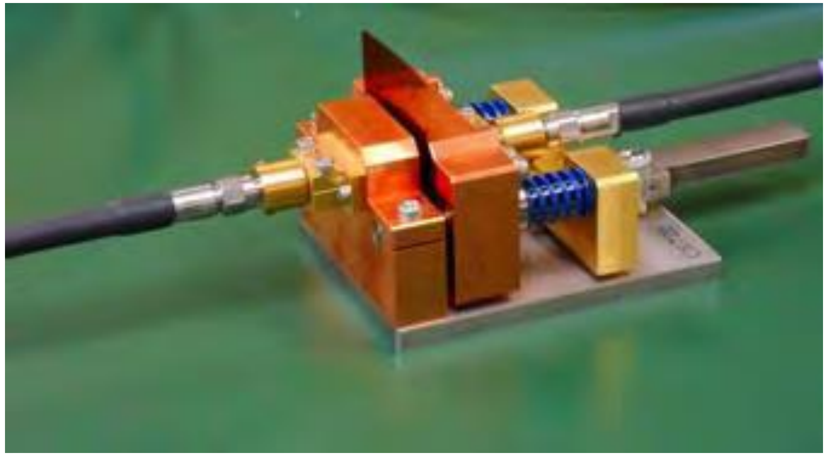
Split Cylinder Resonator (SCR) – basics & operation



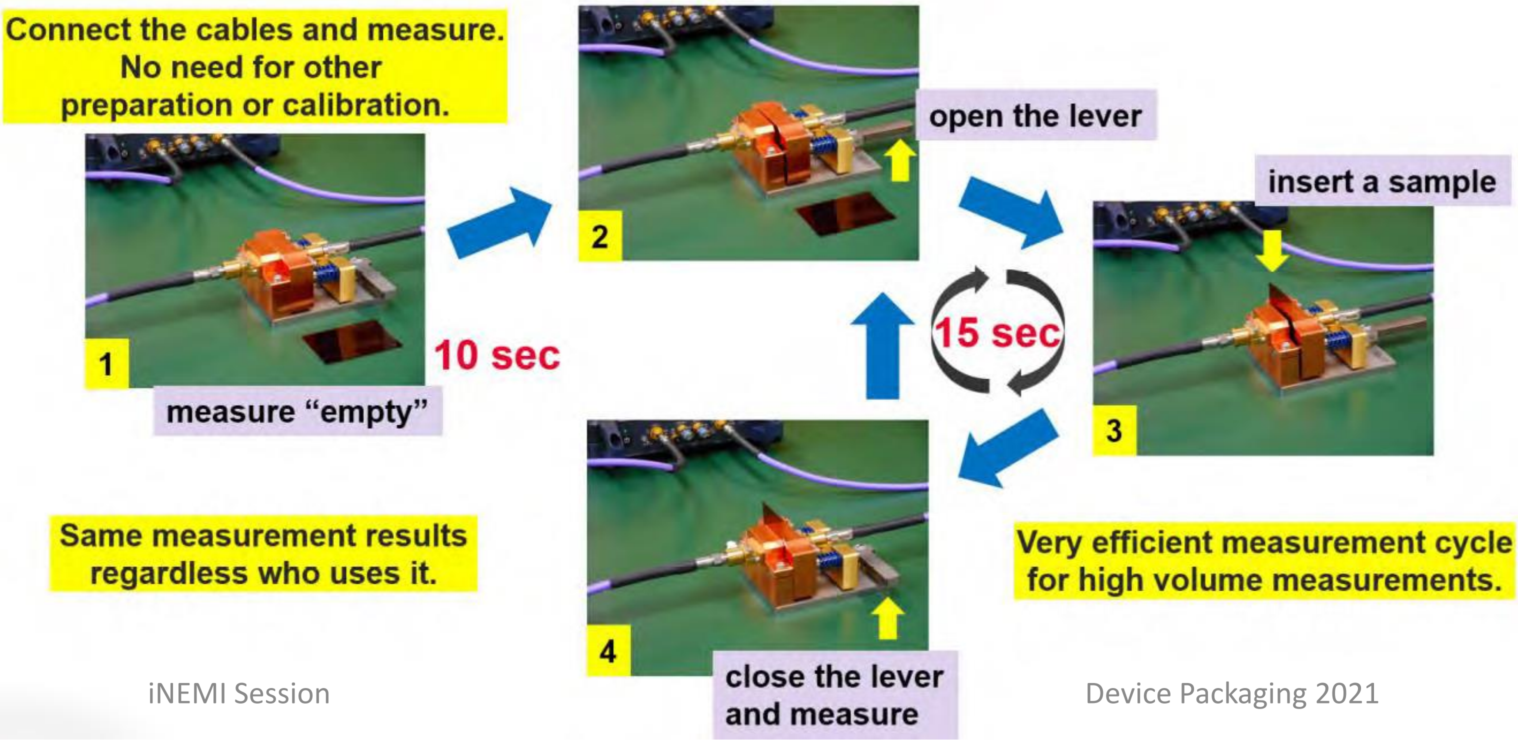




TE011 mode



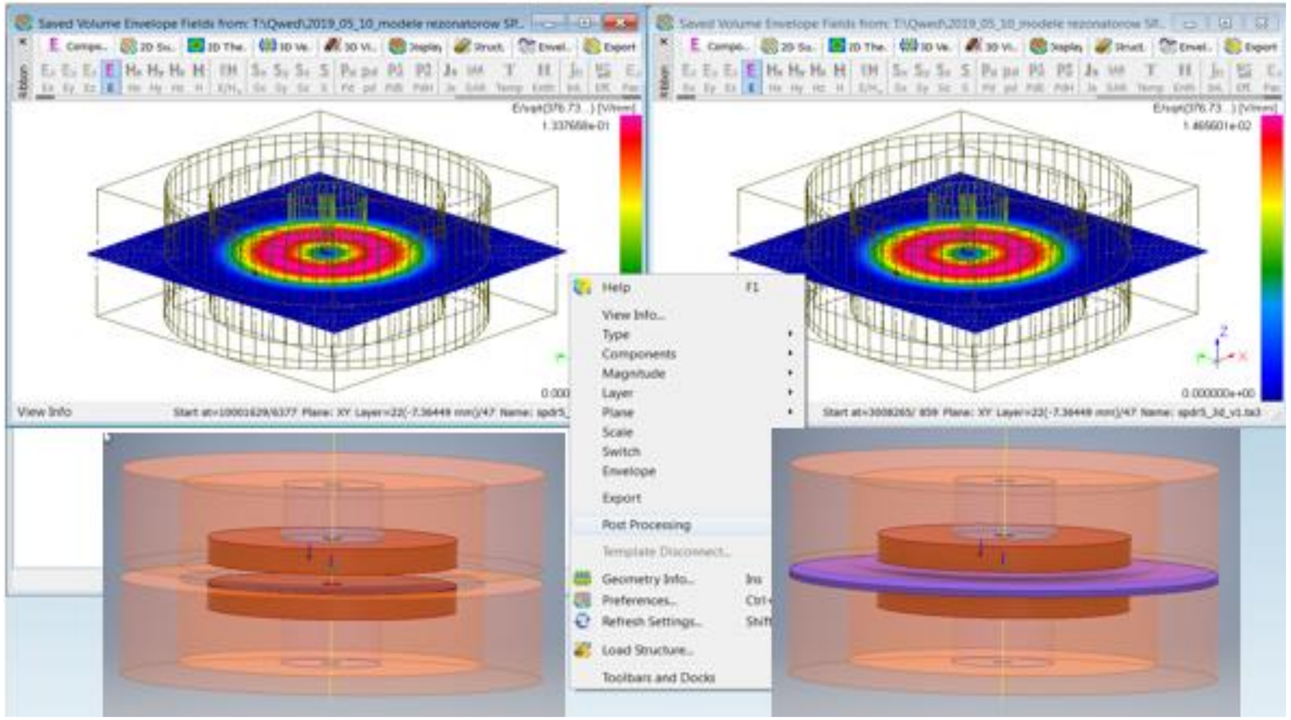
Operation workflow



Discrete frequency points from 10 GHz up to 80 GHz

- High measurement precision
- Can be sensitive to many user errors
- Typically interpolated to 5G mmWaves
- Typically in-plane component of permittivity
- Typical sample thicknesses around 100 um
- Support temperature sweep measurement
- IPC-TM-650 2.5.5.13
- https://www.keysight.com/us/en/assets/7018-06384/brochures/5992-3438.pdf

Split-Post Dielectric Resonator (SPDR) - basics



- resonant mode with EM fields mostly confined in and between those ceramic posts

→ minimial losses in metal enclosure

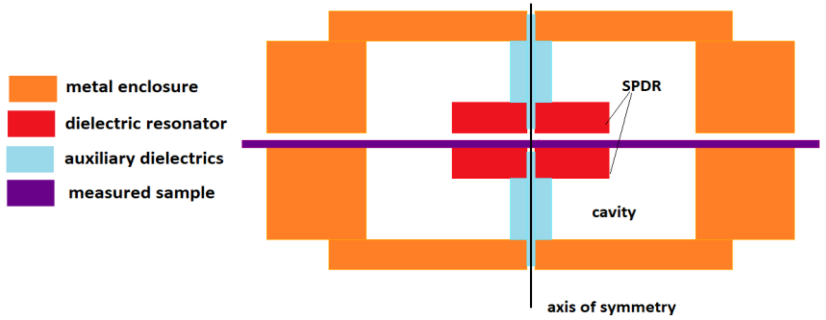
- H-field is only vertical at the side wall of the enclosure → circumferential currents

→ no radiation through slot

- E-field tangential to SUT

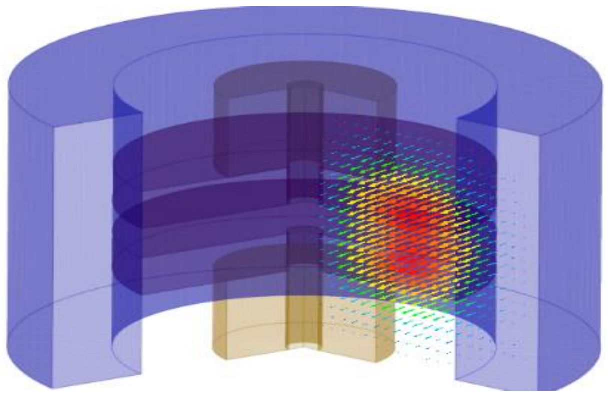
→ air slots between SUT and posts have negligible effect

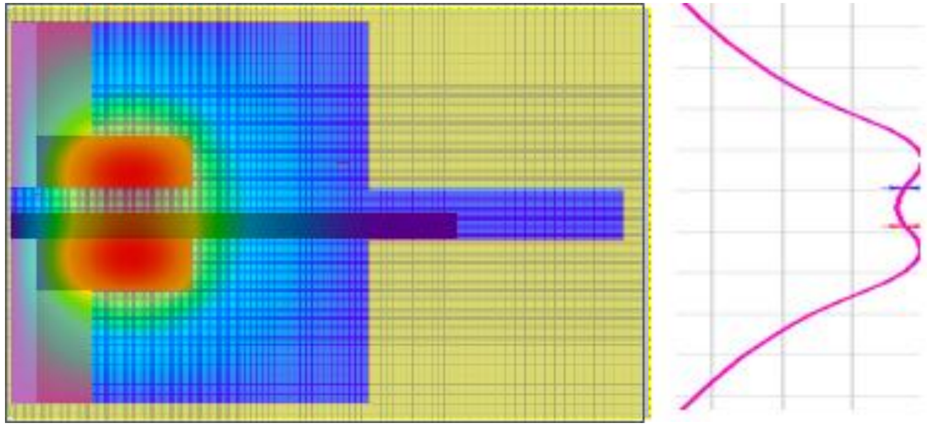
- **easy SUT insertion through slot, no dismatling**

