IMS2012 MONTRÉAL
MICROWAVES WITHOUT BORDERS
MICRO-ONDES SANS FRONTIÈRES
International Microwave Symposium
IEEE 17-22 June 2012, Montréal, Canada MTT-S
http://ims2012.mtt.org/
MTT IMS NEW YORK 1952 MONTRÉAL 2012 60 YEARS 60

Measurement of Powders and High-loss Liquids using Resonant Cavities

José M. Catalá-Civera
Universidad Politécnica de Valencia, Spain

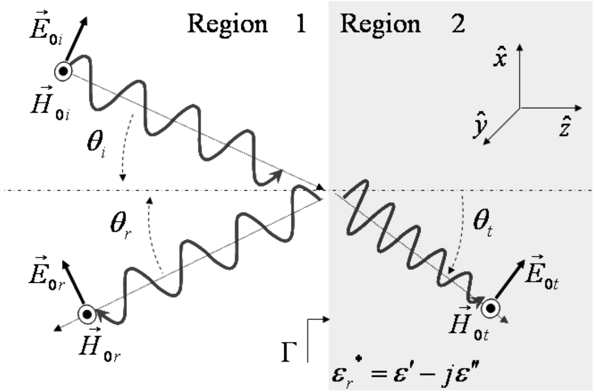
WMA: Overview of Advanced Dielectric Measurement Techniques

Outline

- Introduction
- Measurement techniques for dielectrics
- Transmission line methods (nonresonant)
- Cavity methods (resonant)
- Coupling of microwave resonators
- Results of measurements of high and low loss dielectrics
- Conclusions

Measurement Techniques

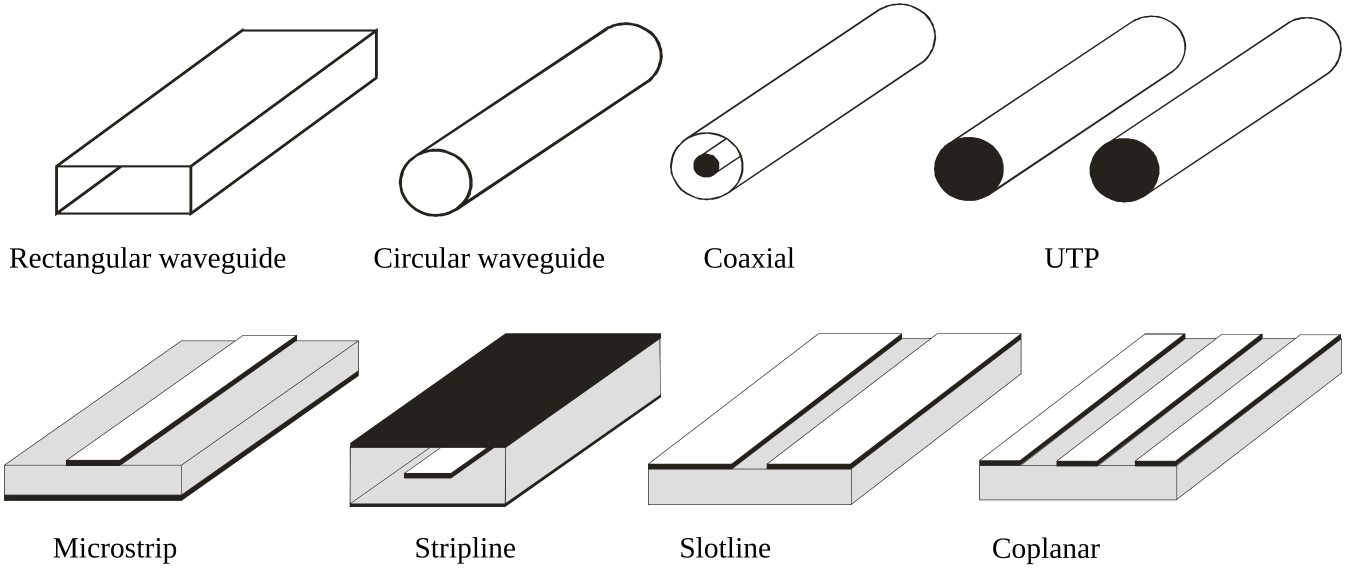
- Transmission lines (Nonresonant)
  - Wave velocity slower,
  - Wavelength shorter
  - Impedance lower,
  - Magnitude attenuated
  - Wide frequency range
  - Good accuracy for dielectric constant
  - Not suitable for low losses (*)



- Cavity Methods (Resonant)
  - Resonant frequency shifted
  - Q-factor lower
  - Measurement at one frequency only
  - Accurate for dielectric constant and loss factor

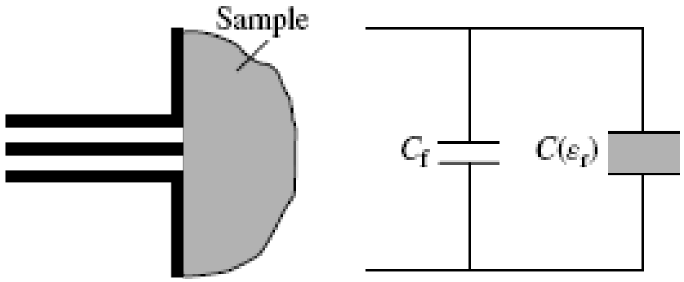
Transmission Lines

- Examples of transmission lines: waveguides of rectangular, circular section, coaxial cables, planar circuits, etc.



