Modelling a Resonant Near Field Scanning Microwave Microscope (RNSMM) Probe

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EMINDA

Electromagnetic Characterisation of Materials for Industrial Applications up to Microwave Frequencies

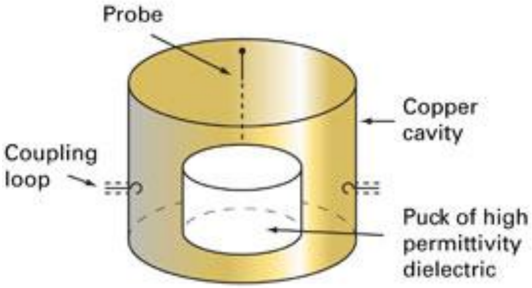
- Develop traceable electromagnetic and functional materials metrology.

- Enable uptake of these materials within EU industry, especially important for electronics and ICT-related companies.

- NPL research of key advanced measurement techniques to give broader infrastructure for EM materials metrology in Europe.

http://projects.npl.co.uk/eminda/

- Develop Micrometre-scale **Near-Field Scanning Microwave Microscope (NSMM)** metrology.



- Allow **traceable** measurements of **complex permittivity** on micron scales.

- A **dielectric resonator (RNSMM)** design may be employed which improves sensitivity.

- Scan surface complex permittivity of **composites, electro-ceramics, semiconductors, thin films**.

Modelling a RNSMM

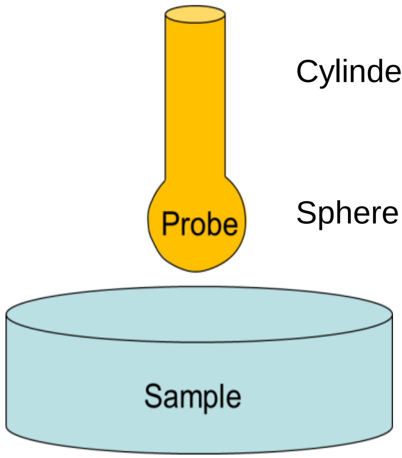
A RNSMM consists of two parts:

- **Microwave resonator**
  Dimensions ~ cm
- **Probe/tip** that interacts with **sample**
  Dimensions ~ 100 μm

Assumption: Probe cylinder is sufficiently long that ***resonator*** and other parts of the device ***can be neglected*** so that only the probe and the sample need to be considered.

Simplified model of probe and sample:

- Understand the **probe/sample interaction** of a RNSMM
- Account for **non-flatness** and **non-uniformity** of specimens in RNSMM measurements

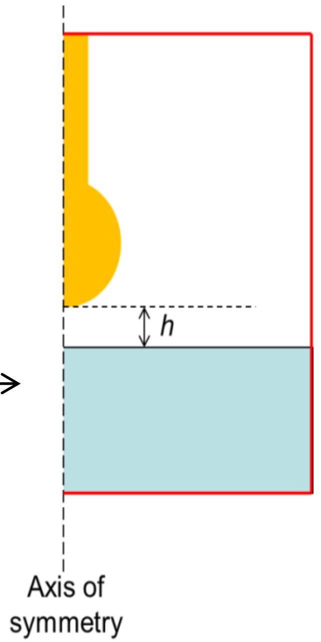


Cylinder: 0.08 mm diameter
0.32 mm long shaft

Sphere: 0.1 mm diameter

Disc: 4 mm diameter
2 mm thickness

2D simplification



Gaps of interest:
0 - 10 μm
5 mm

Governing equations

A **high frequency alternating current** is applied to the probe, which generates an **electric field** around the probe.

This **field is affected by the sample**, and the effect can be sensed by looking at the current running through the probe.

$$\mathbf{E} = -\nabla V$$

$$\nabla \cdot \mathbf{J} = -j\omega\rho$$

$$\mathbf{J} = (\sigma + j\omega\varepsilon_0\varepsilon_r)\mathbf{E} + \mathbf{J_e}$$

J: current density
E: electric field
ρ: charge density
ω: angular frequency
ε_0: permittivity of vacuum
ε_r: relative permittivity of the material
σ: electrical conductivity of the material
$\mathbf{J_e}$: externally generated current.

