ELECTRICALLY CONTROLLABLE PCs & METAMATERIALS and THEIR INDUSTRIAL APPLICATIONS.

Frédérique GADOT

Université Paris Sud - IEF,

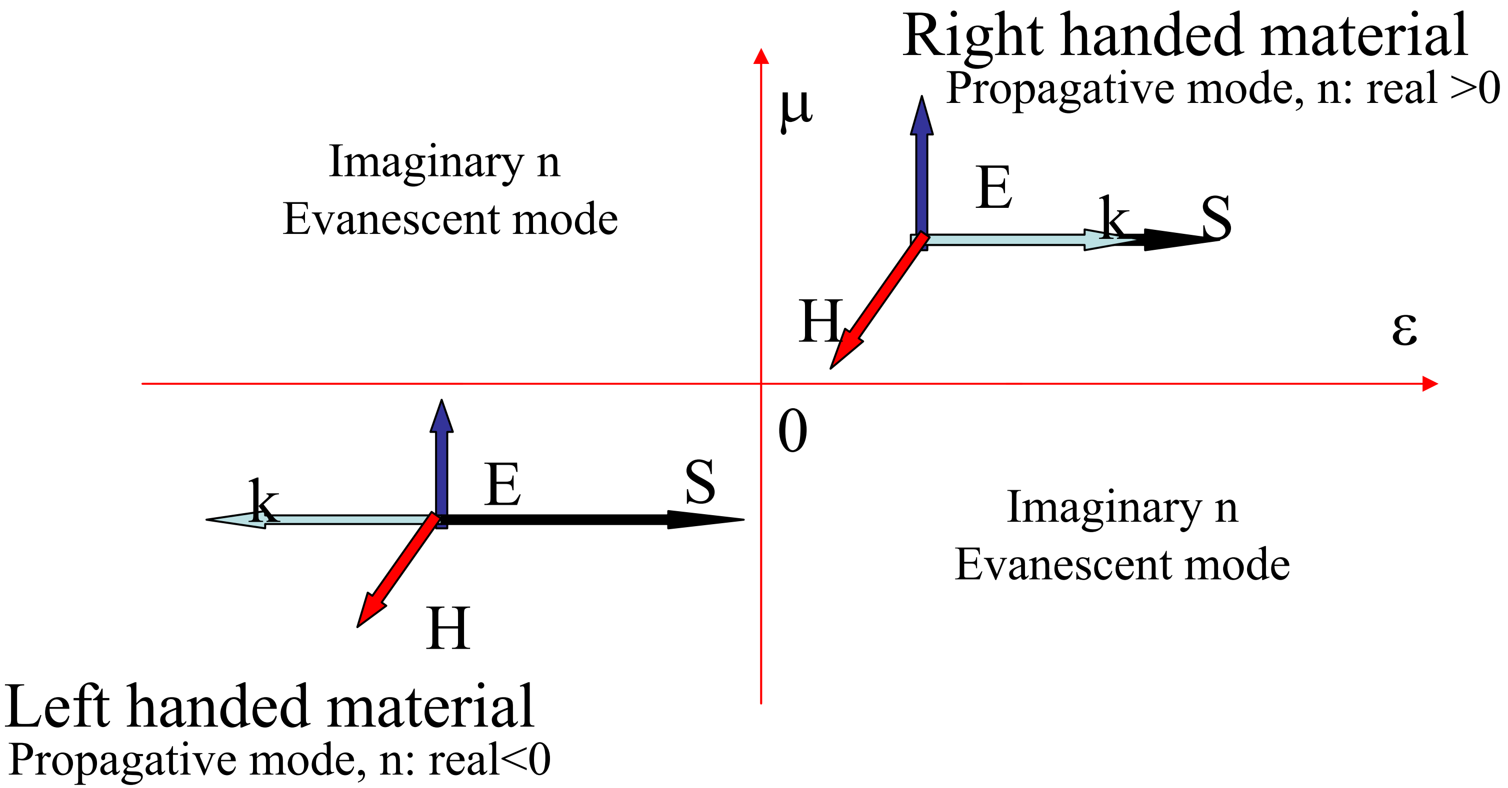
Bât. 220, 91405 Orsay, FRANCE

Outline

1. Brief summary on « left handed material » (called LHM)
2. Controllable wire array
3. First industrial applications
4. From the wire lattice to the LHM
5. Antenna based on controllable metamaterial
6. Conclusion

Brief story of LHM

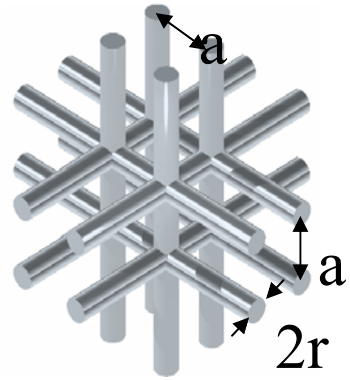
The 4 electromagnetic states of materials.

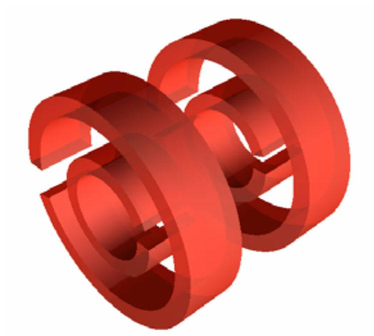


V.G. Veselago, Soviet Physics Uspekhi 10 (1968)

Material with ε<0 or μ<0

(by J.B. Pendry, Imperial College)





•A lattice of thin metallic wires is a material with a negative permittivity (for $\omega < \omega_p$) where ω_p is the plasmon frequency.

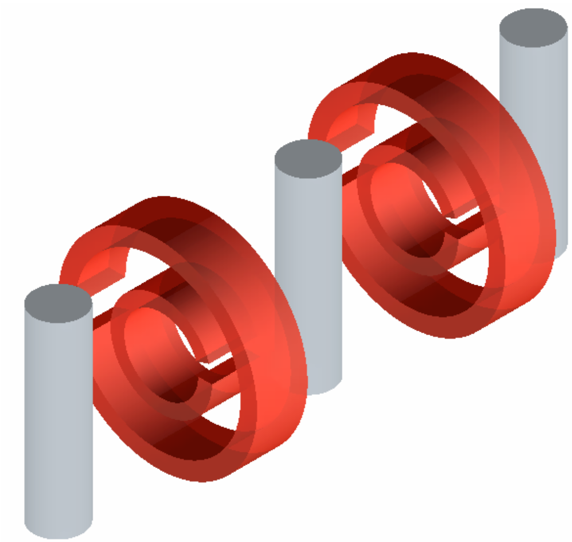
▪A lattice of metallic split ring resonators has a negative permeability in some frequency range.

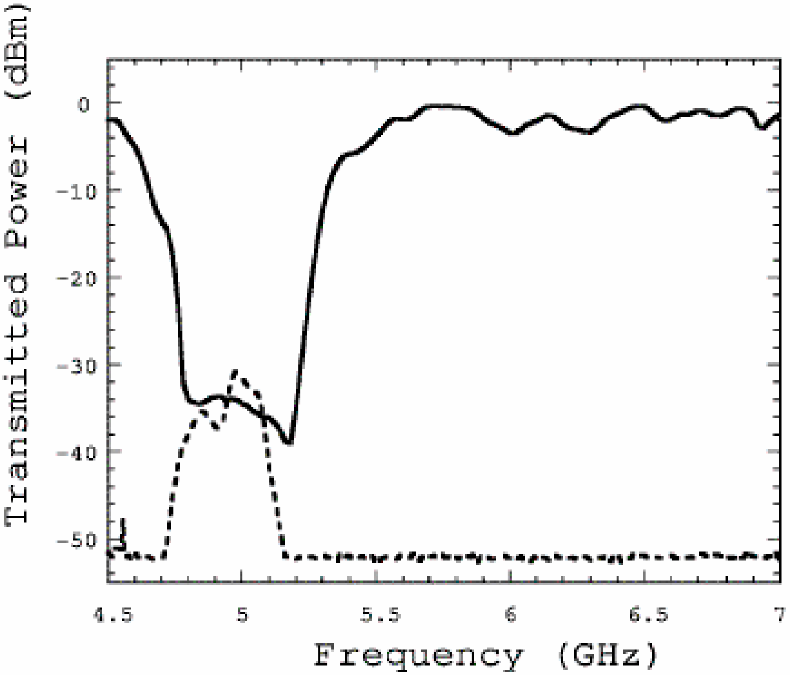
J.B. Pendry, PRL 76, pp.4773-4776 (1996)

J.B. Pendry, IEEE MTT 47, pp.2075-2084 (1999)

Left handed material

Association of the 2 preceding metallic lattices

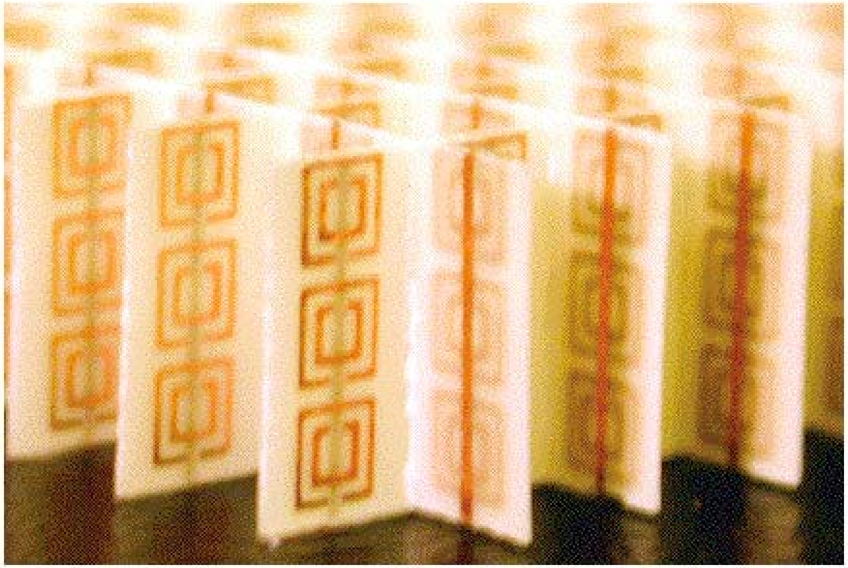




Composite Medium with Simultaneously Negative Permeability and Permittivity
D. R. Smith *et al.*, PRL 84, pp. 4184-4187 (2000)

