TU1C-3

Enhanced resolution material imaging with dielectric resonators:

a new implicit space - domain technique

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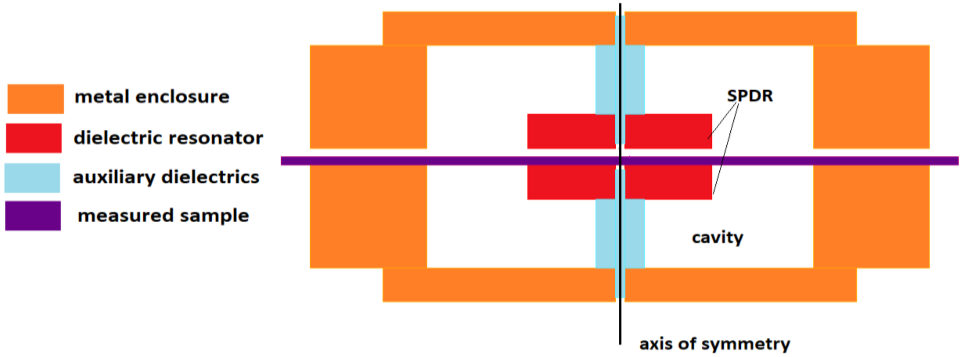
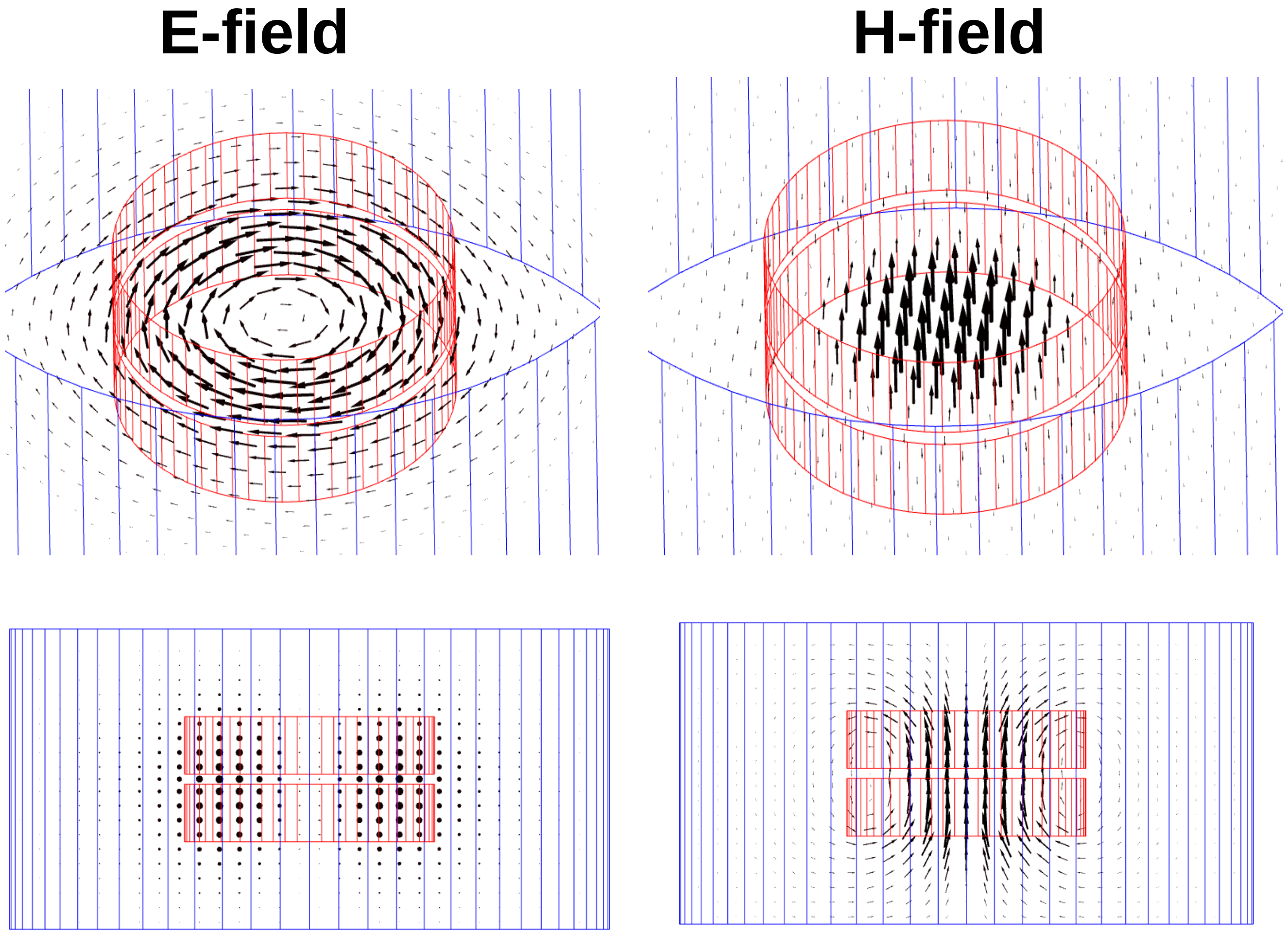
Presentation Plan

- Introduction: application of dielectric resonators to planar material measurements
- Room for improvement of resolution based on redundant information typically not used
- Formulation of the implicit problem and practical questions of its applicability in imperfect environment
- The Singular Value Decomposition method and dependence of the results on the level of the truncation of the singularities
- Measured results and optimised application of SVD method
- Conclusions

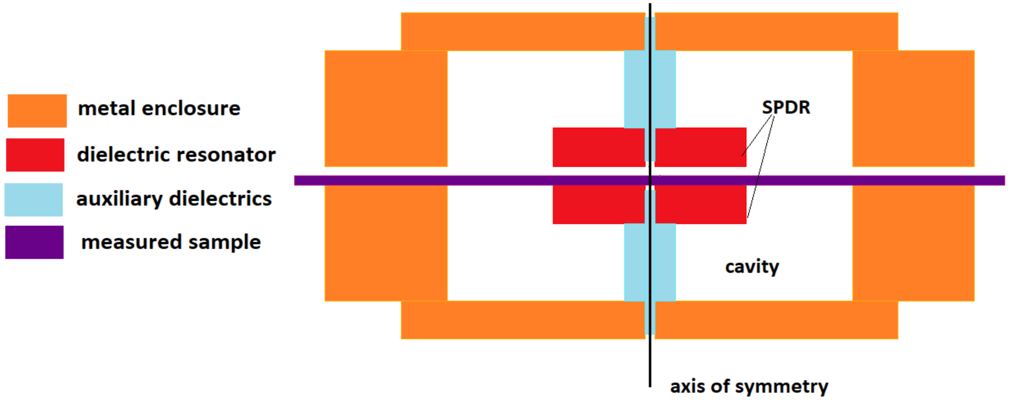
Basic properties of Split Post Dielectric Resonators (SPDR) working in TE01δ mode





- With high permittivity of the ceramic (typically 25-35) about 95 % of energy of EM fields is accumulated in and between those ceramic posts.
- E-field has only horizontal components forming loops with maximum close to the ceramic circumference.
- H-field makes vertical loops with maximum in the centre of SPDR and no horizontal components at the side walls of the enclosure.

Dielectric resonator method for material measurements

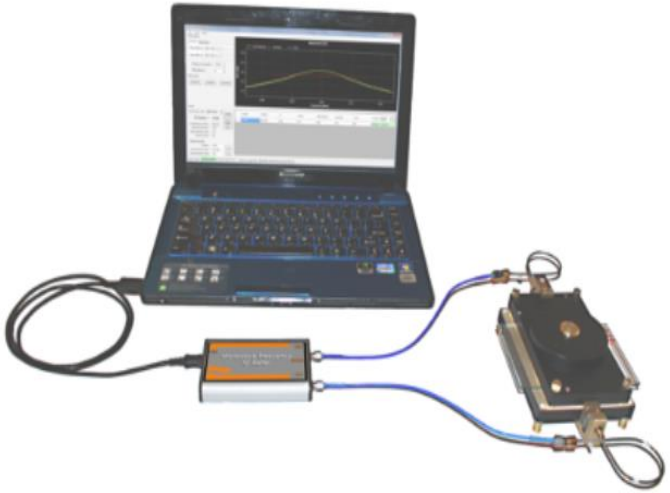


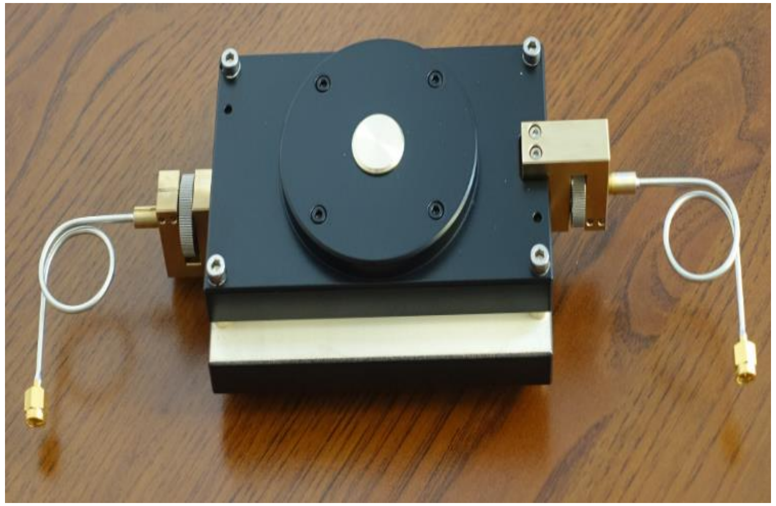
Sample Under Test of $\varepsilon_s = \varepsilon_s' - j\, \varepsilon_s''$ is inserted into *DR.*
Resonant frequency changes from f_e to f_s
Q-factor changes from Q_e to Q_s.

$$\frac{f_e - f_s}{f_e} \approx \frac{h}{2C} \iint_S \left[\varepsilon_s'(x,y) - 1 \right] \left| E(x,y) \right|^2 dS$$

$$\frac{1}{Q_s} - \frac{1}{Q_e} \approx \frac{h}{C} \iint_S \varepsilon_s''(x,y) E^2(x,y) dS$$

$$C = \iiint_V \left| E(x,y) \right|^2 dV$$





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Why SPDRs are so valuable for planar material measurements ?

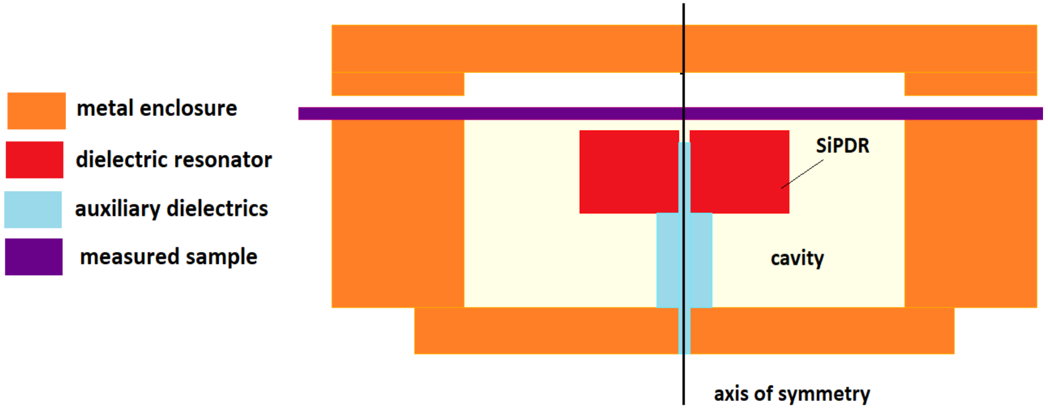
- Planar material samples can be measured with tangential E-field which makes the results practically independent of the air slots. We only need to know precisely the thickness of the sample.
- There are no horizontal magnetic fields (which would have imposed vertical currents) at the side walls and thus the resonator slot can be kept open for inserting the sample without any dismantling operations.
- Magnetic fields at the metal walls are quite small and that is why we can have a high unloaded Q-factor of the resonator. It typically ranges from about 20 000 at 1GHz down to about 10 000 at 10GHz depending mostly on the losses in the ceramic.
- Such a high unloaded Q-factor is important since it allows measurements of low loss materials (even of $\tan\delta = 5\ 10^{-5}$ or resistivity of wafers up to about 10^{5} [Ω cm]).