These equations are completed with the following **boundary conditions**:

- **Terminal**: V=1 V, on the top boundary of the probe.
- **Ground plane**: V=0 V on the bottom of the sample.
- **Electric insulation**: $\mathbf{n} \cdot \mathbf{J} = 0$ elsewhere.

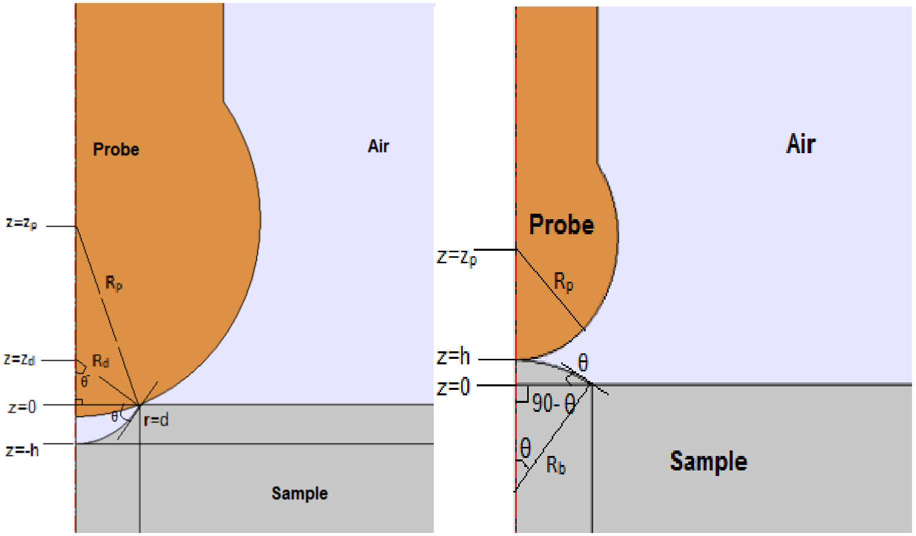
The result of interest is **capacitance** of the system, which can be extracted directly as a lumped parameter from the model.

Use of COMSOL Multiphysics

- Required the AC/DC module, specifically the electric currents capability in the frequency domain.
- The use of a terminal node enabled the computation of the lumped parameters of the system: capacitance and resistance.
- Model run at the operating frequencies of the NPL RNSMM: 240 MHz, 1.5 GHz, and 3.9 GHz.
- As the probe is small compared with the microwave wavelength, the capacitance is effectively frequency independent, so for all the frequencies run the capacitance results are found to be the same
- The mesh in the gap between the sphere and the sample, and in the first few microns of the sample, has to be very fine.

Sample configurations to be investigated

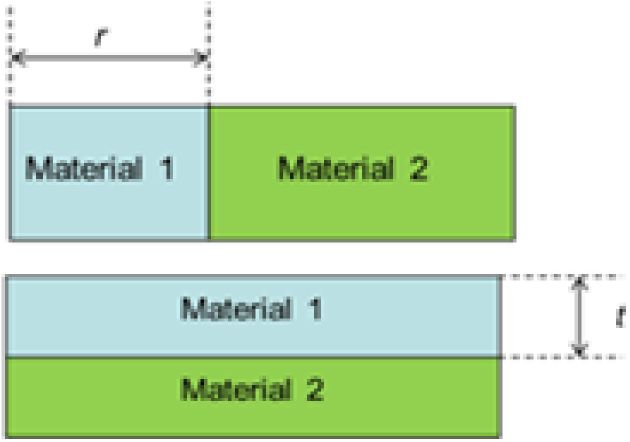
Geometric imperfections: Valley / Hill



Two varying parameters:

- ***h***: height of the dip into (or bump off) the surface. Range: 1, 3, 6, and 10 µm
- ***Θ***: angle into (or off) the sample. Range: 30° 60° 90°