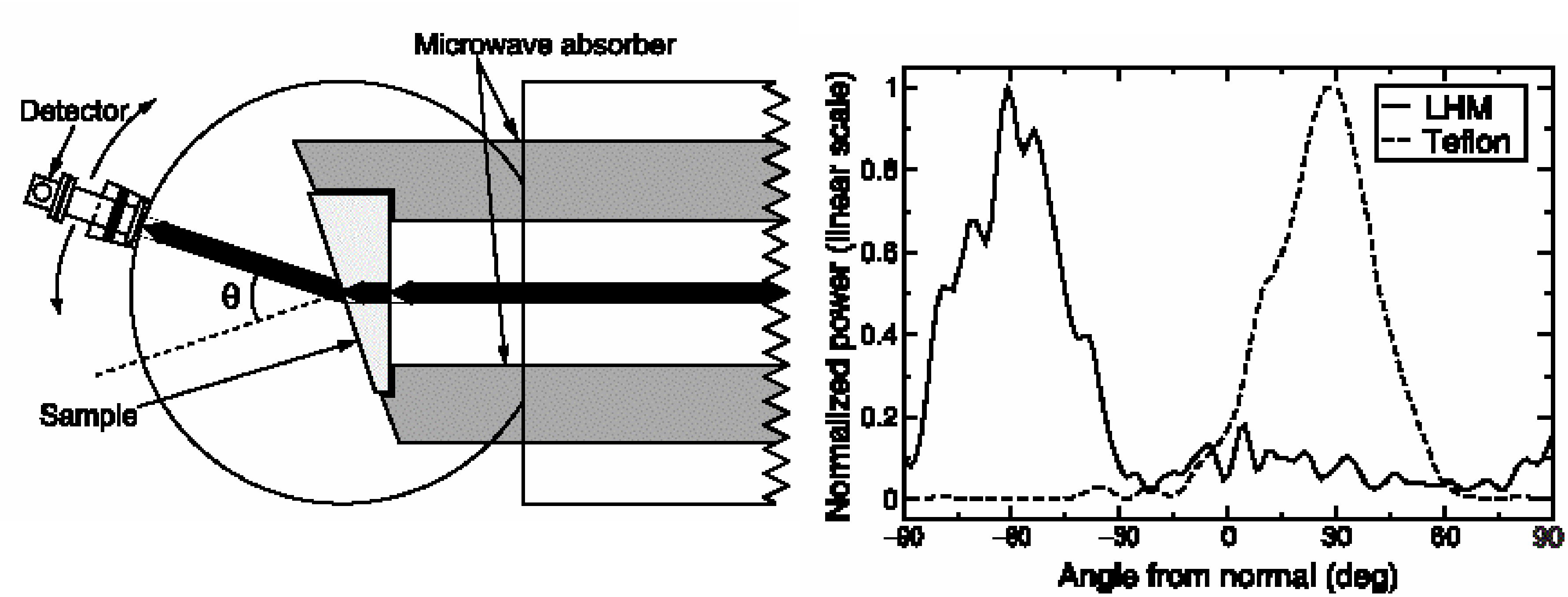
FIG. 3. A transmission experiment for the case of $H_{\parallel}$. The upper curve (solid line) is that of the SRR array with lattice parameter $a = 8.0$ mm. By adding wires uniformly between split rings, a passband occurs where μ and ε are both negative (dashed curve). The transmitted power of the wires alone is coincident with that of the instrumental noise floor (-52 dB).

How to measure the index of refraction of a LHM?



Experimental verification of a negative index of refraction
R. Shelby, D. R. Smith and S. Schultz, *Science*, **292**, 77 (2001)

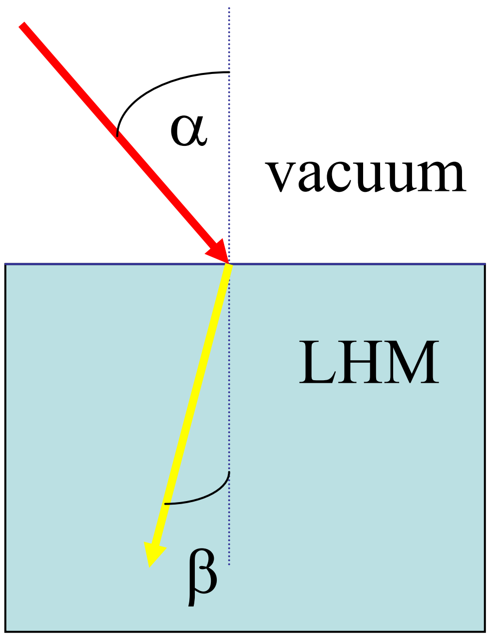
Index of refraction of a LHM: measurement



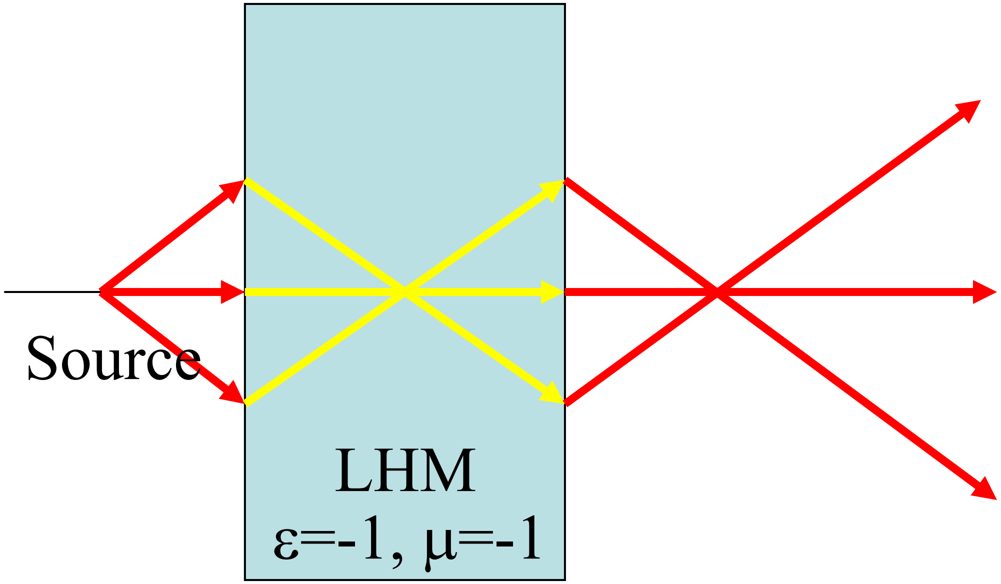
Experimental verification of a negative index of refraction
R. Shelby, D. R. Smith and S. Schultz, *Science*, **292**, 77 (2001)

Applications of left handed materials (LHM)

Negative refraction



Perfect lens



$$n = \sqrt{\varepsilon \mu}$$

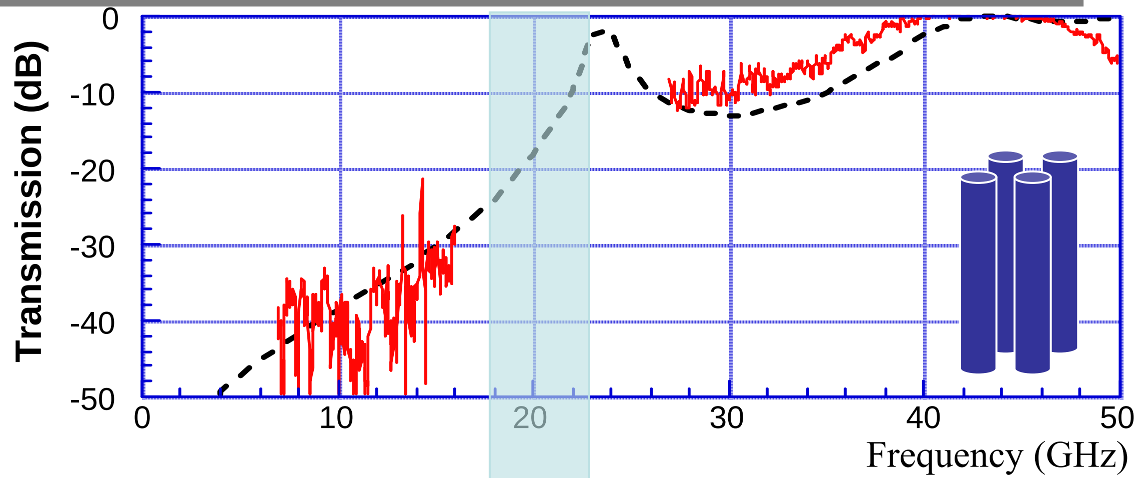
Negative refraction makes a perfect lens
J. B. Pendry, Phys. Rev. Lett., 85, 3966 (2000)

Controllable wire array

Controllable structure: the concept

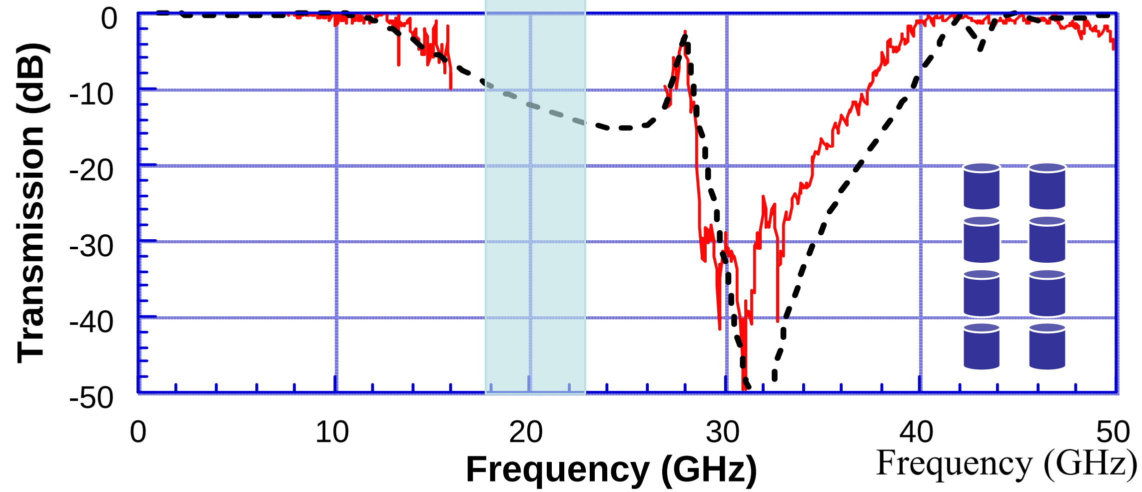
Lattice of continuous metallic wires:

a first forbidden band appears from 0Hz.



