Microwave Resonant Sensor

(Review of fundamentals)

Fernando Rangel de Sousa

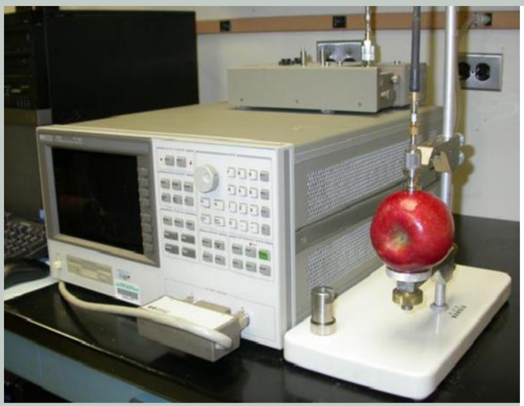
RF Laboratory

Motivation

- The motivation behind the development of resonant sensors is a very well know necessity, elegantly expressed by Lord Kelvin in the 19th century.

What do we want to know?

- Materials have distinct electrical characteristics which depend on the dielectric properties.



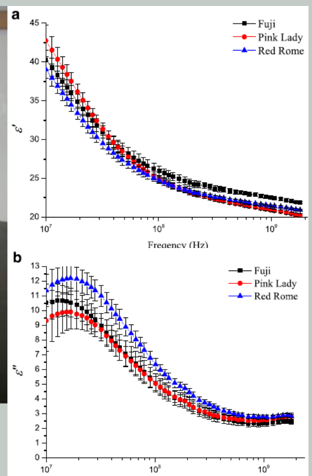


Table 1 The mean values and standard deviations of internal qualities of the three varieties of apples used in the study

Varieties	Moisture content (% wet basis)	Firmness (kg/cm^2)	Soluble solids content (%)	pH
Fuji	80.48±1.31 a *	7.52±1.39 a	18.32±1.32 a	3.64±0.22 a
Pink Lady	83.21±0.69 b	6.69±1.13 b	15.18±0.57 b	3.41±0.12 b
Red Rome	83.83±0.88 b	4.26±0.76 c	14.57±0.84 c	3.45±0.18 b

* means within a column followed by different letters are significantly different at the 5 % probability level

Apple Variety Identification Based on Dielectric Spectra and Chemometric Methods

Liang Shang · Wenchuan Guo · Stuart O. Nelson

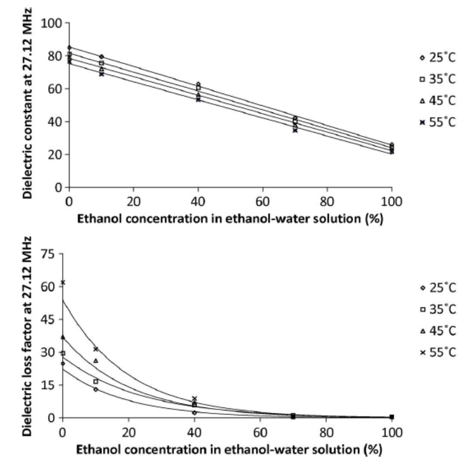


Fig. 3. Effect of ethanol concentration on the dielectric properties of ethanol–water solutions at four levels of temperatures.

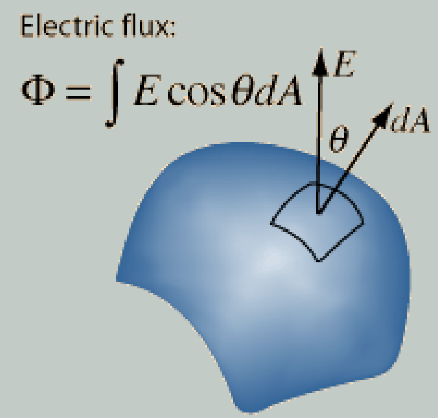
IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, VOL. 60, NO. 8, AUGUST 2011 2861

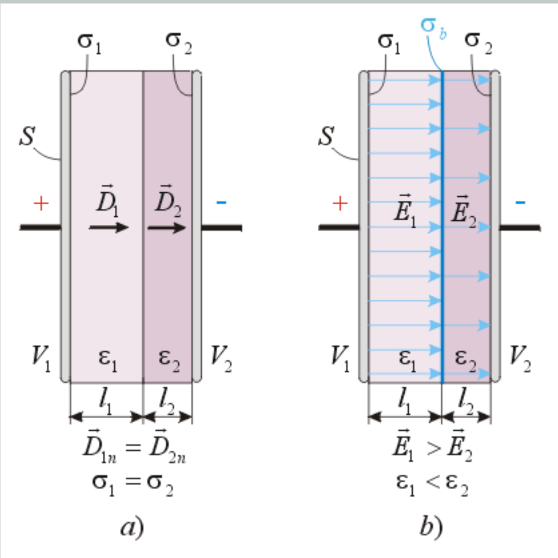
Permittivity of Mixtures of *Saponaria vaccaria* and Ethanol–Water Solution for RF Heating Assisted Extraction of Saponins

Bijay L. Shrestha and Oon-Doo Baik

Permittivity

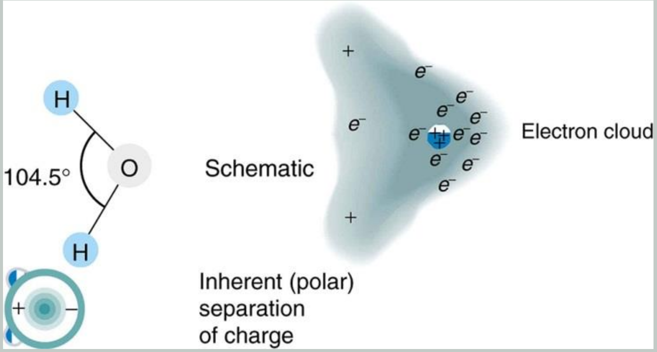
- ***Permittivity is a measure of the electric flux generated in a medium as a result of an applied electric field***
  - $\nabla \cdot \vec{D} = \rho$
  - $\vec{D} = \varepsilon_0 \vec{E} + \vec{P}$
  - $\vec{P} = \varepsilon_0 \chi \vec{E}$
  - $\vec{D} = \varepsilon_0 (1 + \chi) \vec{E} = \varepsilon_r \varepsilon_0 \vec{E}$
  - $\varepsilon_r = (1 + \chi)$

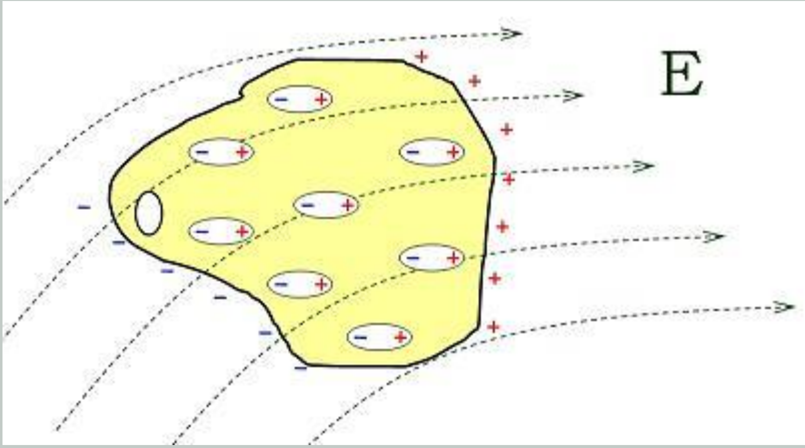


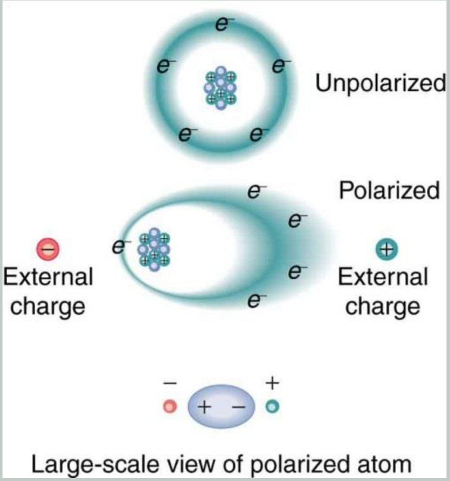


Polarization

- Dielectrics are polarized by sevral mechanisms, such as:
  - Dipolar polarization
  - Atomic and Ionic Polarization
  - Electronic polarization





