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Signals and Systems

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A Microwave Measurement System for Measurement of Dielectric Properties

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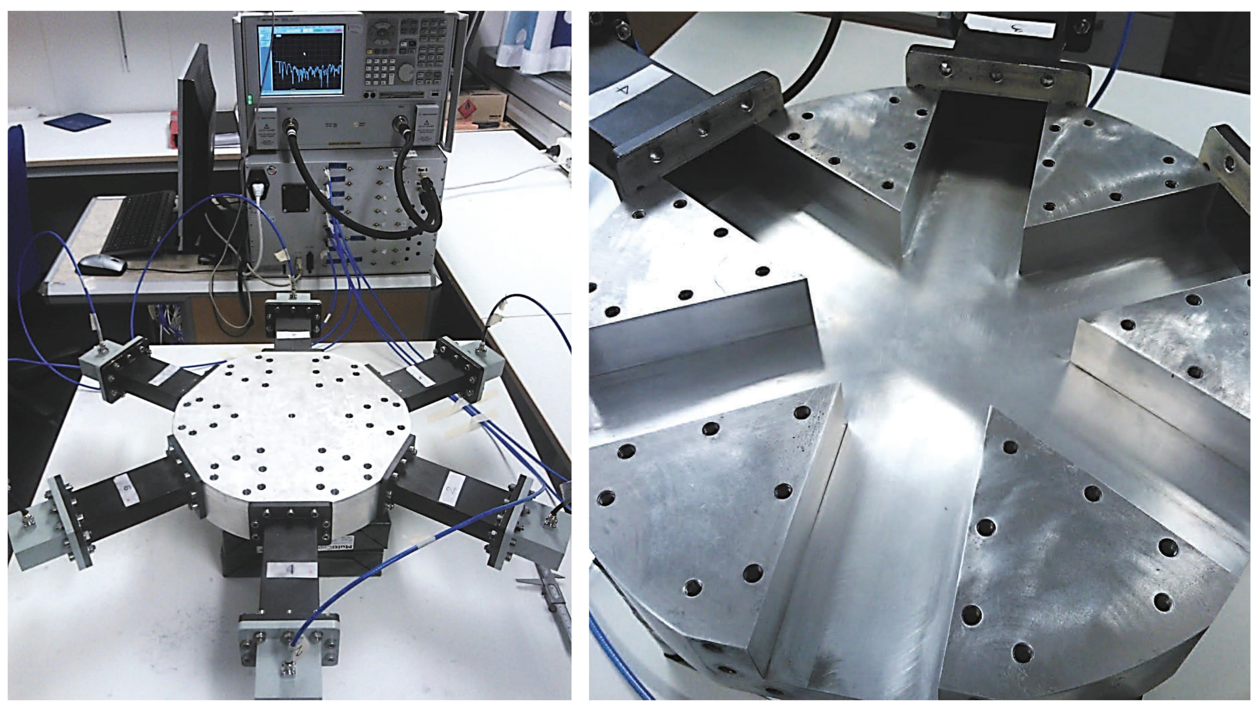
Measurement System

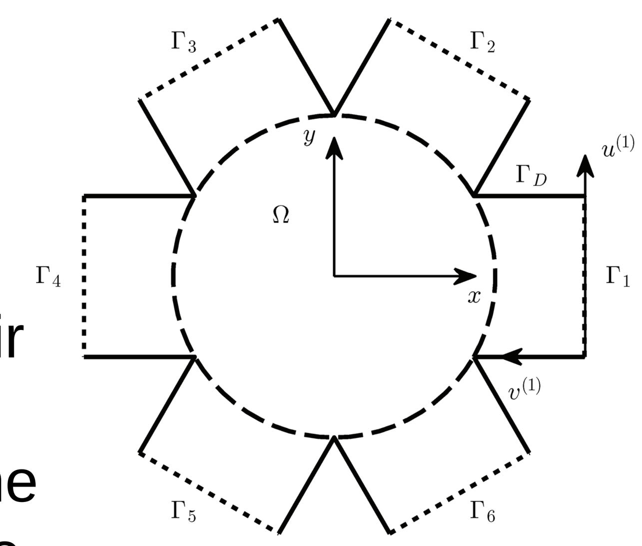
We present a prototype of a microwave measurement system for the estimation of dispersive dielectric properties. The measurement system consists of a metal cavity that features a measurement region in the center formed by the intersection of six rectangular waveguides. The waveguides are terminated by adapters connected to coaxial cables. We exploit the frequency band 2.7-5.1 GHz and a connected network analyzer and switch allows for automatic measurements of the 6-by-6 scattering matrix $\overline{\mathbf{S}^{\mathrm{s}}}$.