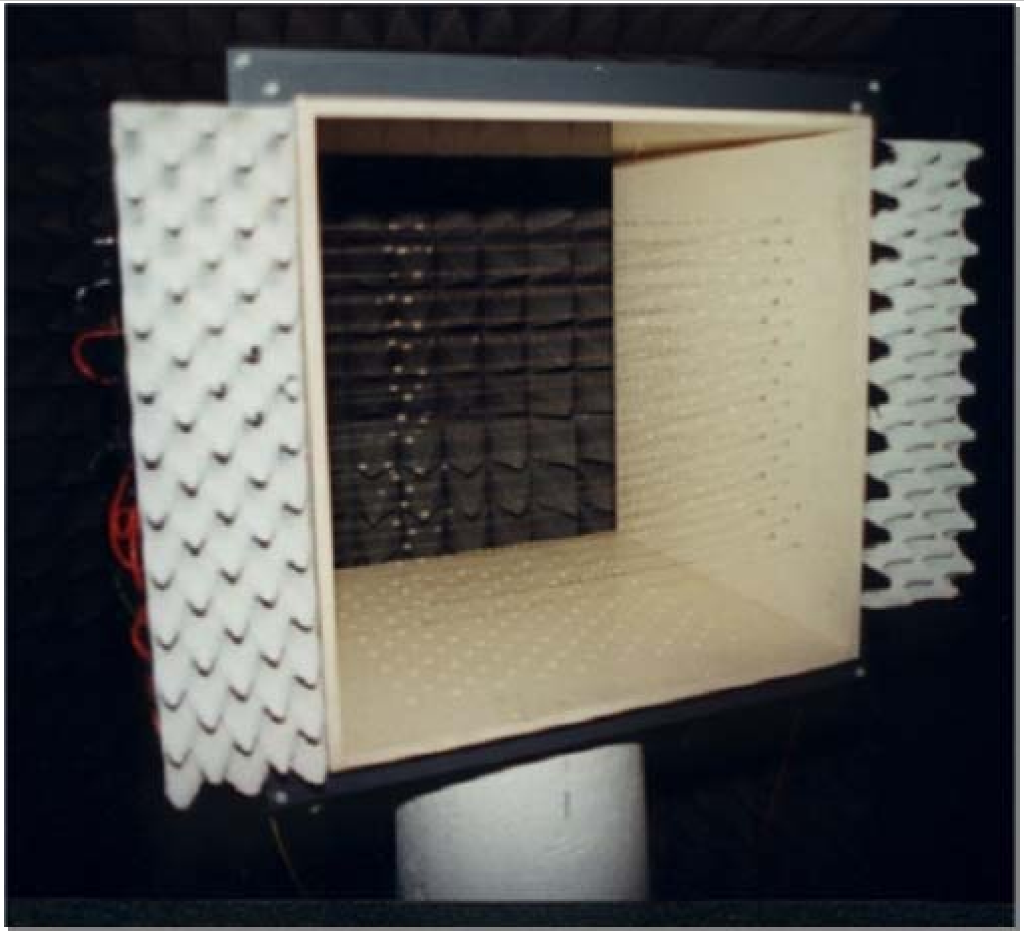
Lattice of discontinuous metallic wires:

an allowed band replaces the first forbidden band.