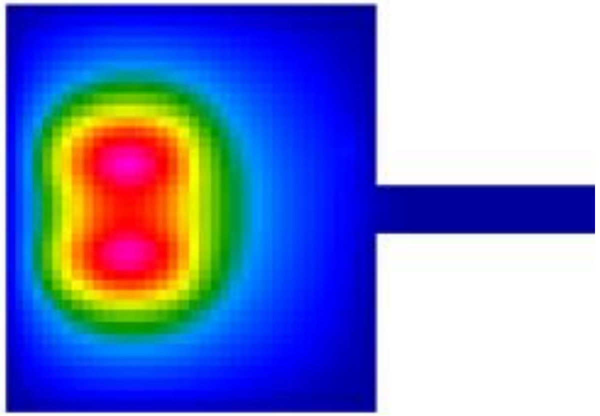


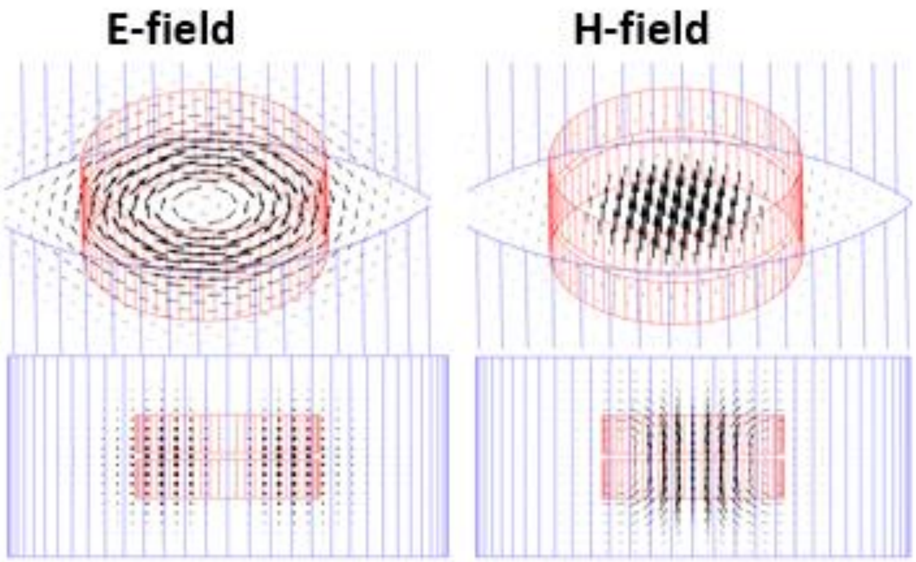
Split-post dielectric resonator (SPDR)	Discrete frequency points from 1 GHz up to 15 GHz	• High measurement precision • Easy to use • Insensitive to many user errors • Typically in-plane component of permittivity • Typically extrapolated to 5G mmWaves • Typical sample thicknesses less than 1 mm • IEC 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

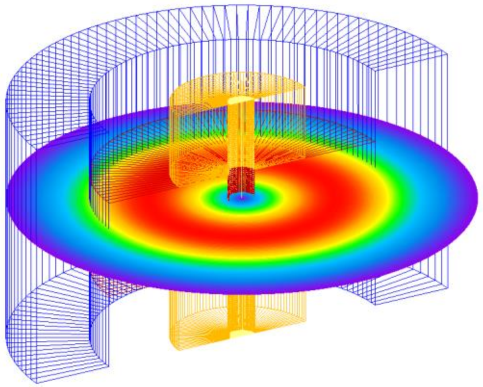
Split-Post Dielectric Resonator (SPDR) – modelling results

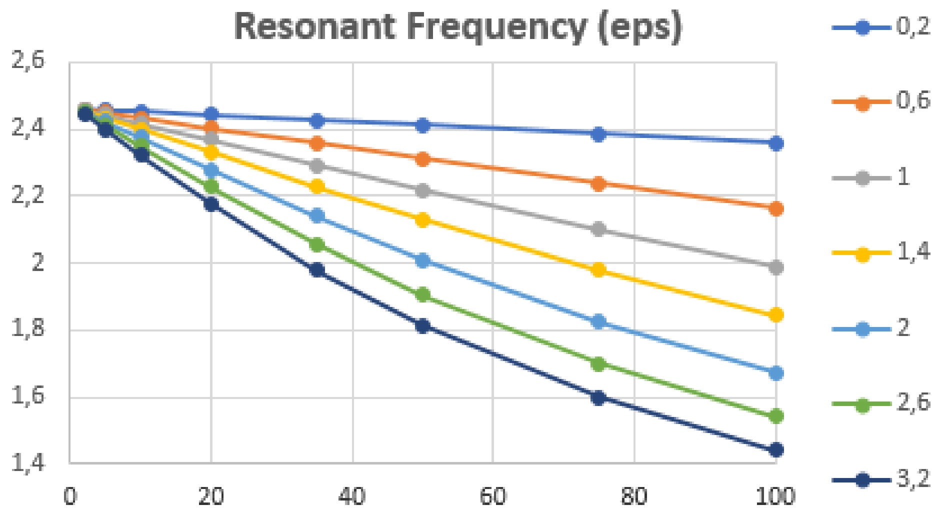






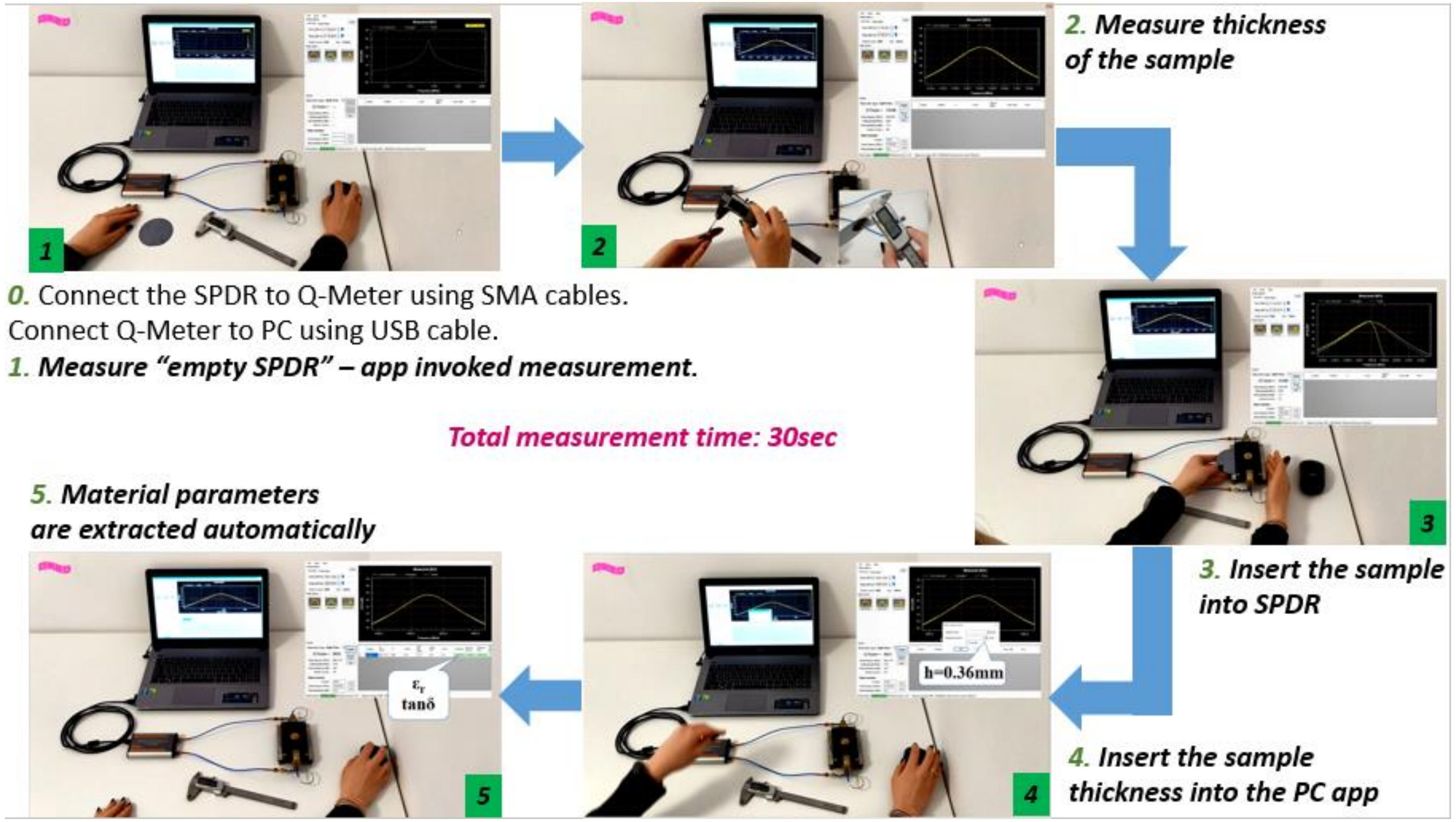


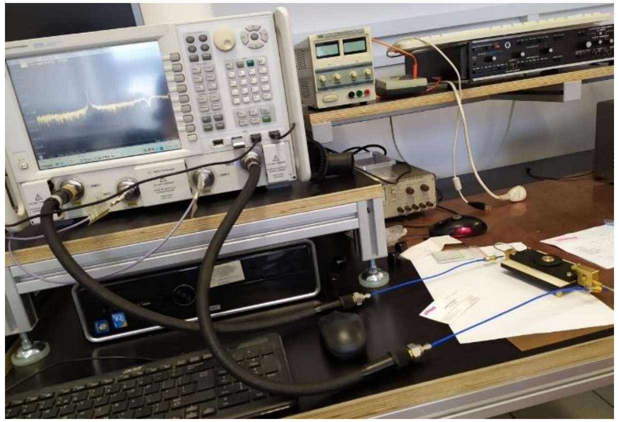




Split-Post Dielectric Resonator (SPDR) – operation (1)

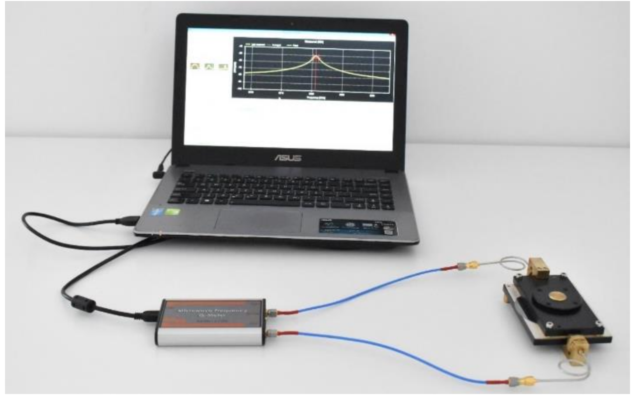
Operation workflow





SPDR use in labs...

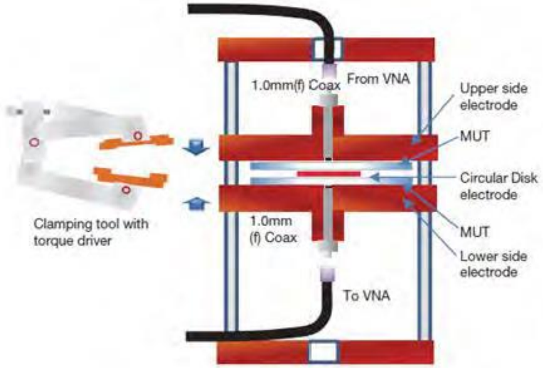
...and at home

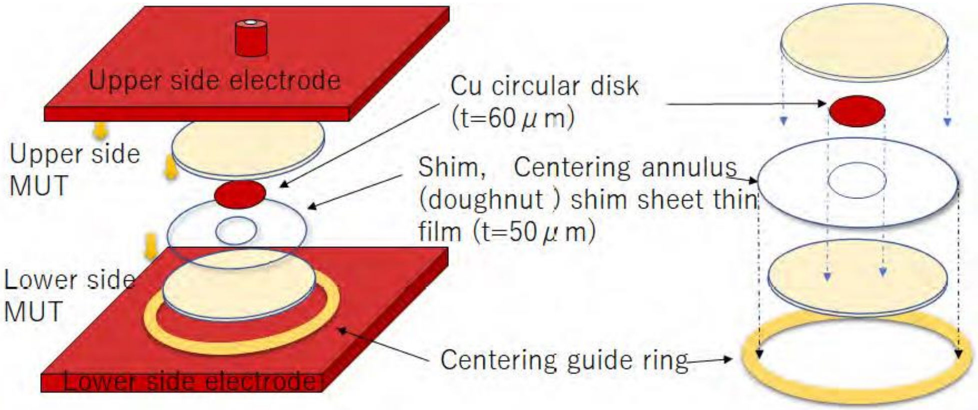


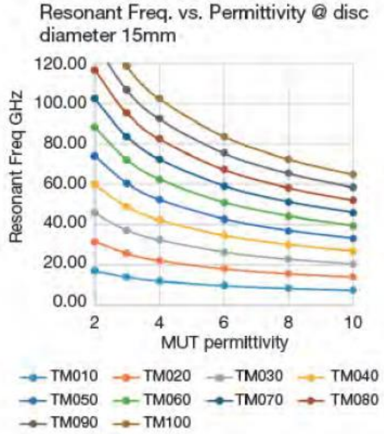
For many practical materials, measuring only abs (S21) provides appropriate accuracy.