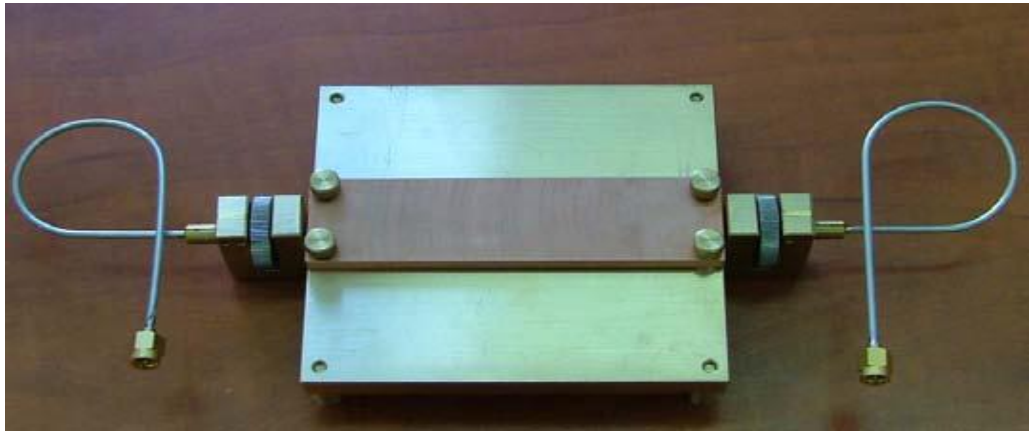
As a result the SPDR method has become an industrial/scientific standard described in the international norm IEC 61189-2-721:2015.

Single Post Dielectric Resonator (SiPDR) as an extension of SPDR for high-loss materials

SPDR cannot be applied for high-loss materials since it would dump too much its resonance. The remedy is to place the sample outside the dielectric resonator where electric field has lower amplitude.

This way we obtain Single **Post Dielectric Resonator (SiPDR).**

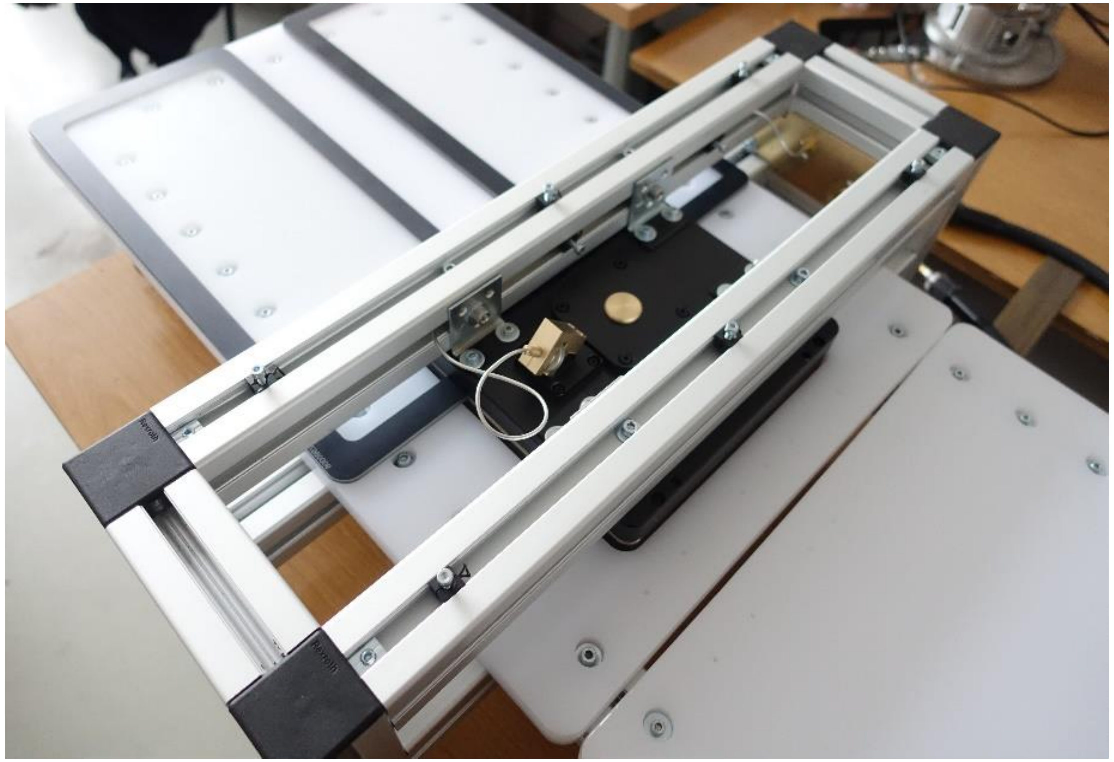




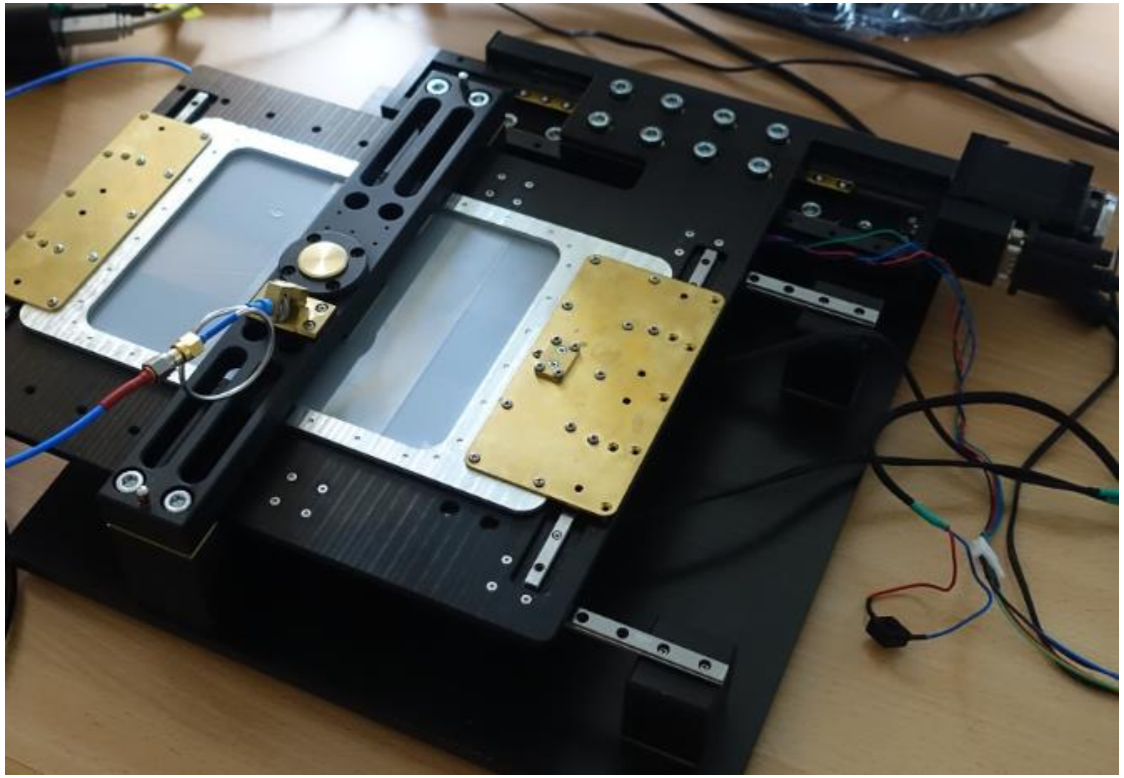
SiPDR is mostly applied for measurements of resistive sheets (like microwave susceptors) and also for doped semiconductor wafers. In the latter case it can offer a precious supplement to measurements by the four point probes since it measures the properties at microwave frequency and with purely horizontal electric field. Another advantage is its contactless nature.

Surface scanning with SPDR

manual scanner for large panes of glass
(MW oven window)
SPDR 1.1 GHz



automatic scanner
semiconductor wafers, composites, organic samples
SPDR 10 GHz



Two measurement setups with automatic scanner

working with FieldFox (Keysight hand-held VNA)

working with QWED Q-Meter

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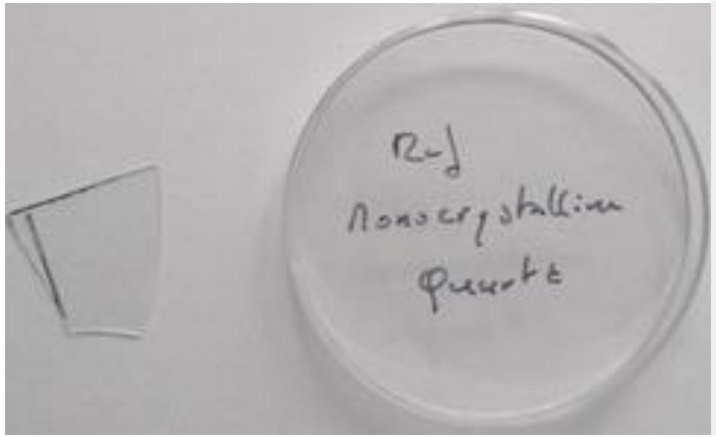
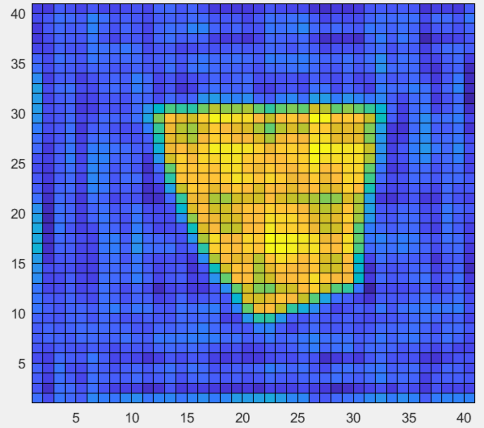
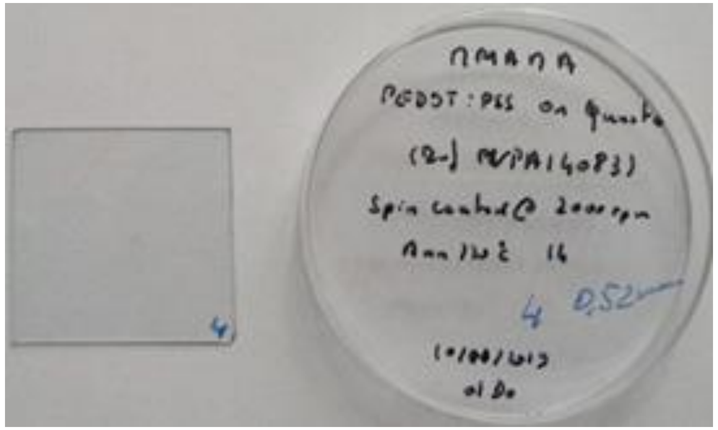
Example of automatic scanning: organic samples from MateriaNova