Layered or inhomogeneous materials

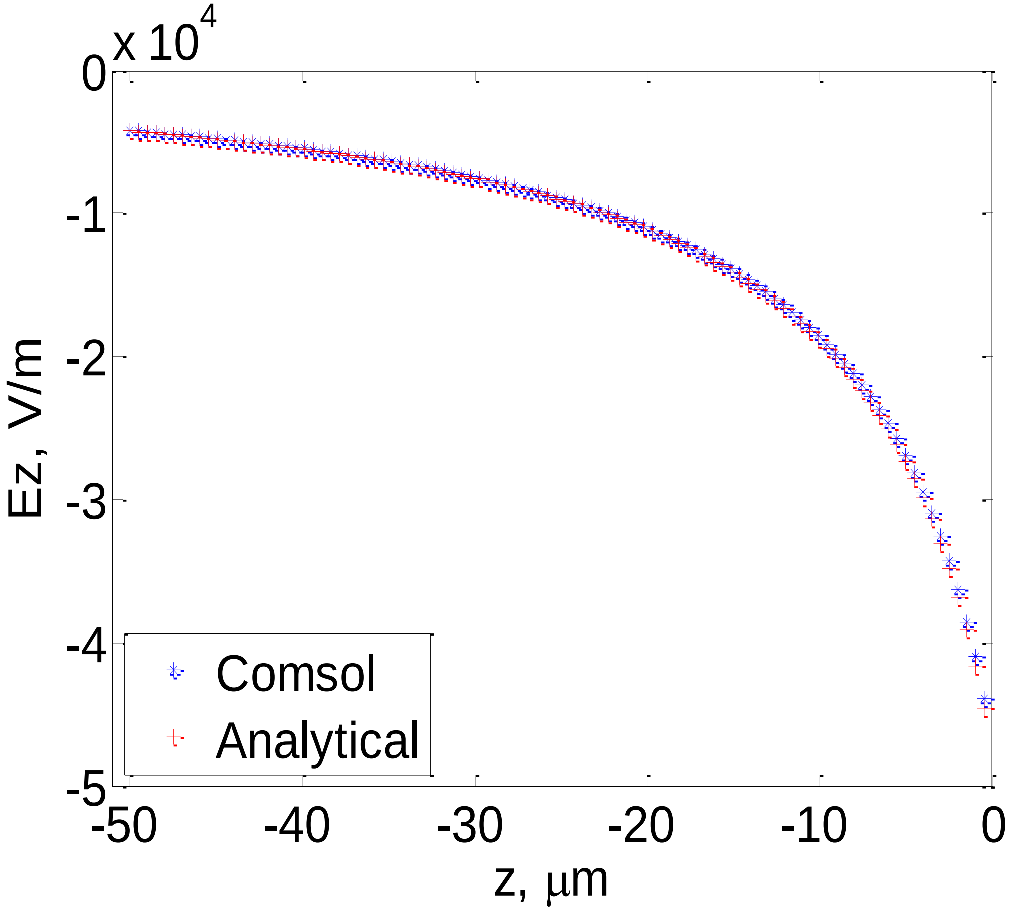


Two varying parameters:

- ***r** and **t**:* set to 1, 2, 5 and 10 times the probe radius, keeping the overall radius and thickness of the sample fixed.
- The value of ***t*** has also been set to 1 µm to set up a thin film model.