Keysight Option N1500A uses S21 (amplitude & phase) which helps enhance accuracy (*under study in iNEMI project*).

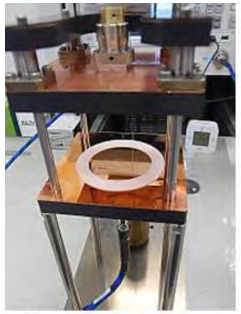
Balanced-type circular disk resonator (BCDR) – basics & operation

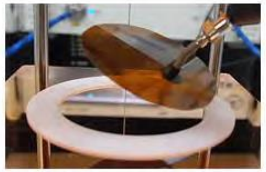


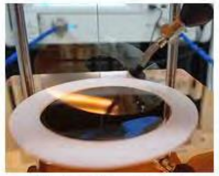


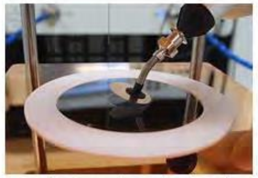


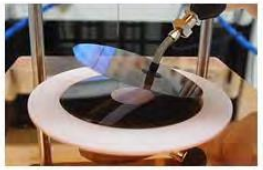
Operation workflow

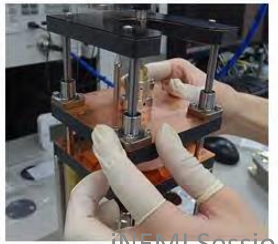

Open the resonator


Set lower side sample


Set shim sheet


Set center electrode

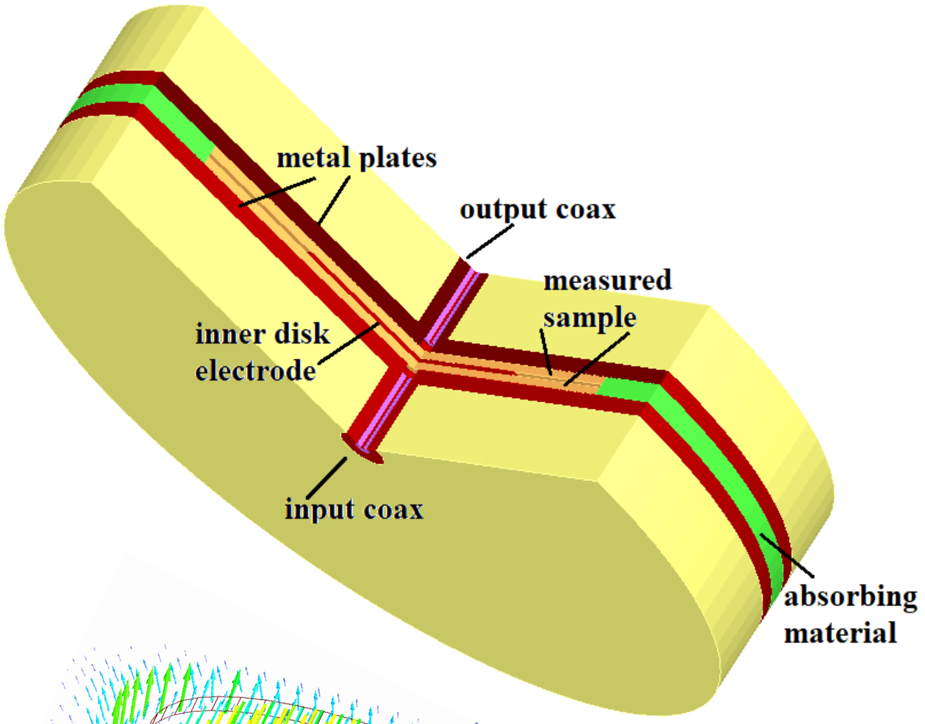

Set upper side sample

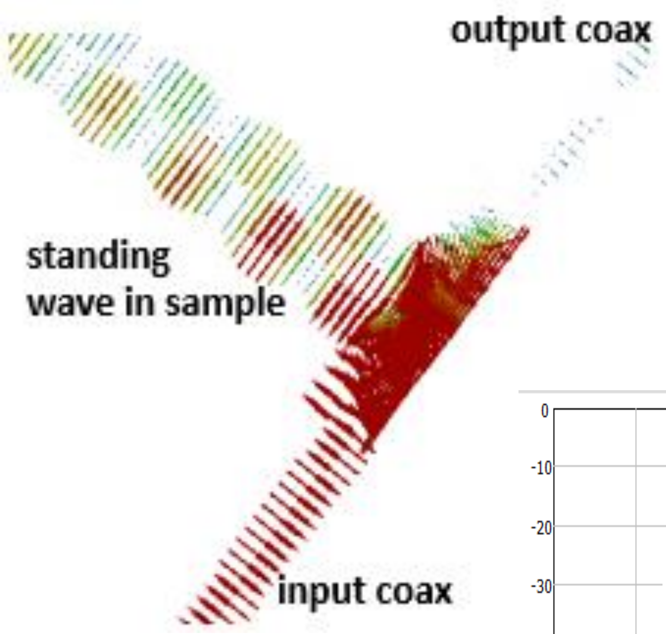

Close the resonator

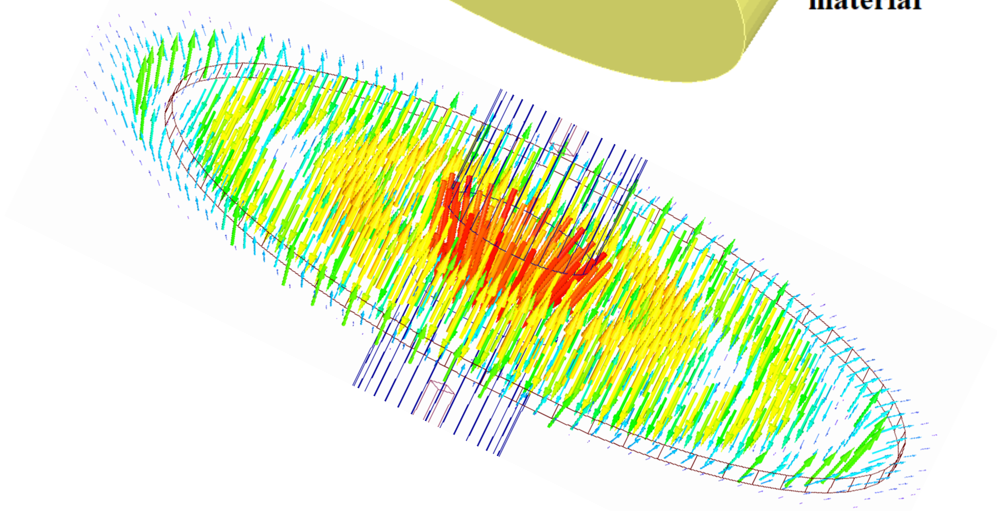

Clamp and measure

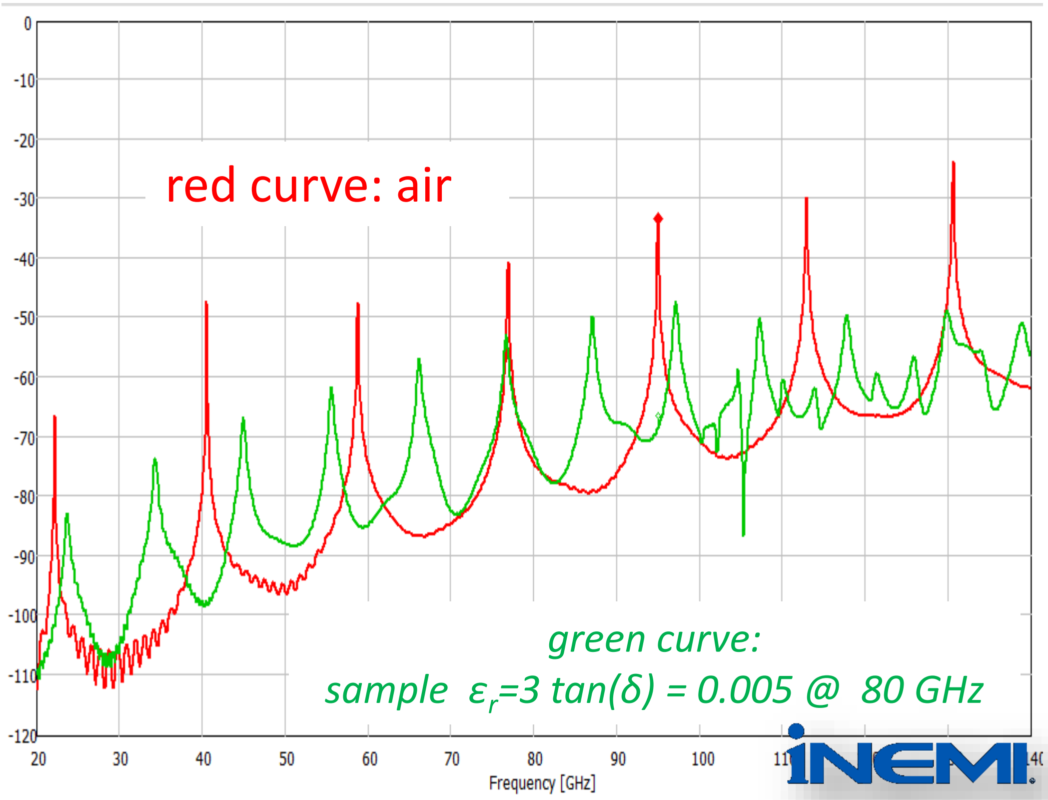
Multiple discrete frequency points from 10 GHz up to 120 GHz	• High measurement precision • Requires full 2-port calibration (mechanical to 110 GHz or electrical to 67 GHz) • Typically out-of-plane component of permittivity • Typical sample thicknesses less than 1 mm • IEC 63185 • https://www.keysight.com/us/en/assets/7120-1214/flyers/N1501AE11-67-Balanced-Type-Circular-Disk-Resonator-BCDR.pdf