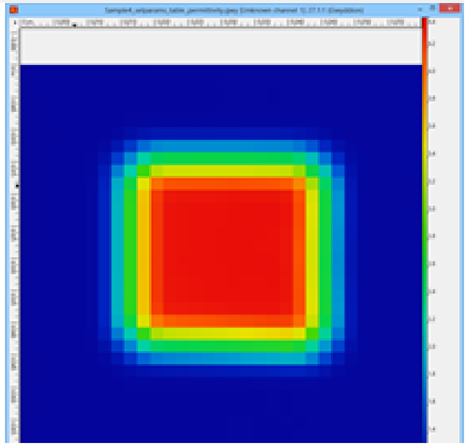
Substrate:
single crystal quartz





Conductive organic material deposited on quartz





Note: *scanning step 1 mm, but spatial resolution dictated by SPDR head, ca. 16 mm → diluted sample edges.*

Limited resolution of the dielectric resonator method (applicable to SPDR but also to SiPDR)

Limited resolution is imposed by the size of dielectric resonator . The result of measurement depends on the field distribution averaged over the resonator. To obtain the actual field distribution we calculated a dielectric resonator scenario shown here using QuickWave 3D software

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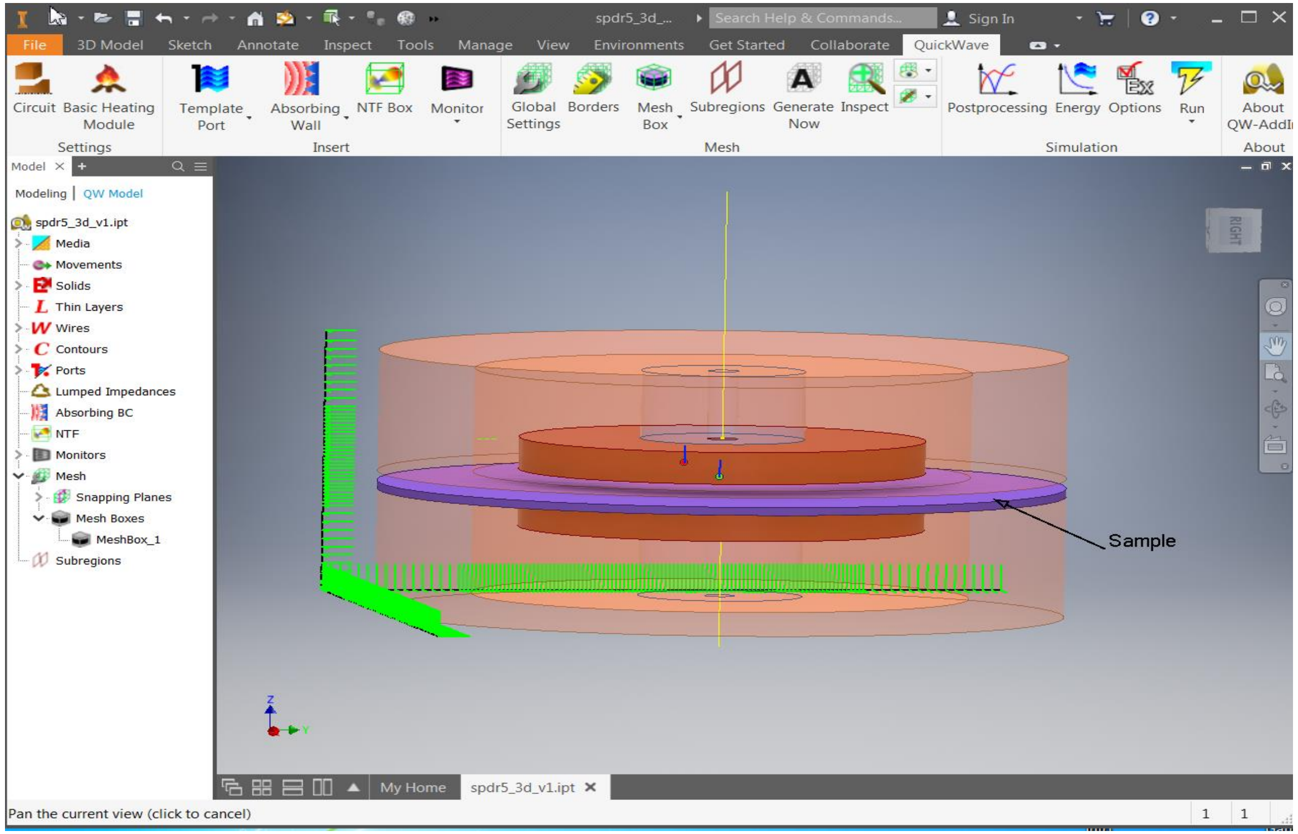
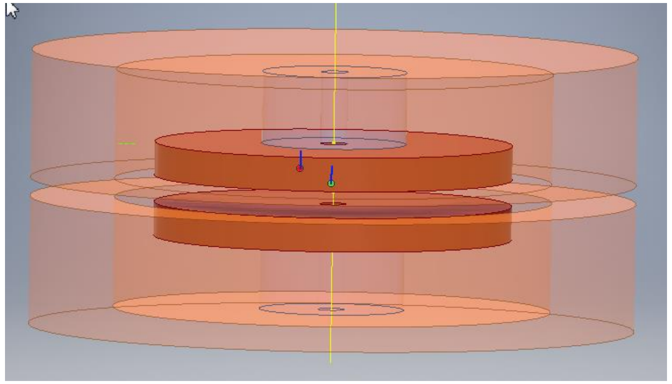
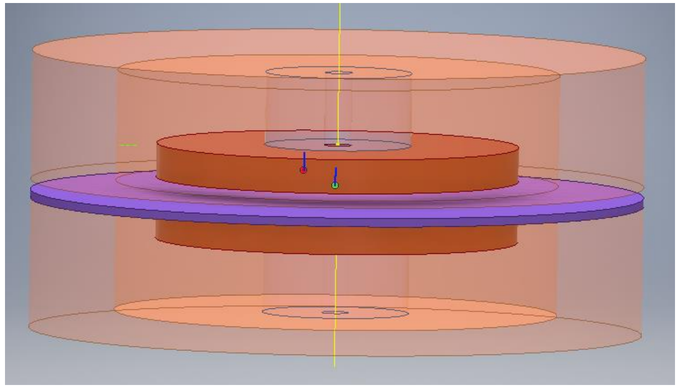


10 GHz SPDR model in QW-AddIn for Autodesk® Inventor® Software

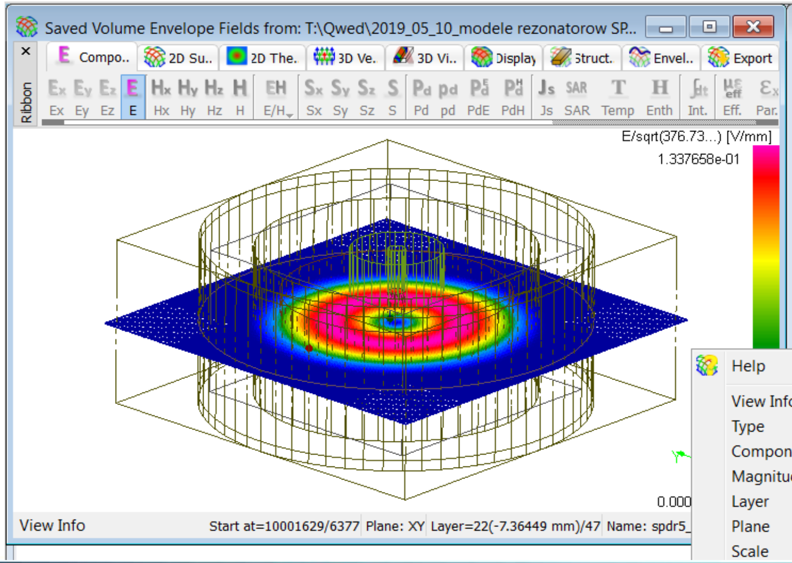
Simulation of E-field distributions in SPDR cavity using QuickWave 3D software

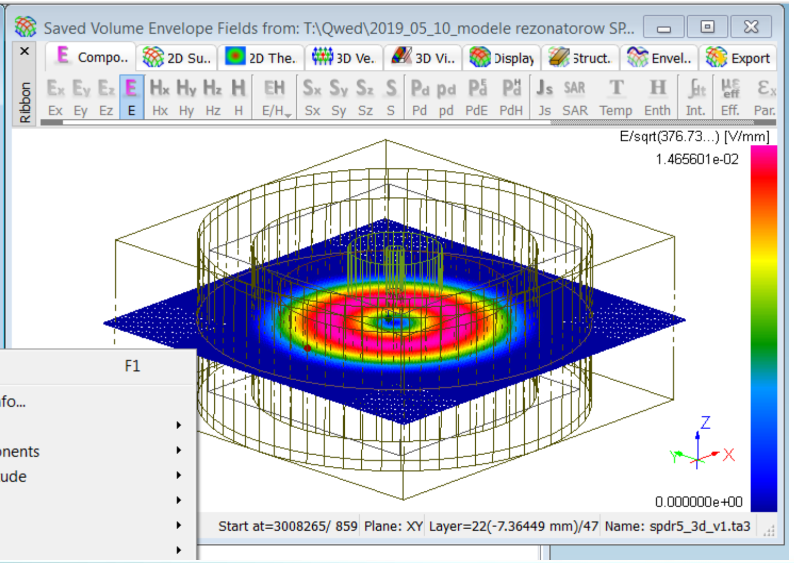




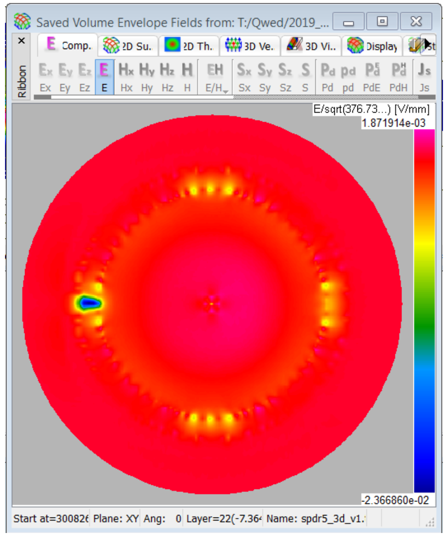
***Note:** field difference shown below has been obtained by new postprocessing, originally implemented for biomedical near-field imaging applications.*

E-field distribution inside the resonator cavity without and with the sample





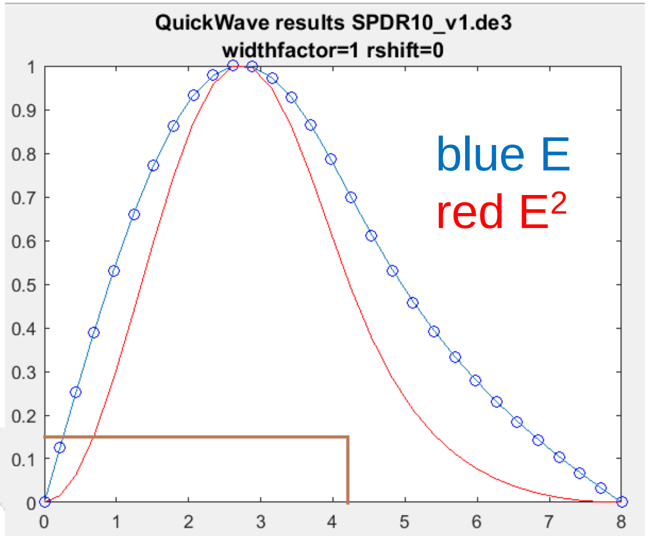
difference between two field distributions (amplified for visibility)



