Broadband free-space characterization of metamaterials

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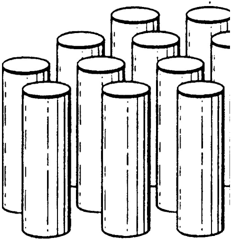
Metamaterials

Artificial periodic structures with exotic electromagnetic properties at the macroscopic scale.

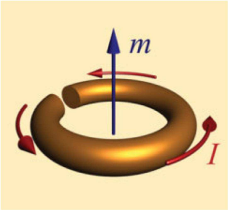
a) Epsilon-negative rods.

b) **S**plit **R**ing **R**esonator (negative permeability)

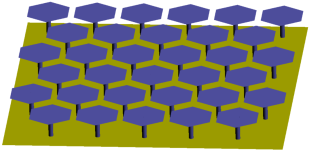
c) **H**igh **I**mpedance **S**urface : Sievenpiper mushrooms.



a



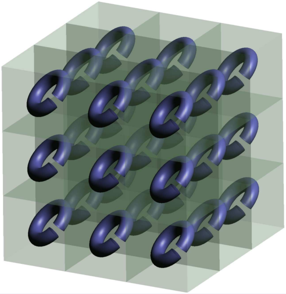
b

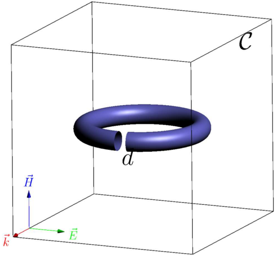


c

Summary

Reference cell

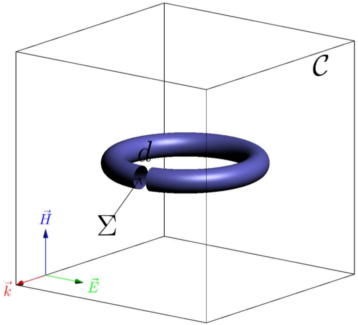


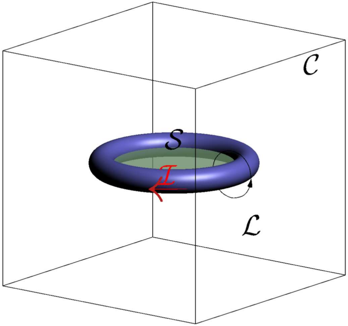


- The SRR acts as an LC resonator.
- We want to compute the effective permeability : $(\vec{B} = \mu_{eff}\vec{H})$.

- Incident plane wave.
- Long wavelength $\lambda \gg a$
- Perfect conductor : $h = 0$ inside the ring.

From the split-ring to a closed ring





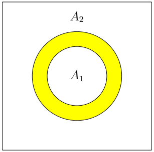
Cell energy

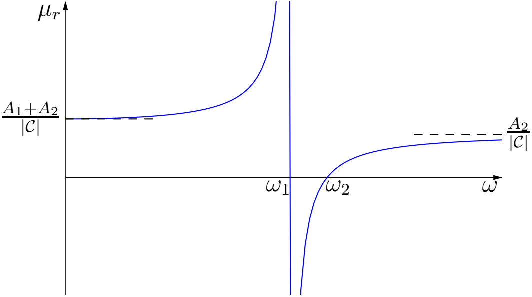
$$|\mathcal{C}|H\bar{\mu}_{eff}\bar{H} = \int_{\mathcal{A}} \mu|\nabla\varphi|^2 + \int_{\partial\mathcal{R}} \frac{1-i}{\sigma\omega\delta}|\nabla_S\varphi|^2 - \frac{1}{C\omega^2}\mathcal{I}^2$$

where φ stands for the magnetic potential.

Polaritonic law for 2D-structures

- $h = h_1$ over A_1 and $h = h_2$ over A_2
- Faraday : $i\omega\Phi + V = 0$ and Ampère : $\mathcal{I} = h_1 - h_2$.
- Magnetic field flux : $|\mathcal{C}|B = \mu\left(|A_1|h_1 + |A_2|h_2\right)$ and $\Phi = \mu h_1 |A_1|$
- Capacitor in the air gap : $\mathcal{I} = i\omega C V$.