Reflection Method

- Reflection from open-ended coaxial probes (10 MHz-50GHz)

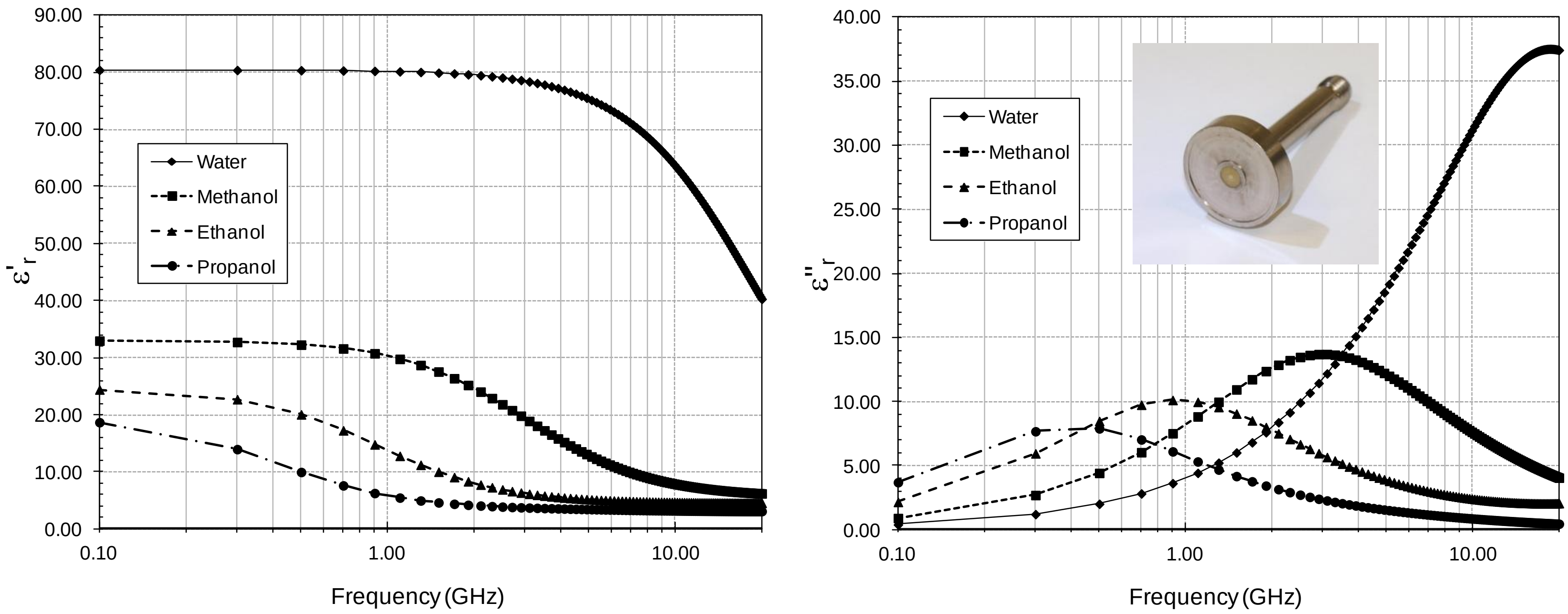


$$Y = j\omega C_f + j\omega\varepsilon C_0(\omega,\varepsilon) + \omega^4\varepsilon^{5/2}G(\omega)$$

(Coaxial), (Material), (Radiation)

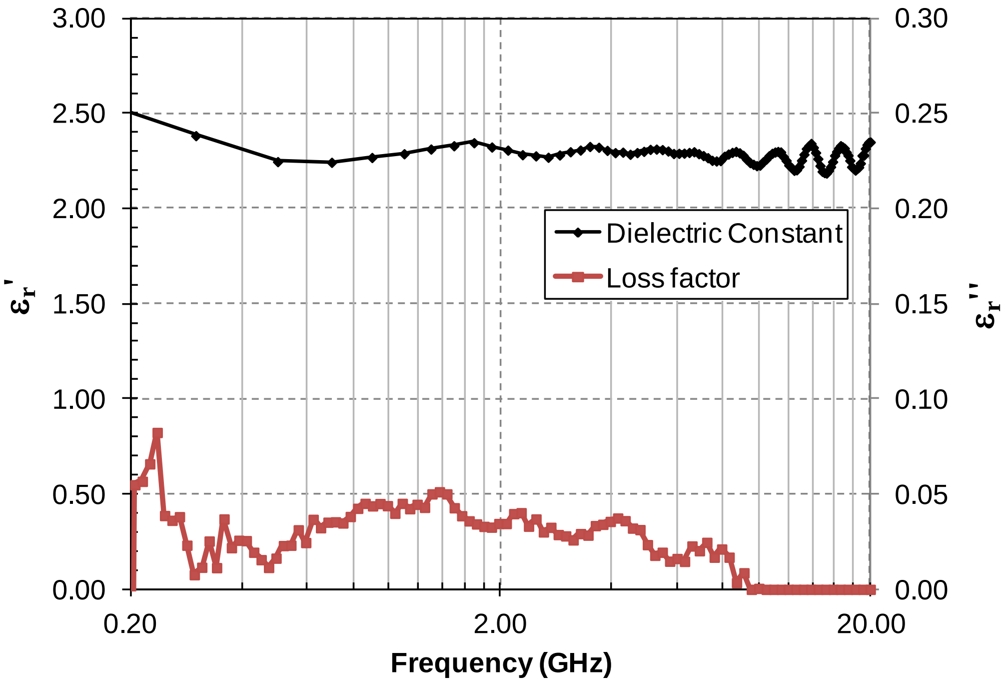
Reflection Method

- Open-ended Coaxial Probe (moderate and high loss materials)