Validation against analytical model

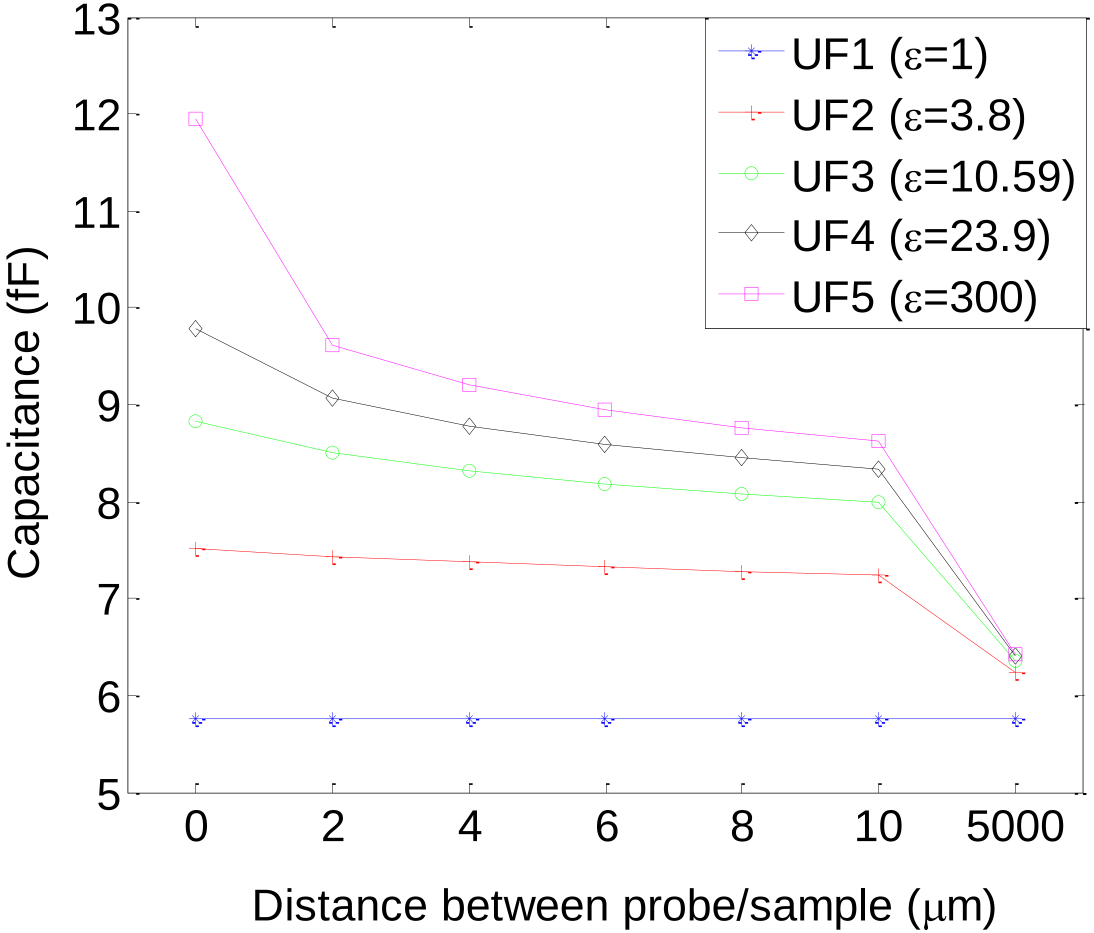
Analytical solution when the probe is treated as a sphere (no cylinder) in contact with a sample which is uniform and perfectly flat