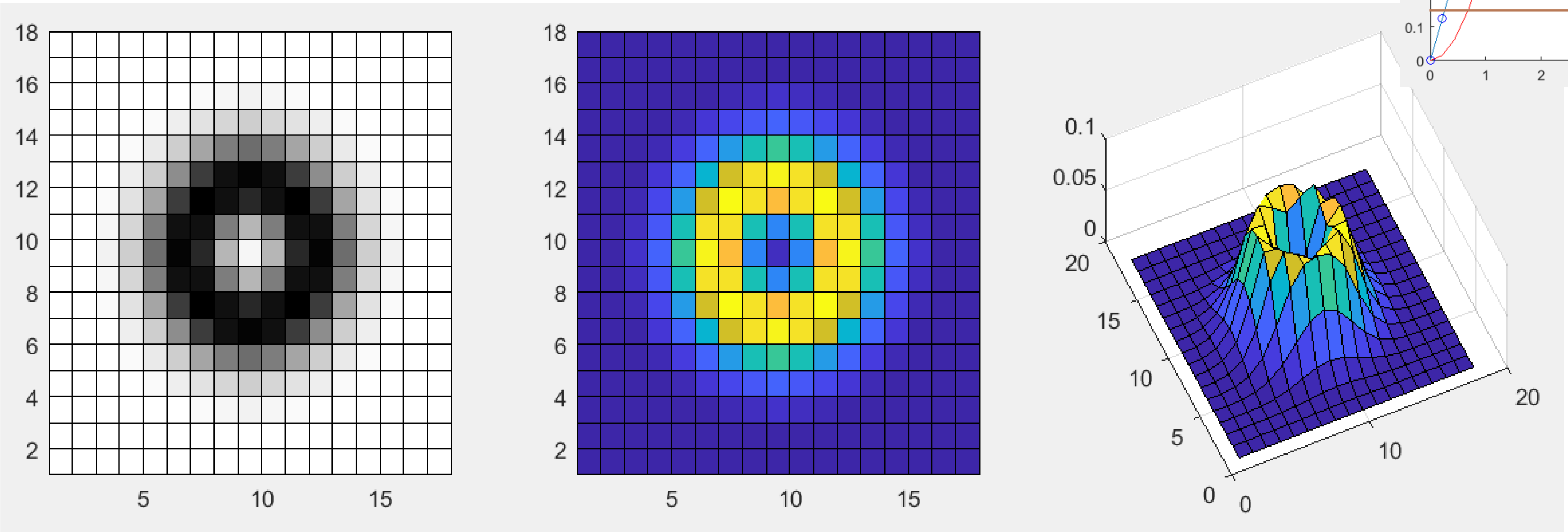
~ 0.2%

- 0.2%

Field distribution applied for resolution enhancement of SPDR imaging



→ **Parameters are "averaged" within DR head**
but we know the field pattern
E-field in our 10 GHz SPDR as simulated in QuickWave:



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Resolution enhancement for SPDR imaging

Consider the head meshed into (2*K* +1) x (2*L*+1) cells whose center with $E_T(0,0)$ is placed at cell (*m*,*n*) the scan.
For clarity, assume that the mesh is equidistant of raster *a* (*a* = 1mm on previous slide).
The measured energy change due to the SUT is:

$$\Delta W_{mn} = \frac{a^2 h}{2} \sum_{k=-K}^{K} \sum_{l=-L}^{L} \left[\varepsilon_s^{'}(m+k, n+l) - 1 \right] E_T^2(k,l)$$

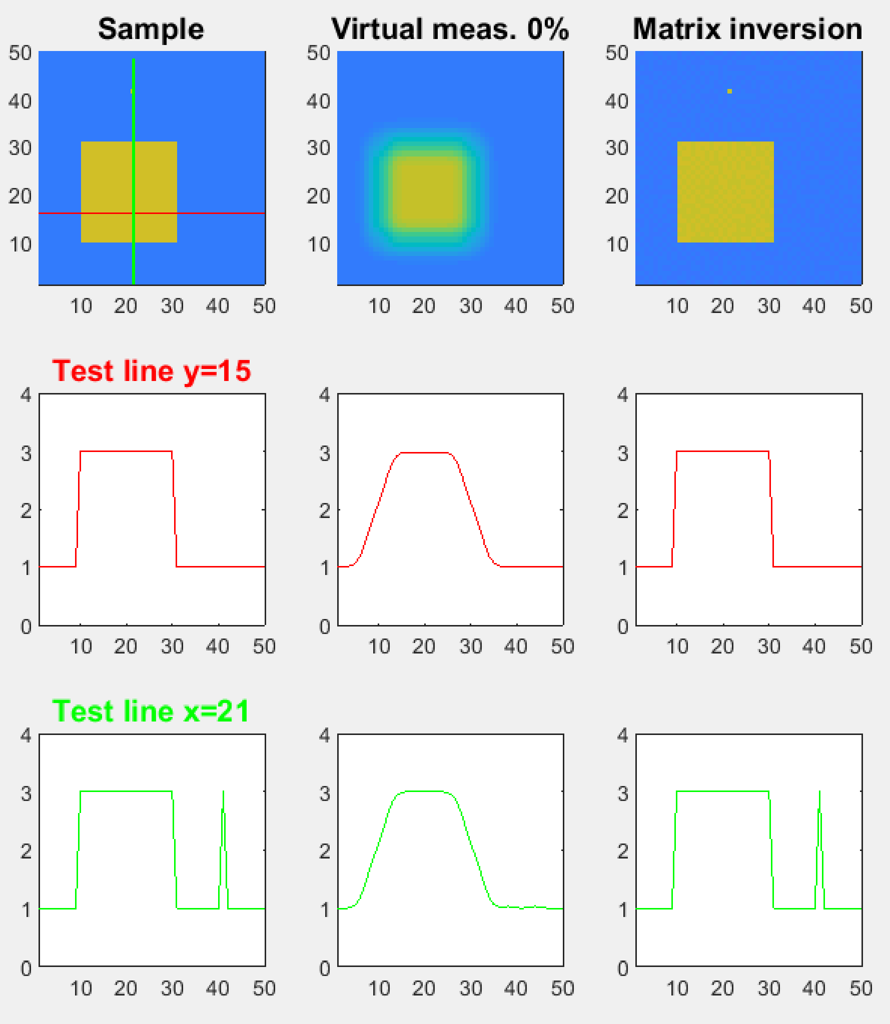
Arranging the 2D array of ΔW_{mn} into a 1D vector *W* of elements ΔW_i, $i=(n-1)*M+m$, $i=1,..,M*N$, and similarly the 2D array of permittivities $p_{s,mn}=(\varepsilon_s'-1)_{mn}$ into vector *P*:

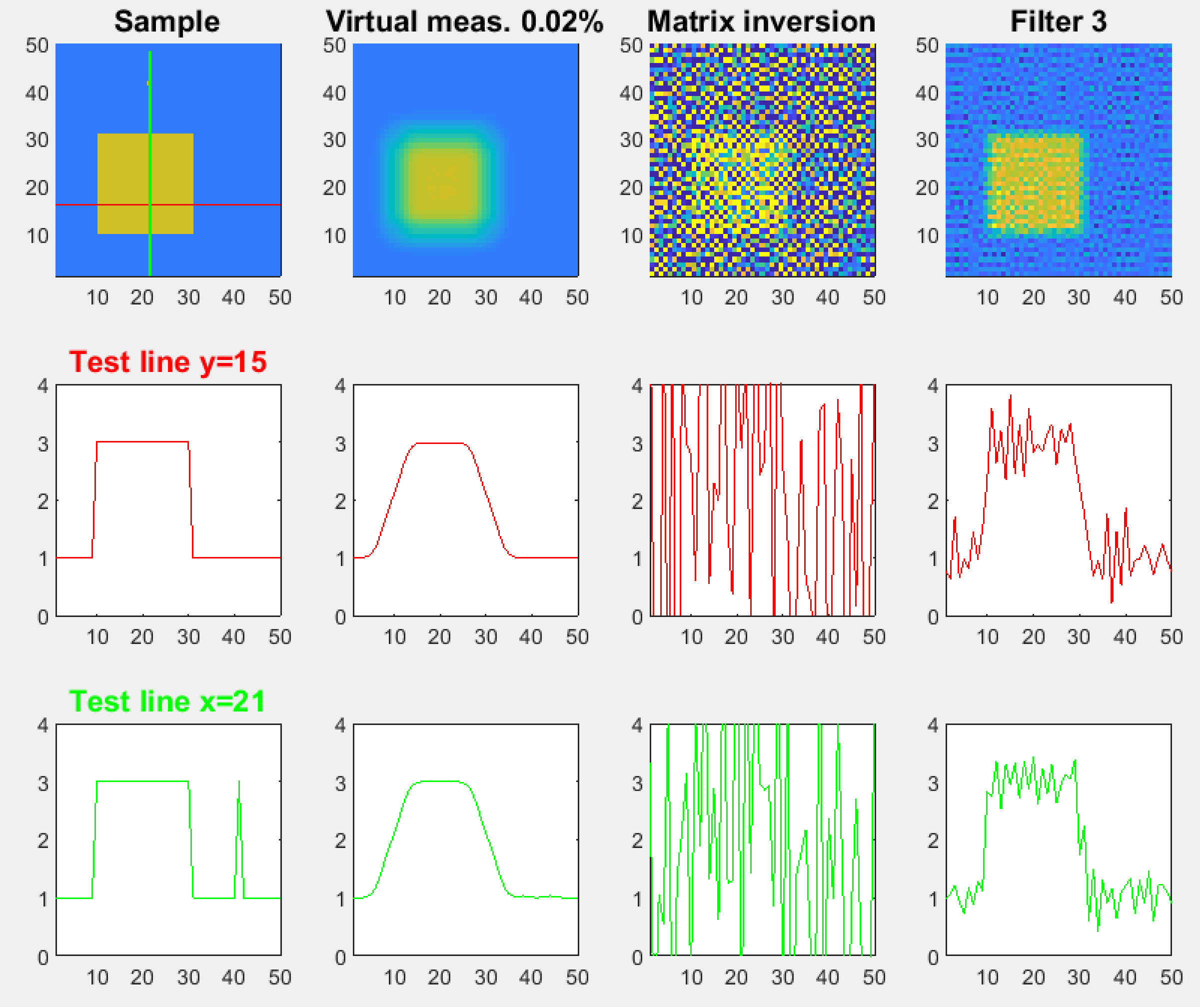
$$[W] = [T]\ [P]$$

Matrix T is generated in such a way that element t_{rs} in row *r* and column *s* is equal to :
- $|E_T(k, l)|^2$ for $s= r+k+M\ l$ for $k=-K..+K$ and $l=-L...+L$)
- 0 for *s* not obeying the above condition.