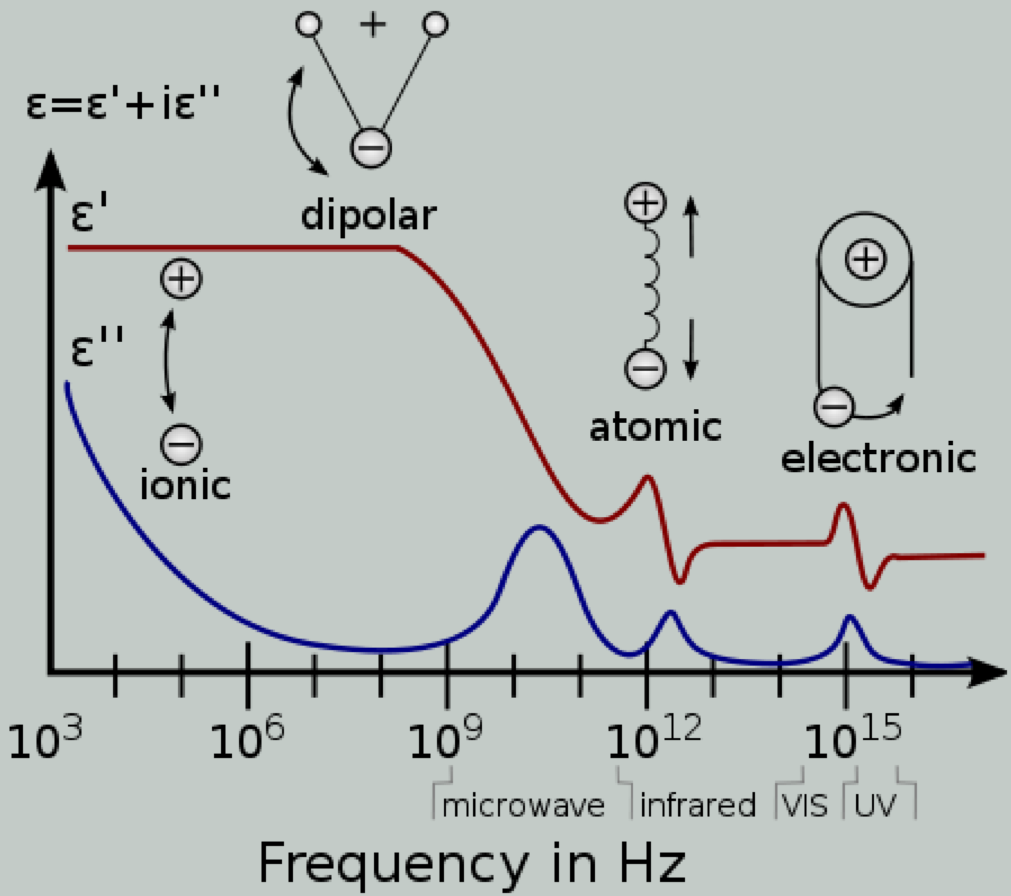


Ionic conductivity and Dielectric Losses

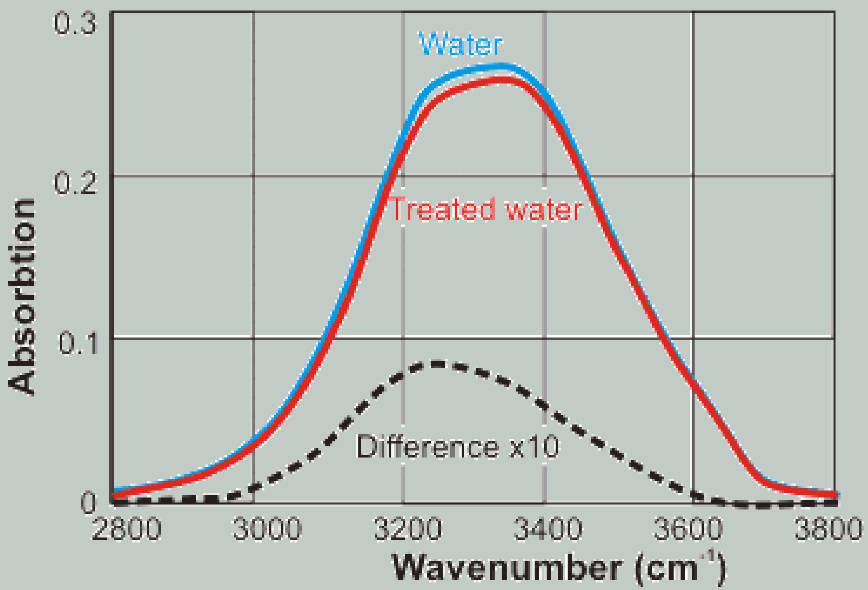
- *Materials can present conductivity (free carriers)*
  - $\vec{J} = \sigma\vec{E}$
- *Losses in dielectrics can appear due to colision of friction between atoms or molecules excited by an external field. It can be model as an imaginary term in the relative permittivity:*
  - $\varepsilon_{rd=}\varepsilon'_{rd} - j\varepsilon''_{rd}$
- *Conductivity and dielectric losses can be combined in the permittivity:*
  - $\varepsilon_{r=}\varepsilon'_{rd} - j\left(\varepsilon''_{rd} + \frac{\sigma}{\omega\varepsilon_0}\right)$

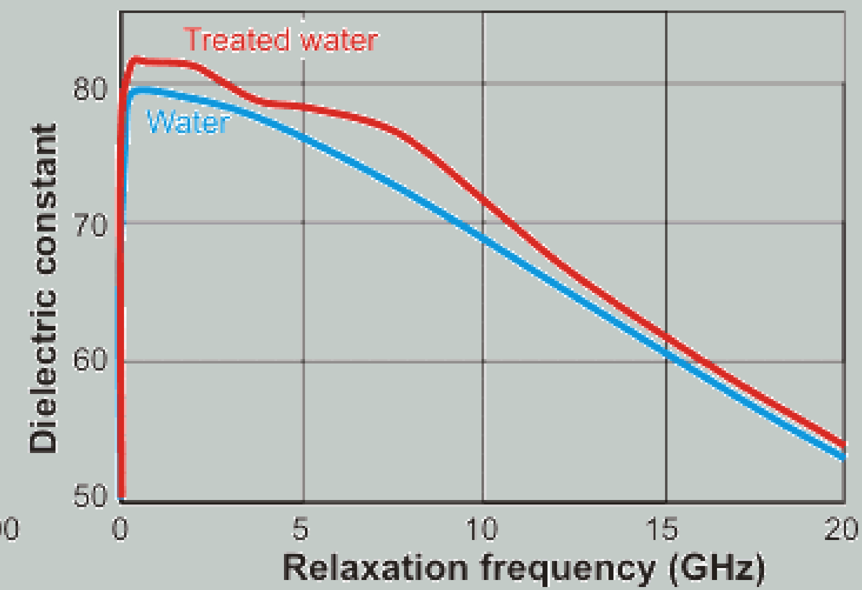
Dispersion

- *The permittivity changes with frequency: dispersion*



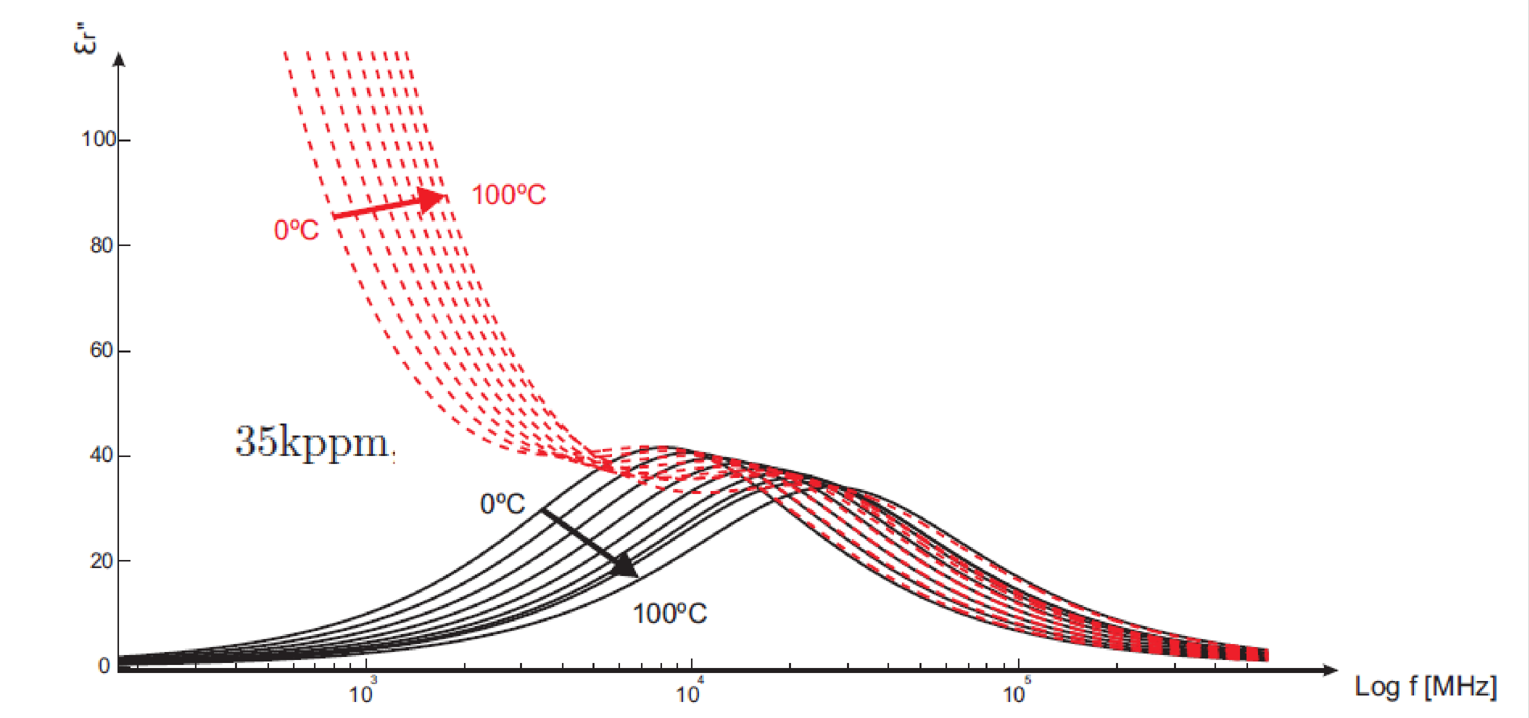
Dispersion effects of water





http://www1.lsbu.ac.uk/water/magnetic_electric_effects.html

Losses in salt water

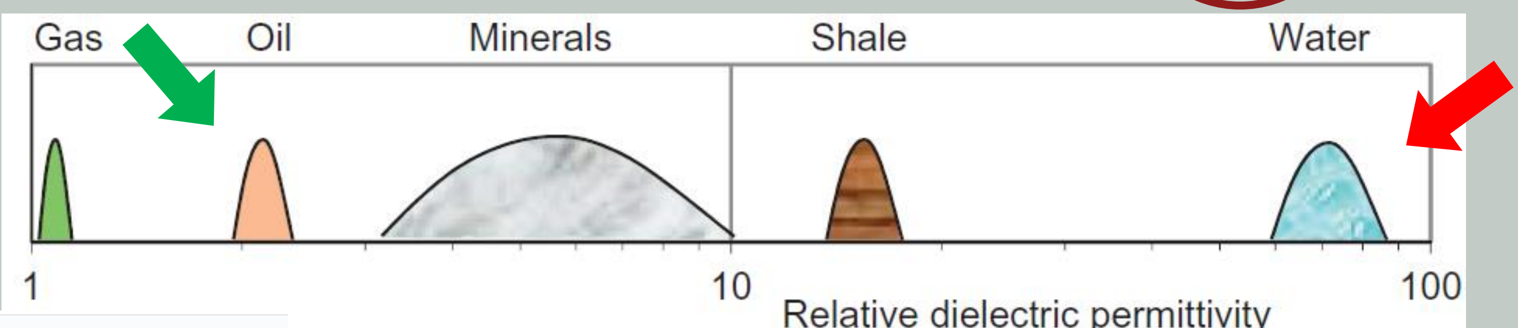


Eduardo Scussiato. Medidor de fração de água para escoamento bifásico (água e óleo) utilizando técnicas de micro-ondas e cavidades ressonantes. 2010. Dissertação (Mestrado em Engenharia de Automação e Sistemas) - Universidade Federal de Santa Catarina

Example of the permittivity of materials that form rocks

TABLE 8.8 Relative Permittivity (at Radio Frequencies) for Rock-Forming Components

Substance	ε_r	Substance	ε_r
Quartz	4.5–4.7	Gas	1
Calcite	6.4–8.5	Oil	2.2
Dolomite	6.1–7.3	Water	80
Anhydrite	5.7–6.5		
Halite	5.7–6.2	Shale (dry)	13–16



Developments in Petroleum Science
Volume 65, 2015, Pages 1–19
Physical Properties of Rocks — Fundamentals and Principles of Petrophysics

Typical properties values of materials

TABLE 8.10 Dielectric Permittivity and Properties of Electromagnetic Wave Propagation