Complete microwave measurement system and measuremet region at the waveguide intersection.

Modeling in 2D

The waveguides and their intersection is accurately simulated in 2D. Using the finite element method, we solve the boundary value problem



Geometry of the 2D model

$$-\nabla^2 E_z - \omega^2\mu_0\epsilon E_z = 0 \quad \text{in } \Omega$$
$$E_z = 0 \quad \text{on } \Gamma_D$$
$$\hat{n}\cdot\nabla E_z + jk_{wg}E_z = 2jk_{wg}E_z^i \quad \text{on } \Gamma_p$$

where $\epsilon(f,x,y)$ is the permittivity distribution that we wish to estimate.

The simulated scattering matrix $\mathbf{S}$ is found from the ratio between the reflected and incident field at each waveguide port.

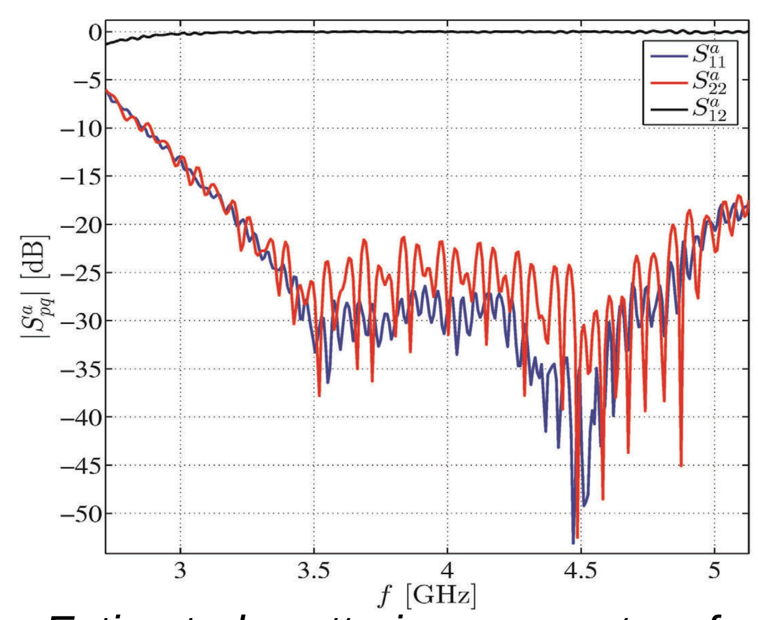
Calibration Procedure

We utilize a simulated and measured scattering matrix for the empty cavity to estimate identical 2-by-2 scattering matrices $\mathbf{S}^{\mathrm{a}}$ for all adapters by solving