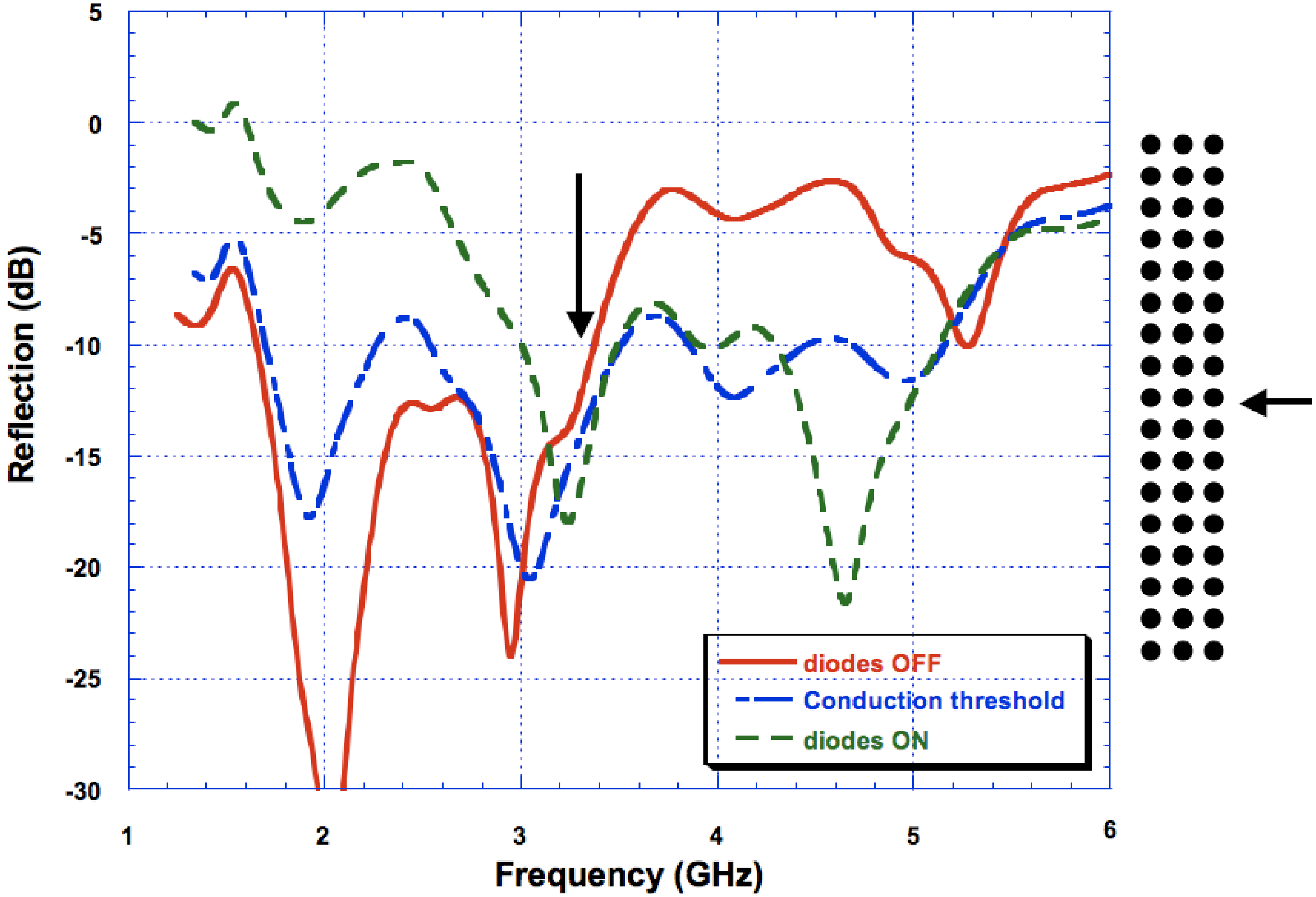


A. de Lustrac *et al*., APL 75 (11), pp.1625-1627 (1999)

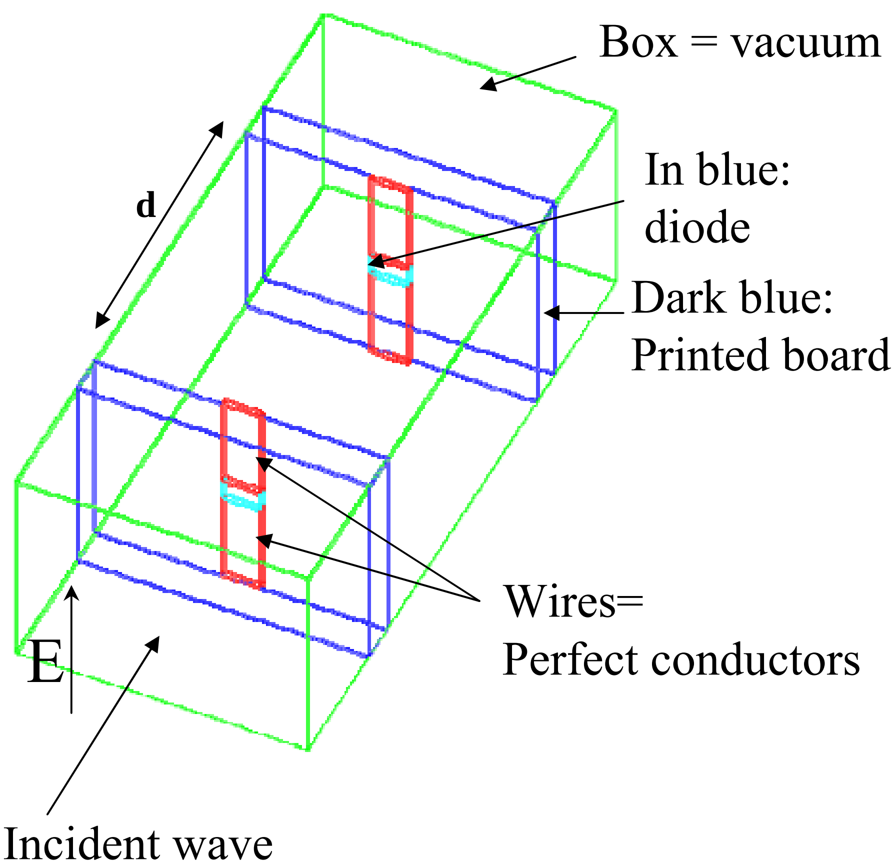
First prototype for EADS (1-5GHz)…

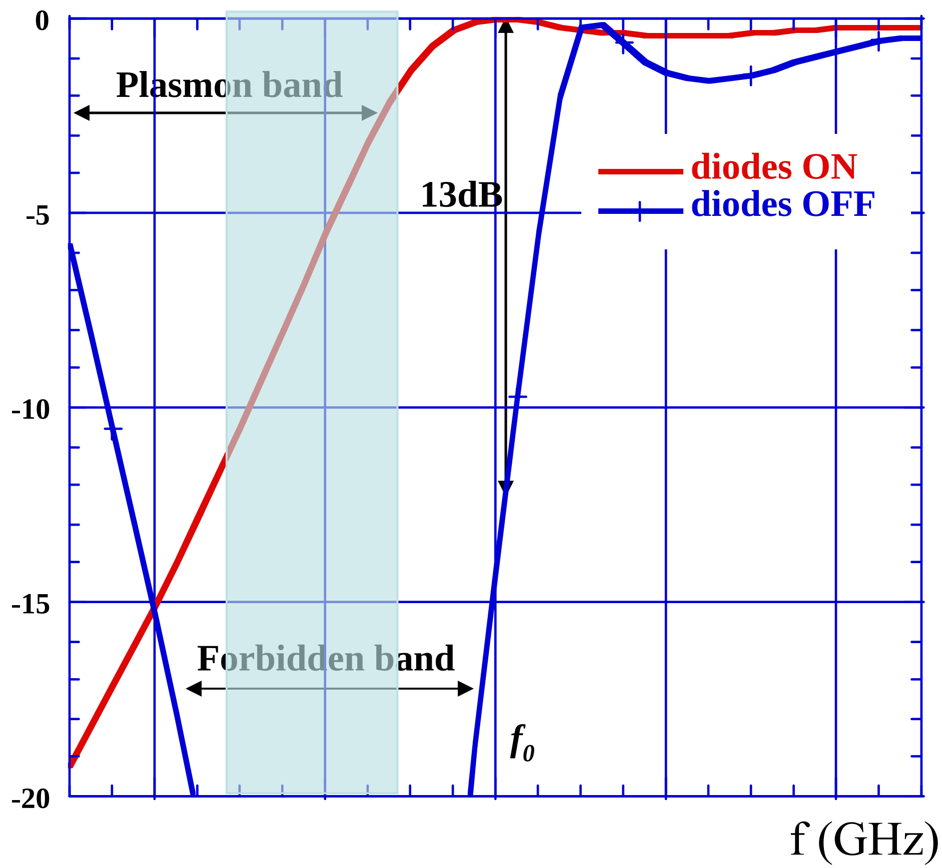


…and its first measurement.