Substance	Permittivity	Propagation Velocity (cm ns^{-1})	Attenuation (dB m^{-1})
Air	1	30	0
Dry sand	4	15	0.01
Water-saturated sand	25	6	0.03–0.3
Clay	5–40	4.7–13	1–300
Peat	60–80	3.4–3.9	0.3
Water (fresh)	80	3.4	0.1
Water (saline)	80	3.4	1000

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Developments in Petroleum Science
Volume 65, 2015, Pages 1–19
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Permittivity is affected by temperature

t	ϵ eq (5)	ϵ eq (5) $-\epsilon$ obs.	$-d\epsilon/dt$	$-\frac{1}{\epsilon}\frac{d\epsilon}{dt}$
°C				
0	87.740	------------	0.4001	4.560×10^{-3}
0.1	87.700	+0.004	----------	------------
5	85.763	−.001	.3908	4.557
10	83.832	−.002	.3817	4.553
15	81.946	−.004	.3729	4.550
20	80.103	+.003	.3642	4.547
25	78.304	+.003	.3557	4.543
30	76.546	+.006	.3475	4.539
35	74.828	−.004	.3395	4.537
40	73.151	+.002	.3317	4.534
45	71.512	+.004	.3241	4.532
50	69.910	−.007	.3167	4.530
55	68.345	.000	.3095	4.529
60	66.815	−.005	.3025	4.528
65	65.319	+.002	.2958	4.528
70	63.857	−.002	.2892	4.529
75	62.427	+.009	.2829	4.531
80	61.027	+.008	.2768	4.535
85	59.659	+.001	.2709	4.541
90	58.319	+.005	.2652	4.547
95	57.007	−.001	.2597	4.555
99	55.977	−.008	----------	------------
100	55.720	------------	.2544	4.566

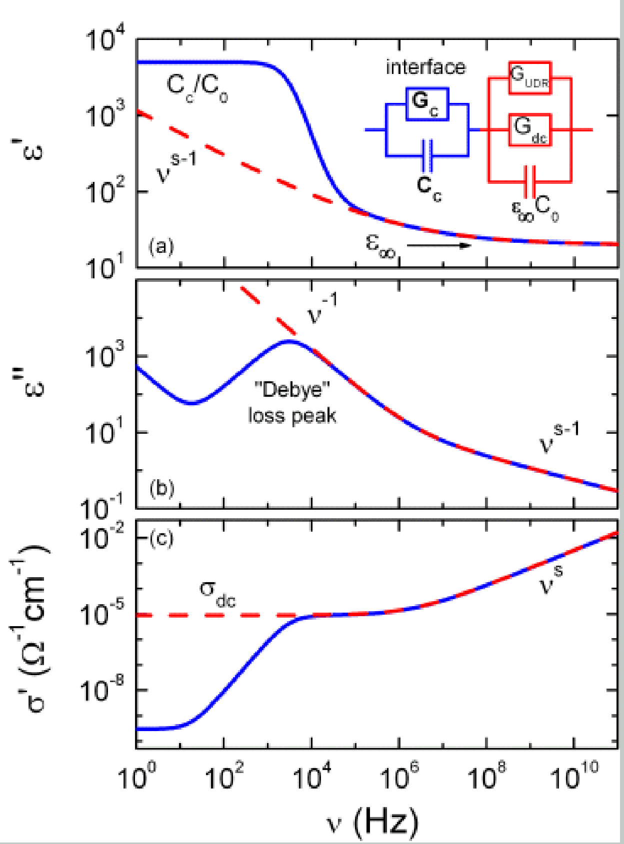
Journal of Research of the National Bureau of Standards Vol. 56, No. 1, January 1956 Research Paper 2641

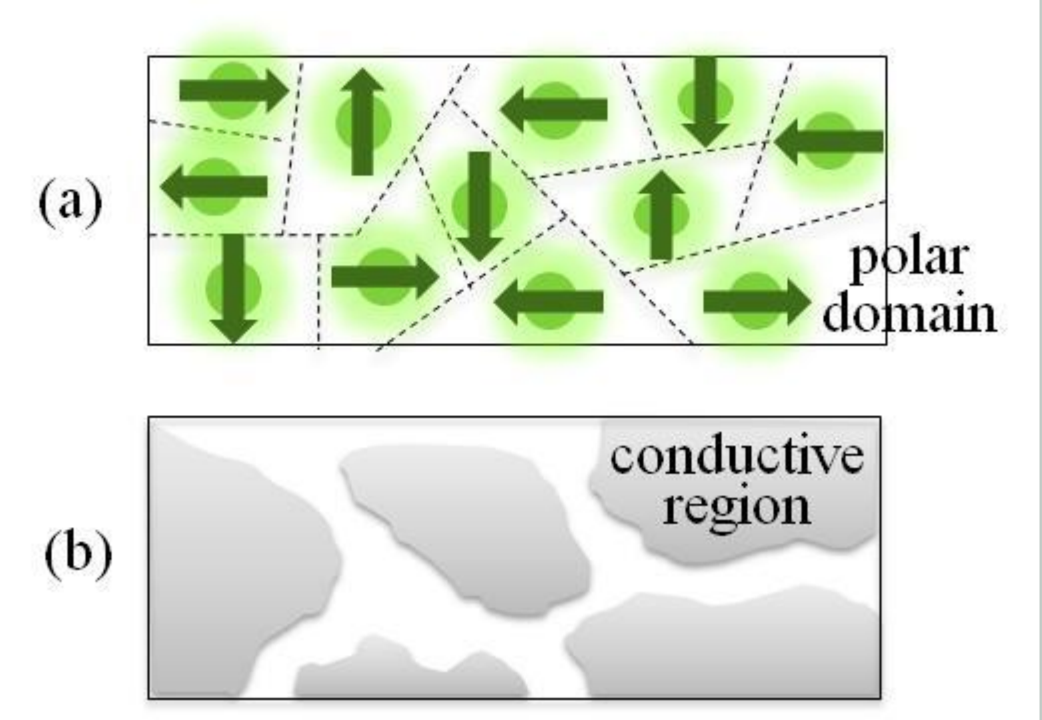
Dielectric Constant of Water from 0° to 100° C

C. G. Malmberg and A. A. Maryott

Mawell-Wegner effect

- Typical in moist wood

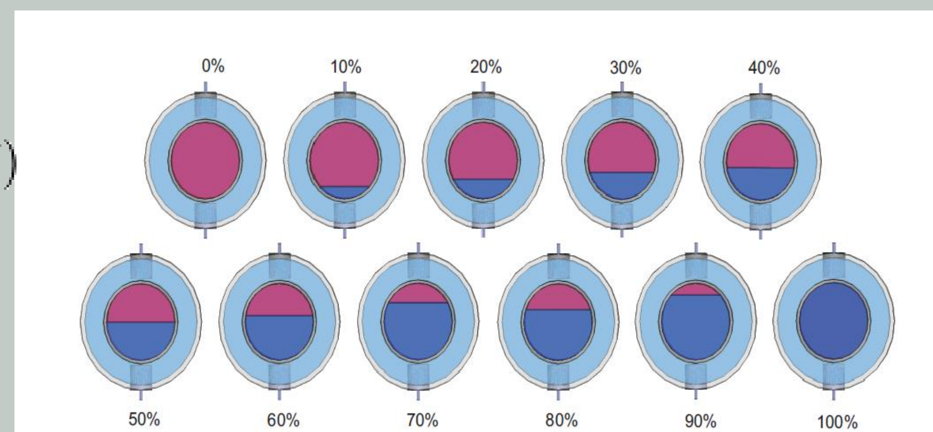




Multi-phase flow measurement

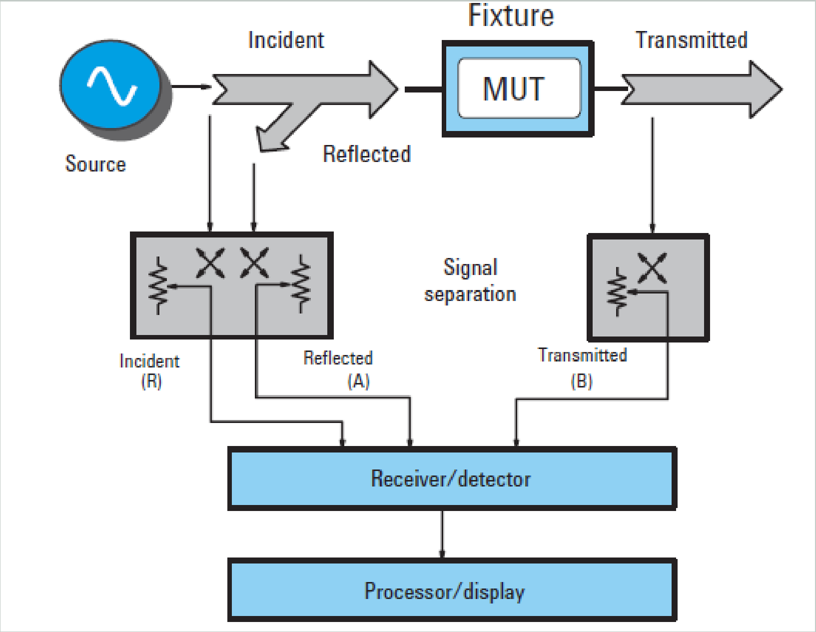
- The effective permittivity is a function of the ratio of flow constituents

$$\varepsilon_{\text{eff}} = \varepsilon_m \frac{2\delta_i(\varepsilon_i - \varepsilon_m) + \varepsilon_i + 2\varepsilon_m}{2\varepsilon_m + \varepsilon_i + \delta_i(\varepsilon_m - \varepsilon_i)}, \qquad (7)$$



Permittivity measuarement

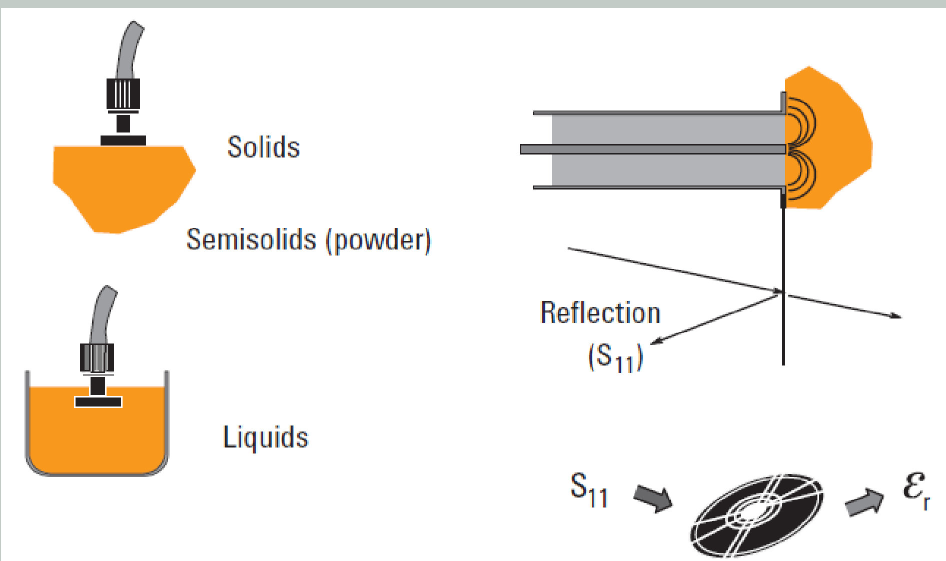
- Basically, two kind of instruments are used (together with appropriate interfaces) :
  - Impedance analyzers
  - Network analyzres