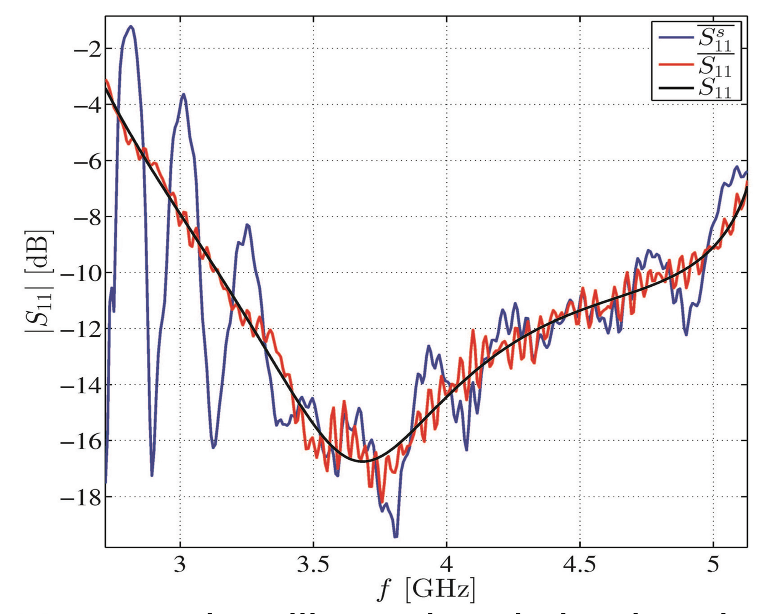
$$S^{\mathrm{a}}_{11}\mathbf{I} + S^{\mathrm{a}}_{22}\overline{\mathbf{S}^{\mathrm{s}}_0}\mathbf{S}_0 + (S^{\mathrm{a}}_{12}S^{\mathrm{a}}_{21} - S^{\mathrm{a}}_{11}S^{\mathrm{a}}_{22})\mathbf{S}_0 = \overline{\mathbf{S}^{\mathrm{s}}_0}$$

Any measured scattering matrix $\overline{\mathbf{S}^{\mathrm{s}}}$ can then be calibrated by removing the estimated adapters. The calibrated scattering matrix $\bar{\mathbf{S}}$ can then be directly compared with the simulated $\mathbf{S}$.

We find that using this calibration procedure we achieve a residual of about -30 dB between our simulated and measured results.



Estimated scattering parameters for the adapters.



Measured, calibrated and simulated reflection coefficient for the empty cavity.

Optimization

Using gradients, we minimize the misfit between the simulated and calibrated scattering matrix

$$g(\mathbf{p}) = ||\mathbf{S}(f,\mathbf{p}) - \bar{\mathbf{S}}(f)||$$

where $\mathbf{p}$ are the parameters defining the permittivity of the material distribution.

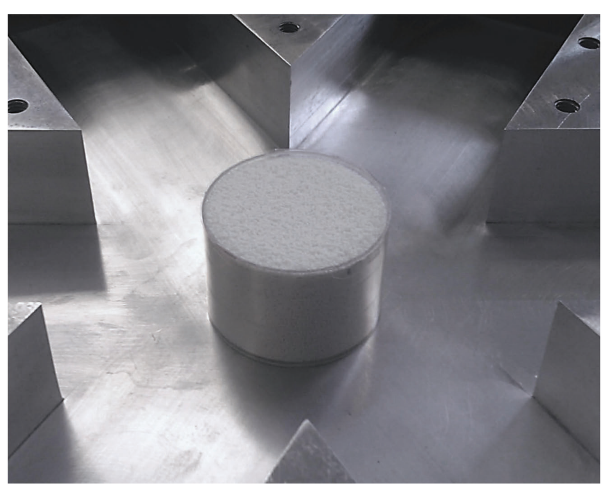
Measurement Results

We estimate the complex effective permittivity of densely packed MCC (micro-crystalline-cellulose) pellets over frequency for different moisture contents. This material is used in pharmaceutical processes.