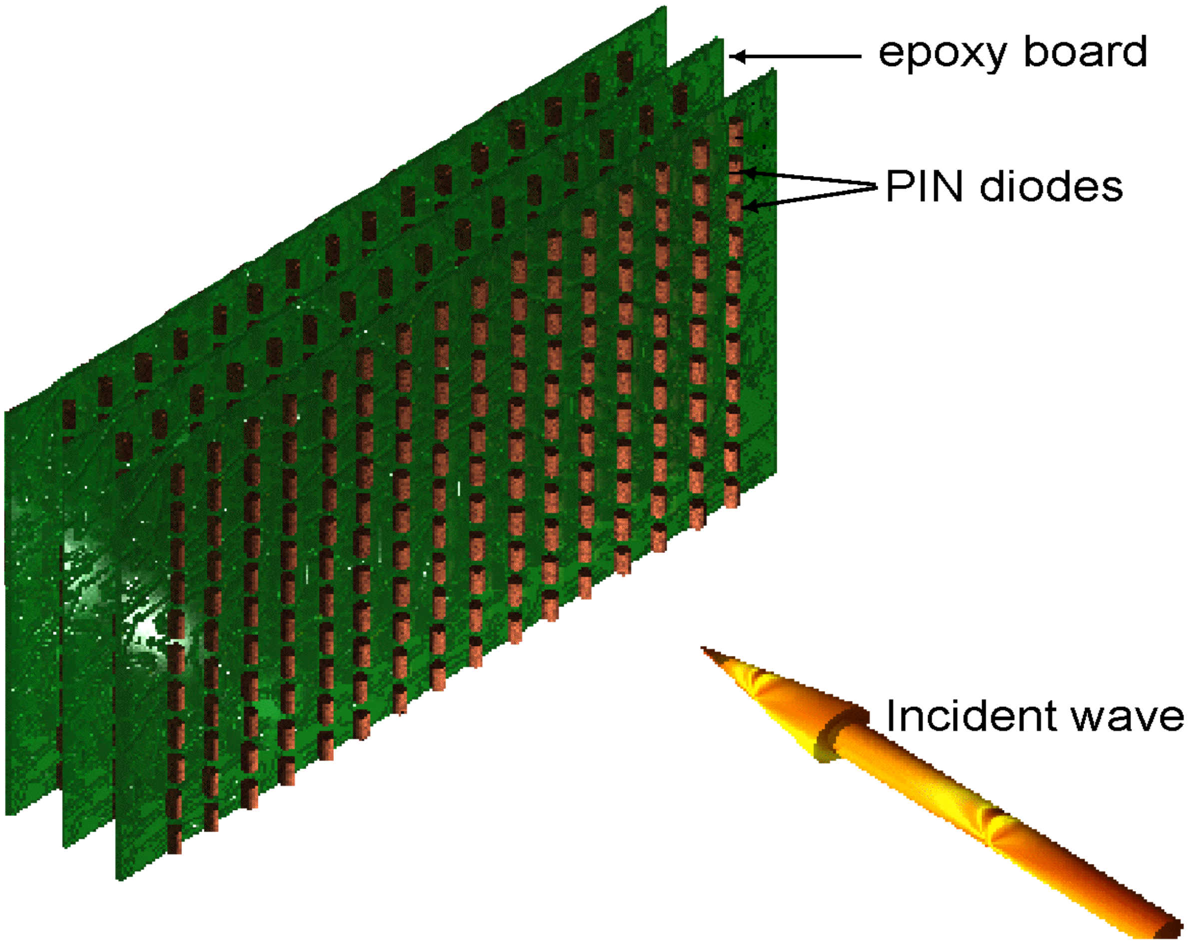
Controllable wires



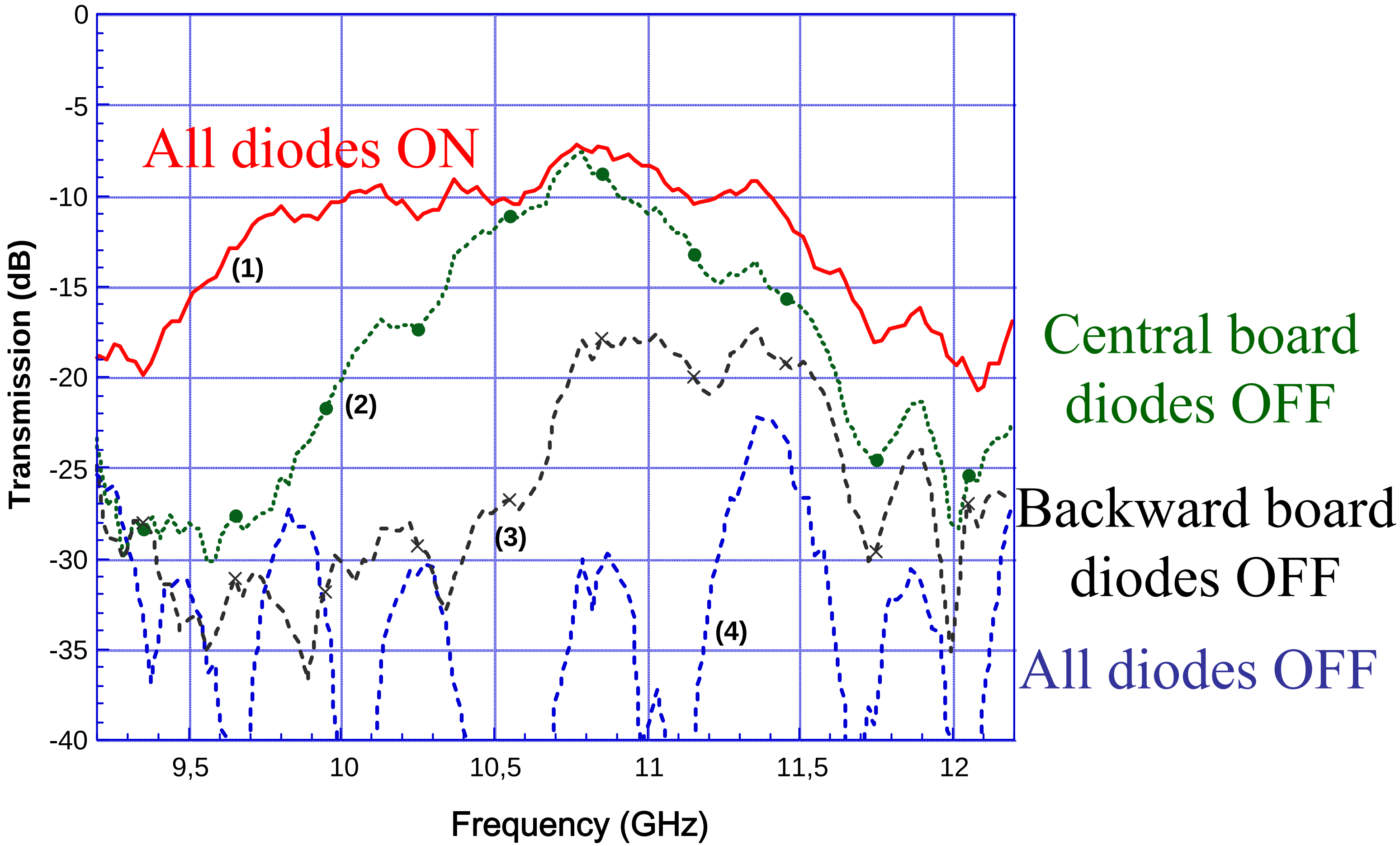


Diodes ON = Continuous wires
Diodes OFF = Cut wires

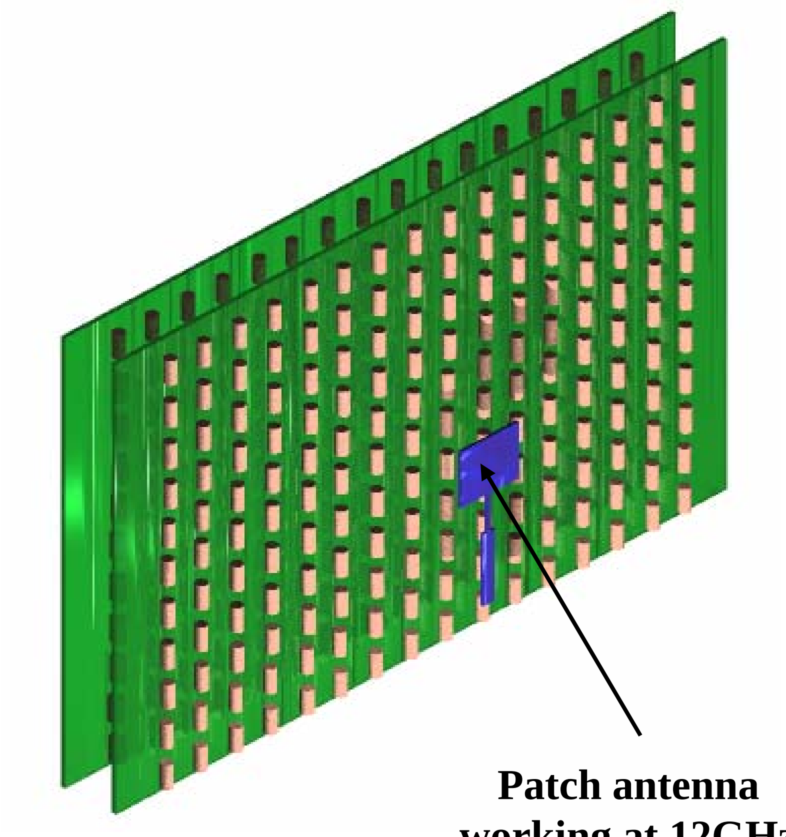
2nd prototype with printed stripes…



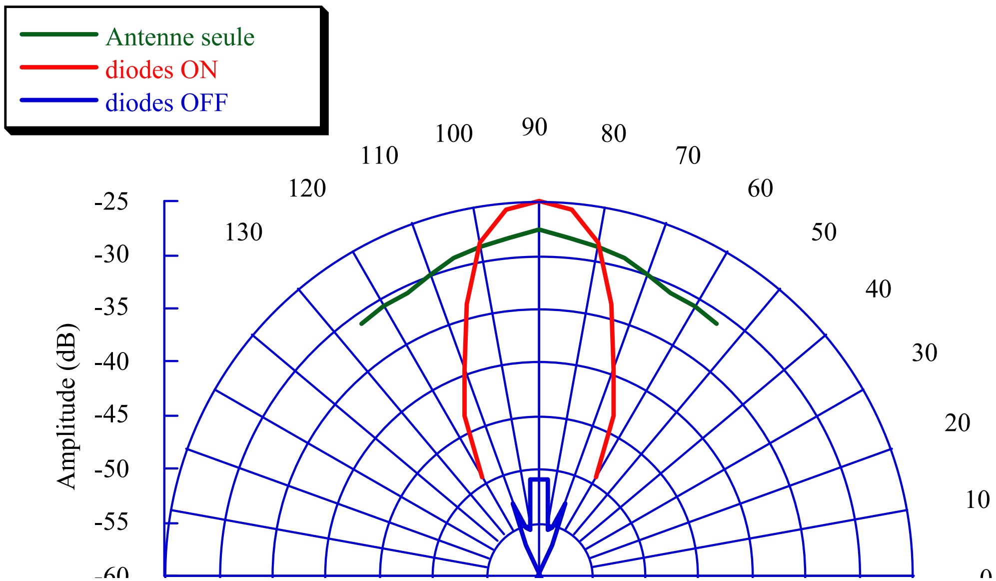
… and its measurements (around 10GHz).



Application: controllable radome



Patch antenna working at 12GHz



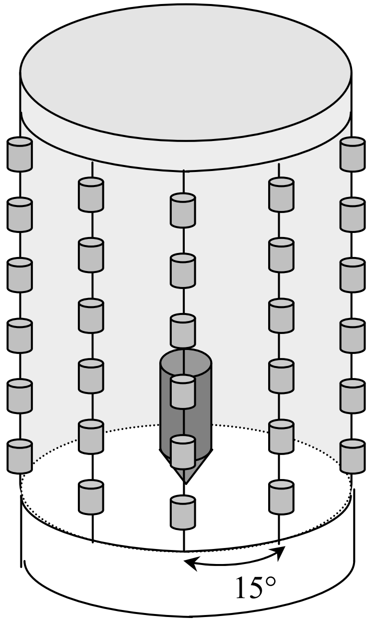
2 plaques espacées de 9 mm devant une antenne patch à 12.01 GHz.

Pattern diagram of the patch antenna with radome at 12,01GHz.

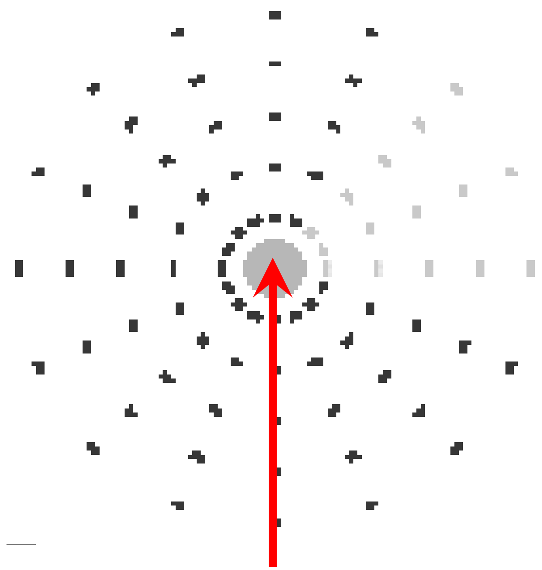
Industrial applications: Conformable and Controllable structures for antennas