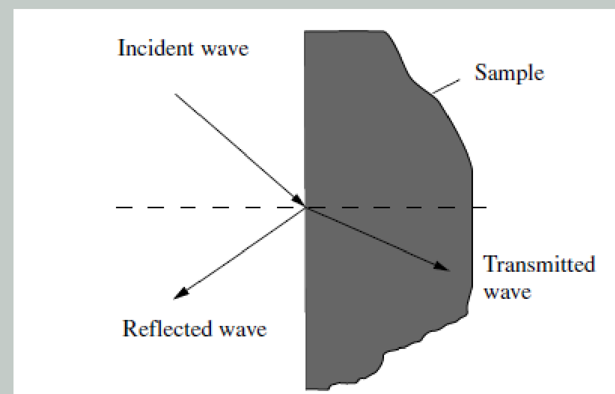


Techniques to measure the permittivity materials

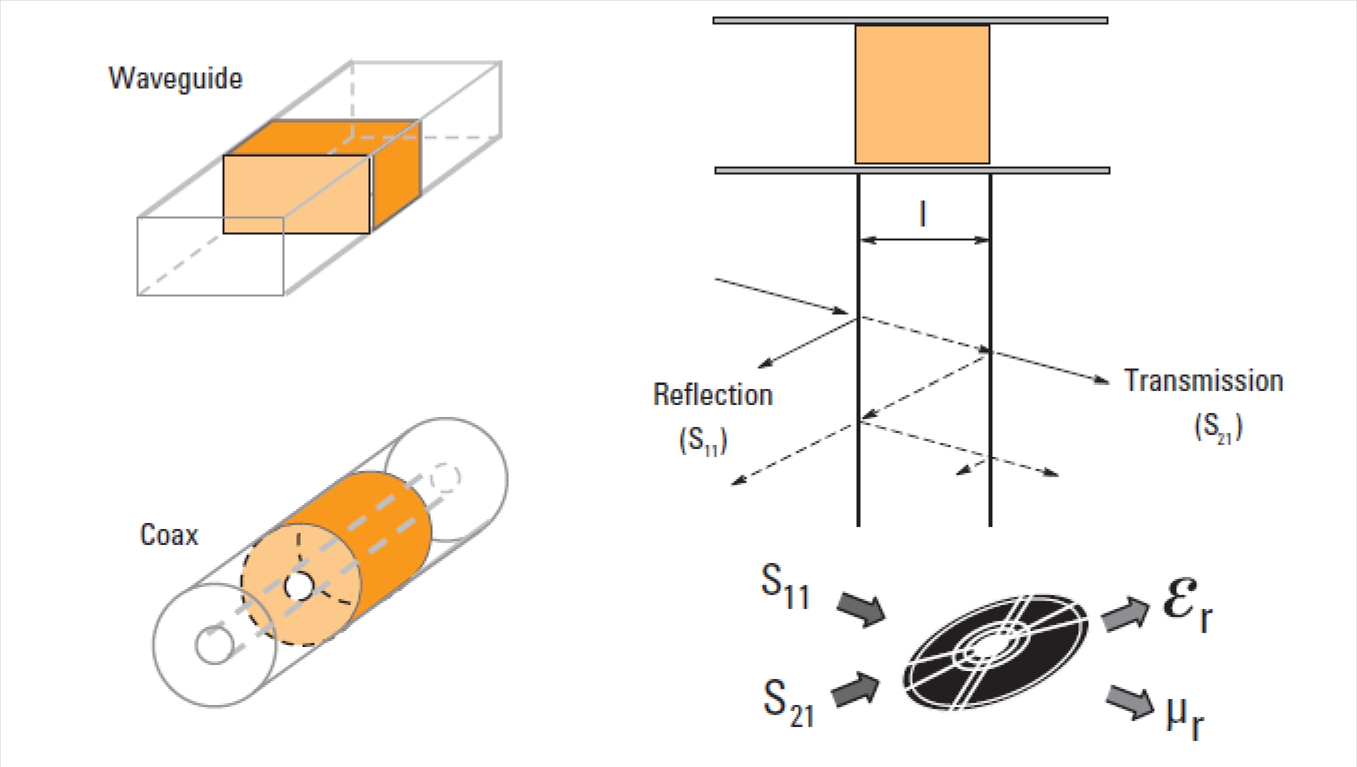
Reflection methods

- *This technique is often associated to the change on the terminatting impedance of a transmission line*

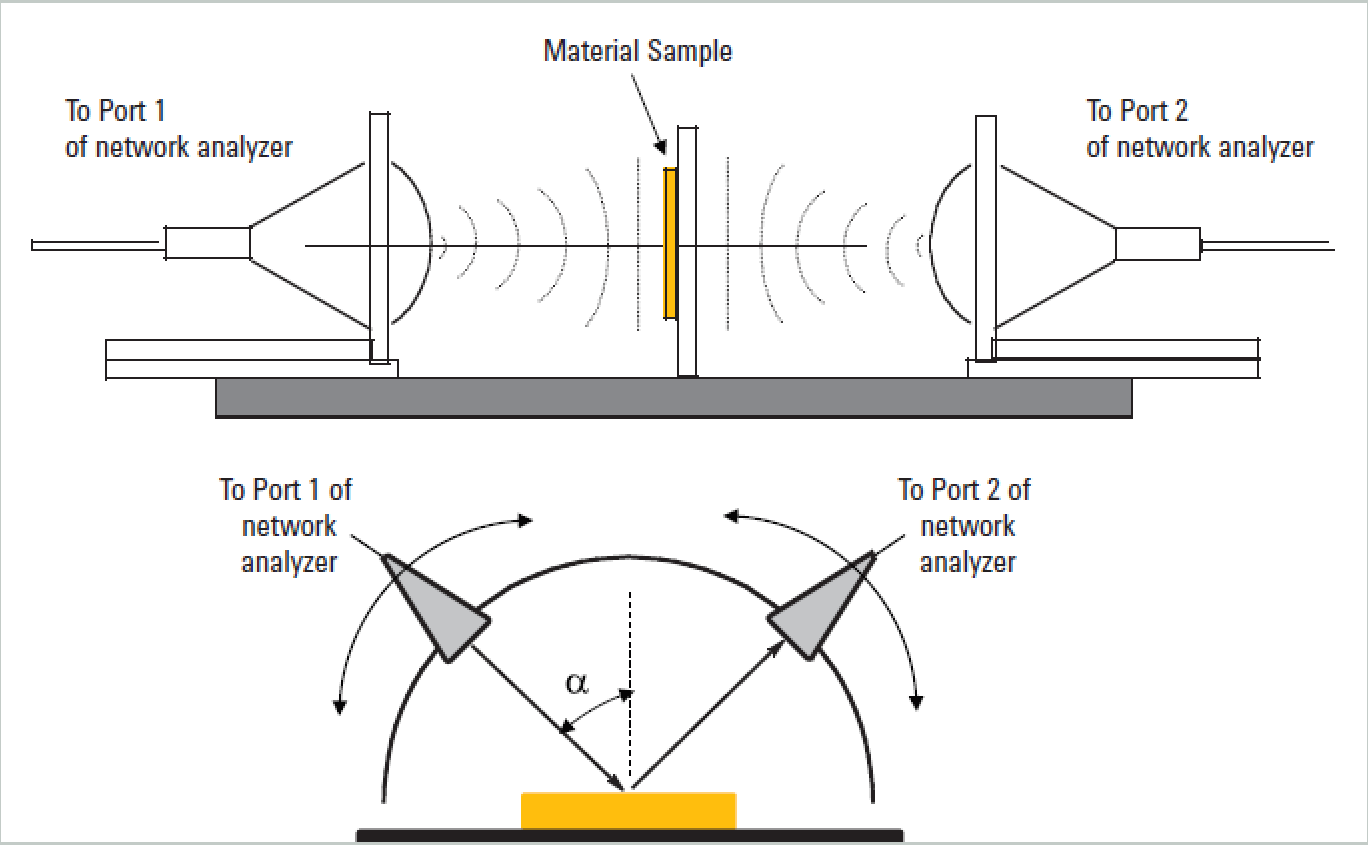




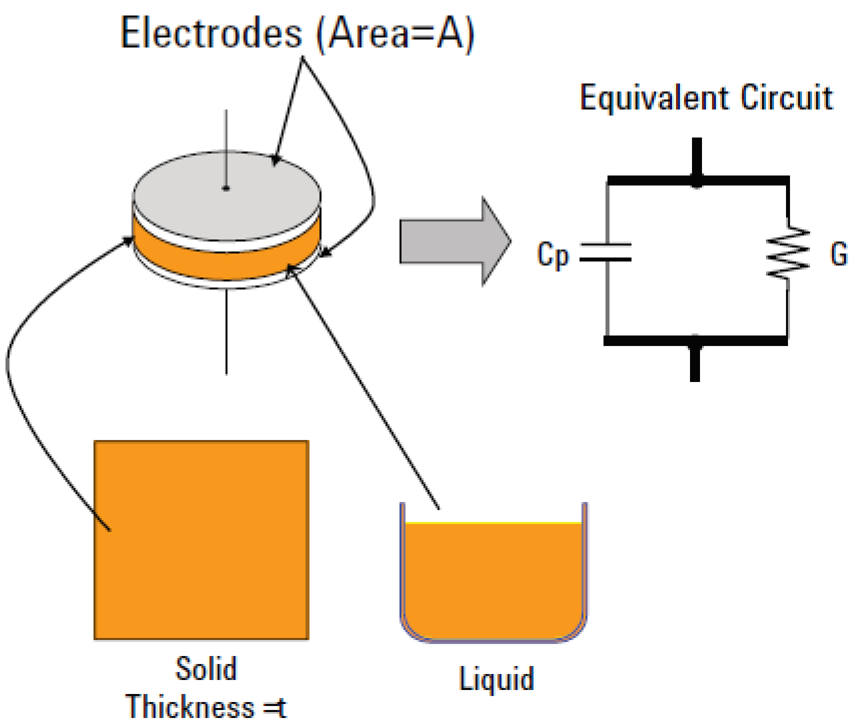
Transmission/reflection methods



Free space meaurements



Paralell plates



$$Y = G + j\omega C_p = j\omega C_0\left(\frac{C_p}{C_0} - j\frac{G}{\omega C_0}\right)$$