Balanced-type circular disk resonator (BCDR) – modelling

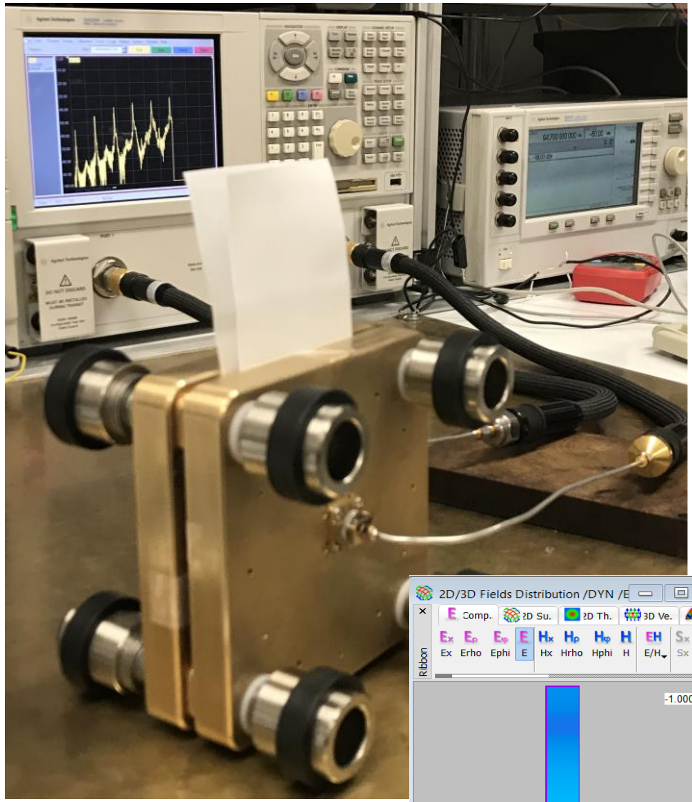






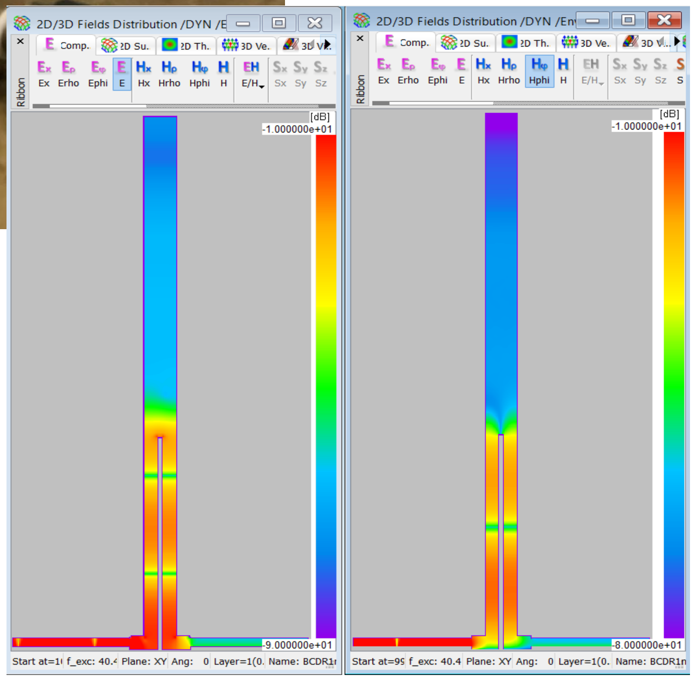


Balanced-type circular disk resonator (BCDR) – modelling

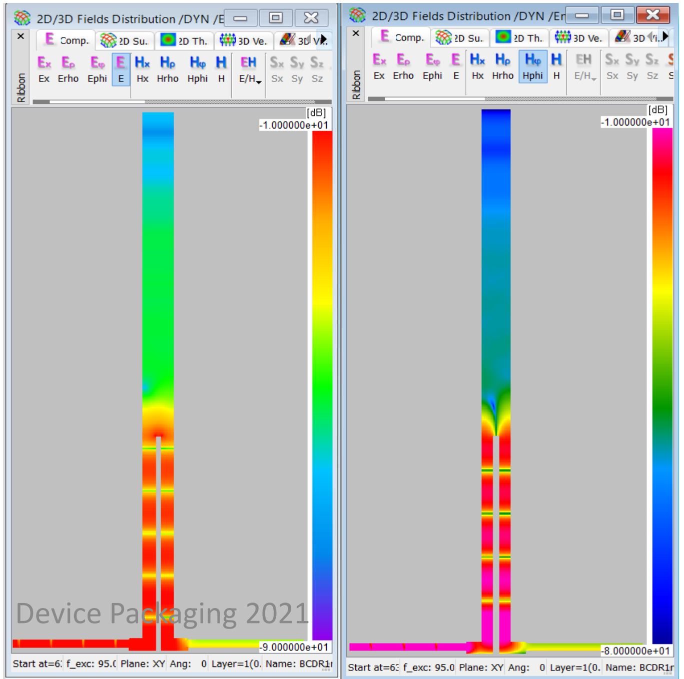


Envelope of |E| and Hphi fields in log scale (-10 to -80 dB)

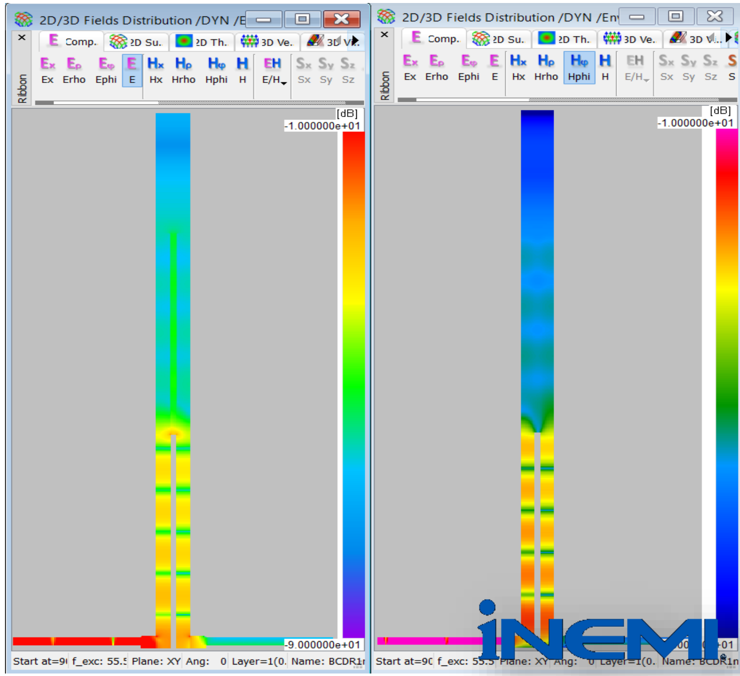
@ 40.49 GHz, air



@ 95.06 GHz, air



@ 55.57 GHz, sample



Fabry-Perot Open Resonator (FPOR)

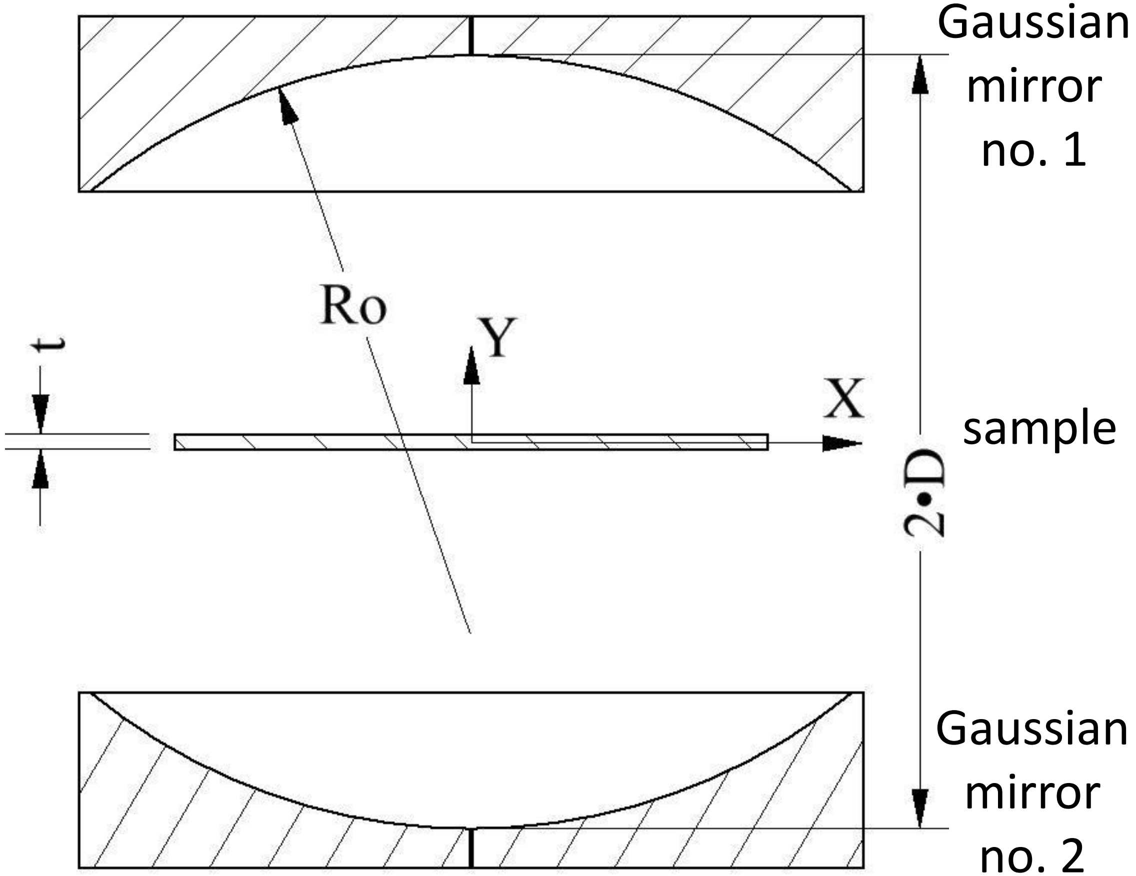
Millimetre – wave characterisation of dielectric materials

- Single device
- Spectrum: 20-110 GHz
- Frequency resolution: ca. 1.5 GHz
- Dk accuracy: $\Delta\varepsilon/\varepsilon < 0.5$ %
- Df range: $10^{-5} < \tan\delta < 10^{-2}$
- Sample diameter: > 3 inches
- Sample thickness: < 2 mm
- Fully automated measurement: (ca. 10 minutes)

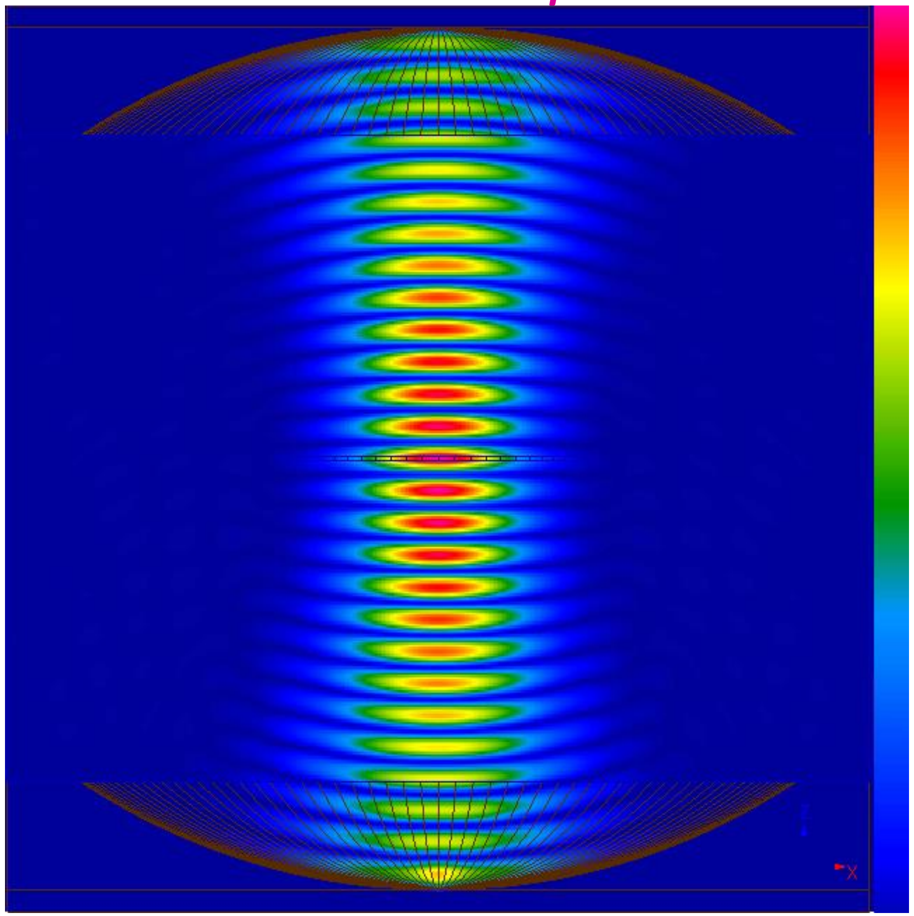
Fabry-Perot open resonator (FPOR, also called open-cavity)	Discrete frequencies between 20 GHz up to 110 GHz	• High measurement precision • Can be sensitive to many user errors • Uncertainty increases with increasing frequency • Typically in-plane component of permittivity • JIS R1660-2 • https://www.qwed.com.pl/resonators.html#ResonatorFPOR • https://www.keysight.com/main/editorial.jspx?cc=US&lc=eng&ckey=2276755&nid=null&id=2276755

Operational frequency range:
Standard: ***20 – 50 GHz***
Advanced: ***75 – 110 GHz***

Fabry-Perot Open Resonator (FPOR) – basics..