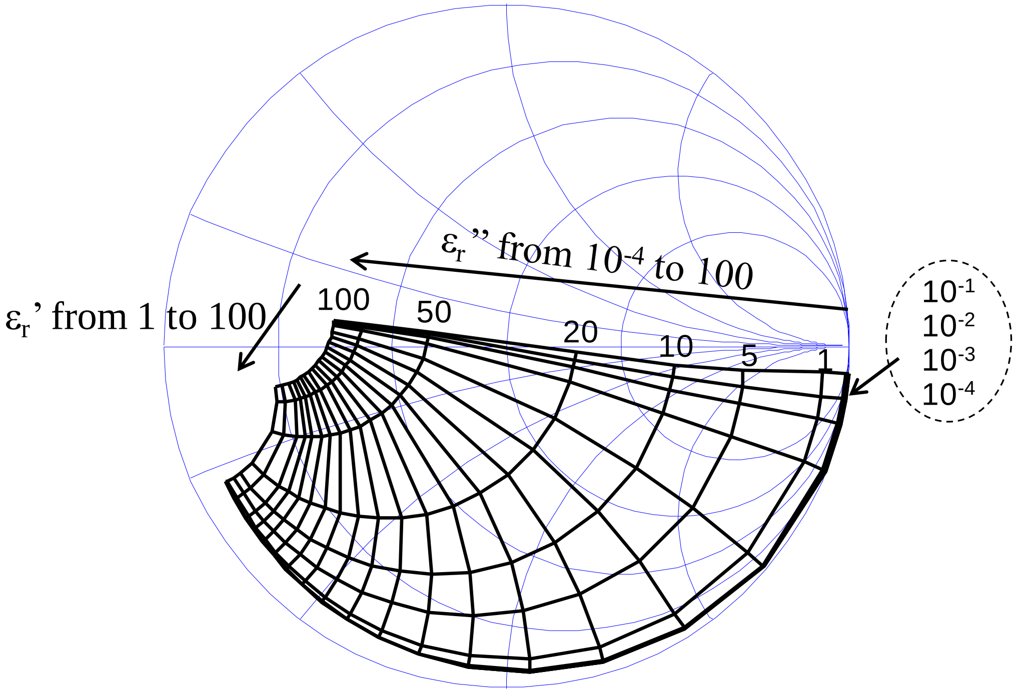
Reflection Method

- Measurement of Cyclohexane (low loss material) with an open-ended Coaxial Probe



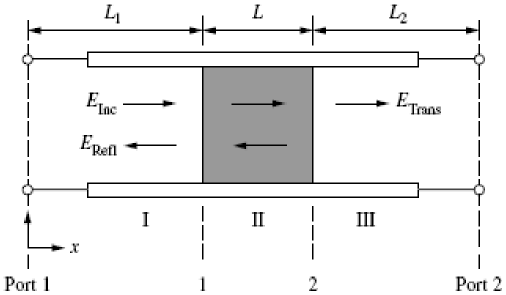
Reflection Method

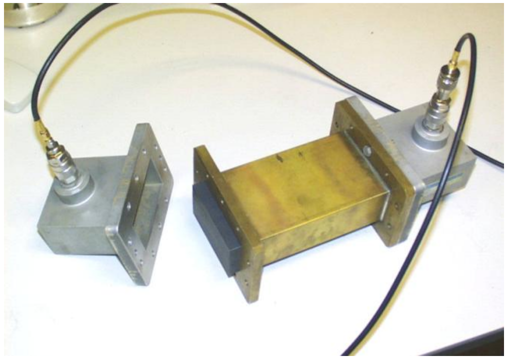
- Open-ended Coaxial Probe Mapping (5 GHz)



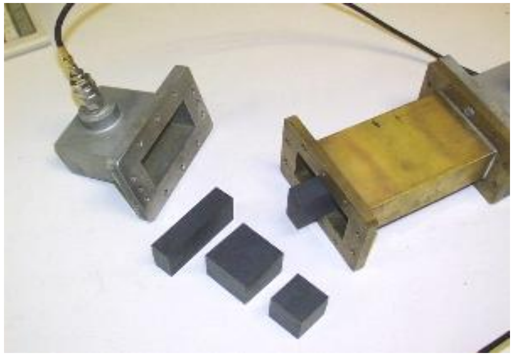
Transmission/Reflection Method

- Dielectric and Magnetic properties are feasible with these methods



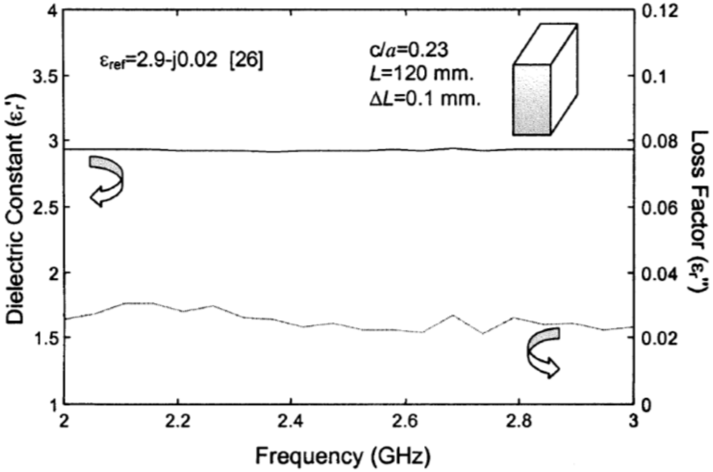


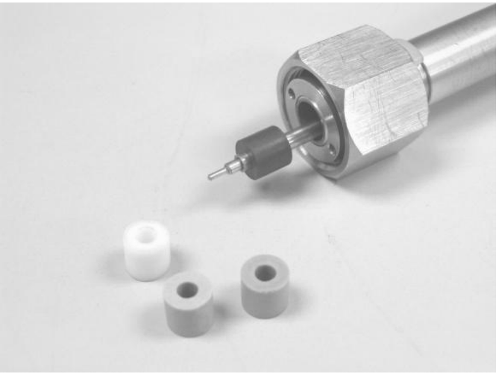
ITACA Institute, Valencia, Spain



ITACA Institute, Valencia, Spain

Catalá-Civera *et al., "Determination of Complex Permittivity of Materials with Transmission Reflection Measurements, IEEE Trans. on MTT, Vol. 51(1), 2003*



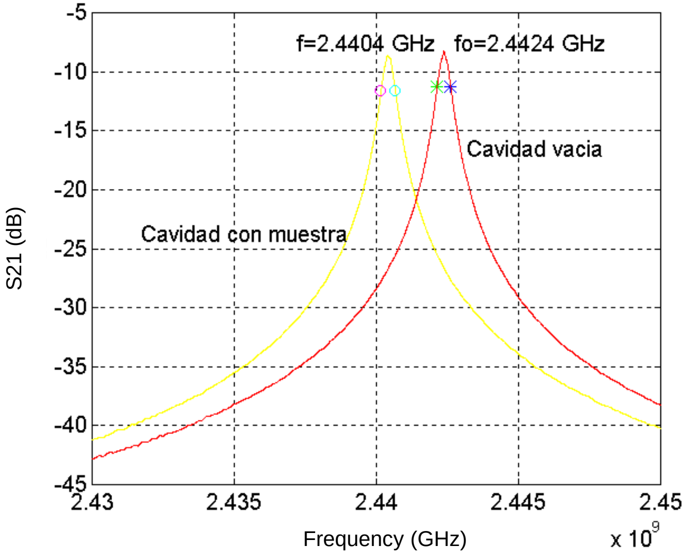


NIST, Boulder, USA

Cavity Methods (Resonant)

- Measurement of resonant frequency and Q-factor of a microwave cavity.