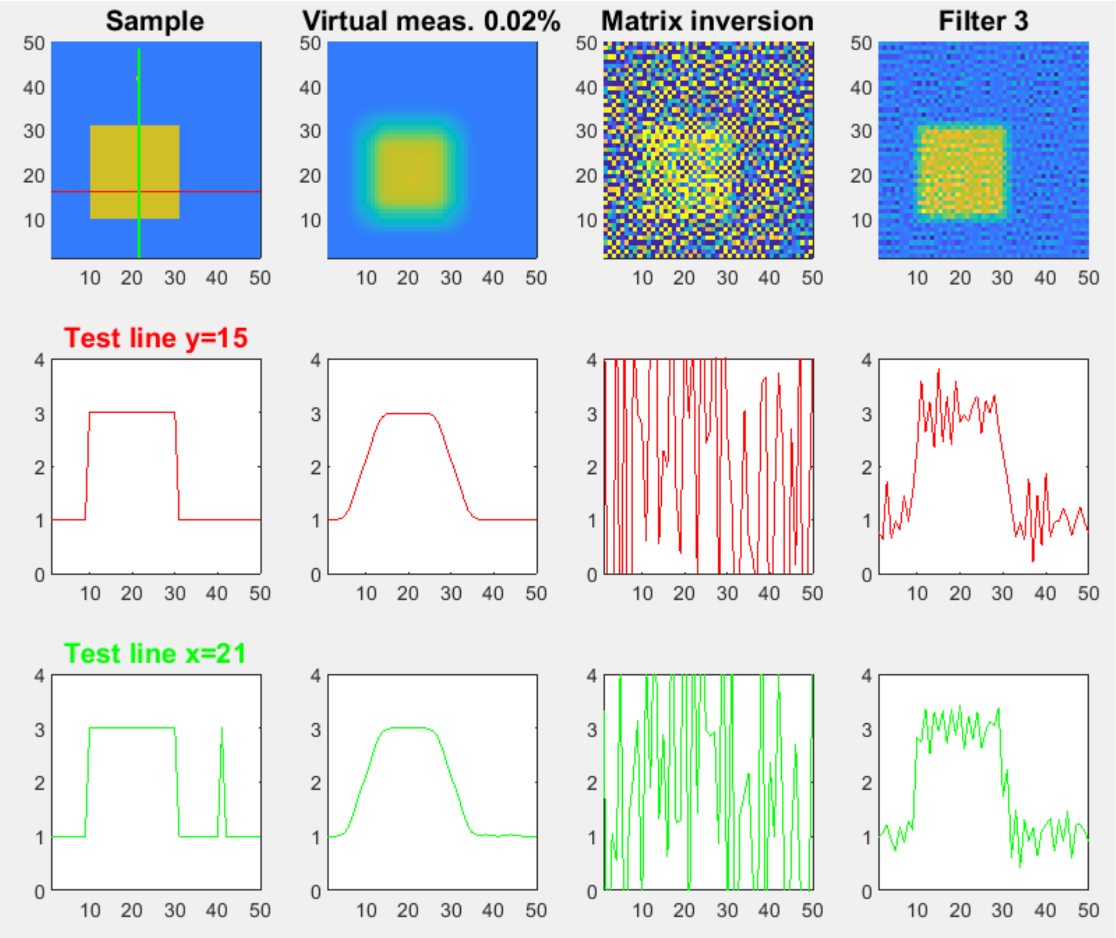
$$[P] = [T]^{-1}\ [W]$$

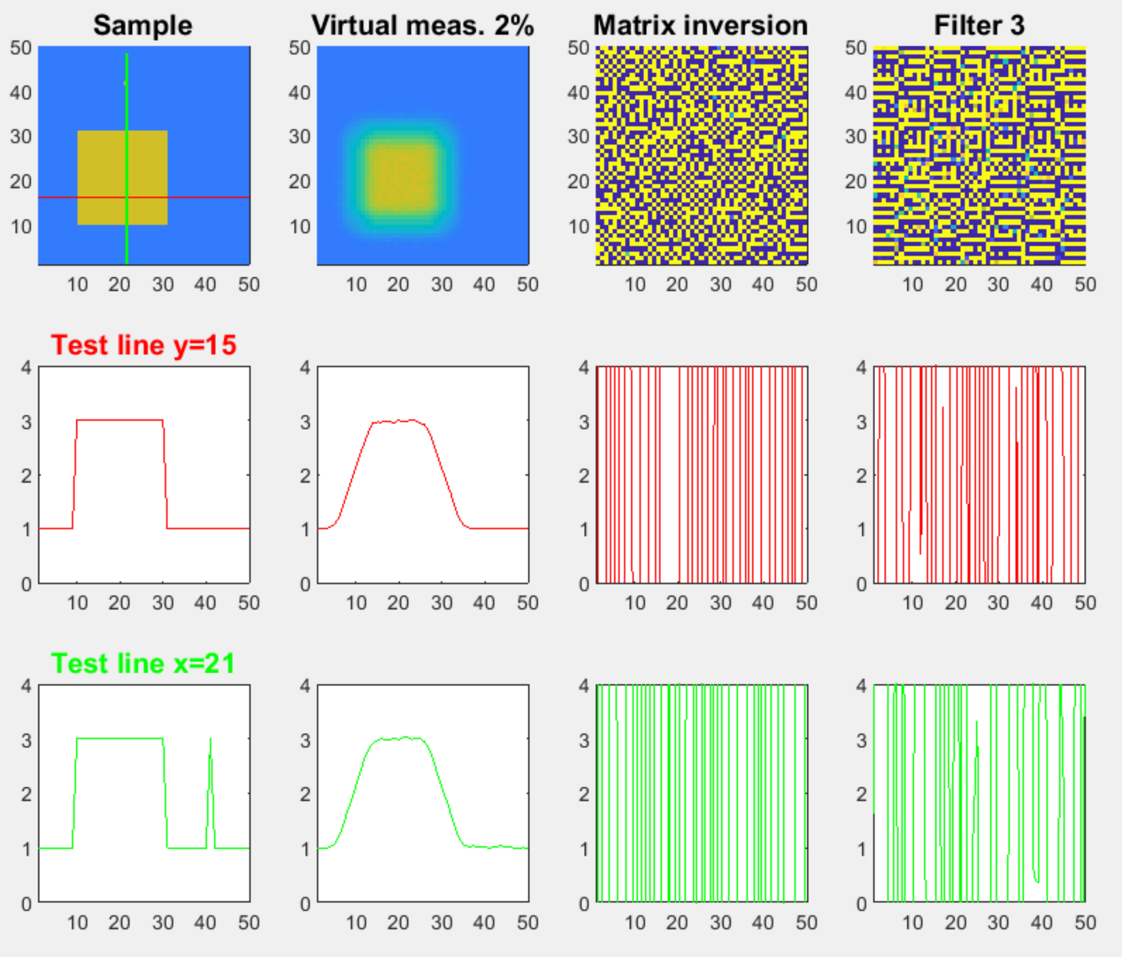
MATLAB experiments with virtual scans: matrix inversion of exact data & with noise



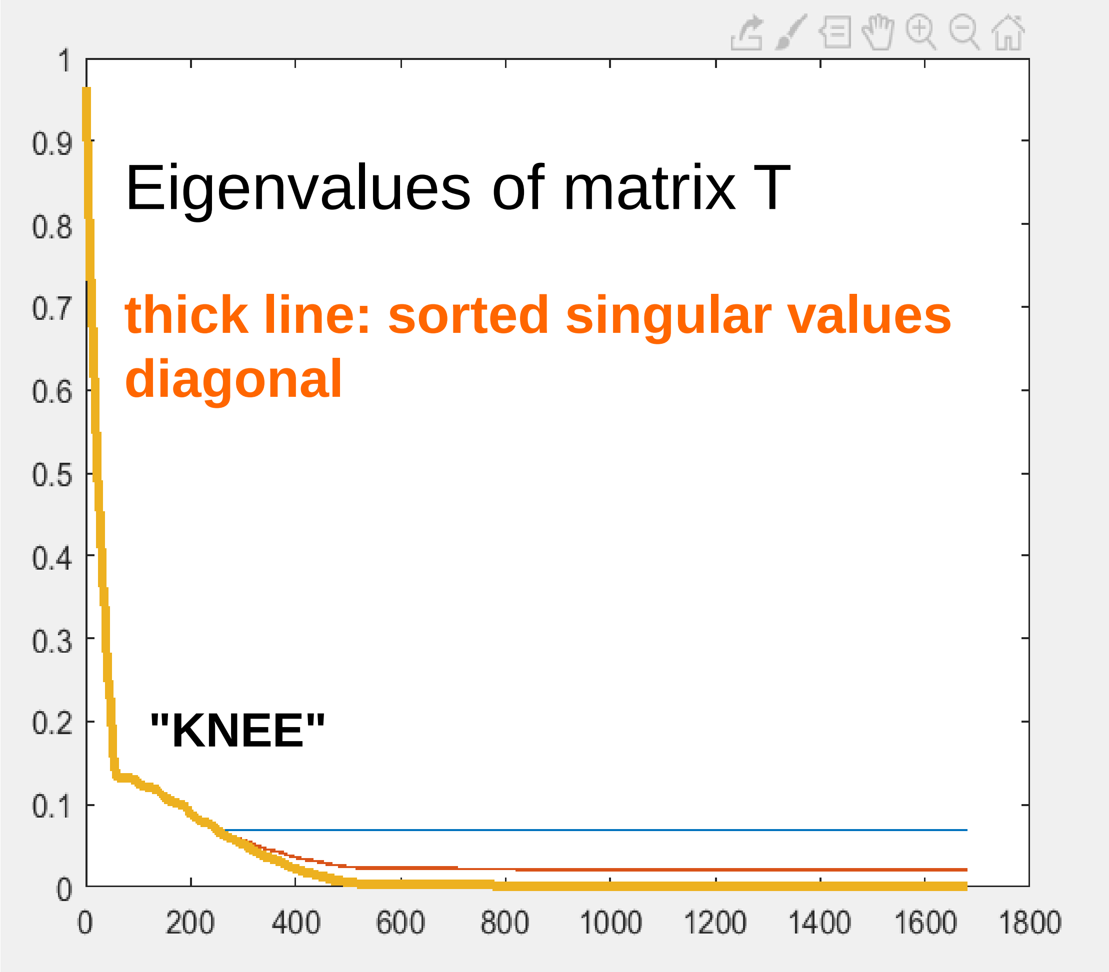


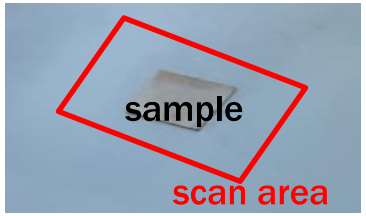
MATLAB experiments with virtual scans: matrix inversion with increased noise