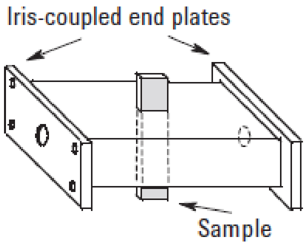
Co : Air Capacitance

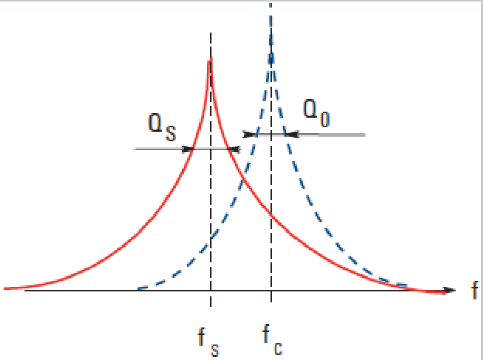
$$\begin{cases} \varepsilon_r^* = \dfrac{C_p}{C_0} - j\dfrac{G}{\omega C_0} \\[2ex] \varepsilon_r' = \dfrac{t \cdot C_p}{A \cdot \varepsilon_0} \\[2ex] \varepsilon_r'' = \dfrac{t}{\omega \cdot R_p \cdot A \cdot \varepsilon_0} \end{cases}$$

Resonant method

$$\varepsilon_r' = \frac{V_c(f_c - f_s)}{2V_s f_s} + 1$$

$$\varepsilon_r'' = \frac{V_c}{4V_s}\left(\frac{1}{Q_s} - \frac{1}{Q_c}\right)$$

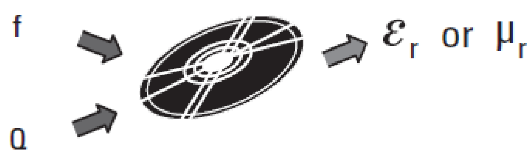




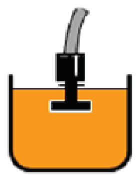
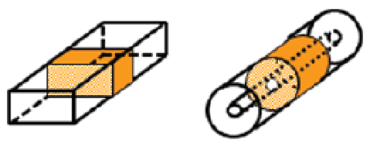
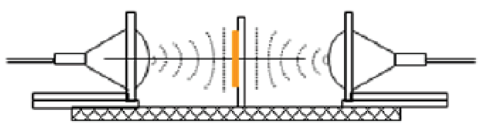
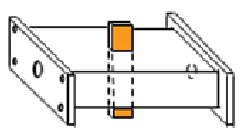
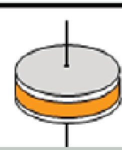
V is the volume

index c is for the empty cavity,

index s is for the sample loaded



Comparison of the methods

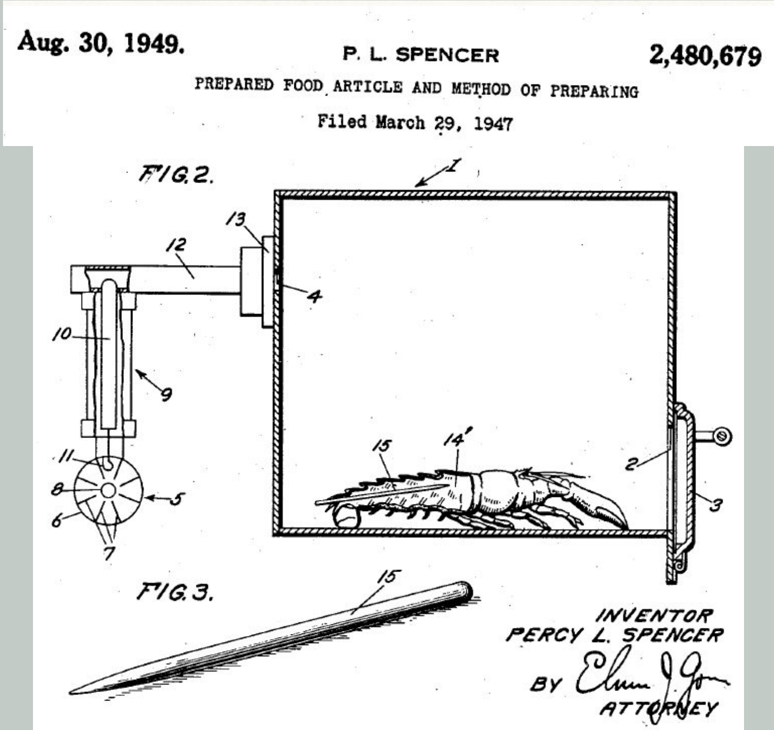
Coaxial Probe ε_r		Broadband, convenient, non-destructive Best for lossy MUTs; liquids and semi-solids
Transmission Line ε_r and μ_r		Broadband Best fpr lossy to low loss MUTs; machineable solids
Free Space ε_r and μ_r		Broadband; Non-contacting Best for flats sheets, powders, high temperatures
Resonant Cavity ε_r		Single frequency; Accurate Best for low loss MUTs; small samples
Parallel Plate ε_r		Accurate Best for low frequencies; thin, flat sheets

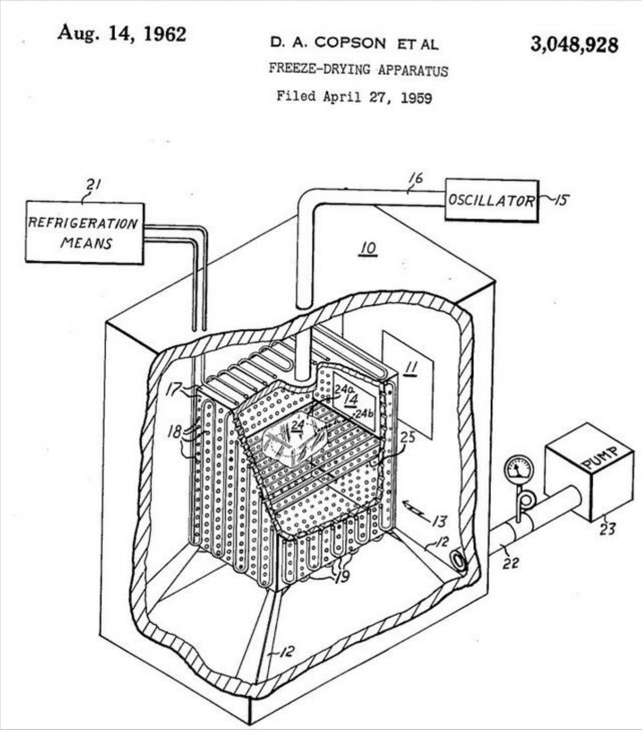
Resonant sensors

INTRODUCTION TO DESIGN

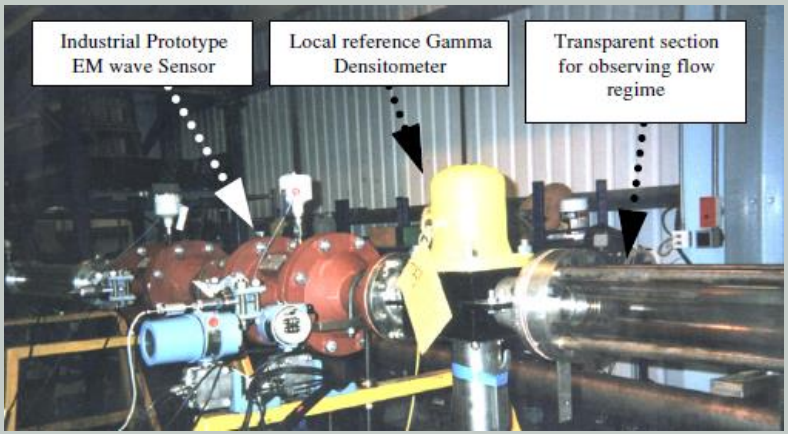
History

- Resonant sensors have been used for long time ago, e.g., microwave heating,



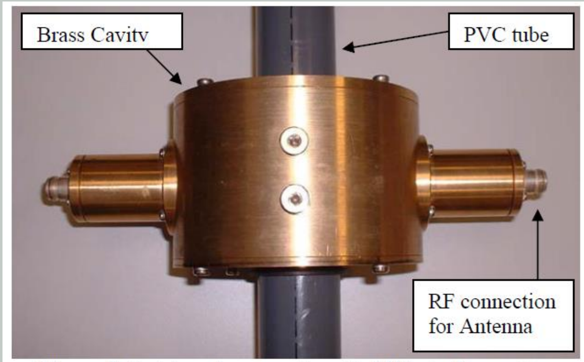


State-of-the-art



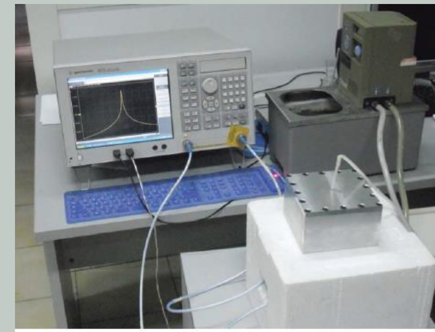
RF sensor for multiphase flow measurement through an oil pipeline

S R Wylie, A Shaw and A I Al-Shamma'a



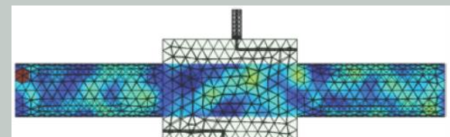
An electromagnetic cavity sensor for multiphase measurement in the oil and gas industry

S Al-Hajeri, S R Wylie, R A Stuart and A I Al-Shamma'a
Liverpool John Moores University, General Engineering Research Institute, RF and Microwave Group, Byrom Street, Liverpool, L3 3AF, UK



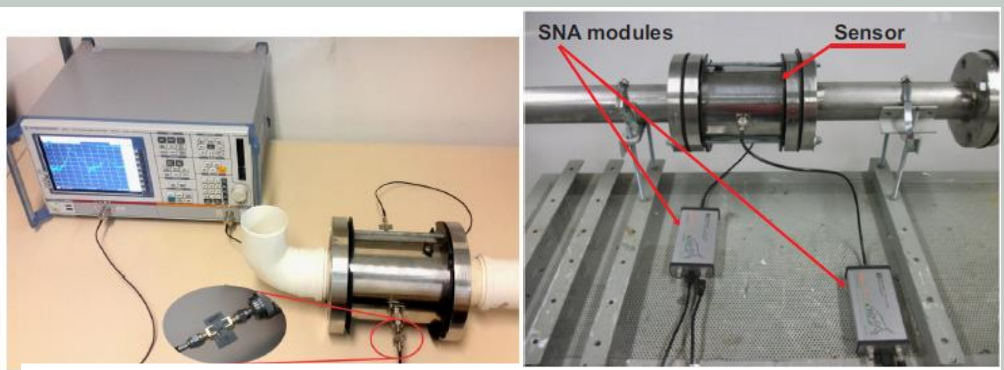
A Microwave Resonant Sensor for Concentration Measurements of Liquid Solutions