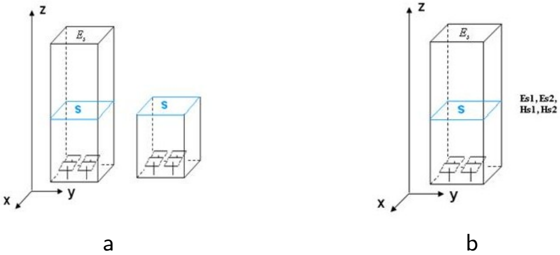


$$\mu_{eff} = \mu \frac{|A_1| + |A_2|}{|\mathcal{C}|} \frac{\left(\frac{\omega}{\omega_2}\right)^2 - 1}{\left(\frac{\omega}{\omega_1}\right)^2 - 1}$$

$$\omega_1 = \left(\mu C |A_1|\right)^{-\frac{1}{2}}$$

$$\omega_2 = \sqrt{1 + |A_1|/|A_2|}\,\omega_1$$

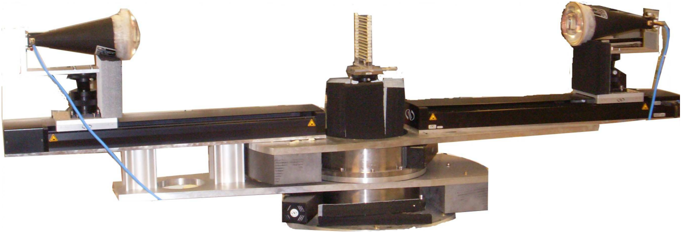
Effective impedance computation



- Symmetric HIS :
  - Impedance extension from 1D $\rightarrow$ 2D
- Asymmetric HIS :
  a) Flux method $\int_{\mathcal{C}} i\omega(\epsilon E_i E_j - \mu H_i H_j) = |\mathcal{S}| E'_{js} \frac{1}{Z_{ij}} E_{is}$
  b) Surface impedance method

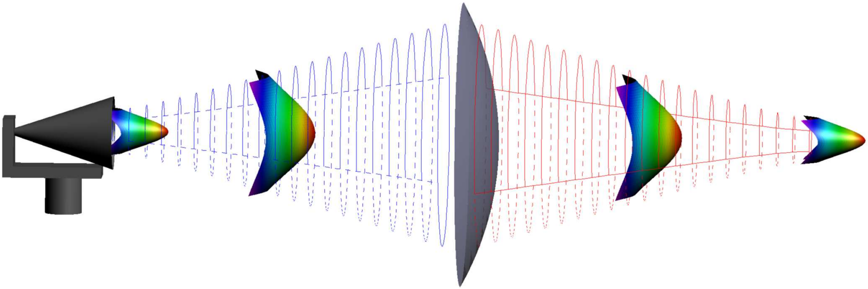
$$\begin{pmatrix} -H_{1sy} & -H_{2sy} \\ H_{1sx} & H_{2sx} \end{pmatrix} = - \begin{pmatrix} Y_{xx} & Y_{xy} \\ Y_{yx} & Y_{yy} \end{pmatrix} \begin{pmatrix} E_{1sx} & E_{2sx} \\ E_{1sy} & E_{2sy} \end{pmatrix}$$

The free-space characterization system



- 2 quad-ridged horn antennas (2-18 GHz), mounted on micrometric stages.
- The beam is focused with Rexolite ($\epsilon_r = 2.54$) lenses.
- Agilent PNA 8364C : S-parameters measurement.