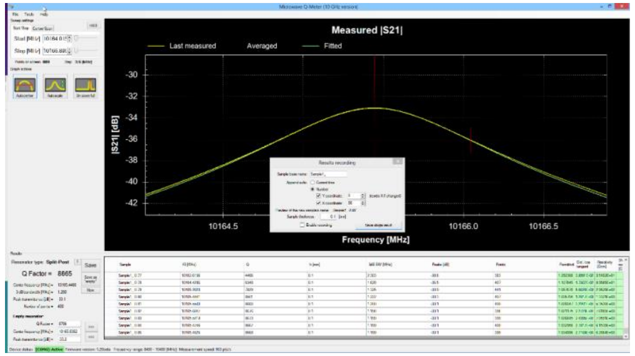
Singular Value Decomposition



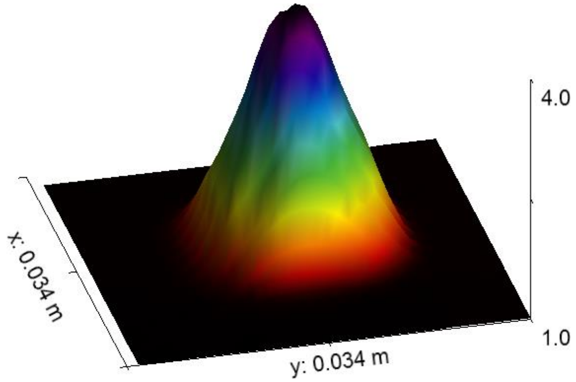


thin blue: suppressing smallest eigenvalues

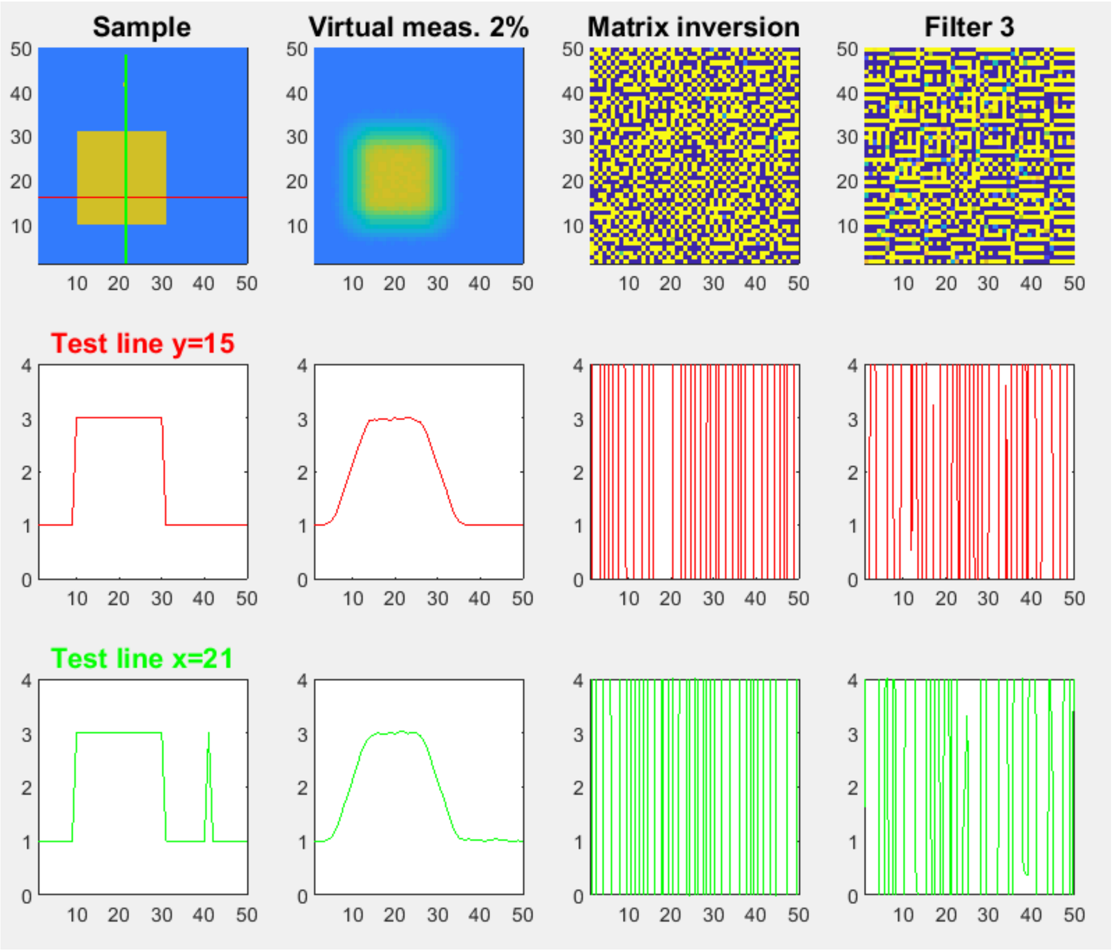
thin red: searching for balance between stability & accuracy

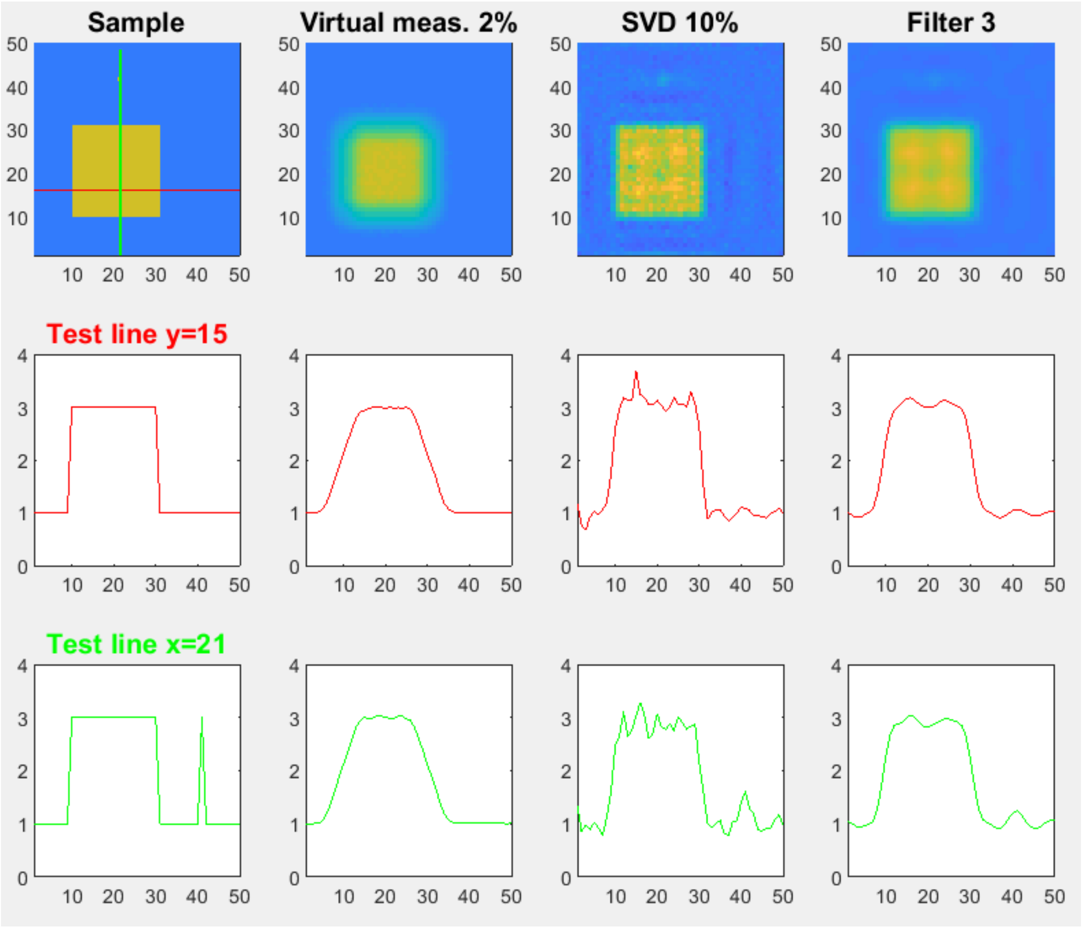


scan area 41x41mm
=> matrix 1681x1681 (step 1mm)
SUT laminate Rogers R4003
h=20mils (0.508 mm)
SUT size 15x15 mm
scan saved in Gwyddion format

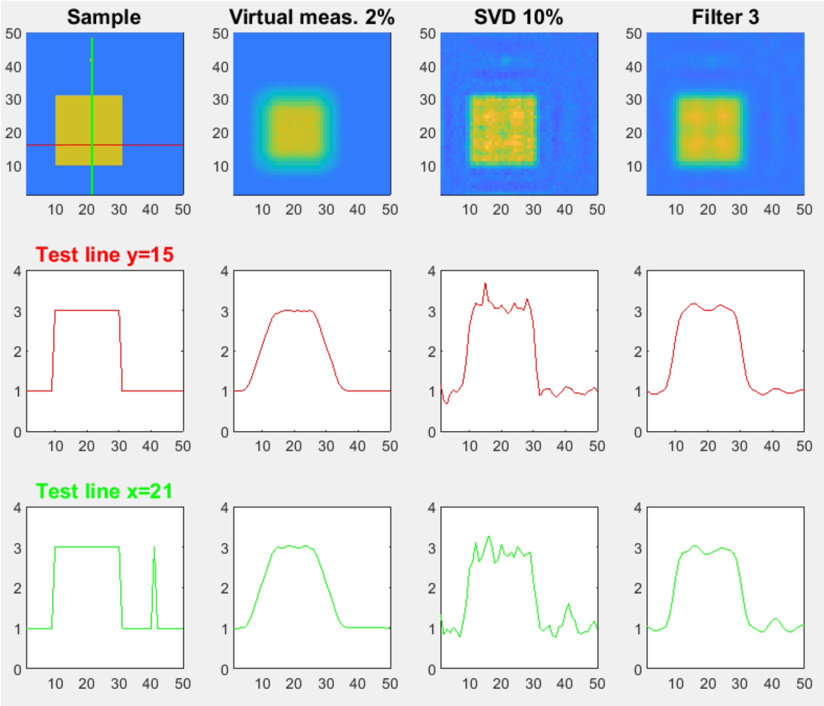


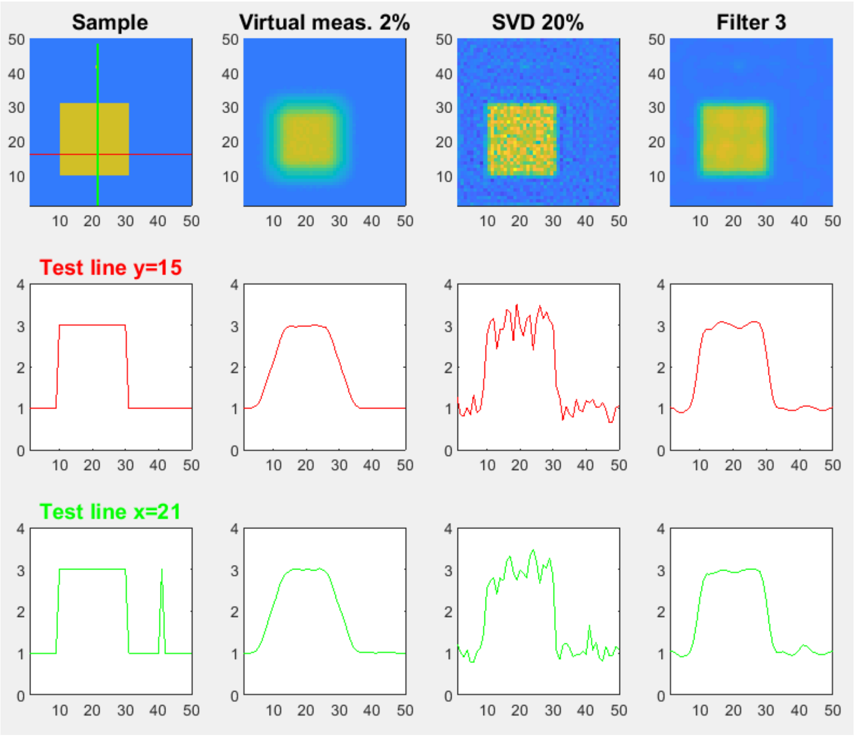
MATLAB experiments with virtual scans: matrix inversion versus SVD approach