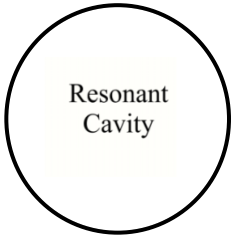
TM_{0n0} Cavity. ITACA Institute, Valencia (Spain)



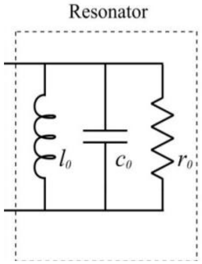
- Measuring a resonator involves using feeding mechanisms (e.g. apertures, slits, probes, current loops, microstrip gaps, etc.) that modify the original unloaded response: resonance frequency is shifted to f_L, and the quality factor is lowered to Q_L.

Unloaded/Loaded Resonant Frequencies

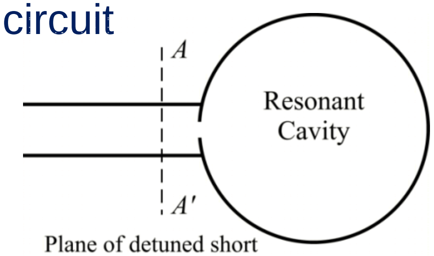
- Theoretical Cavity
  1. The resonant frequency depends on the E-fields of the resonant mode
  2. Resonant frequency named unloaded (f_U).
  3. The Q-factor depends on the losses of the cavity walls and dielectric



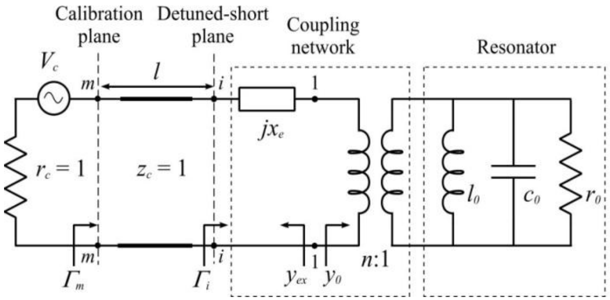
$$\frac{1}{Q_U} = \frac{1}{Q_o} + \frac{1}{Q_d}$$



- Coupled cavity
  1. The resonant frequency depends on both the E-fields of the resonant mode and the coupling circuit.
  2. Resonant frequency named loaded (f_L).
  3. The Q-factor depends on the losses of cavity walls, dielectric and coupling circuit

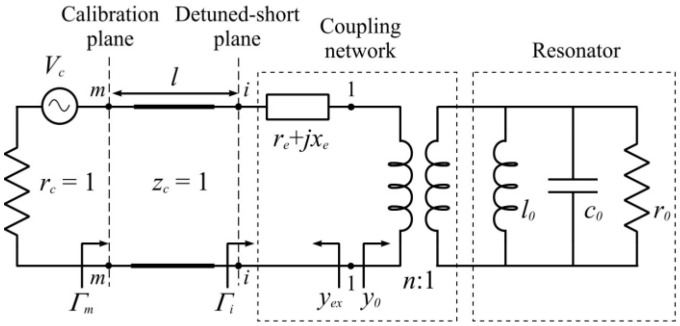


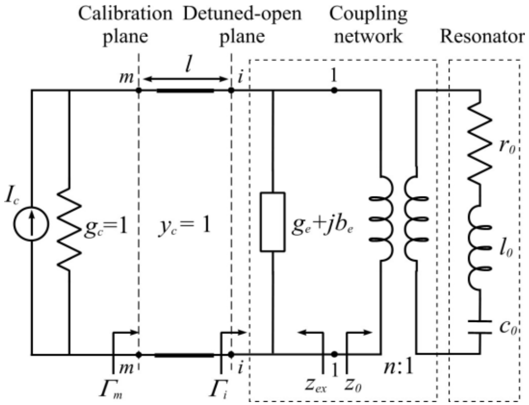
$$\frac{1}{Q_L} = \frac{1}{Q_e} + \frac{1}{Q_U}$$



Equivalent Circuits in the vicinity of the Resonance

- Foster’s forms (1 port)





$$k = \frac{P_{ex}}{P_0} = \frac{r_{ex}}{n^2 r_0} = \frac{Q_U}{Q_e}$$

$$Q_L = \frac{Q_U}{1+k}$$

$$f_L = f_U\left(1+\frac{x_e}{2\cdot Q_e}\right) = f_U\left(1+\frac{kx_e}{2\cdot Q_U}\right)$$

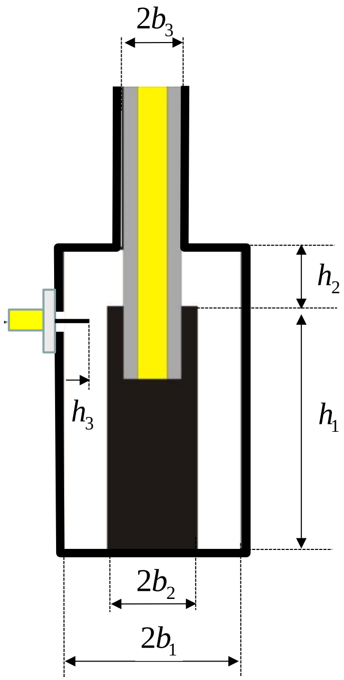
$$f_L = f_U\cdot\left(1+\frac{b_e}{2\cdot Q_e}\right)$$