*Gaussian **TEM00q** modes*



Electric field distribution - simulation model in QuickWave software

Bridging the gap between classical resonant methods and free space methods

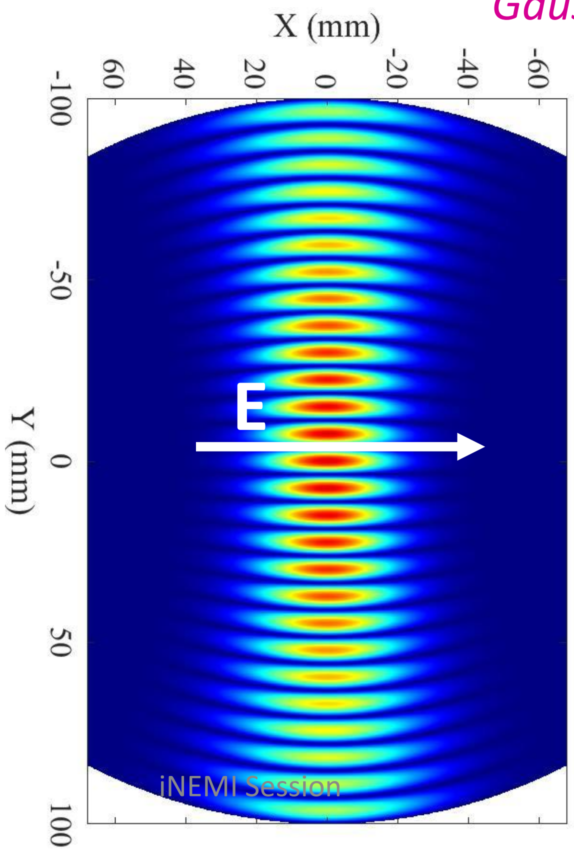
Fabry-Perot Open Resonator (FPOR) – basics..

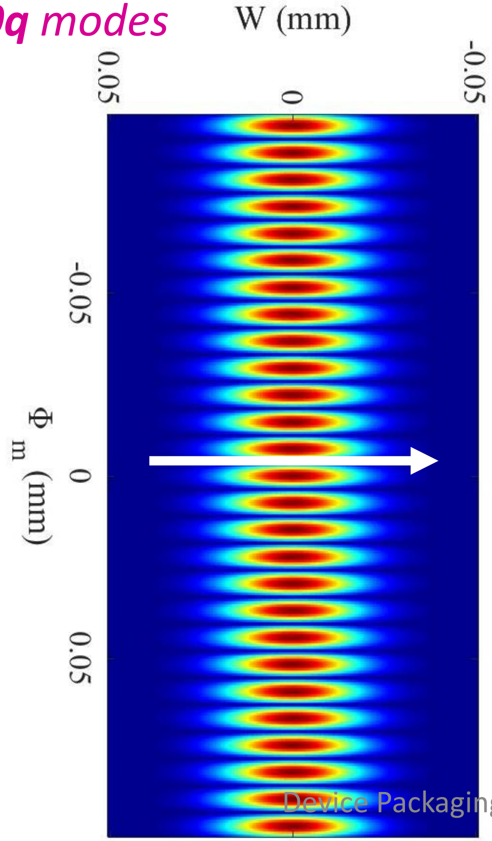
..and modeling

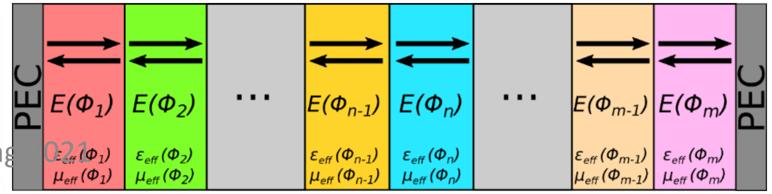
- the extraction of complex permittivity of a dielectric MUT is made with the aid of electromagnetic model
- classical solution is based on a characteristic equation
- novel EM model of the FPOR based on conformal transformation is employed
- reducing the FPOR's model to a scalar one-dimensional multilayer problem

⇒ *better accuracy than alternative solutions*

*Gaussian **TEM00q** modes*







Fabry-Perot Open Resonator (FPOR) – measurement concept

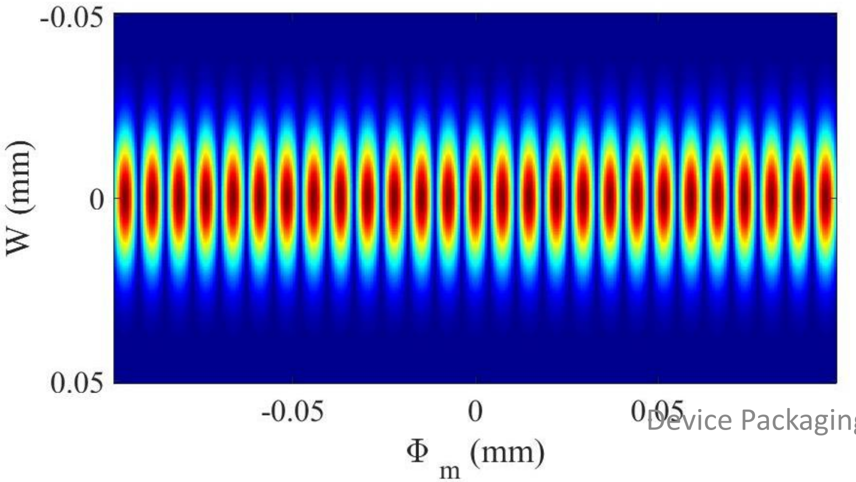
Measurement:

Resonant frequency and Q factor

Electromagnetic model simulation

Dielectric constant and loss tangent

@ multiple frequencies



Challenges for user

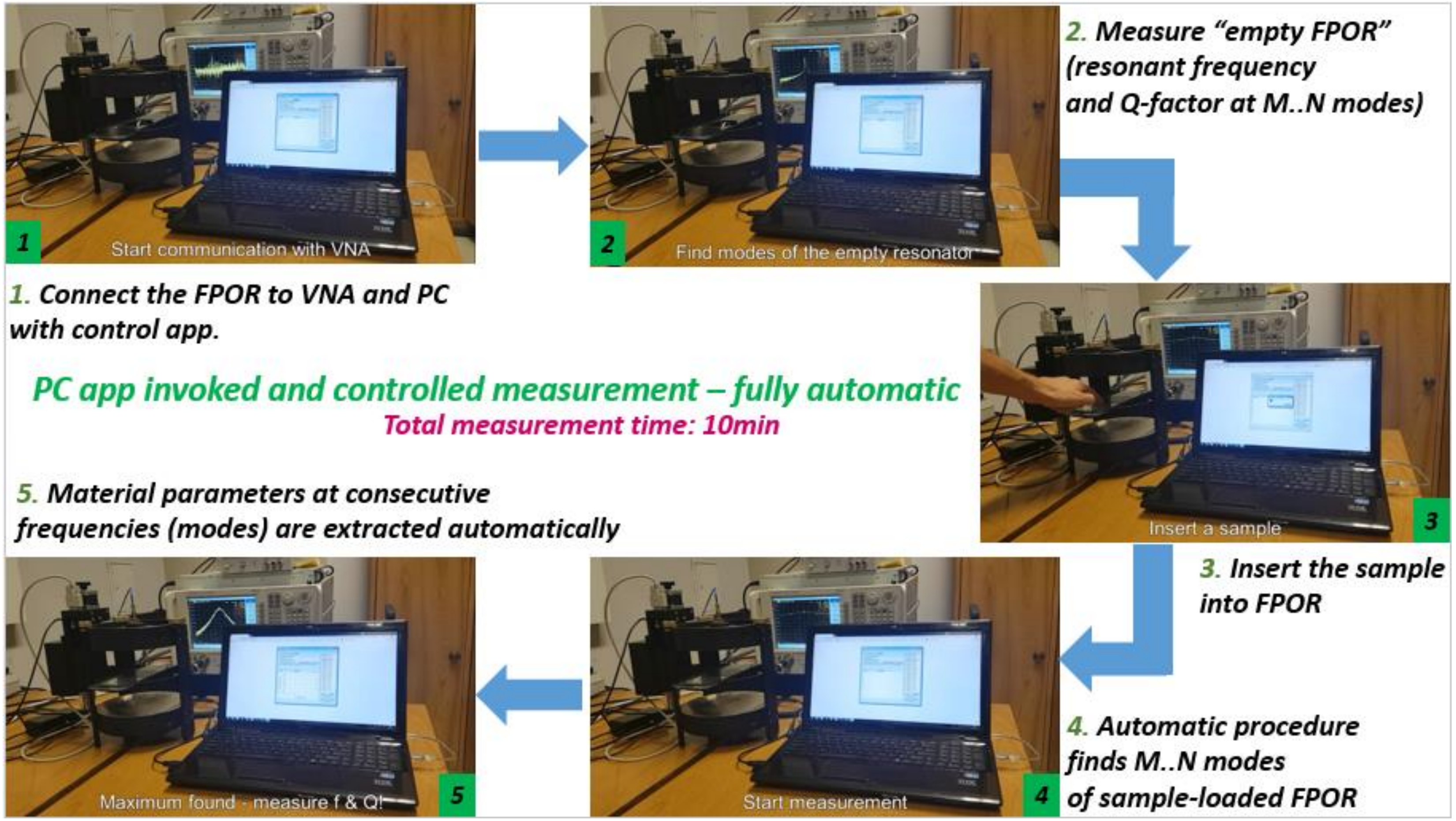
- mode identification
- mode tracking among plenty of other modes occurring in the FPOR

Solution

- Dedicated control software
- Automatic adaptive mode tracking algorithm
- No user intervention needed

Fabry-Perot Open Resonator (FPOR) – operation (1)

Operation workflow



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

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

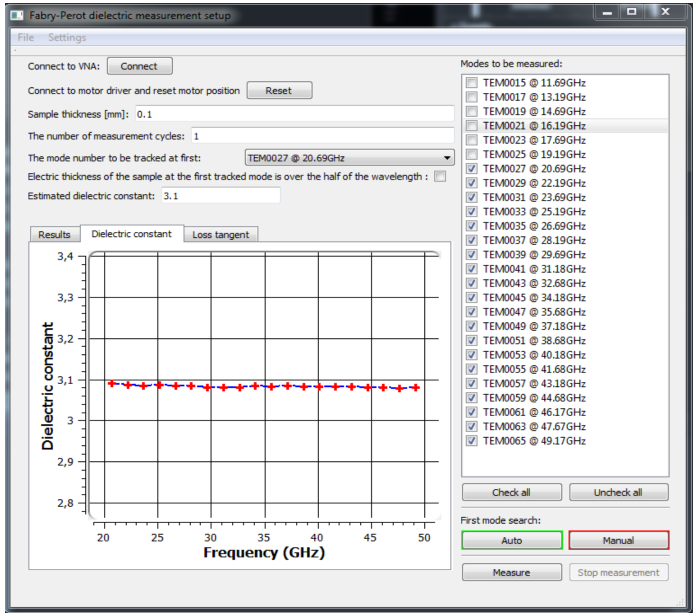
3. Insert the sample into FPOR

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

5. Material parameters at consecutive frequencies (modes) are extracted automatically

PC app invoked and controlled measurement – fully automatic

Total measurement time: 10min



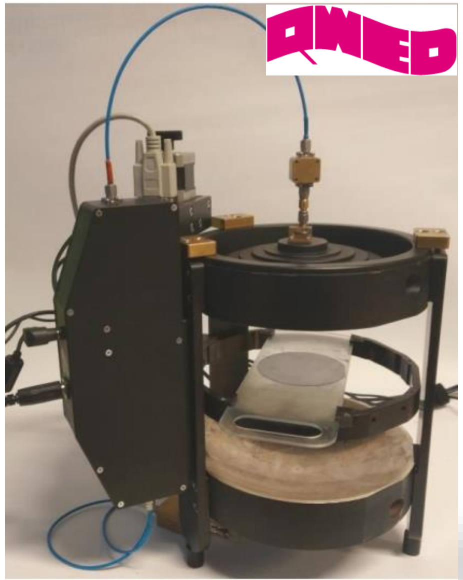
Measurement time for standard 20-50GHz band: 10min