Base Station for mobile communication

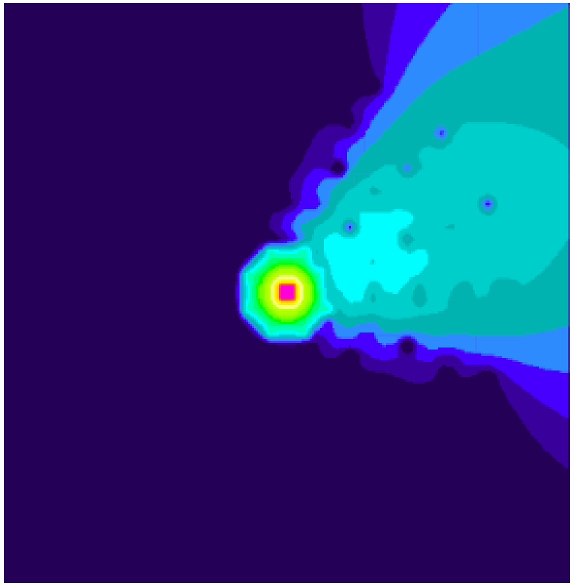
5 layers of wires with diodes



Schematical design of the base station antenna



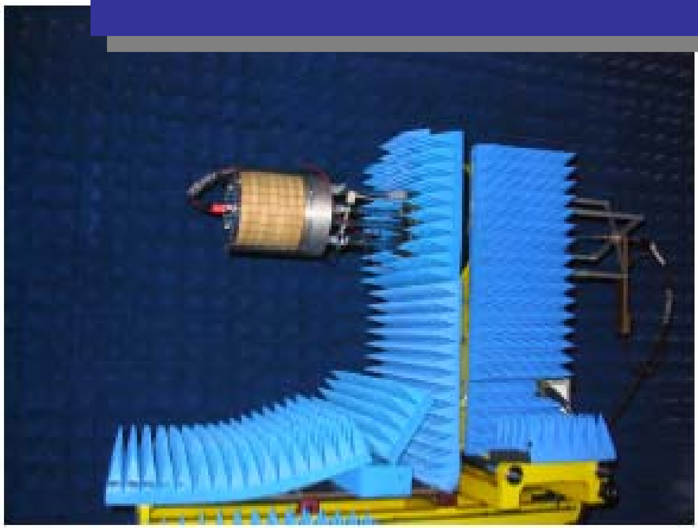
Wide-band antenna 0.8-2.1GHz

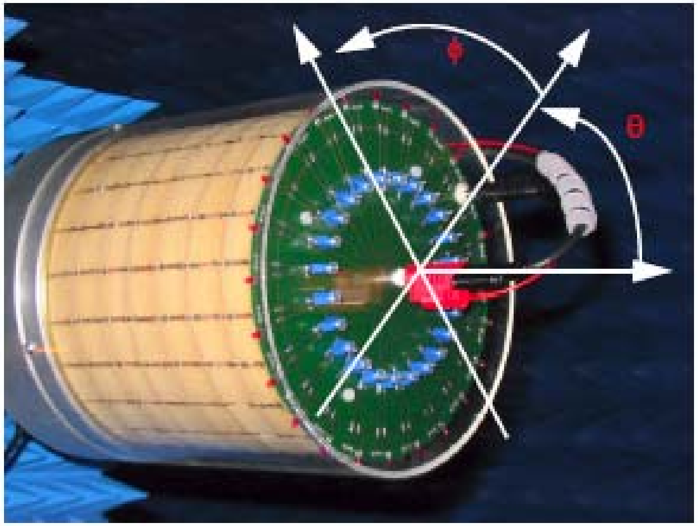


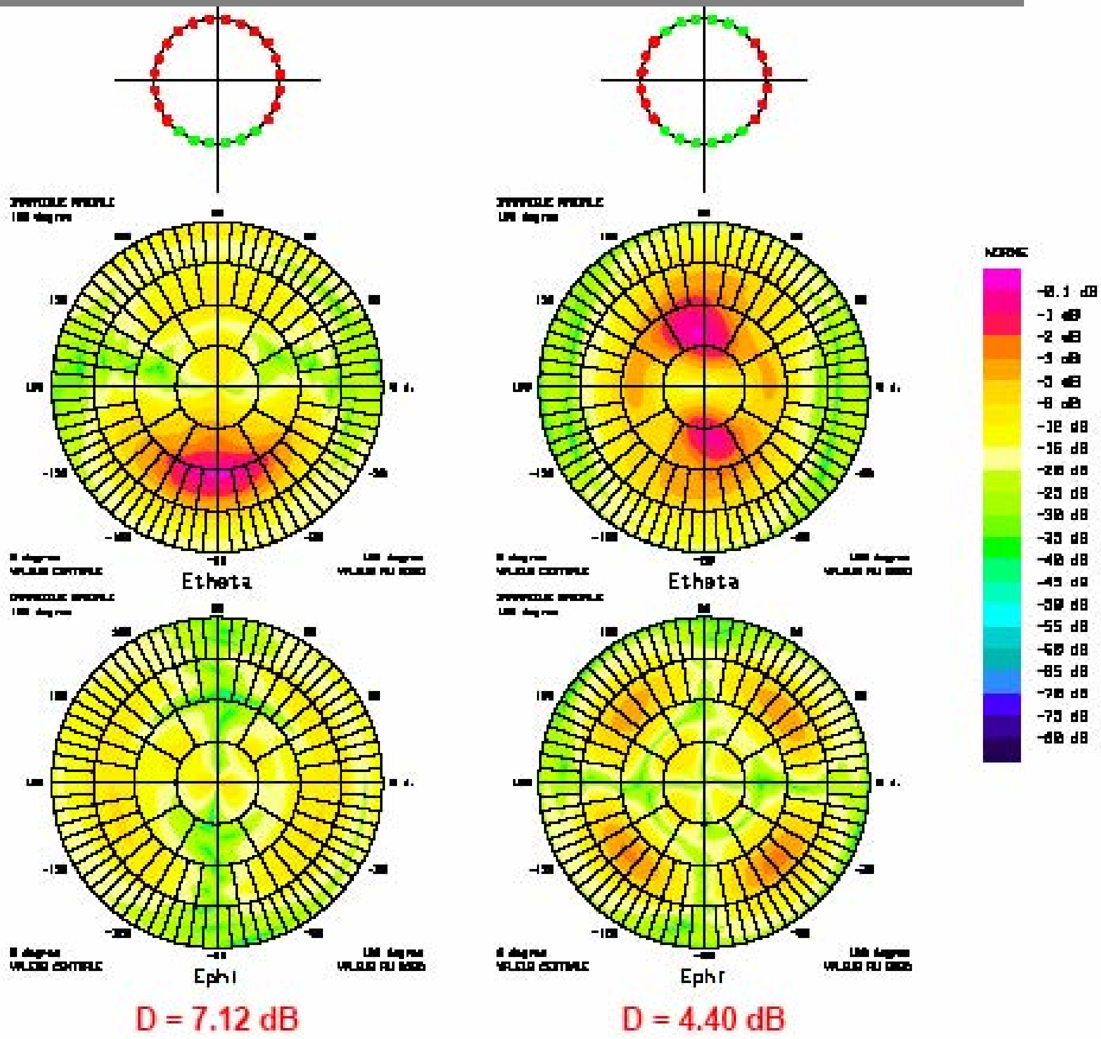
Champ électrique

France Télécom R&D

Characterization of the first prototype at 0.9GHz

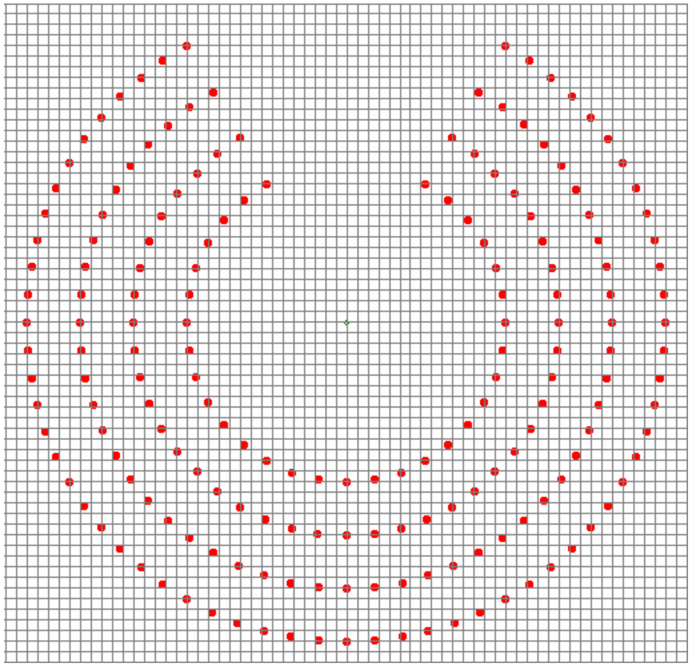


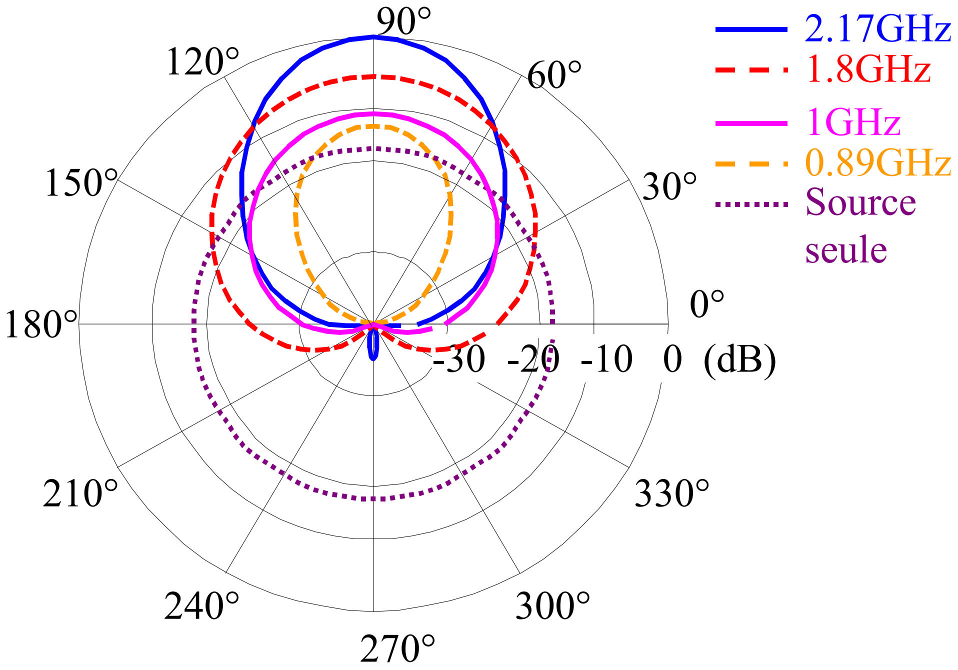




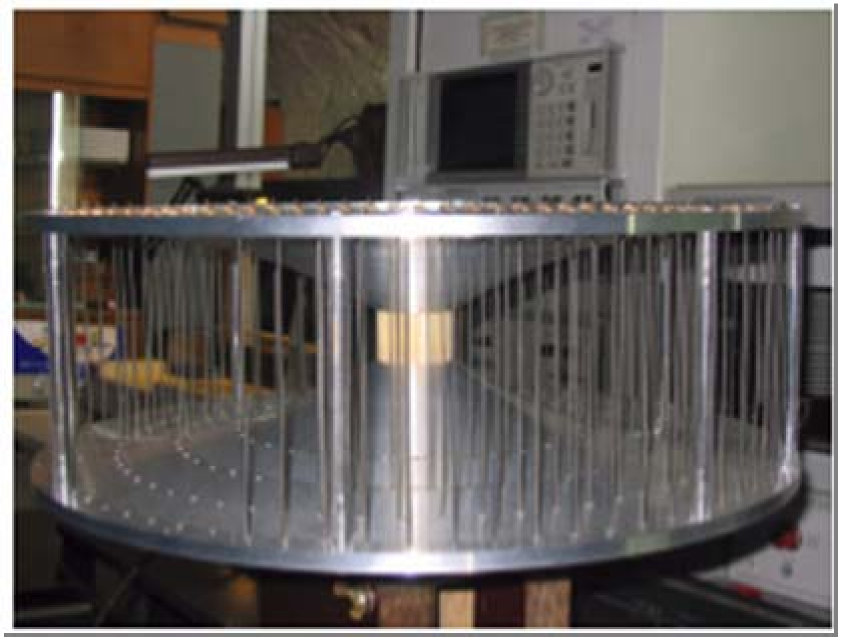
Multilayers structure: optimization of the aperture of the 2nd prototype

Does it work for the 3 frequency bands?





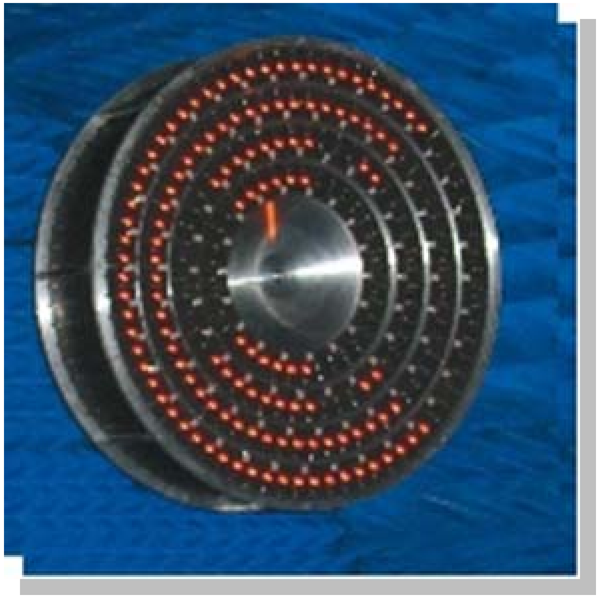
Fabrication of the 2^{nd} prototype



France Télécom R&D

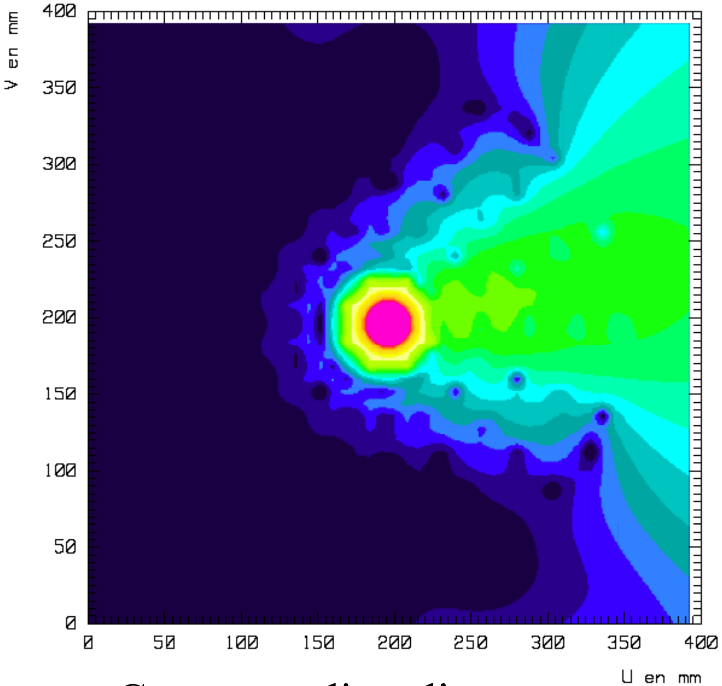
Project "BIP": 3G base station.
Four layers prototype with wide band antenna

Beam control over 360°.
Beam aperture: 30°.