- Low-loss materials (i.e. Q_{U}=5000, k=1, Q_{e}=5000, $f_{\mathrm{L}} \cong f_{\mathrm{U}}$)
- High-loss materials (i.e. Q_{U}=10, k=1, Q_{e}=10, $f_{\mathrm{L}} \neq f_{\mathrm{U}}$)

(High-loss materials require deembedding the coupling network)

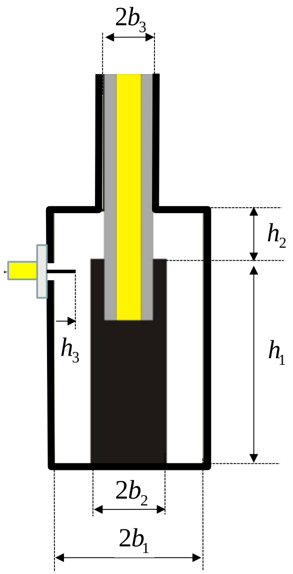
Single-post coaxial reentrant cavity

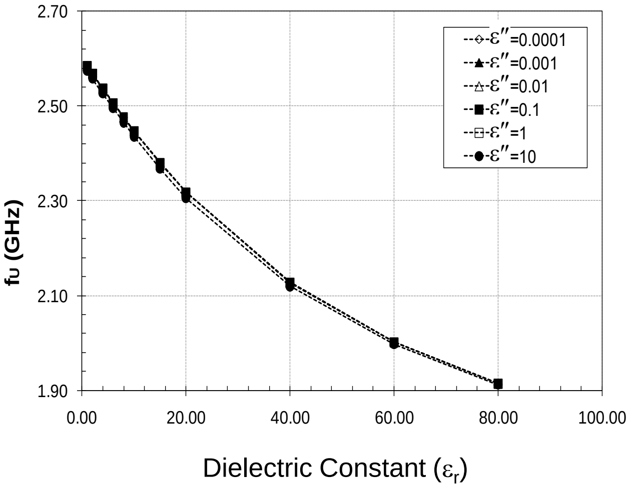
- The dielectric measurement for liquid and powder materials cell is designed as a single-post coaxial reentrant cavity with a partially dielectric filled gap.

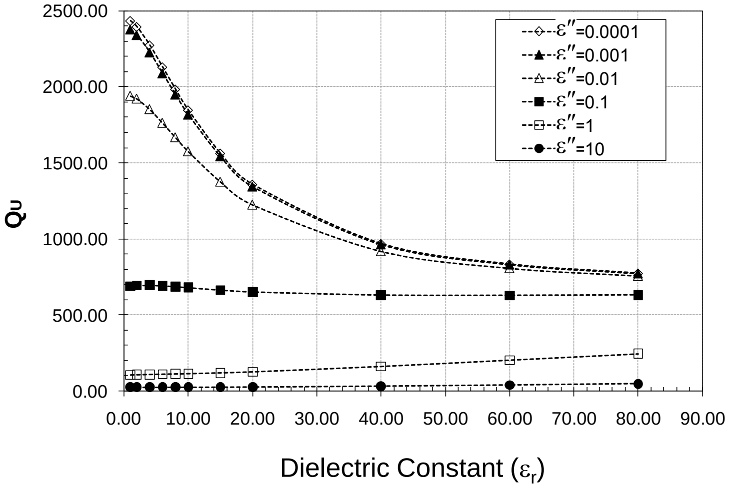


Single-post coaxial reentrant cavity

- Representation of the relationship of the dielectric properties and the resonant frequency and factor calculated by mode-matching method of the measurement cell.

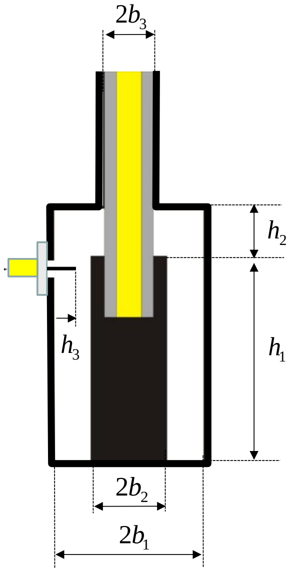


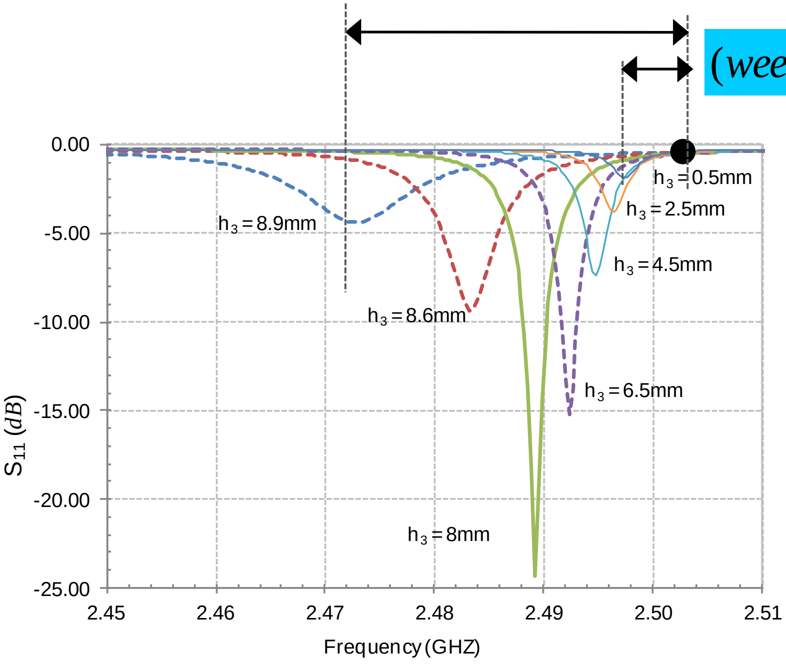




Coupling Network of the cavity

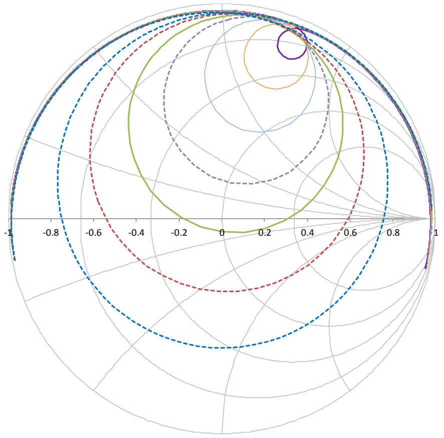
- The shift of the loaded resonant frequency (f_L) from the unloaded resonant frequency (f_U) increases as the coupling increases.
- The external Q-factor (Q_e) reduces when the coupling increases.