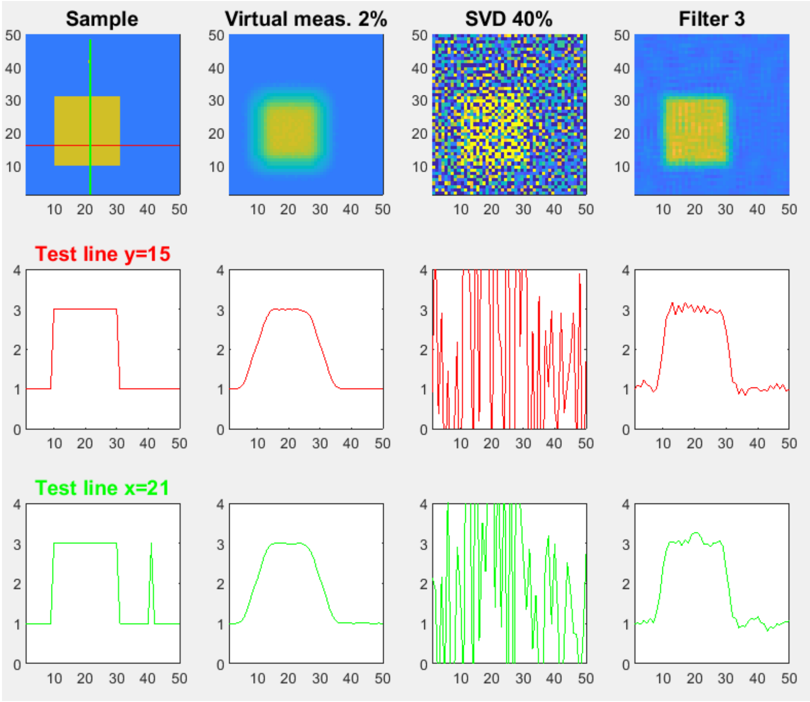




MATLAB experiments with virtual scans with error: experimenting with SVD parameters







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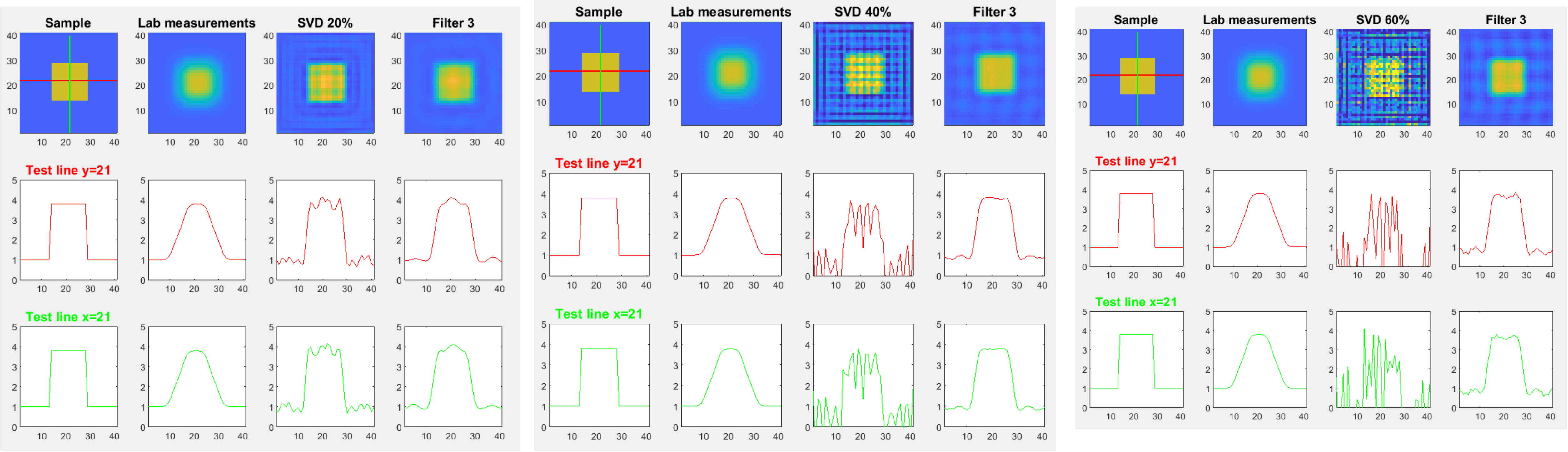
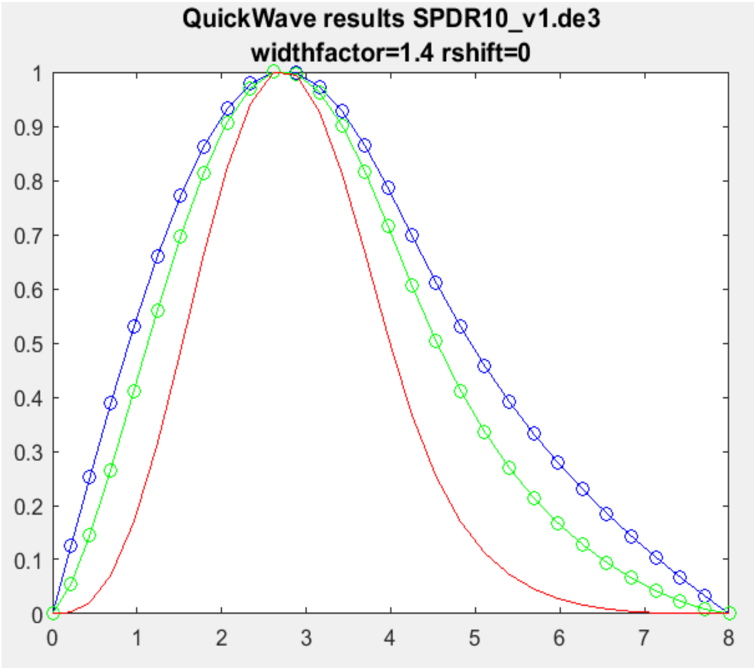
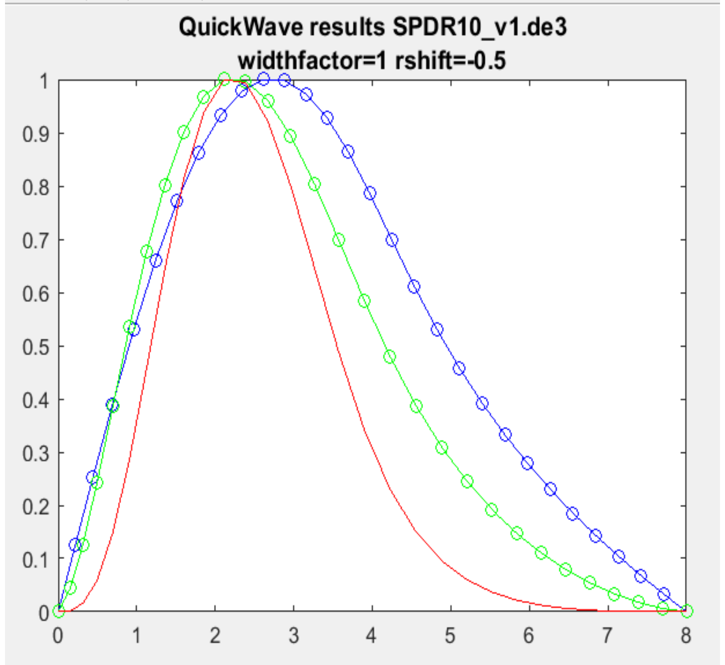
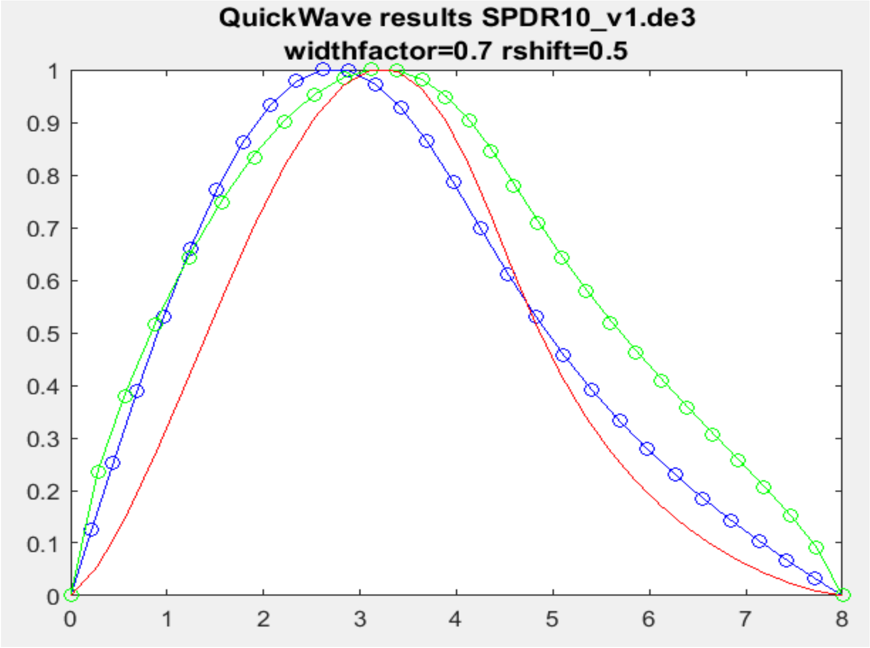
MATLAB experiments with laboratory scans: experimenting with SVD parameters



MATLAB experiments with laboratory scans: experimenting with templates







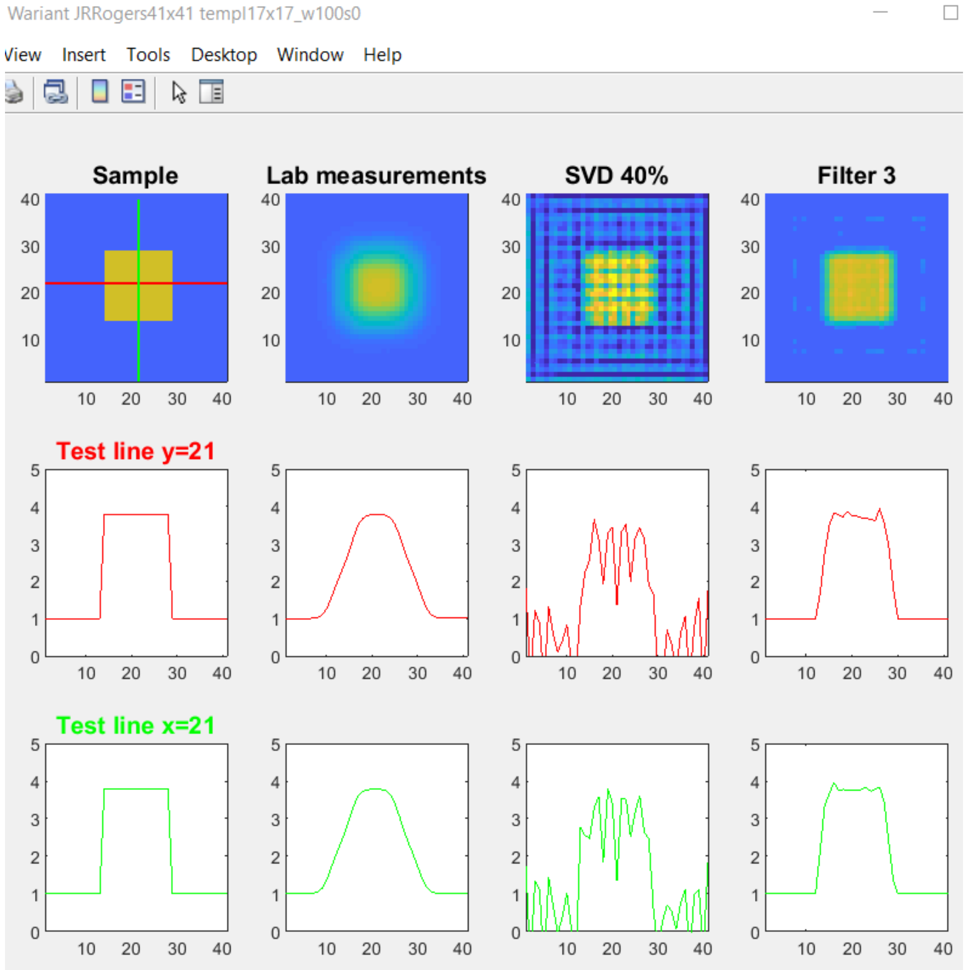
We should consider that the influence of the field template may be somewhat different from the theoretical one (due to manufacturing differences and discretization of the model)

blue – QuickWave simulation of E-field for theoretical SPDR design, interpolated in MATLAB