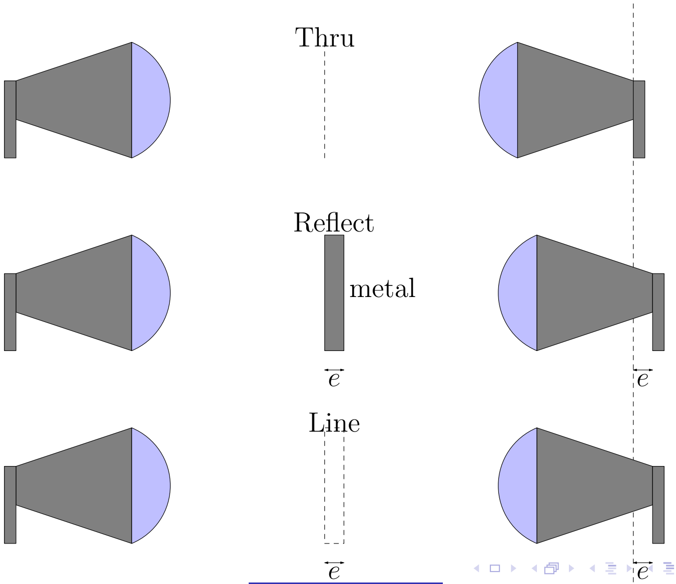
Gaussian beam



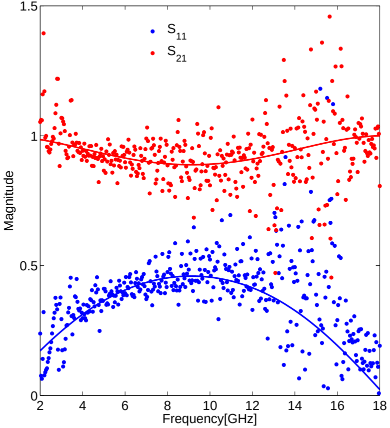
- Gaussian beam.
- We must have an incident planar wave on the sample to compute the effective parameters.
- Negligible diffraction if the sample dimension is 3 times the beam's radius.

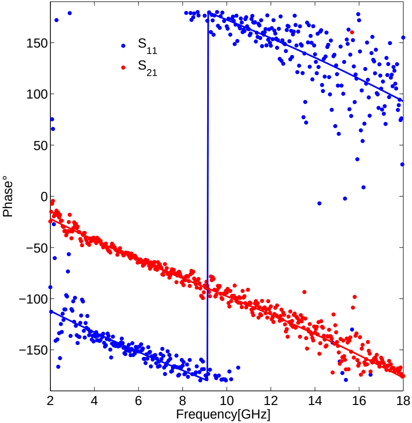
- A focused bench is much smaller.

Thru Reflect Line calibration

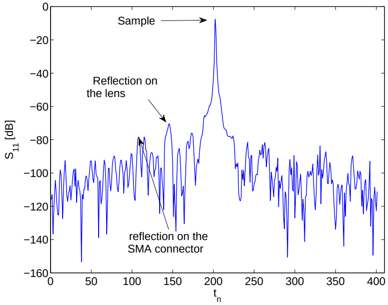


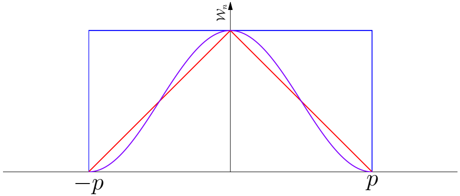
S parameters of a plexiglas sample (e=5 mm)





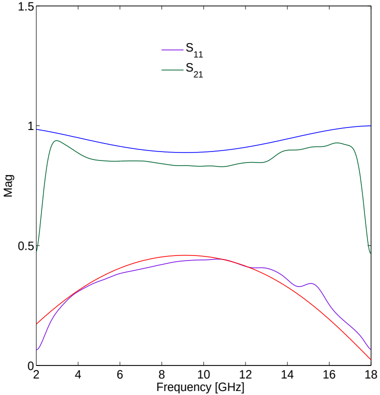
Time domain analysis



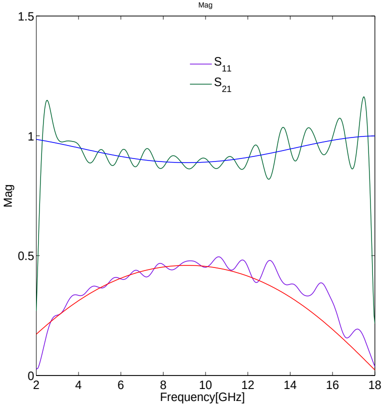


- The calibrated S parameters are transfered to the time domain.
- A window is applied to eliminate the parasite reflections.
- Gibbs phenomenon limits the selectivity of the filter.

Influence of the filter type (Plexiglas, e = 5 mm)

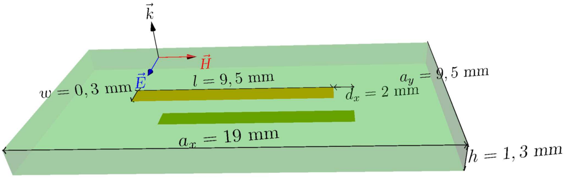


Hanning

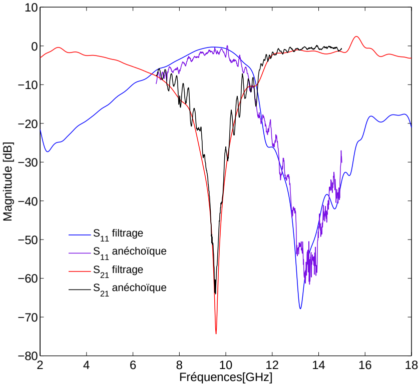


Window

Shifted metallic wire rods



- Characterization in an anechoic chamber.
- Time domain with a Hamming window.