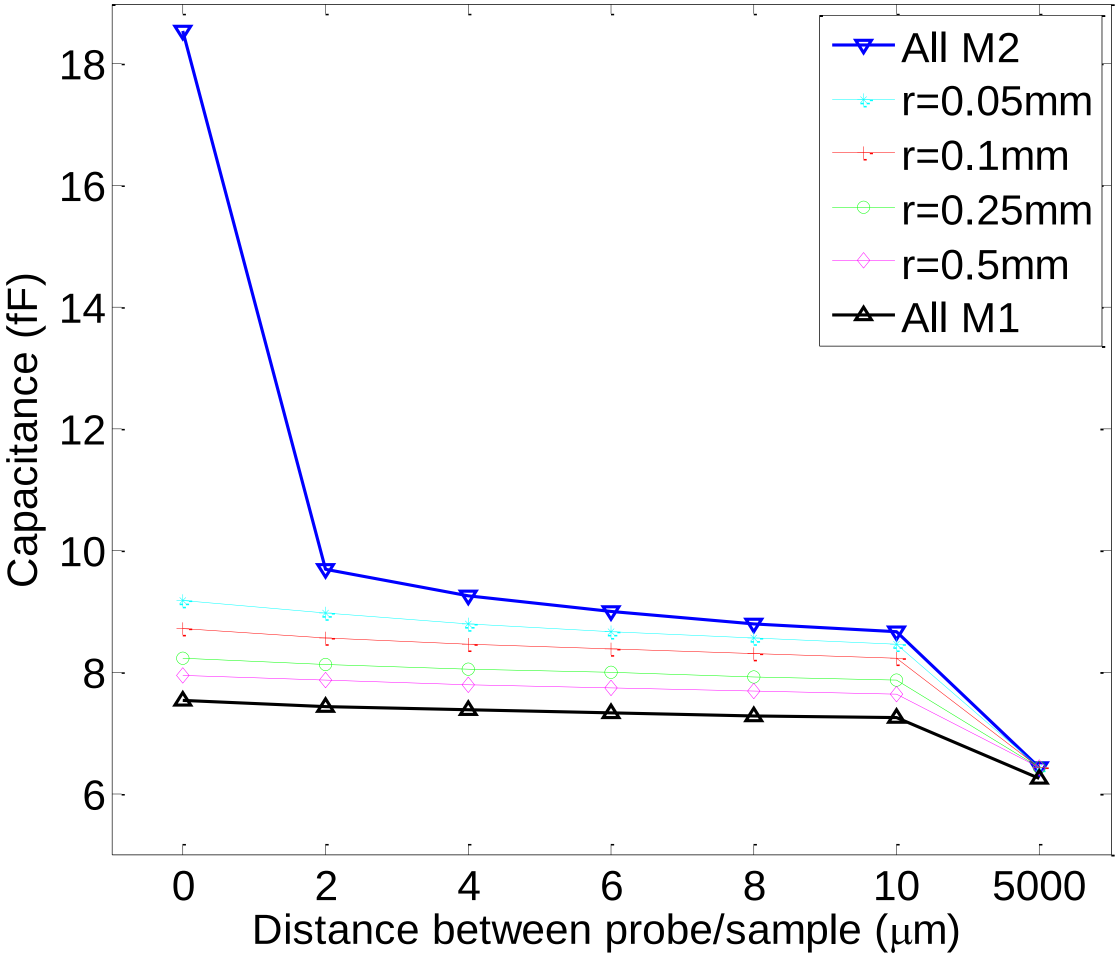
C. Gao and X.-D. Xiang, Quantative microwave near-field microscopy ofdielectric properties, *Review of Scientific Instrument, 69 (11), 3846-3851 (1998)*.