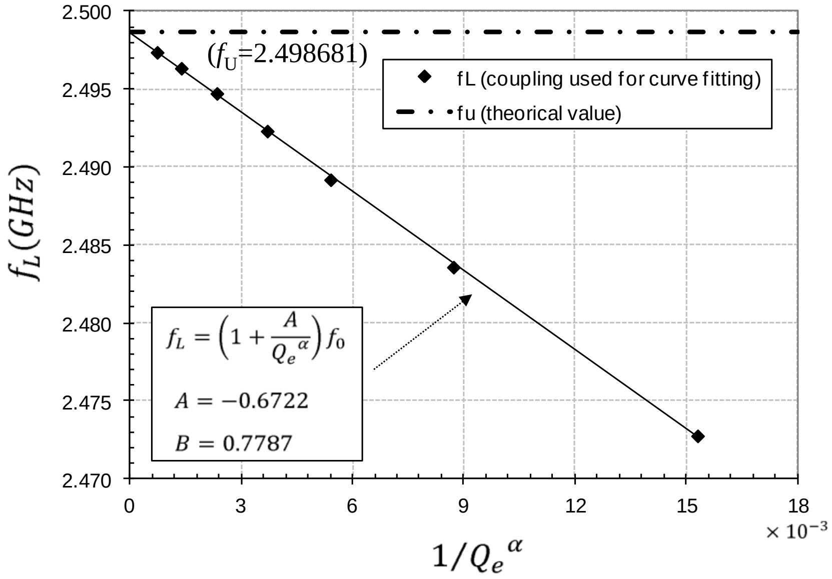
(*strong*) ↑↑ *coupling*.

(*week*) ↓↓ *coupling*.



Equivalent Circuits in the vicinity of the Resonance

- The measurement of several resonances (f_L,Q_L,Q_e) under different coupling conditions can provide the evolution of the loaded resonance (f_L) towards the unloaded resonance (f_U).



Antoni J. Canos, et al., "*A Novel Technique for Deembedding the Unloaded Resonance Frequency From Measurements of Microwave Cavities*", IEEE Trans. on MTT, Vol. 54(8), 2006.

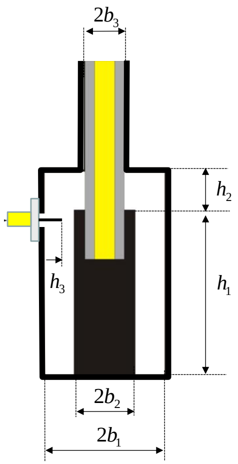
h_3 (mm)	f_L (GHz)	Q_e	Q_u	x_e
0.5	2.497397	9660.42	872.42	4.4212
2.5	2.496378	4316.41	874.23	3.9511
4.5	2.494762	2213.51	873.18	3.6117
6.5	2.492348	1238.53	873.82	3.3694
8.0	2.489226	764.57	871.35	3.2153
8.6	2.483620	416.68	871.61	3.1539
8.9	2.472800	203.80	872.87	3.1356

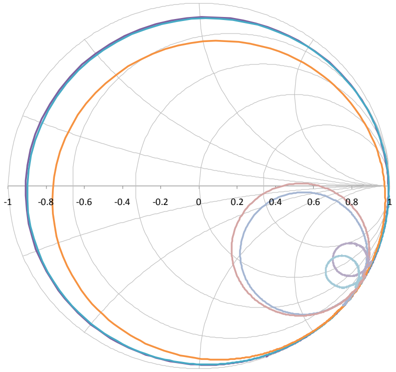
$$f_L = \left(1+\frac{A}{Q_e^\alpha}\right) f_0 \qquad (5)$$

Unloaded/Loaded Resonant Frequencies

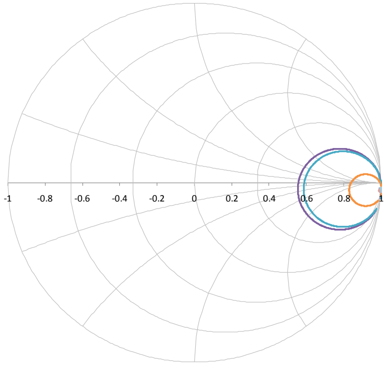
- Measurement of resonant frequency and Q-factor in a cavity with different coupling conditions (Q_e=110 and Q_e=9000).

$$\frac{1}{Q_L}=\frac{1}{Q_e}+\frac{1}{Q_o}+\frac{1}{Q_d}$$





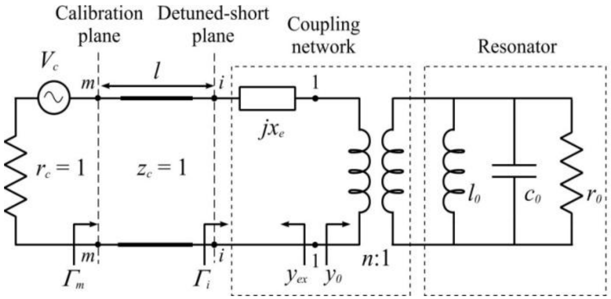
Material (25ºC)	ε'	ε''	f_L (GHz))	Q_L	f_U (GHz)	Q_U *
AIR	1.00	0	2.54110	116.38	2.57943	2859.38
Quartz sand	2.58	0.0026	2.49984	110.97	2.54002	2510.03
Oleic acid	2.44	0.0421	2.50210	102.30	2.54270	1100.02
SiC (F100)	8.91	1.3228	2.40183	39.26	2.44883	70.95
Distilled water	76.9	6.3199	1.99804	33.16	2.04598	57.44
Methanol	7.37	8.6316	2.22390	10.05	2.45345	10.7658
Ethanol	21.7	13.938	2.41113	11.00	2.29088	9.83