Antenna realized by France Télécom R&D

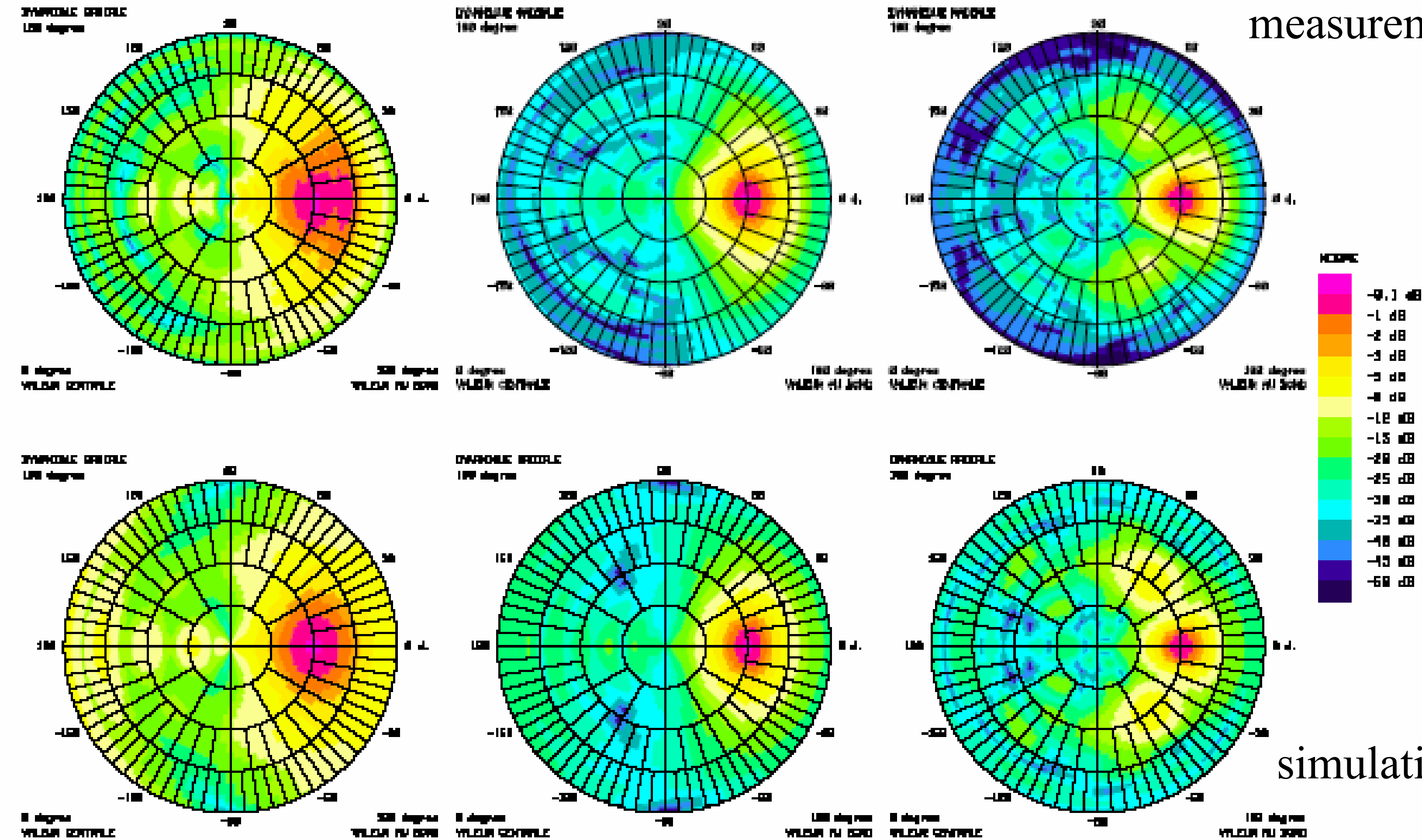
Wide band antenna:
(0.8 -> 2.1GHz).



Corresponding diagram pattern

4 layers 2nd prototype: one aperture – one beam
Measurements and simulations at 0.9, 1.75 and 2.0GHz

measurements



simulations

Spherical and Controllable radome

Goals

- Conformal EBG structure on a spherical radome.

- Commutation of the transmitted signal at around 10GHz.

- 2 configurations:

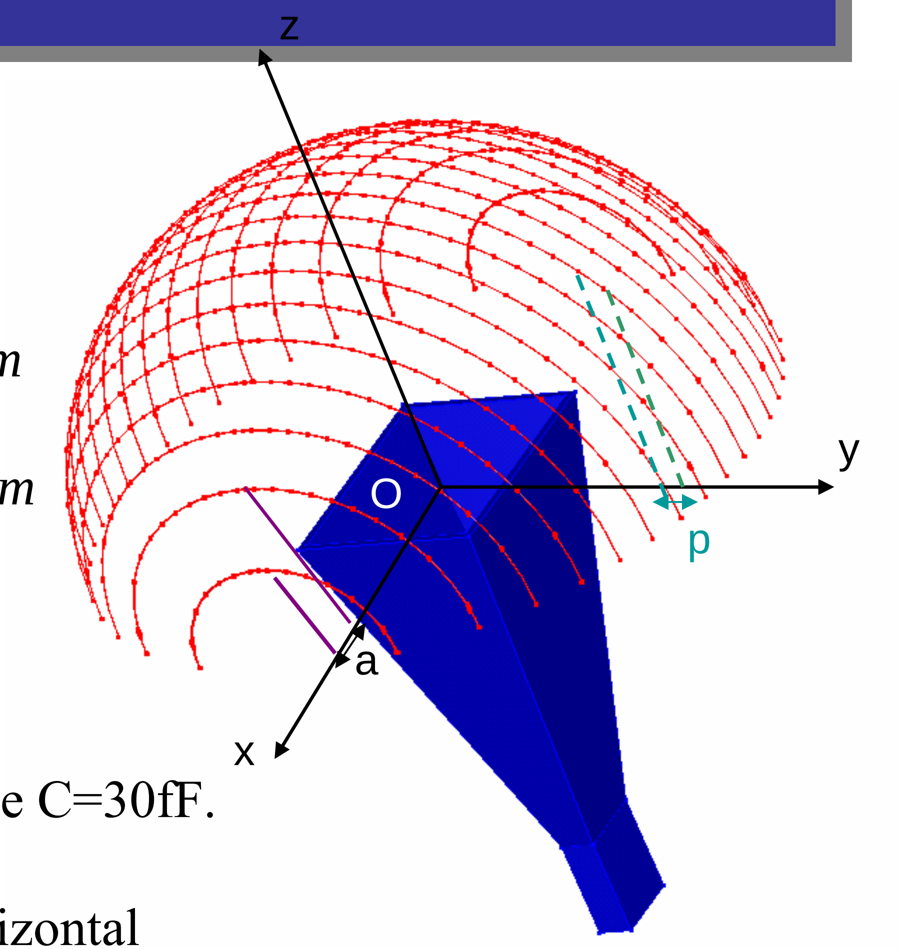
1. A set of continuous and discontinuous metallic wires
2. A set of two discontinuous metallic wires with different discontinuities' periods.

- Electronically active radome in aeronautic field with active switches like PIN diodes and/or photoresistances.

Design of the structure

3 configurations :

- •Continuous wires (allowed band)
- •Discontinuous wires with *p1=11mm (forbidden band)*
- •Discontinuous wires with *p2=5.5mm* (allowed band)



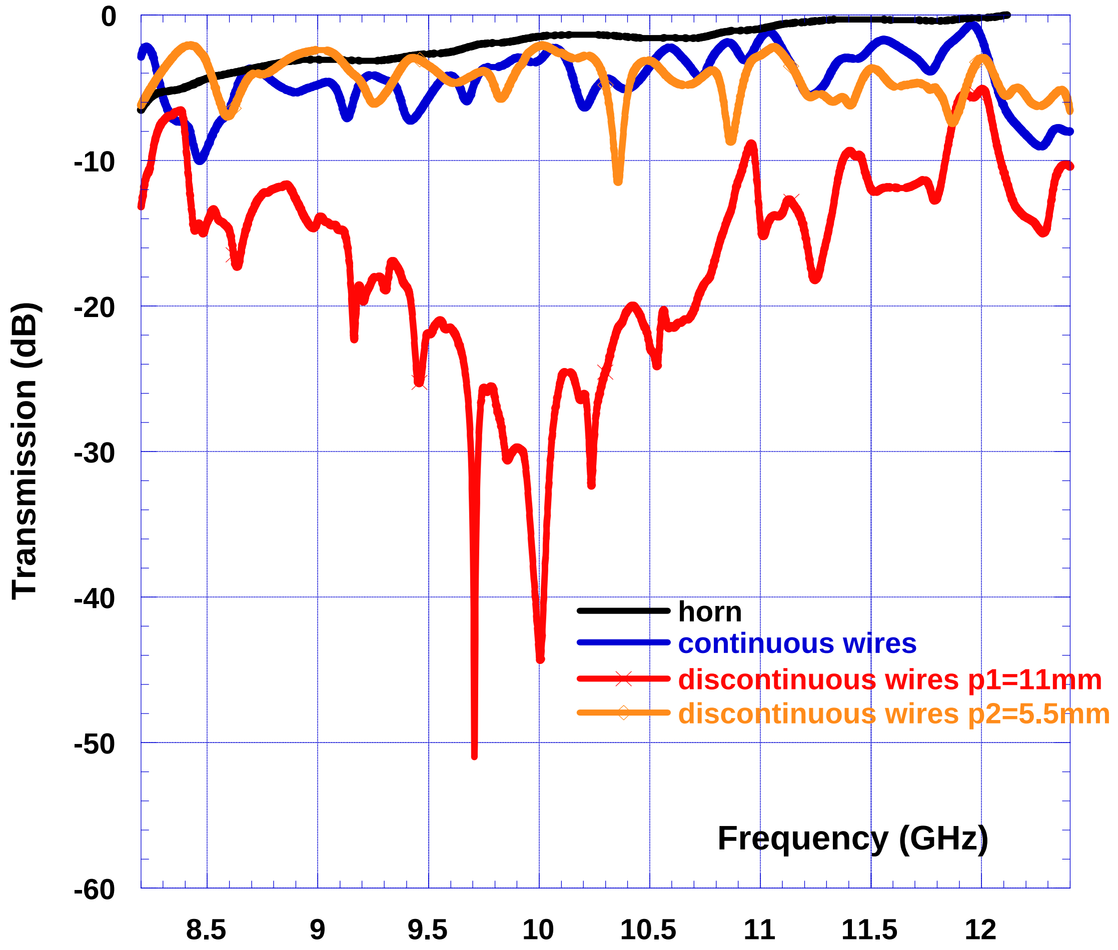
•Discontinuities simulated as capacitance C=30fF.