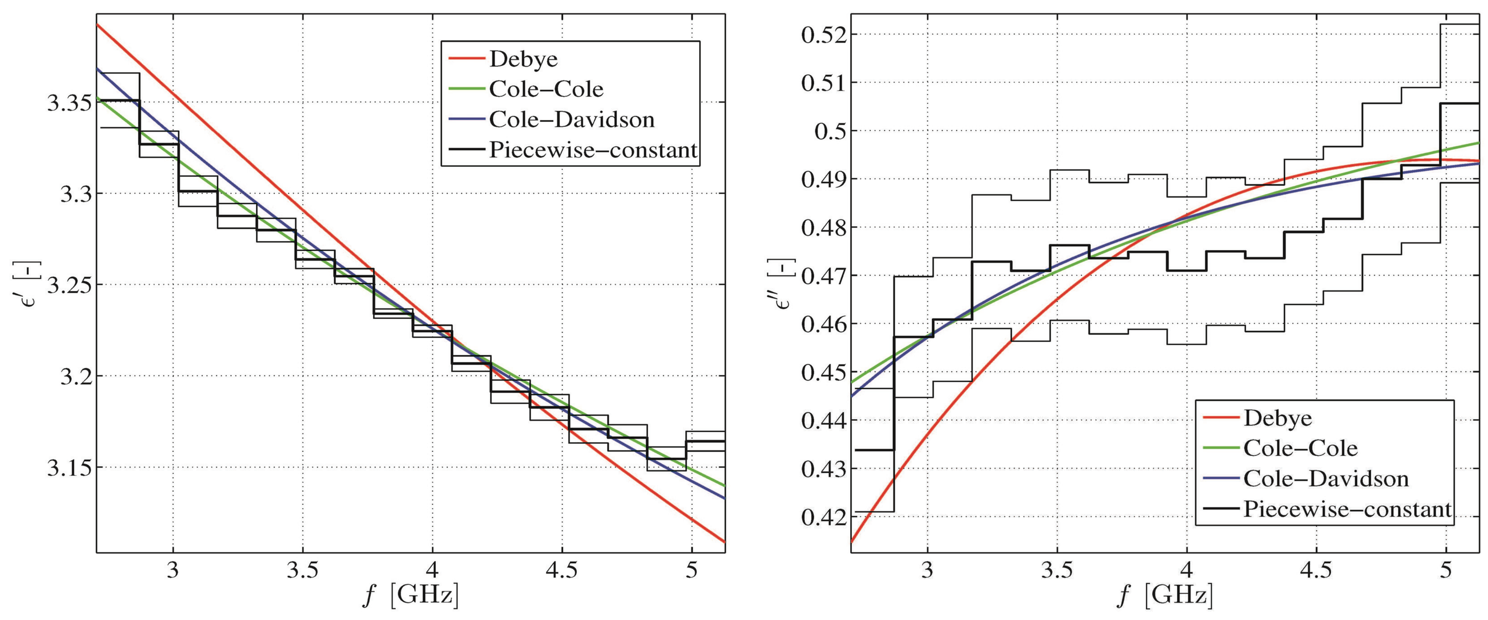
Moisture	ϵ_s [-]	ϵ_∞ [-]	τ [ps]
9.2 %	3.62±0.02	2.63±0.03	32.0±0.9
12.2 %	4.27±0.04	2.85±0.05	24.2±0.8
16.8 %	4.88±0.05	2.79±0.12	15.5±0.8
22.8 %	5.49±0.07	2.36±0.26	10.3±0.8

Estimated Debye parameters for the MCC pellets.

Four different types of frequency dependent dispersive models are tested; Debye, Cole-Cole, Cole-Davidsson and piecewise-constant in small frequency intervals. All models yield similar results.



Plastic holder with MCC pellets. The holder contains about 31g of MCC, which is in the form of spherical particles.



Real and imaginary relative permittivity vs frequency for 4 different models. The thin black curves are an estimate of the uncertainty, here about 1-3%. The MCC has a moisture content of about 9.2 mass-percent.

Conclusions

- A measurement system for determining dispersive dielectric properties
- The calibration procedure is important to compensate for the adapters and other effects not included in the 2D model
- Low uncertainties in the Debye parameters and consistent results for the different permittivity models as a function of frequency
- Measured permittivity can be related to moisture content

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