FPOR & in-house Q-meter

20-40 GHz operation range

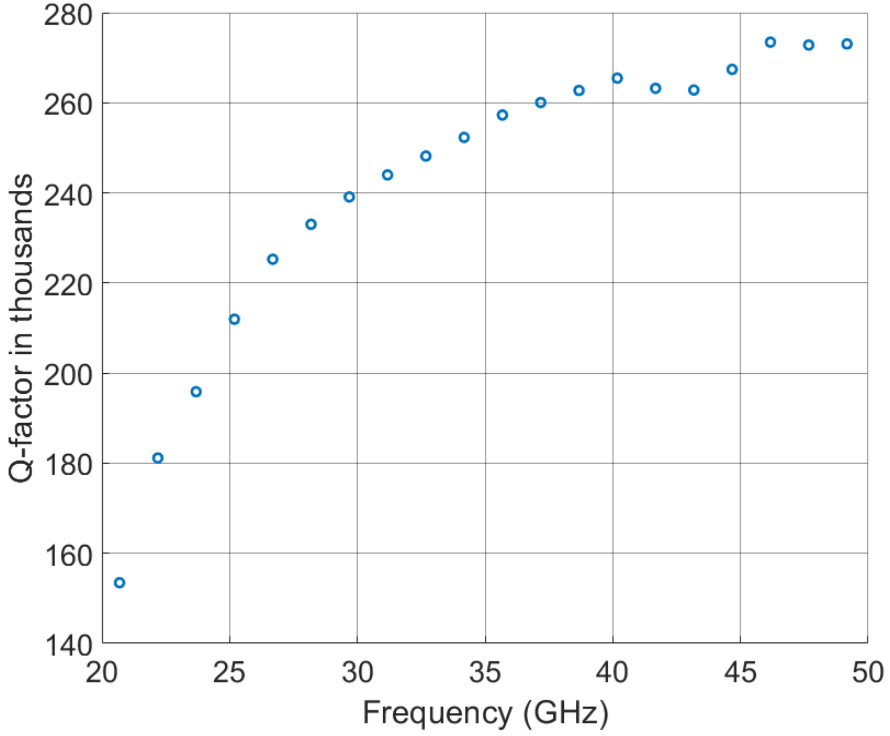
14 frequency points

20s per frequency point



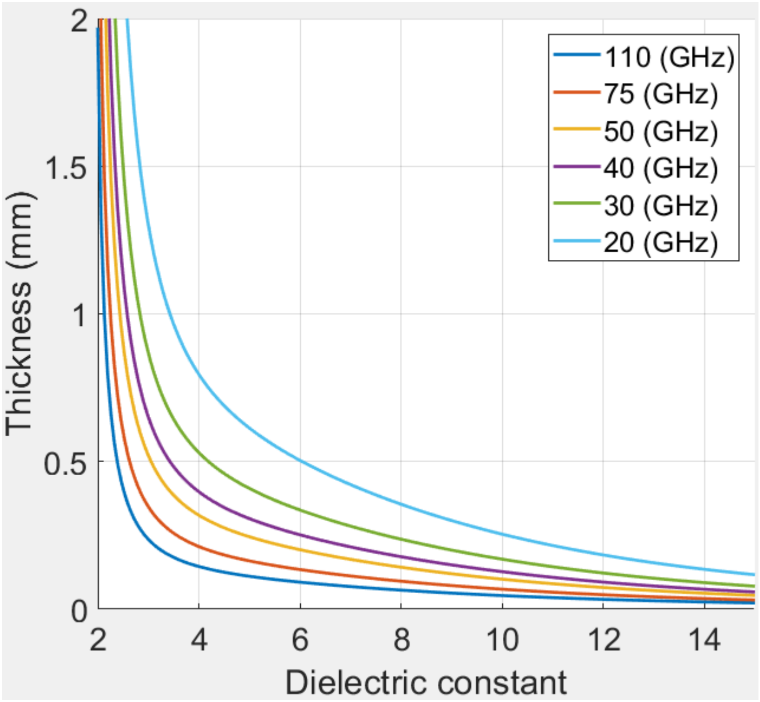
Fabry-Perot Open Resonator (FPOR) – operation (2)

Q-factor of an empty FPOR



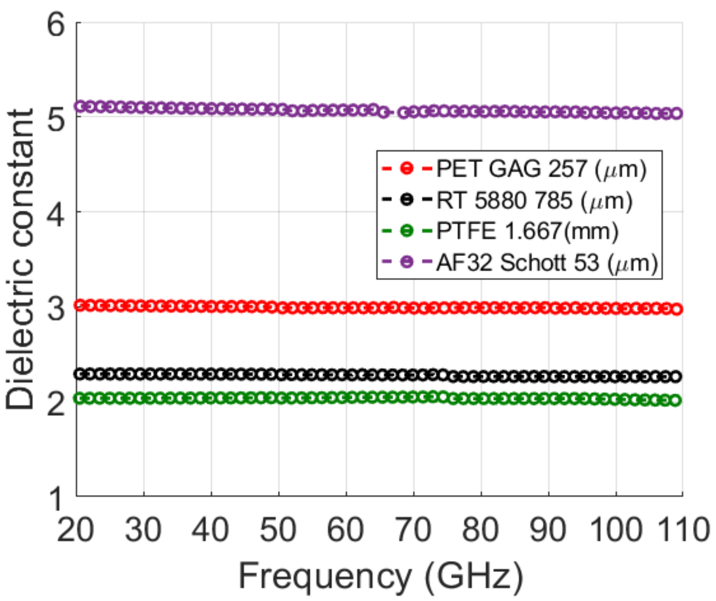
Q-factor of an empty Fabry-Perot Open Resonator increases with frequency from ca. 1.5×10^5 at 20 GHz up to ca. 2.7×10^5 at 50 GHz.

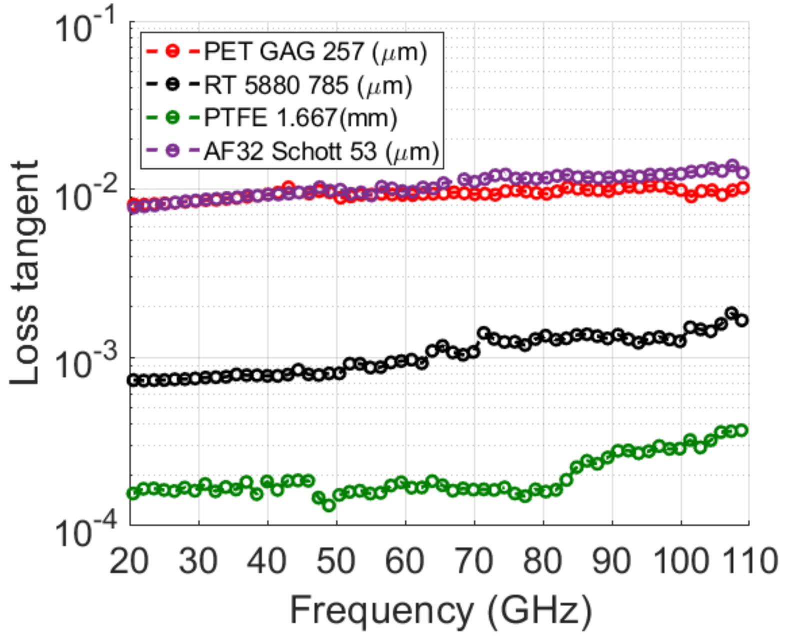
Estimated thickness limitation

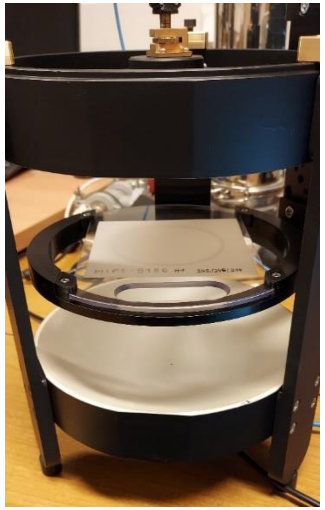


Due to coupling with spurious modes that slightly alter resonant frequencies of the measured modes, the thickness of the sample of known dielectric constant is limited.

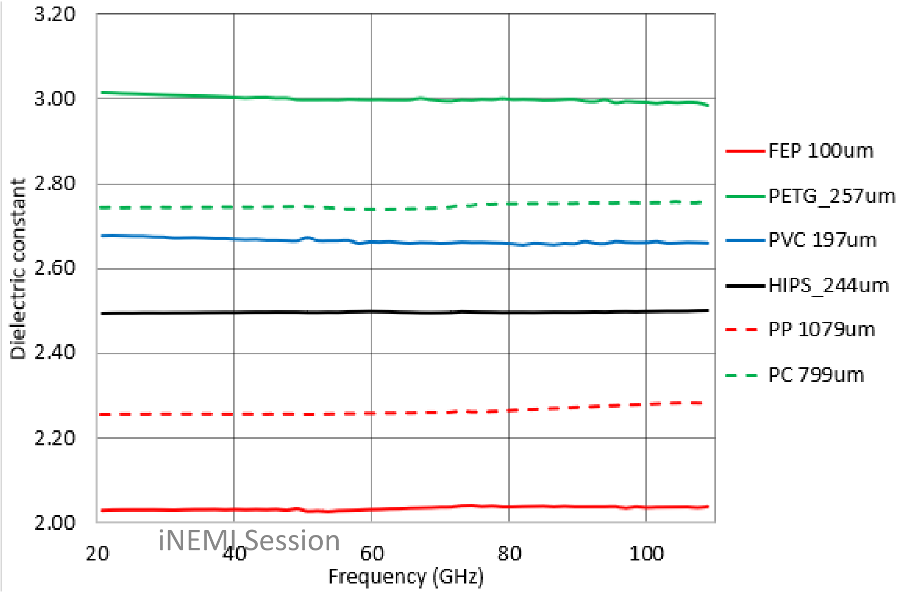
Fabry-Perot Open Resonator (FPOR) – results (1)