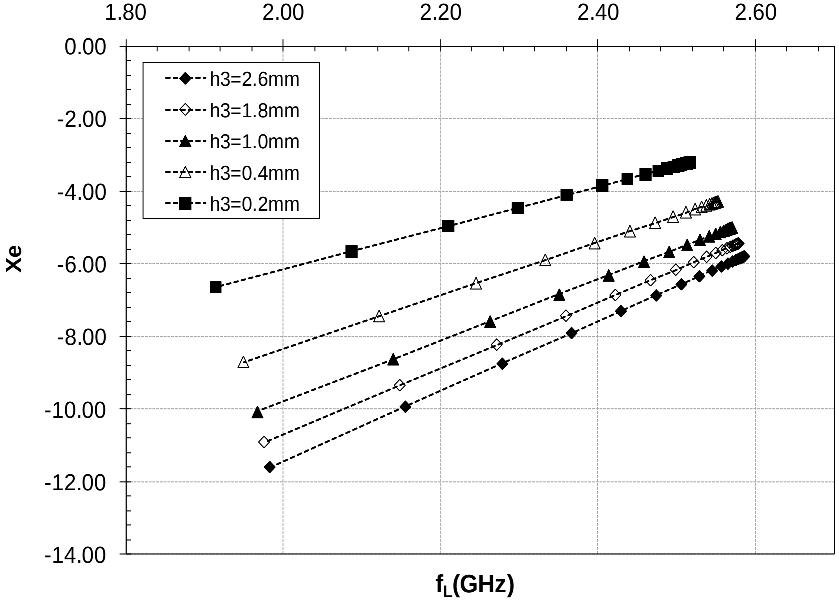


Material (25ºC)	ε'	ε''	f_L (GHz))	Q_L	f_U (GHz)	Q_U *
AIR	1.00	0	2.57866	2122.01	2.57943	2859.38
Quartz sand	2.58	0.0026	2.53957	1872.99	2.54002	2510.03
Oleic acid	2.44	0.0421	2.54175	797.63	2.54270	1100.02
SiC (F100)	8.91	1.3228	2.44801	66.28	2.44883	70.95
Distilled water	76.9	6.3199	-	-	2.04598	57.44
Methanol	7.37	8.6316	-	-	2.45345	10.7658
Ethanol	21.7	13.938	-	-	2.29088	9.83

Coupling Network of the cavity

- The microwave cavity is coupled trough a feeding network which couples the energy from the source. In this cavity, the feeding network is an electric probe which penetrates a certain distance (h_3) into the cavity.



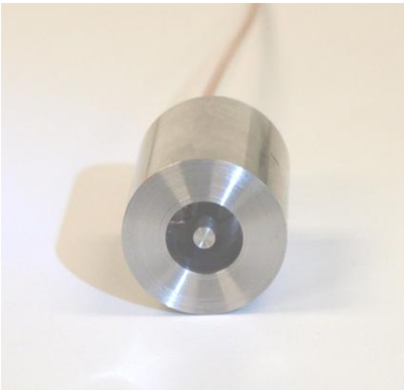


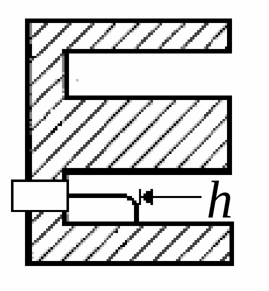
$$f_L = f_U\left(1 + \frac{k\,x_e}{2Q_U}\right) \qquad Q_L = \frac{Q_U}{1+k}$$

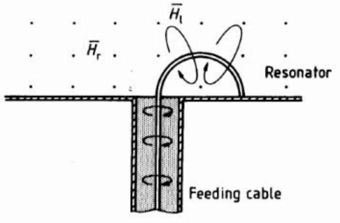
Antoni J. Canos, et al., "*A Novel Technique for Deembedding the Unloaded Resonance Frequency From Measurements of Microwave Cavities*", IEEE Trans. on MTT, Vol. 54(8), 2006.