Gianluca Gennarelli, Stefania Romeo, Maria Rosaria Scarfi, and Francesco Soldovieri, *Member, IEEE*



Microwave Resonator Sensor for Detection of Dielectric Objects in Metal Pipes

Johan Nohlert*, Thomas Rylander*, Tomas McKelvey*

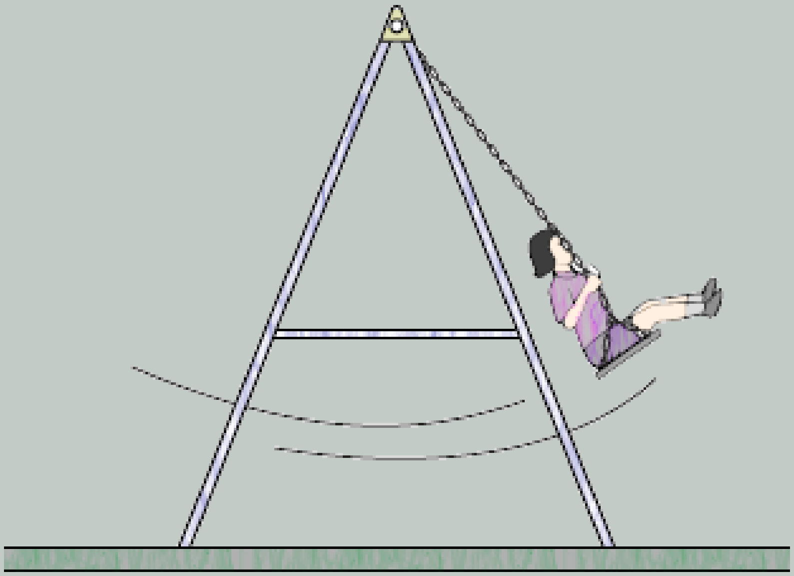


Improving the performance of an RF resonant cavity water-cut meter using an impedance matching network

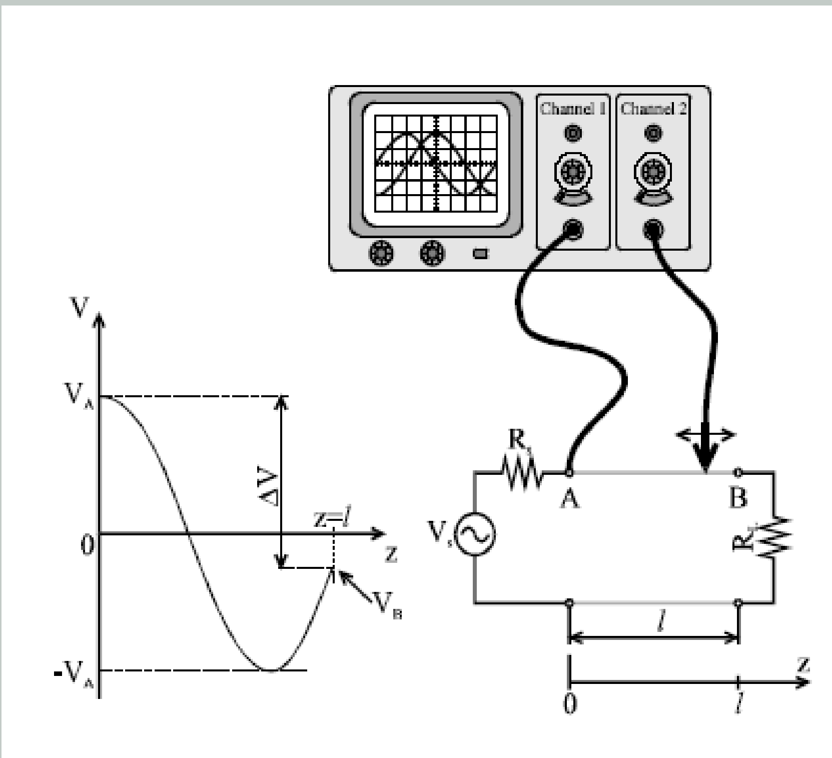
Heron Eduardo de Lima Ávila [a,b,*], Daniel J. Pagano [b], Fernando Rangel de Sousa [a]

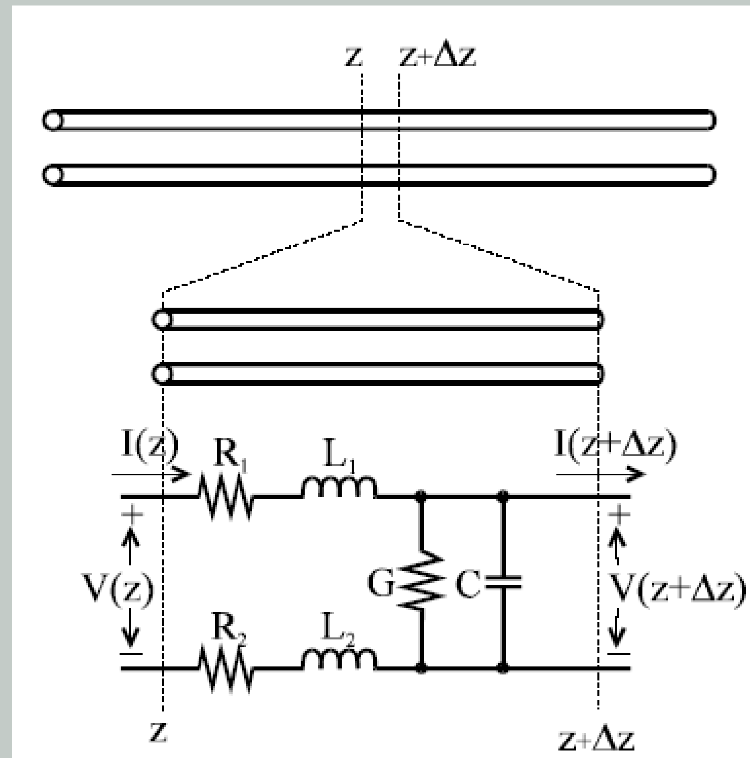
Resonance

- Resonance is about coherence. In the case of the swig, it happens between kinect and potential energy exchanges.