Results and discussion

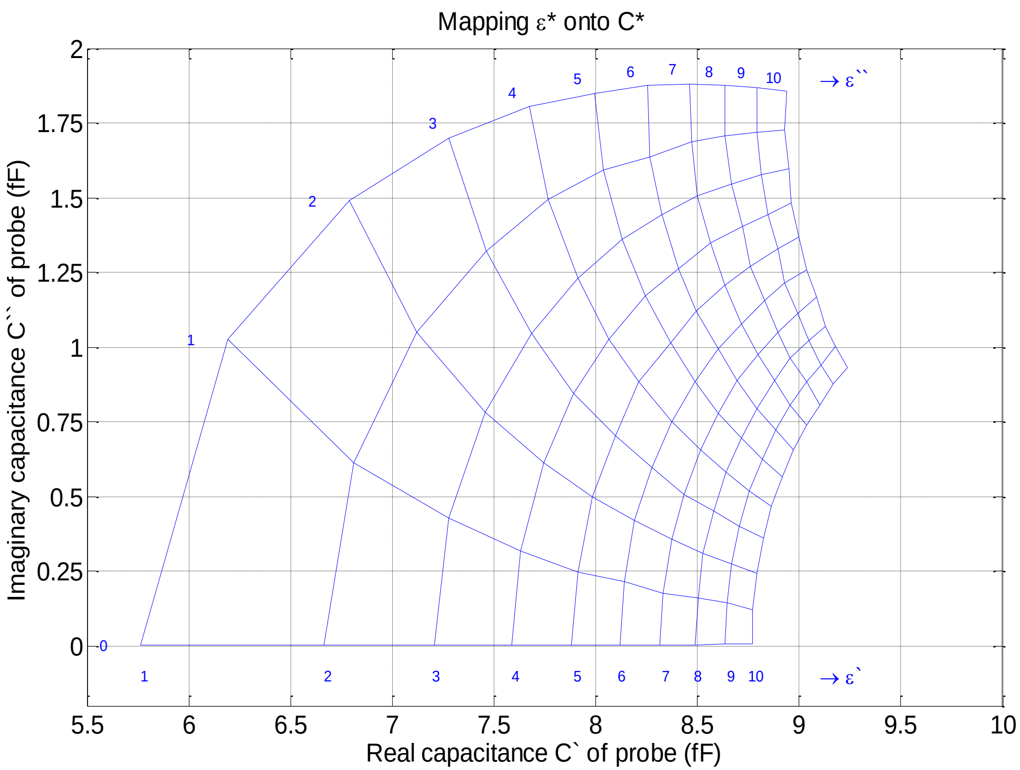
Uniform material with a flat surface



Concentric material with a flat surface



M1: ε = 3.8
M2: copper



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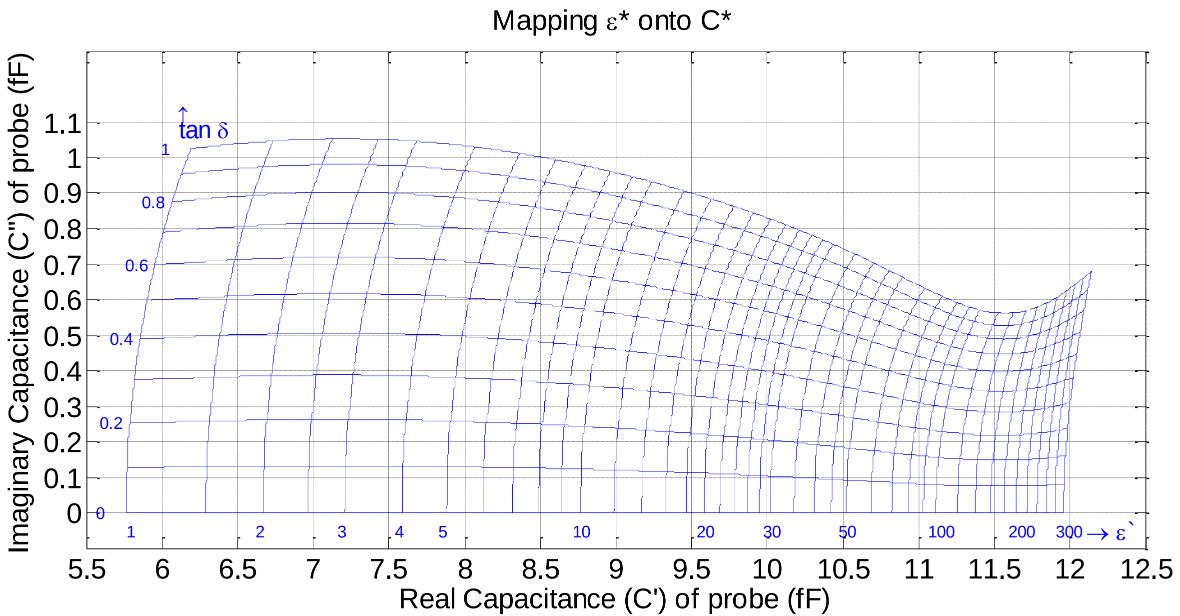
Mappings from the complex permittivity plane to the complex capacitance plane for **lossy dielectrics** (imaginary permittivity is non-zero)

Enables to read off the material complex permittivity corresponding to a given complex capacitance.



Summary

- Very useful tool to provide insight into the effects of likely imperfections in the real measurement technique.

- Modelling studies of this kind can help answer questions such as:
  - how accurately does the separation between the probe and the sample need to be known?
  - how flat does the surface need to be?
  - if the sample is composed of two materials, how accurately can the permittivity of either of them be measured?

- Simple capacitive models of probe/sample interaction cannot capture many of the effects described above, and this fact in turn demonstrates the importance of this form of modelling for RNSMM metrology to be made fully traceable.

Acknowledgments

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