Coupling Network of the cavity

- Open-ended coaxial resonator excited by a magnetic loop

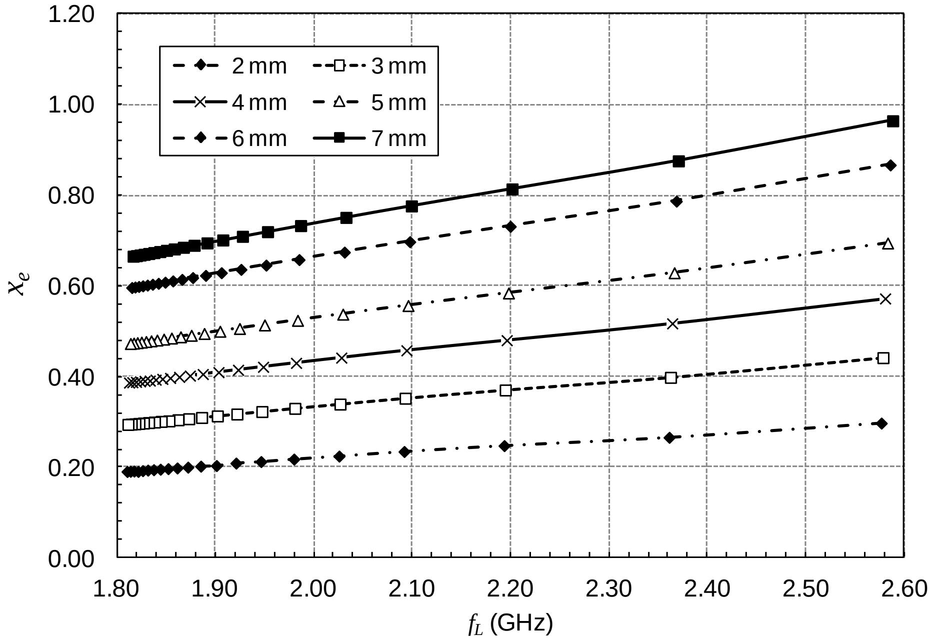




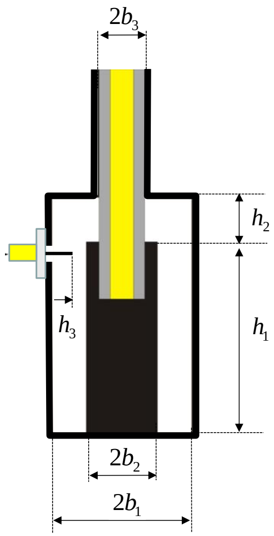


The magnetic field ($\hat{\mathbf{H}}_l$) of a coupling loop couples to the resonance mode through the magnetic field ($\hat{\mathbf{H}}_r$) perpendicular to the plane of the loop.

$$f_L = f_U\left(1 + \frac{k\,x_e}{2Q_U}\right)$$



Measurement Results



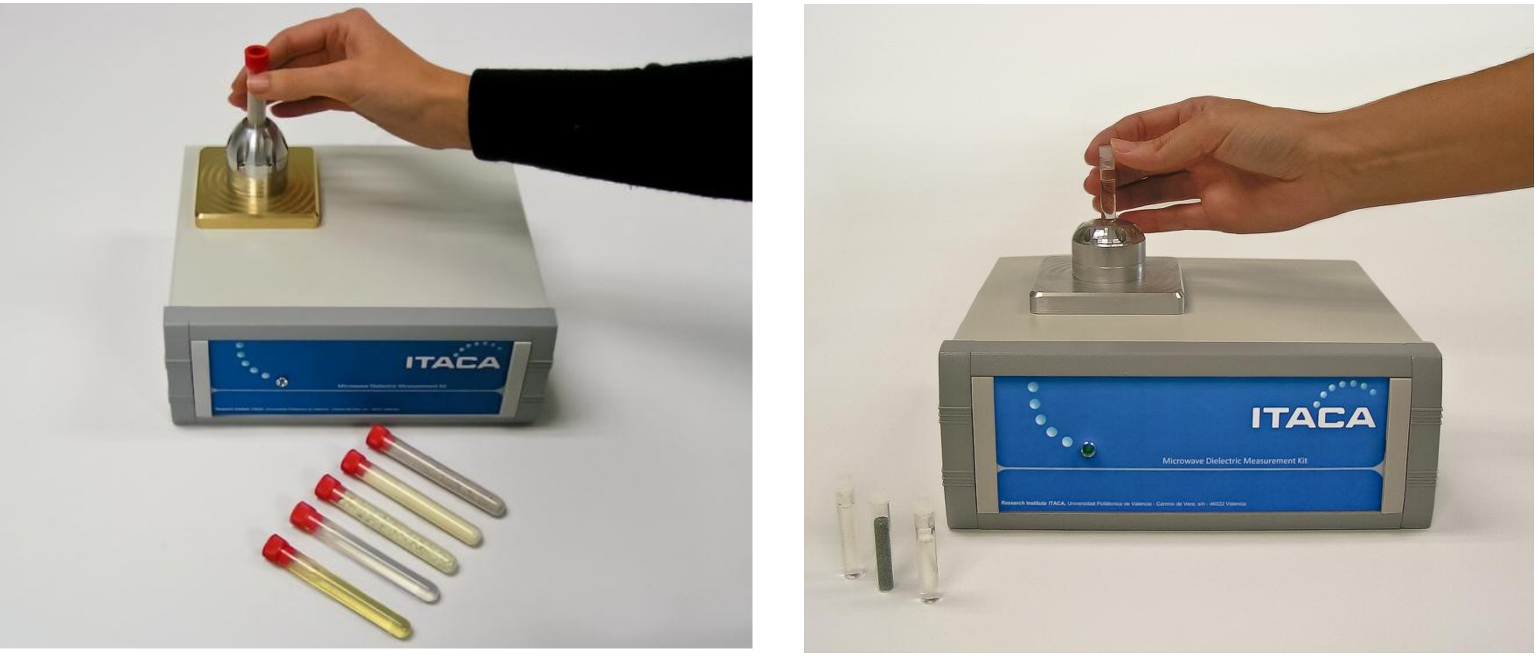
Material (25ºC)	f_U (GHz)	Q_U	ε'	ε''	ε' [Ref]	ε'' [Ref]	References
Air	2.57053	2440.13	1.00	0.0000	1.000	0.0000	
Distilled Water	1.91201	39.55	76.95	6.3250	77.83	6.789	[*]
Dimethyl Sulphoxide	2.06868	17.51	44.27	9.0110	45.02	8.966	[*]
Methanol	2.21512	7.35	23.89	14.7540	24.96	14.188	[*]
2-Propanol	2.50933	24.28	4.20	2.9250	3.89	2.724	[*]
Quartz Sand	2.54251	2086.47	2.49	0.0032	2.27	0.012	[**]
F100 – (powder)	2.44193	59.08	8.40	1.2890	8.49	1.335	[**]
Paraphyn – granulated	2.55722	2274.78	1.719	0.0008	1.77	0.011	[**]

[*] A.P. Gregory et al, "Tables of the complex permittivity of dielectric reference liquids at frequencies up to 5GHz" NPL Report MAT 23, 2009.

[**] Measurements performed with Agilent coaxial probe HP-85070B. (Not suitable for low losses materials).

Measurement Results

- Dielectric kit for Vials



Conclusions

- Transmission Line (nonresonant) techniques for dielectrics can provide accurate and broadband measurements of moderate and high loss dielectric and magnetic materials.
- Cavity techniques (resonant) provide accurate values for dielectric or magnetic low loss materials at the resonant frequencies.
- Cavity techniques (resonant) applied to high-loss materials require deembedding the coupling network of the cavity.
- The resonant cavity allows for the characterization of both low and high loss materials.
- Measurement results are in good agreement with measurements performed by other techniques.