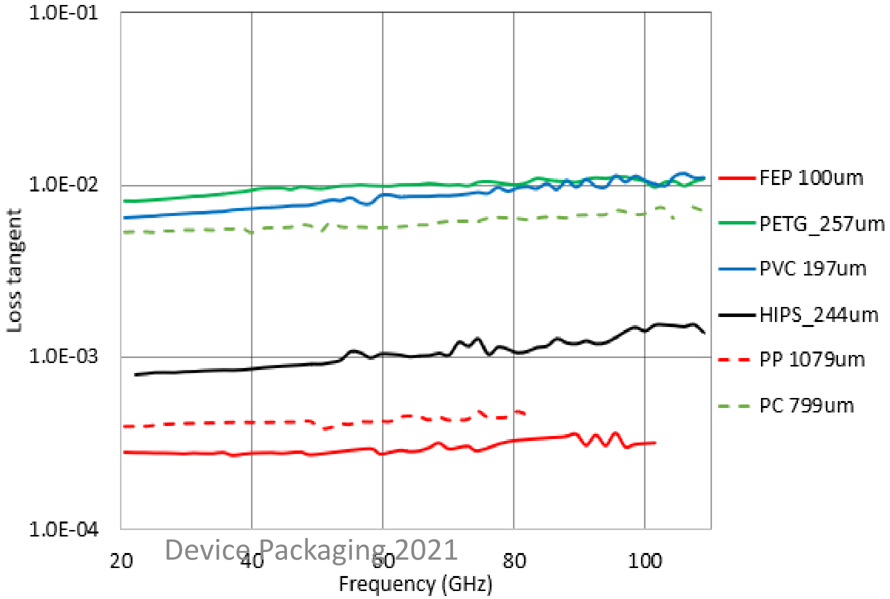


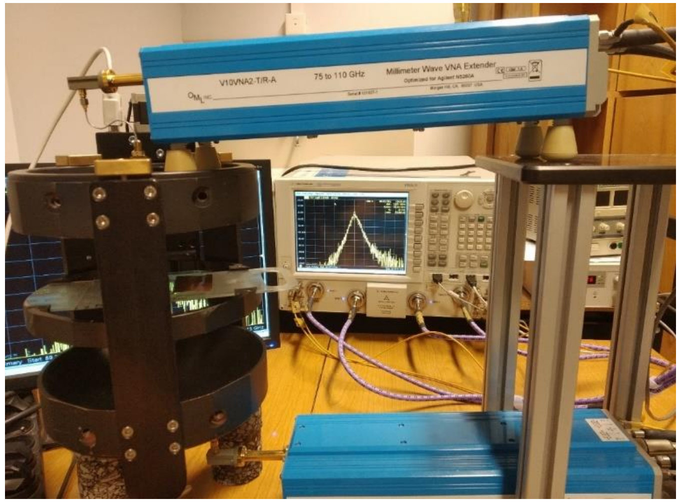




FPOR with a polystyrene (HIPS) sample placed on a sample holder

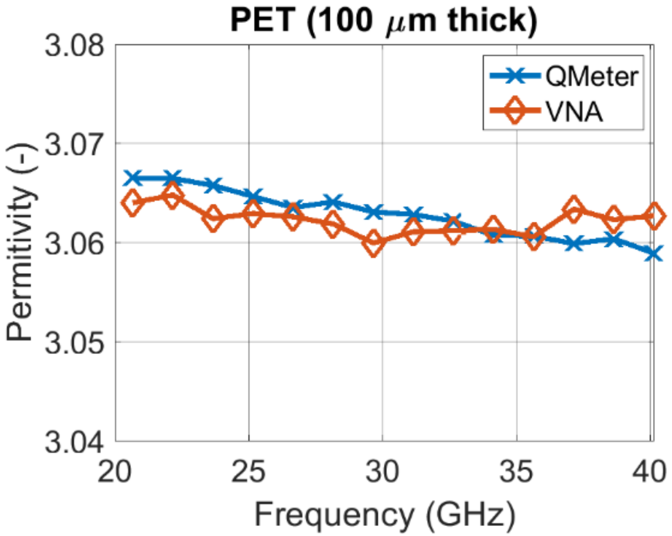


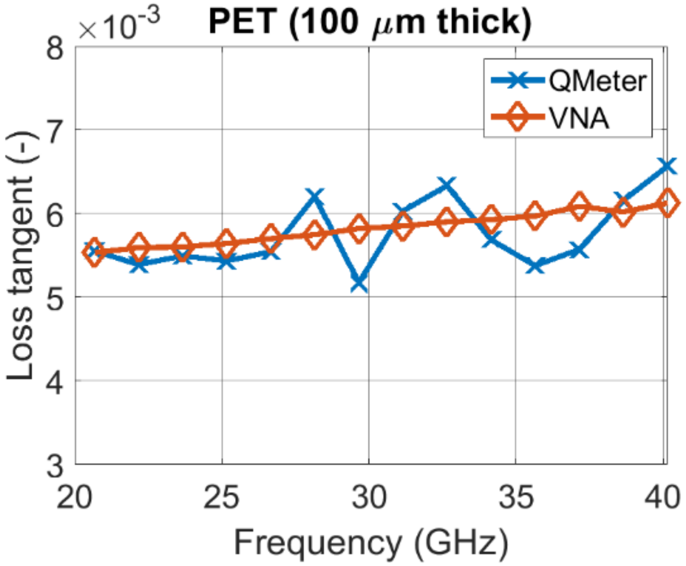


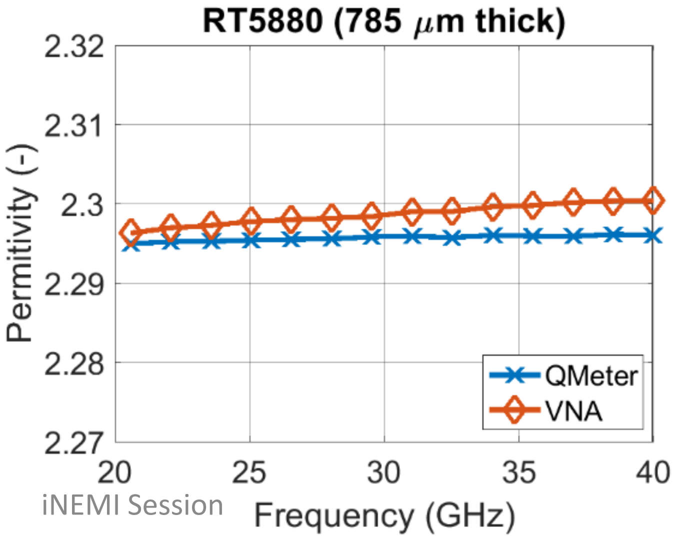


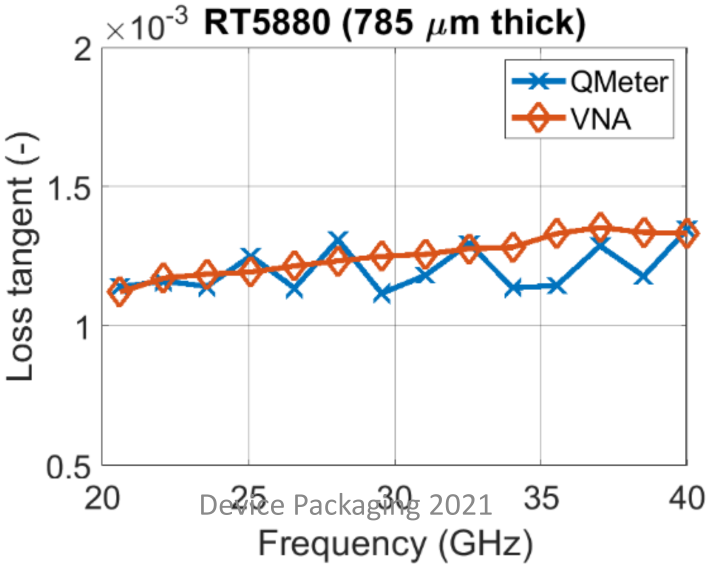
FPOR with OML frequency extenders operating in 75-110 GHz range.

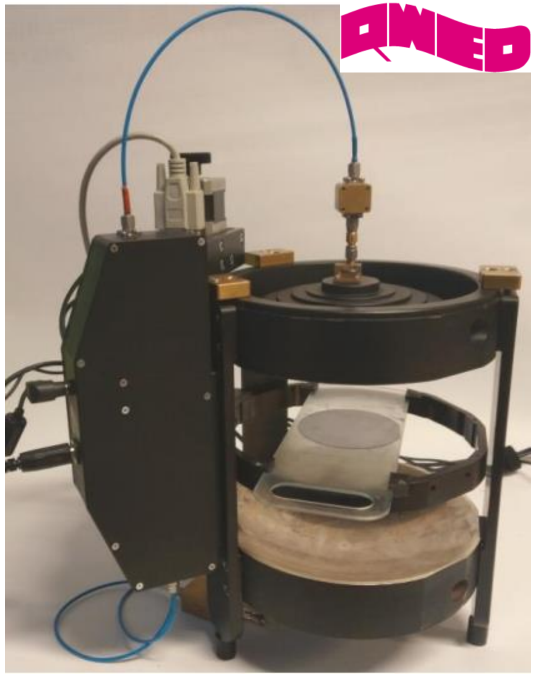
Fabry-Perot Open Resonator (FPOR) – results (2)







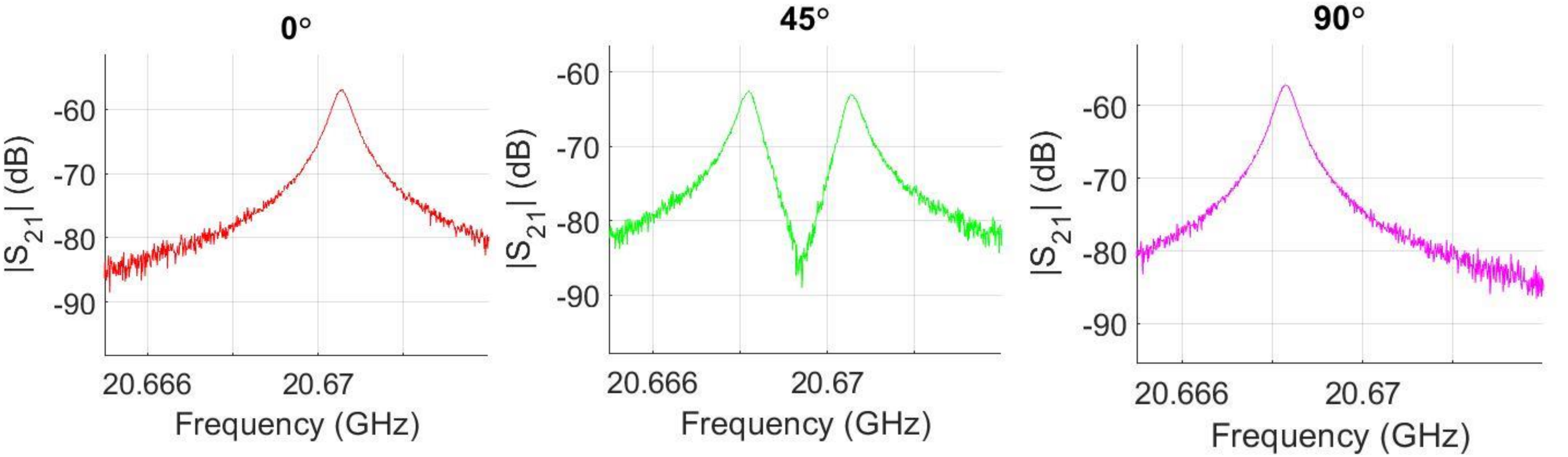


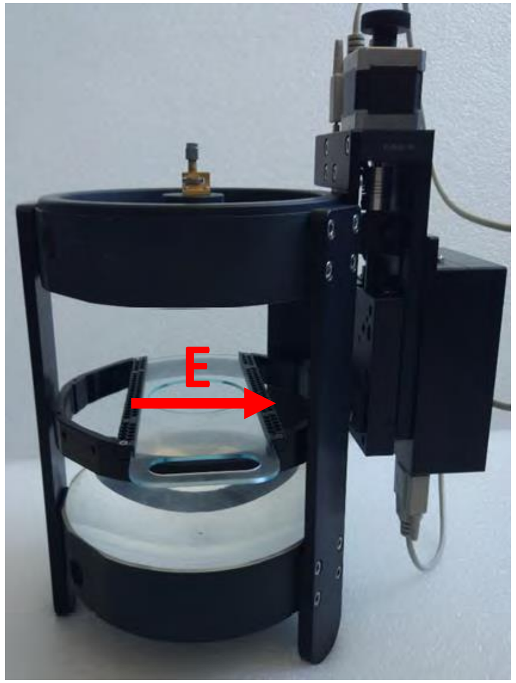


FPOR & in-house Q-meter

Fabry-Perot Open Resonator (FPOR) – in-plane anisotropy

With appropriately designed feeding loops, FPOR is capable of linear E-field polarization and hence detecting in-plane anisotropy:





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

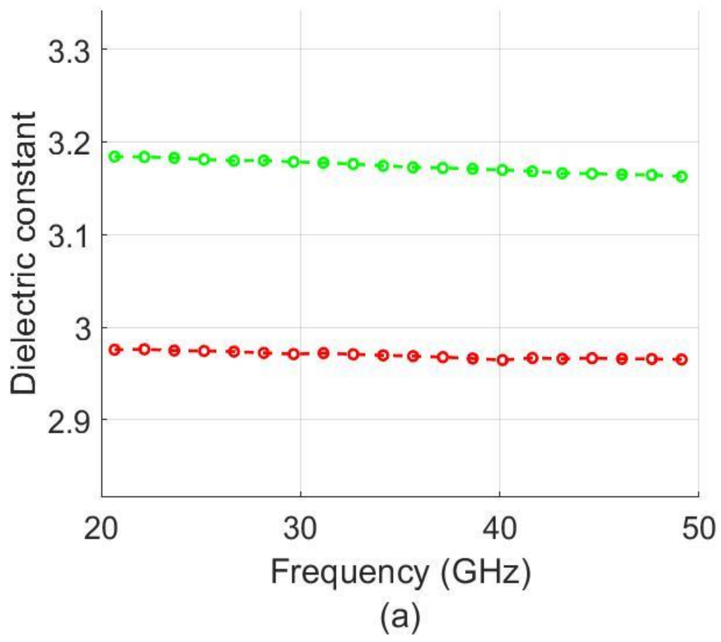
BoPET (biaxially-oriented PET) involves thermal drawing in two in-plane directions with substantially different draw ratios, followed by crystallization. Hence, it is in-plane anisotropic.

For PETG (non-crystalline copolyesters, isotropic), resonant frequency does not depend on angular position of the sample.

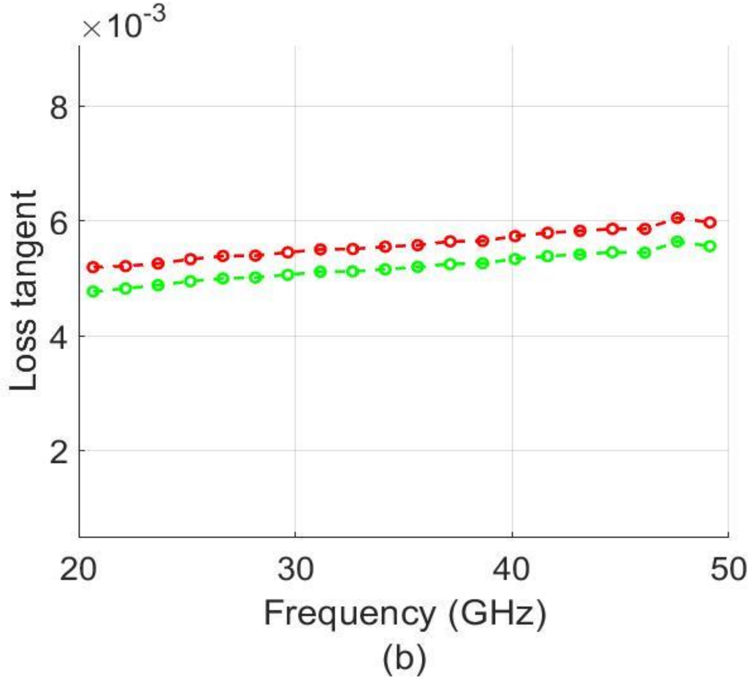
T.Karpisz et al, " Measurement of in-plane anisotropy of dielectric materials with a Fabry-Perot open resonator", Proc. MIKON 2020

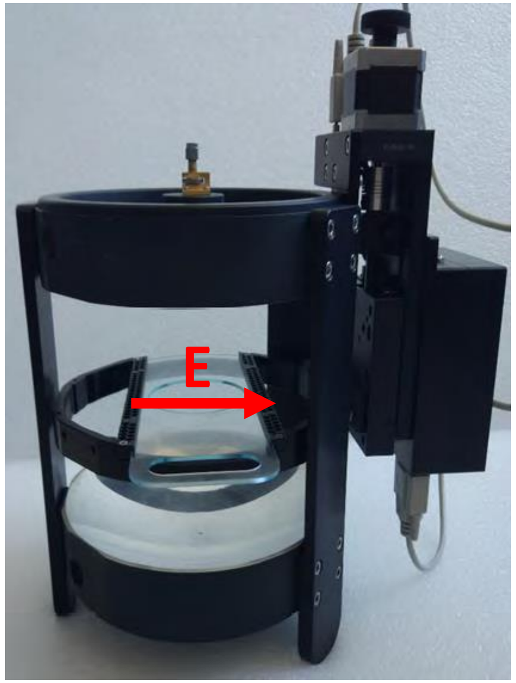
Fabry-Perot Open Resonator (FPOR) – in-plane anisotropy results

0 deg, 90 deg



0 deg, 90 deg

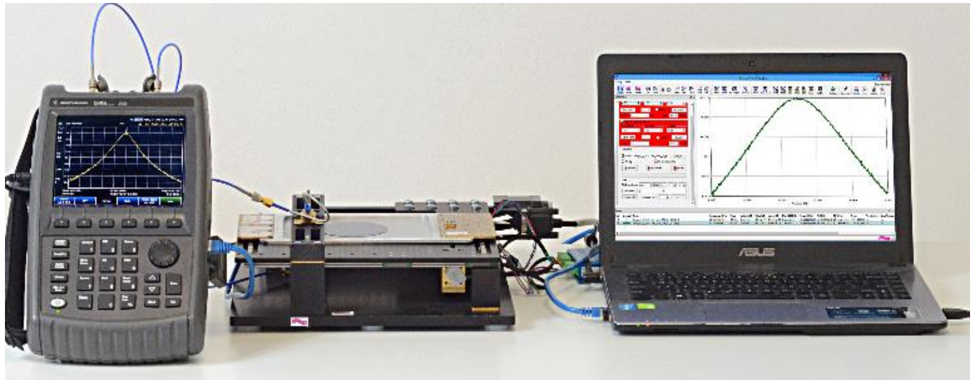


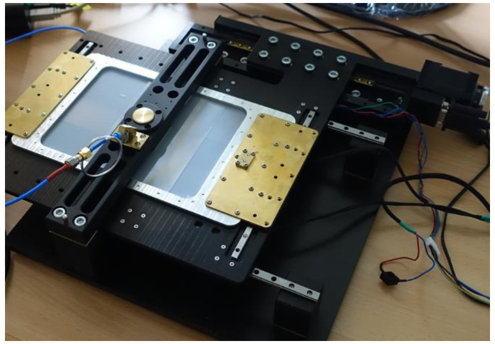


T.Karpisz et al, " Measurement of in-plane anisotropy of dielectric materials with a Fabry-Perot open resonator", Proc. MIKON 2020

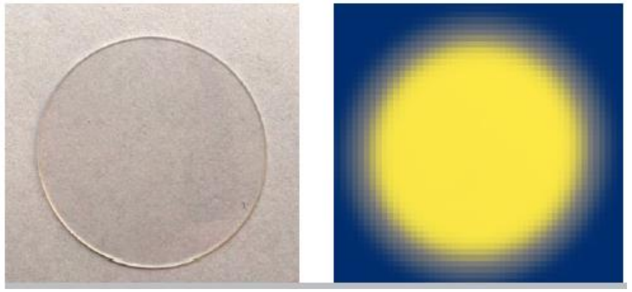
2D imaging of material parameters

2D SPDR scanner @ 10GHz

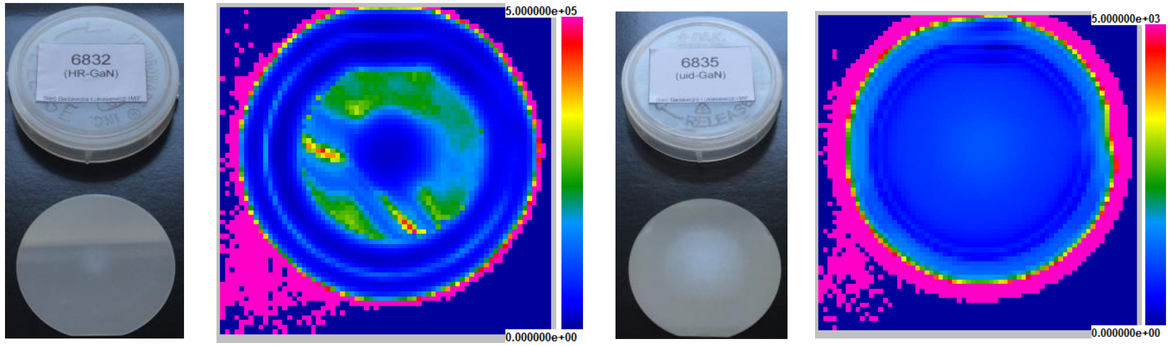




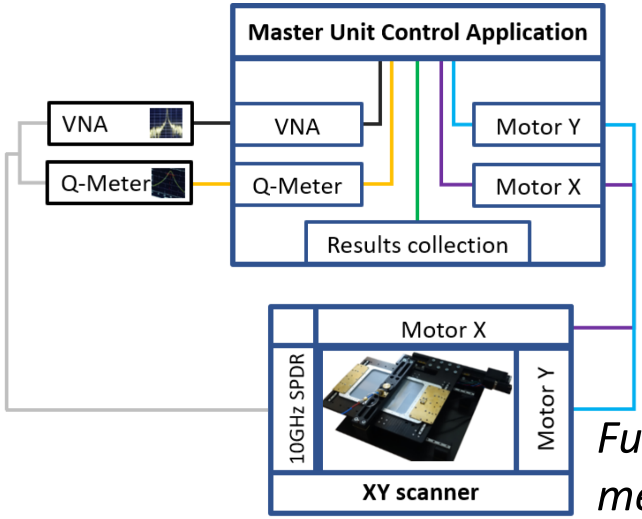
2D surface map of dielectric constant of quartz



2D surface map of resistivity of semiconductor wafers

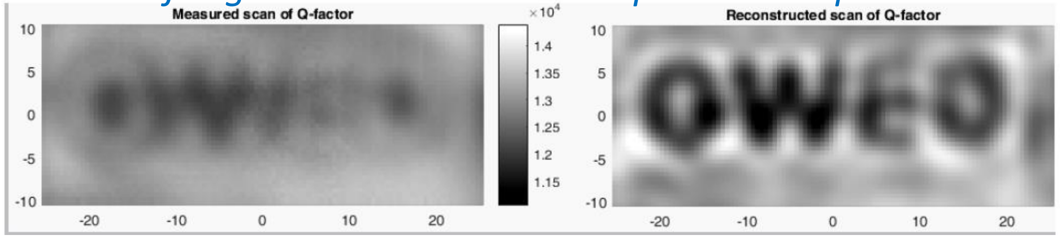


**courtesy L-IMP, Poland*



Fully automated measurement procedure

2D surface map of measured Q-factor of „QWED" pattern made of organic semiconductor deposited on quartz



**courtesy MateriaNova, Belgium*

Material homogeneity testing

For qualitative and quantitative material testing

For low-loss dielectrics and high-resistivity semiconductors

Concluding remarks

- Growing interest and need for broadband material characterisation (e.g. due to advances in telecommunication systems)
- Frequency spectrum covered by several different methods & full spectrum methods
- Each method has specific features, which can make it preferable for a particular application (e.g., different sample Dk / Df, thickness, expected anisotropy; frequency & temperature range of use)
- iNEMI project benchmarks resonant methods for material characterisation (popular and recent developments)
- iNEMI initiative will bring practical guidelines for the industry

Acknowledgement

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NanoBat No 861962.

(website: www.nanobat.eu)

Thank you for your attention!!!