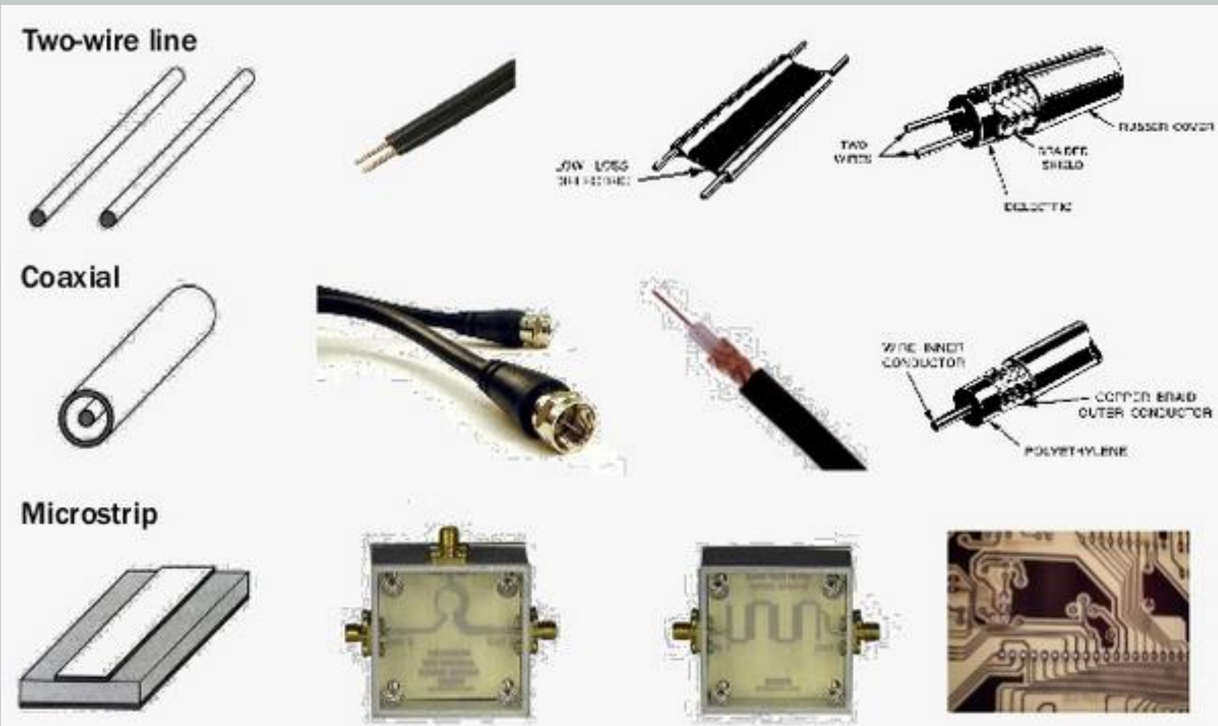


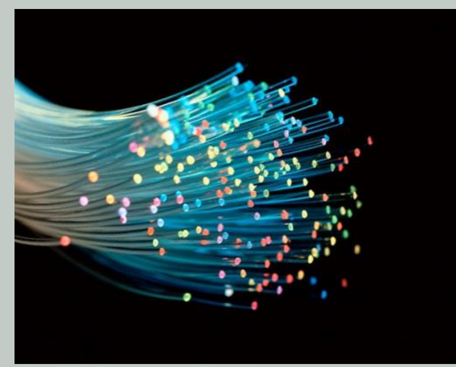
Transmission lines



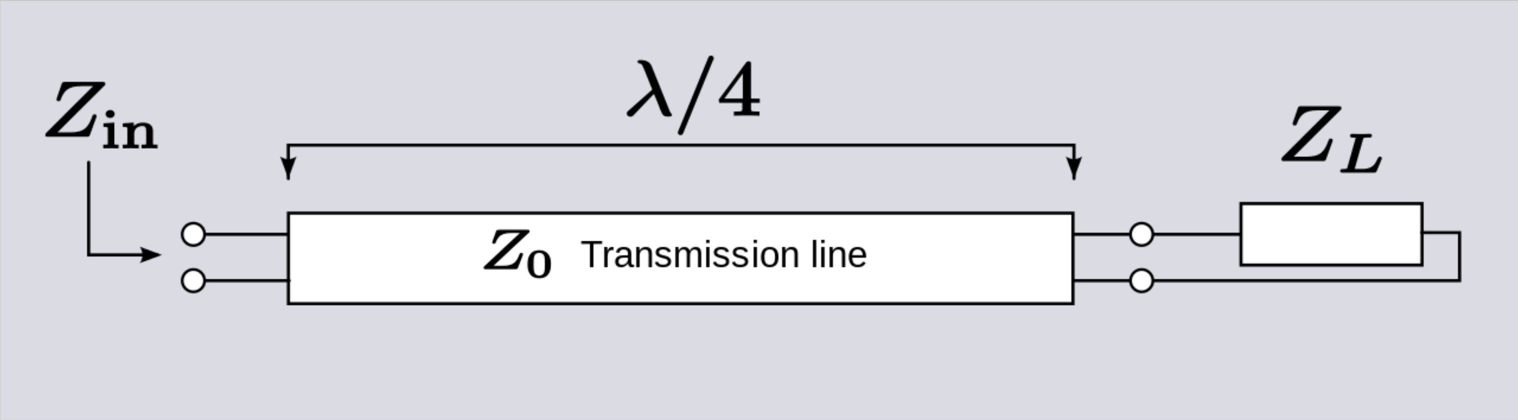


Typical transmission lines

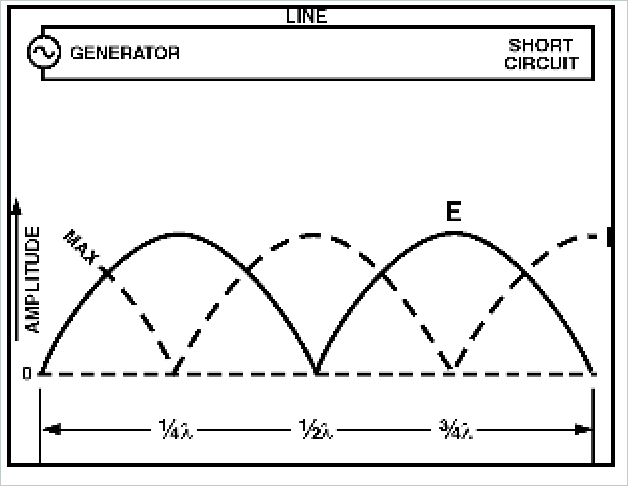




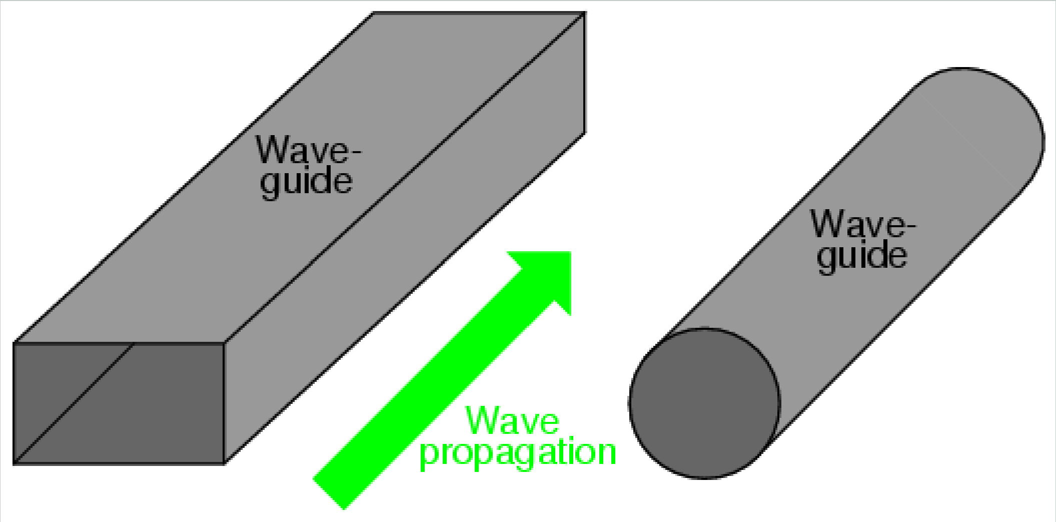
Quarter-wave resonator

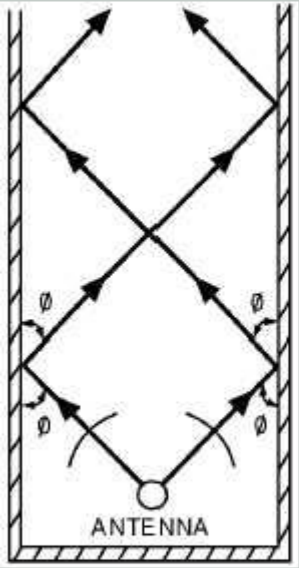


$$Z_{IN}(\lambda/4) = \frac{Z_0^2}{Z_L}$$

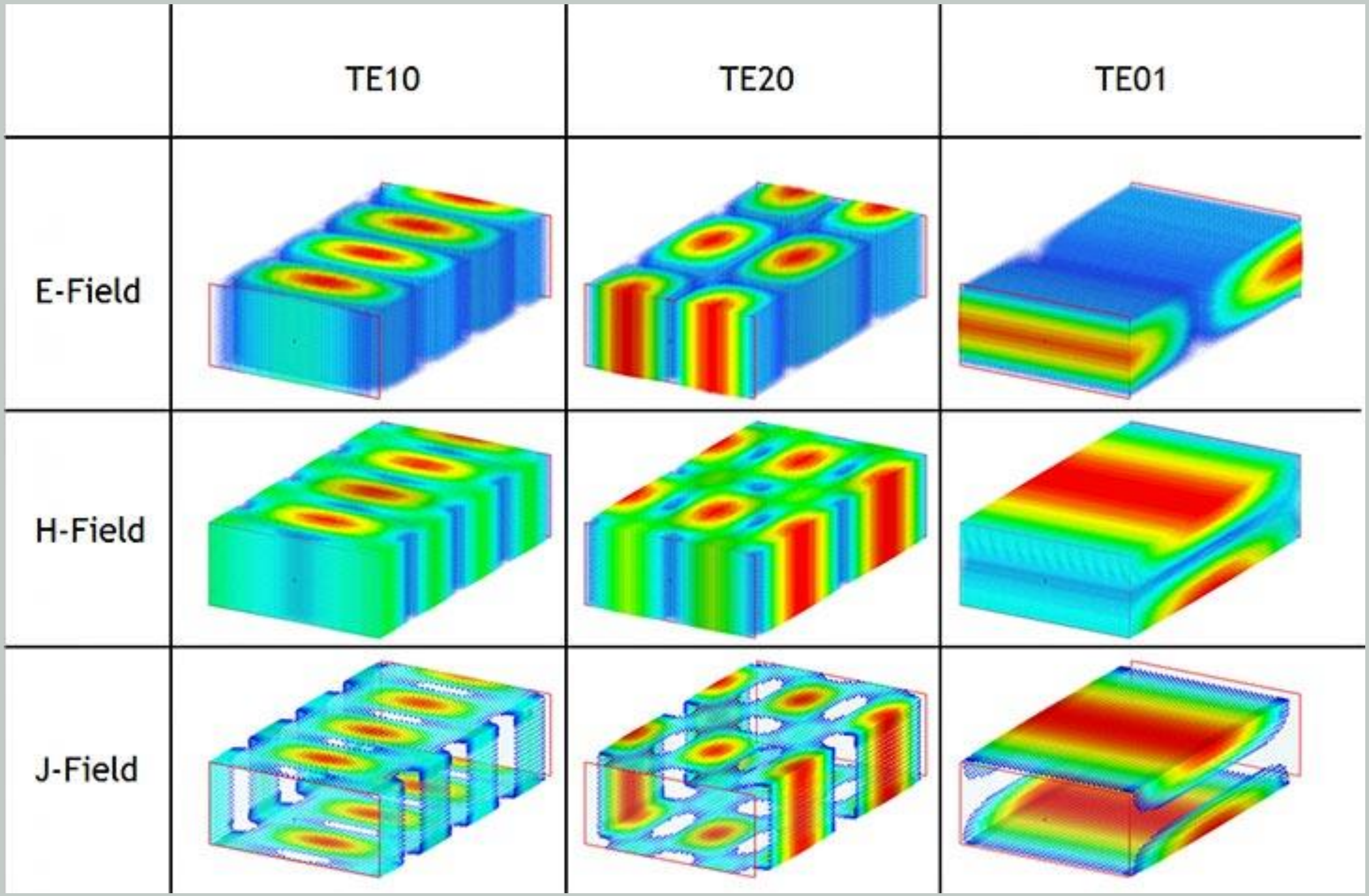


Waveguide

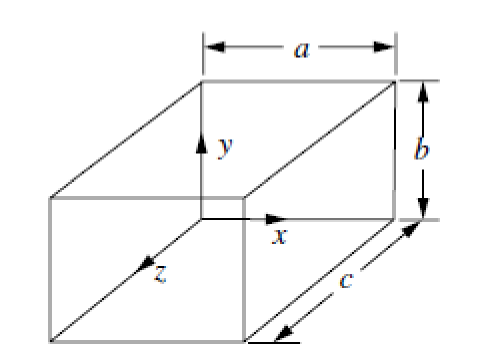


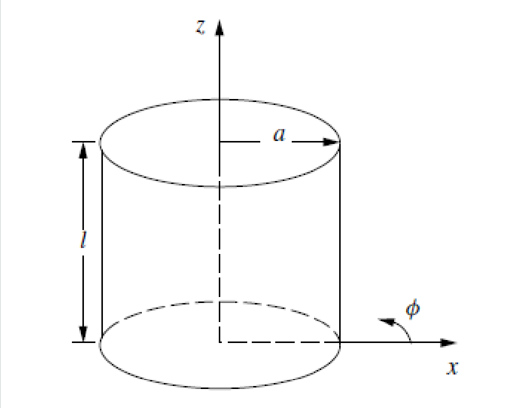


Propagation modes



Waveguide resonators





$$\lambda_0 = \frac{2}{\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{p}{c}\right)^2}}$$