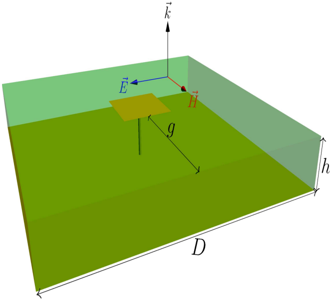


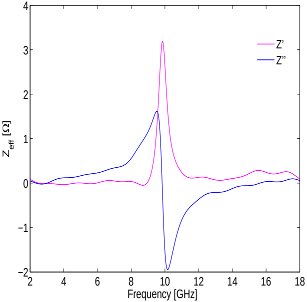
HIS characterization

Epoxy $\epsilon_r = 4,4$
$h = 2.4$ mm

Sievenpiper

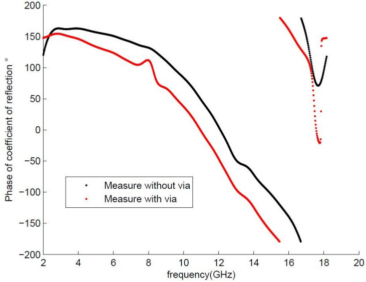
$$Z_{eff} = \frac{j\omega L}{1 - LC\omega^2}$$

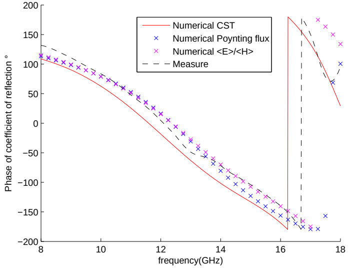




D [mm]	g [mm]	Measured [GHz]	Analytical [GHz]
10	4	9,84	9,4
7	2	10	9,3
6	2	10,85	10,86
10	5	11,75	11,2

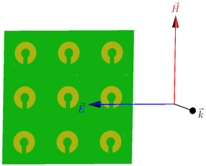
Comparison with the simulations



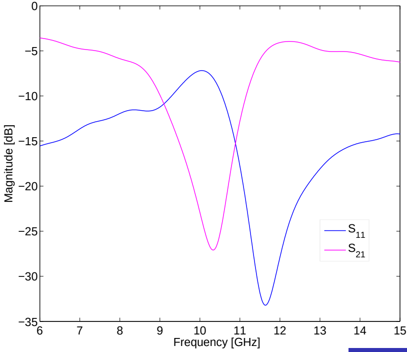


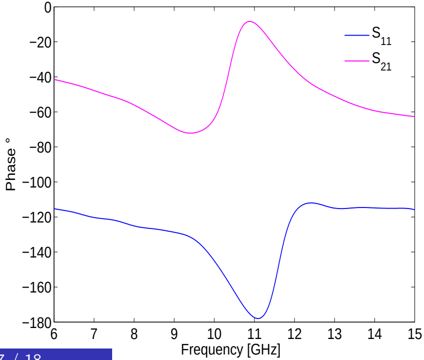
Method	Frequency [GHz]	Sample (D,g)			
		(10,4)	(10,5)	(7,2)	(6,2)
Measurements	Resonance	10,35	11,74	10	10,84
	Bandwidth	9,3-11,37	10,33-12,77	8-11,25	7,06-12,34
$\langle E\rangle / \langle H\rangle$	Resonance	9,9	11,74	10,3	11,9
	Bandwidth	8,8-10,8	10,3-12,7	8,9-11,7	10,25-13,75
Poynting flux	Resonance	9,4	11,5	10,8	12
	Bandwidth	8,3-10,3	10,2-12,4	9,3-12,2	10,6-13,75
CST	Resonance	9,54	11,23	10,1	11,82
	Bandwidth	8,56-10,42	10-12,17	8,7-11,42	9,97-13,76

SRR characterization : $r_{int} = 1$ mm, $r_{ext} = 2,5$ mm



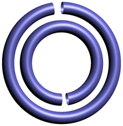
d (mm)	Resonance frequency [GHz]		
	Measured	Analytical	Homogenization
0,8	9,4	9,37	9,47
0,9	9,6	9,94	10,05
1	10,32	10,47	10,59

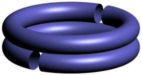


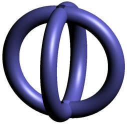


Conclusions and outlook

- Homogenization of SRR and HIS.
- Realization of a compact characterization system.
- The S-parameters are filtered in the time domain.







- Computation ϵ_{eff} (split-ring).
- Homogenization of SRR based structures.
- Homogenization of metallic wireds arrays.
- Gated Reflect Line calibration.