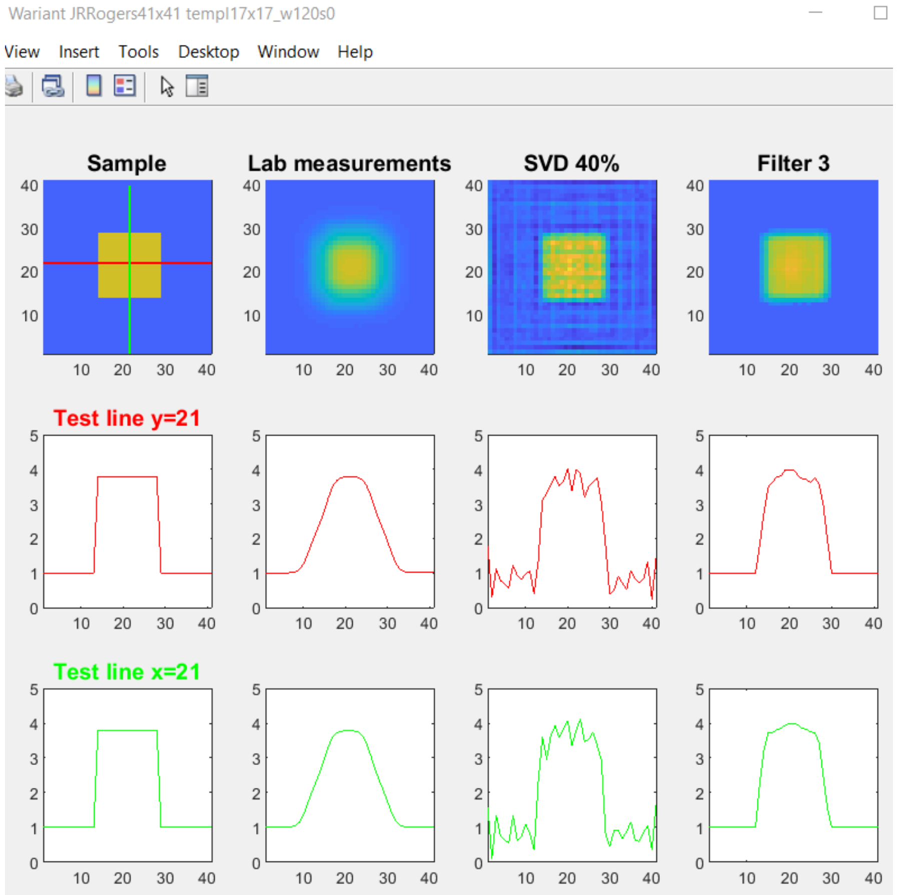
green – modified ("narrowing" or shift)

red – modified squared

MATLAB experiments with laboratory scans: experimenting with templates (1)

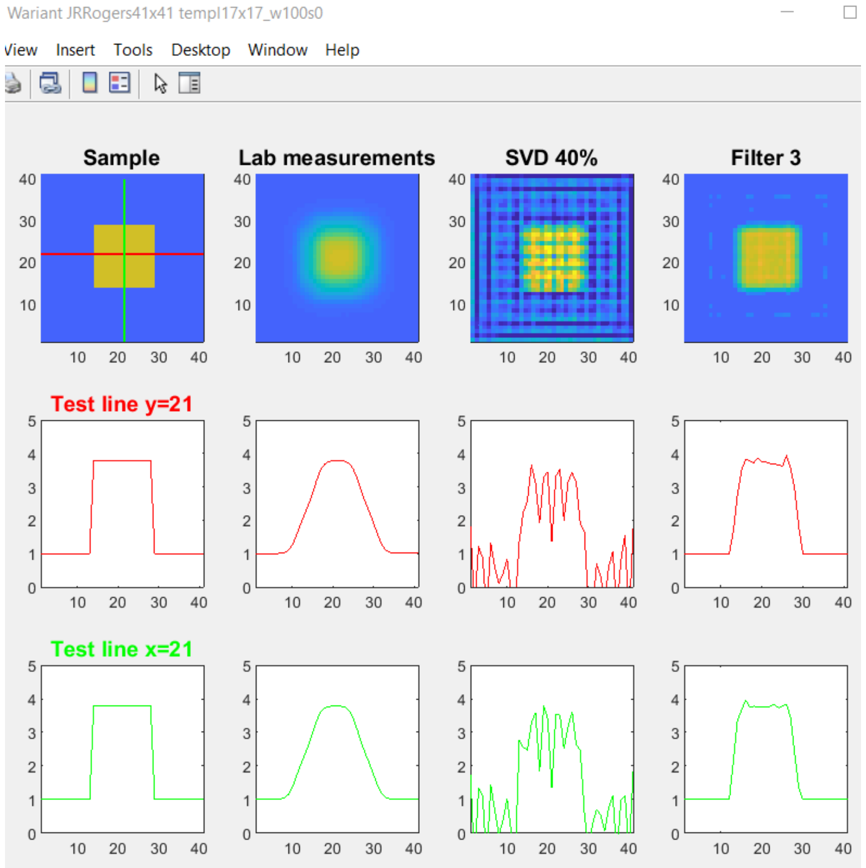


original template

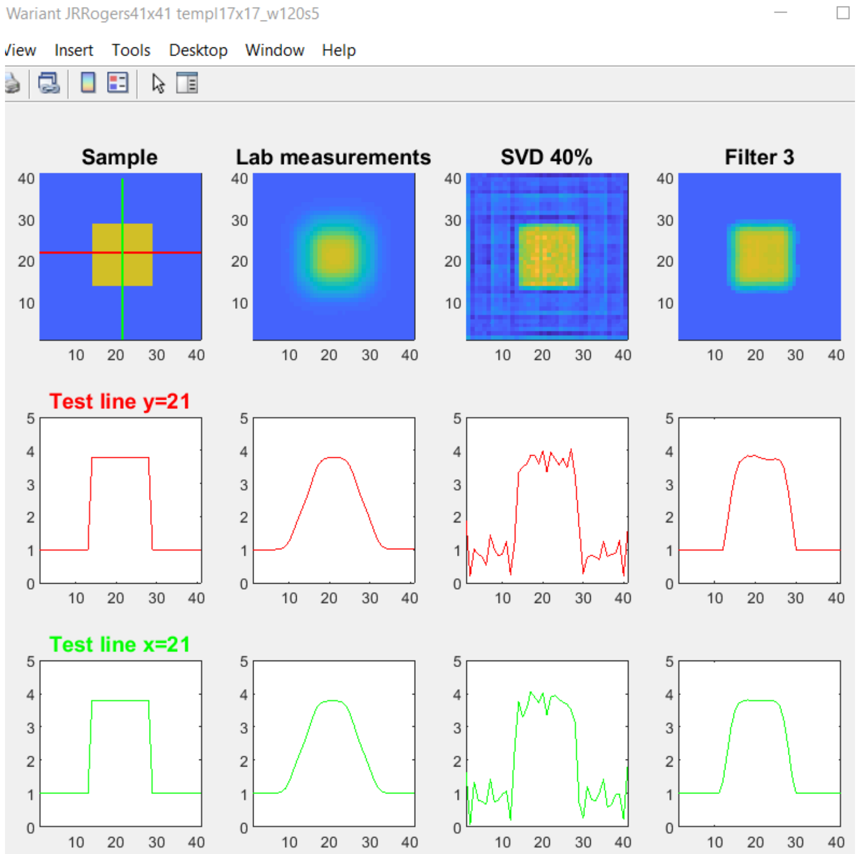


stronger energy concentration in ring: "narrower" template $E^{1.2}$

MATLAB experiments with laboratory scans: experimenting with templates (2)



original template



"narrower" template, stronger energy concentration in ring: template $E^{1.2}$ further shifted by 0.05 mm

Conclusions

- Setups including dielectric resonators (especially SPDR and SiPDR) are widely applied in science and industry for accurate measurements of permittivity and loss tangent at microwave frequencies. They are valued for their high accuracy and convenience of use.
- SPDRs have also been implemented in scanners for industrial testing of planar materials . However, their application has been restricted by limited resolution of the scanning (related to the size of the SPDR head).
- An implicit method has been proposed for decisive improvement of that resolution. However since the problem is ill-conditioned, direct application of matrix inversion does not lead to good results in real measurements.
- Optimised application of the mathematical method called “Singular Value Decomposition” leads to interesting and practically promising results.

Acknowledgement

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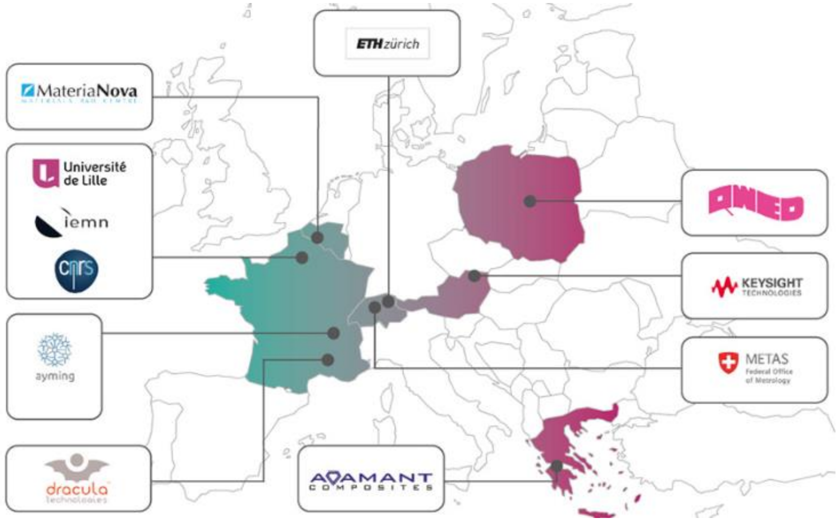
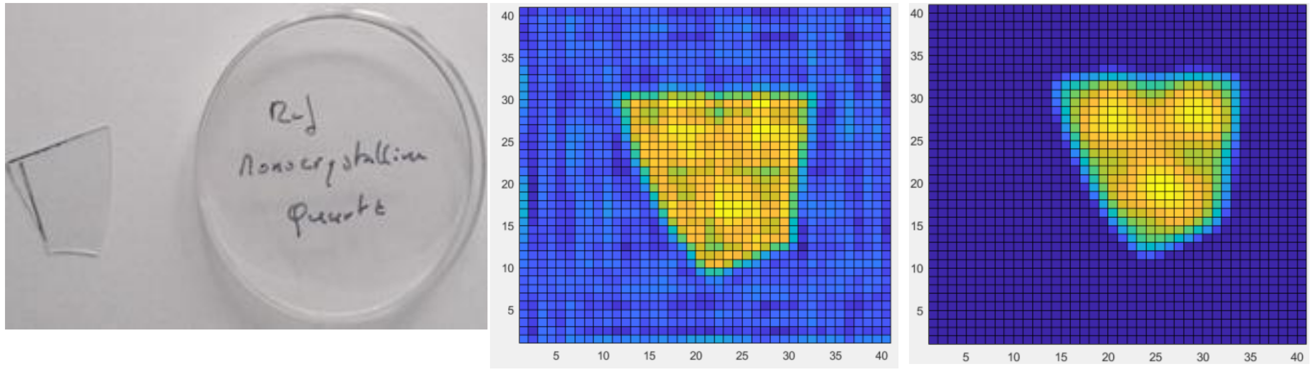
MMAMA n° 761036.

(website: www.mmama.eu)





For more technical details, come and see us in Booth # 882.