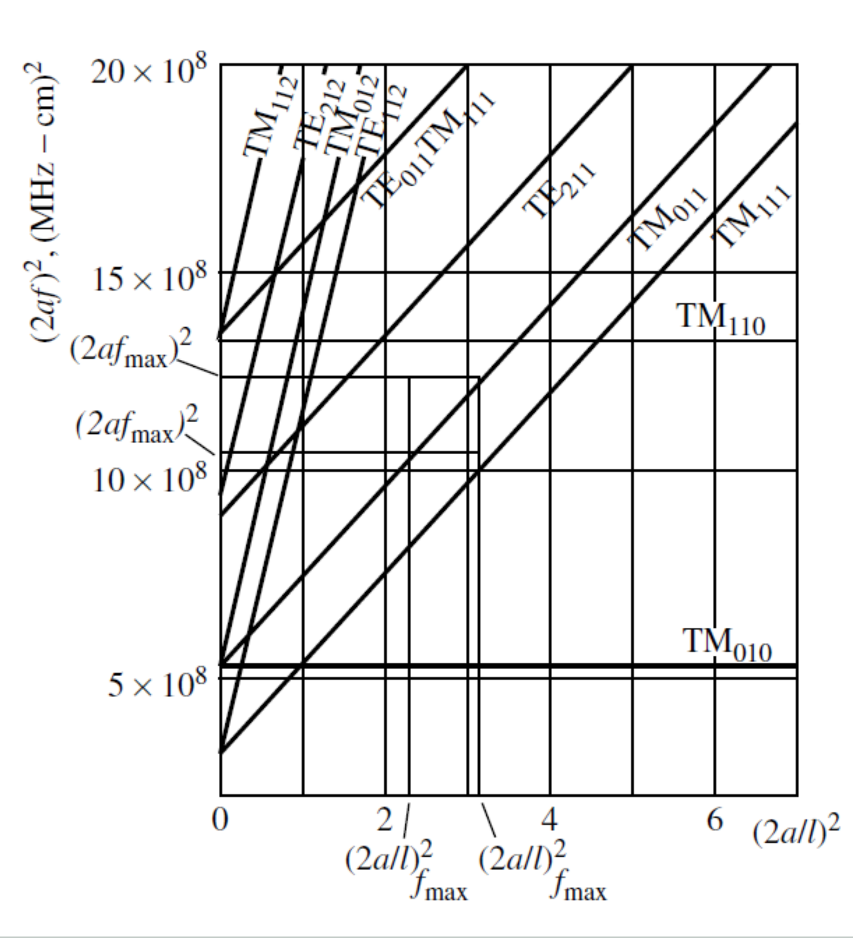
$$\lambda_0 = \frac{1}{\sqrt{\left(\frac{v_{ni}}{2\pi a}\right)^2 + \left(\frac{p}{2l}\right)^2}}$$

Choice of the operating point

$$\lambda_0 = \frac{1}{\sqrt{\left(\frac{u_{ni}}{2\pi a}\right)^2 + \left(\frac{p}{2l}\right)^2}} \tag{2.392}$$

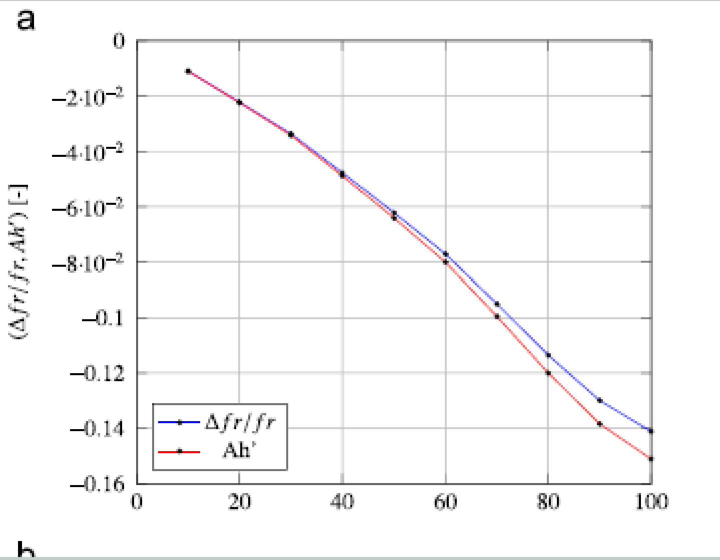
Equation (2.392) can be further modified as

$$(2af_0)^2 = \left(\frac{cu_{ni}}{\pi}\right)^2 + \left(\frac{cp}{2}\right)^2 \left(\frac{2a}{l}\right)^2, \tag{2.393}$$



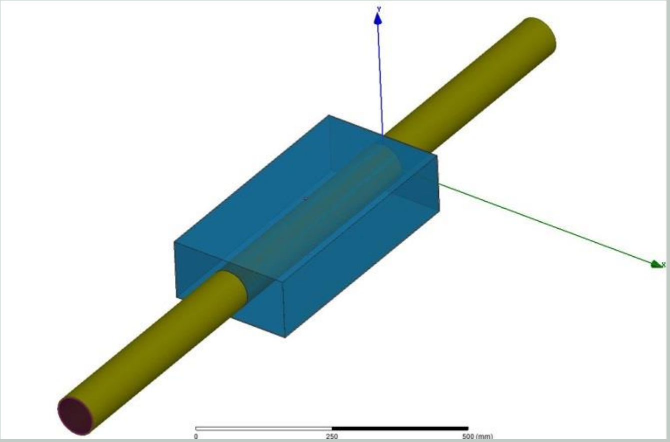
Permittivity neasurement for two-phase

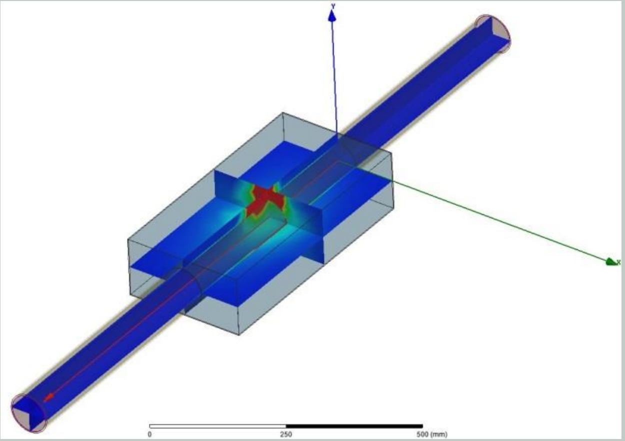
$$\varepsilon_{\text{eff}} = \varepsilon_m \frac{2\delta_i(\varepsilon_i - \varepsilon_m) + \varepsilon_i + 2\varepsilon_m}{2\varepsilon_m + \varepsilon_i + \delta_i(\varepsilon_m - \varepsilon_i)}, \qquad (7)$$

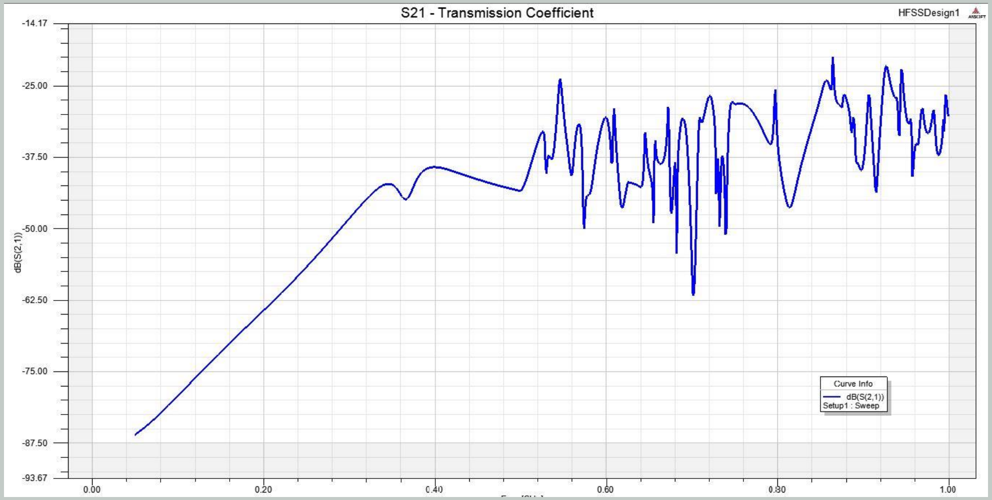


$$f_{r,nml} = \frac{1}{2\sqrt{\mu\varepsilon}}\left[\left(\frac{p_{nm}}{\pi a}\right)^2 + \left(\frac{l}{d}\right)^2\right]^{1/2},$$

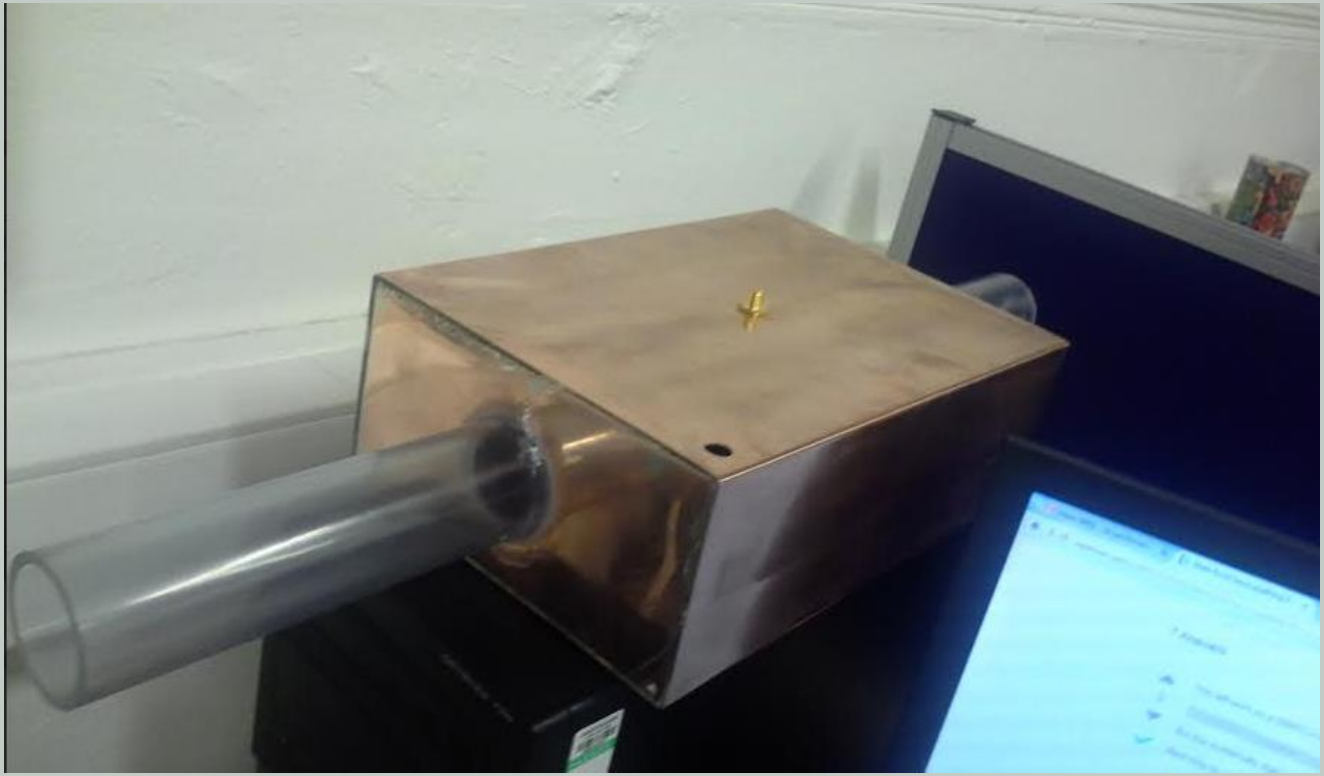
Sensor designed







Sensor measured



Measurements