•Diameter 32 cm.

•p1 and p2 are the projections on the horizontal plane.

Schematic structure simulated in Microstripes

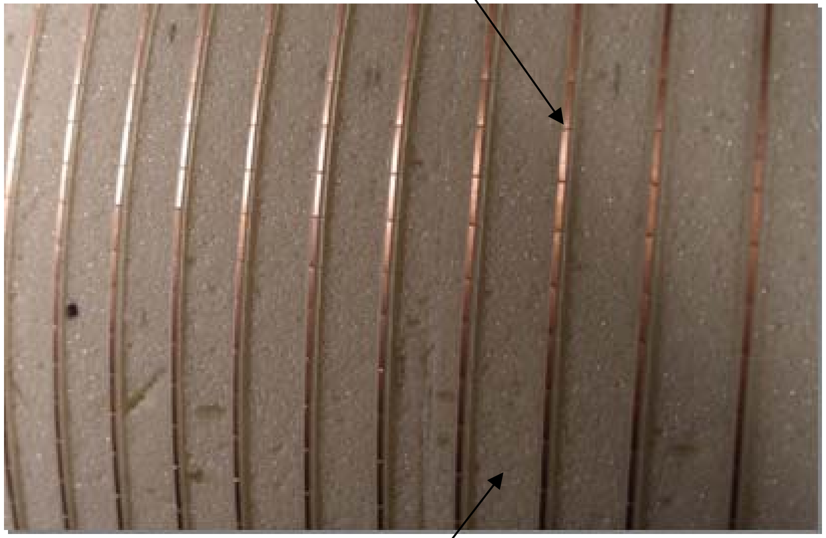
Simulations of the spherical and controllable radome



Prototype: Design and Test with a horn antenna.

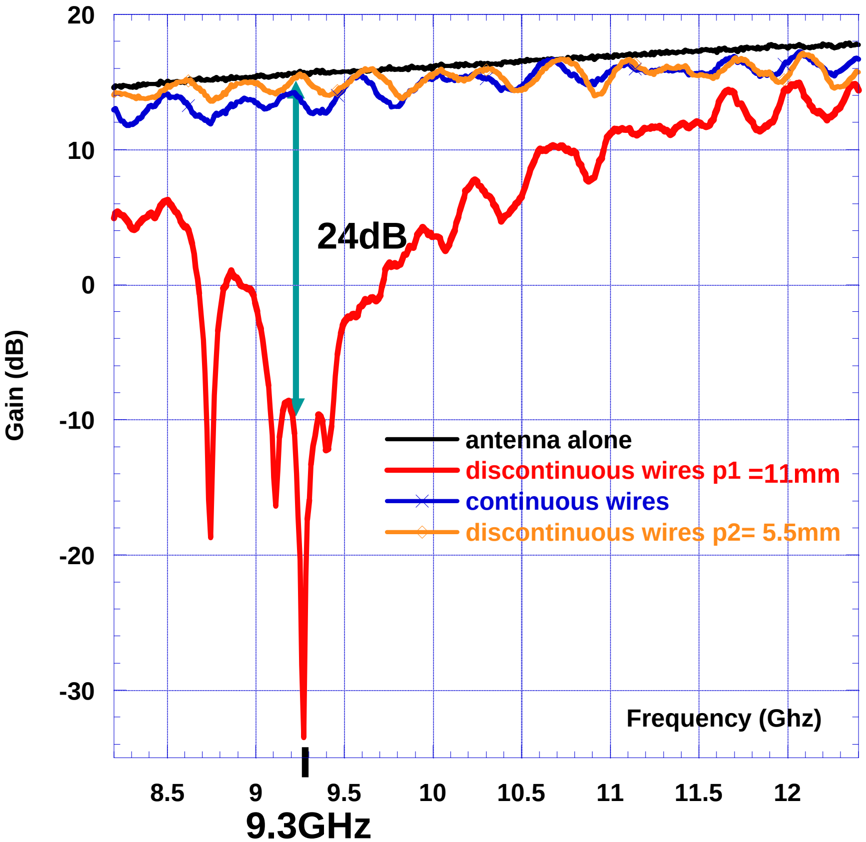
Horn antenna inside the radome.

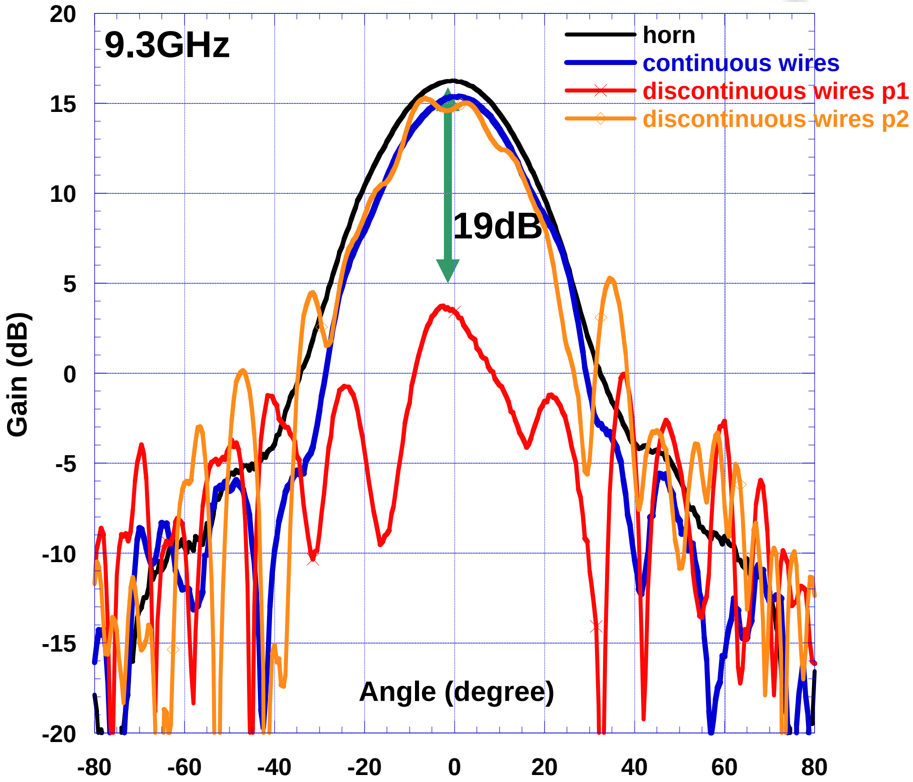
•Discontinuities' width 0.1mm
•Wires' width 1mm printed on a flexible support



Foam (permittivity close to 1)

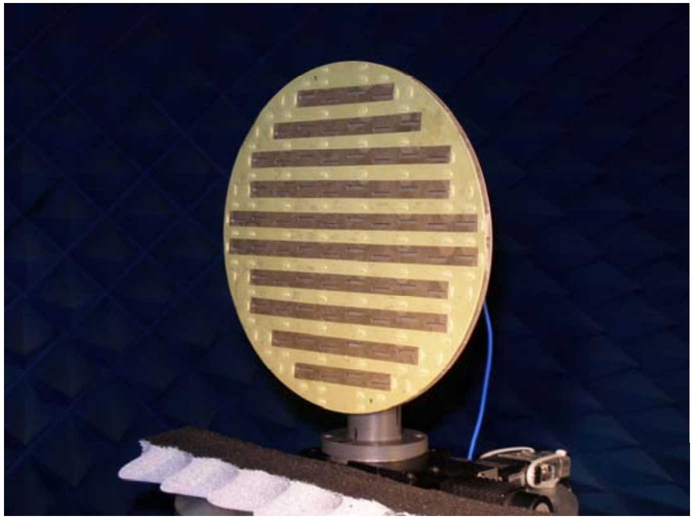
Measurements of the prototype with the antenna

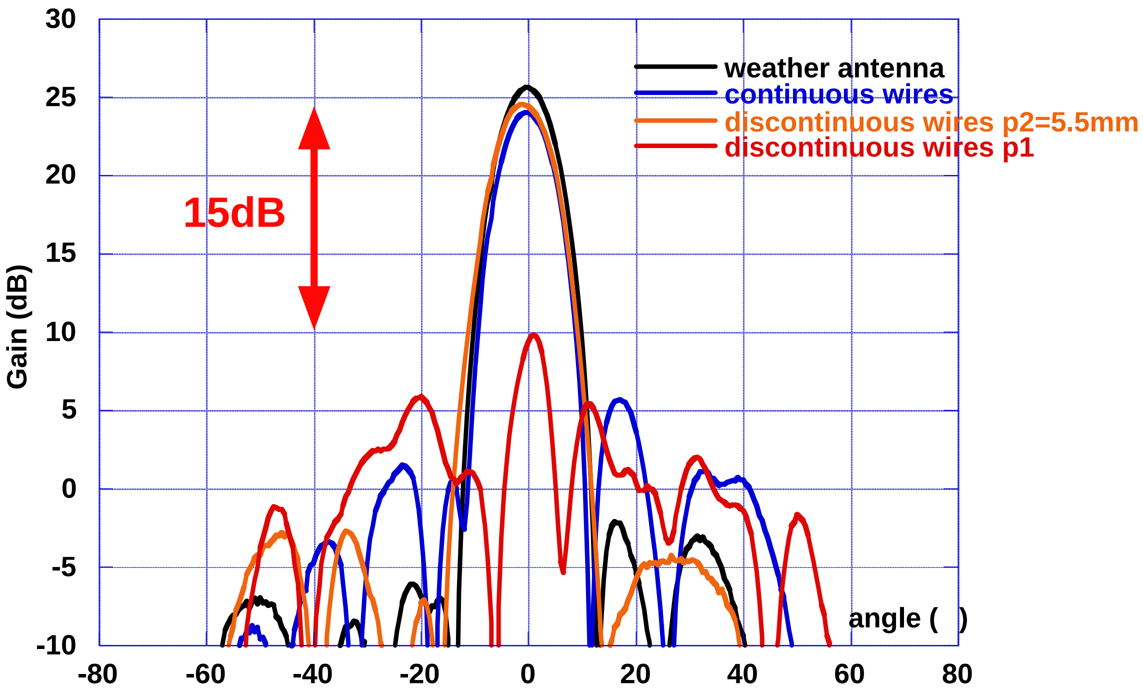




Measurements of the prototype with the weather radar antenna

Weather radar antenna

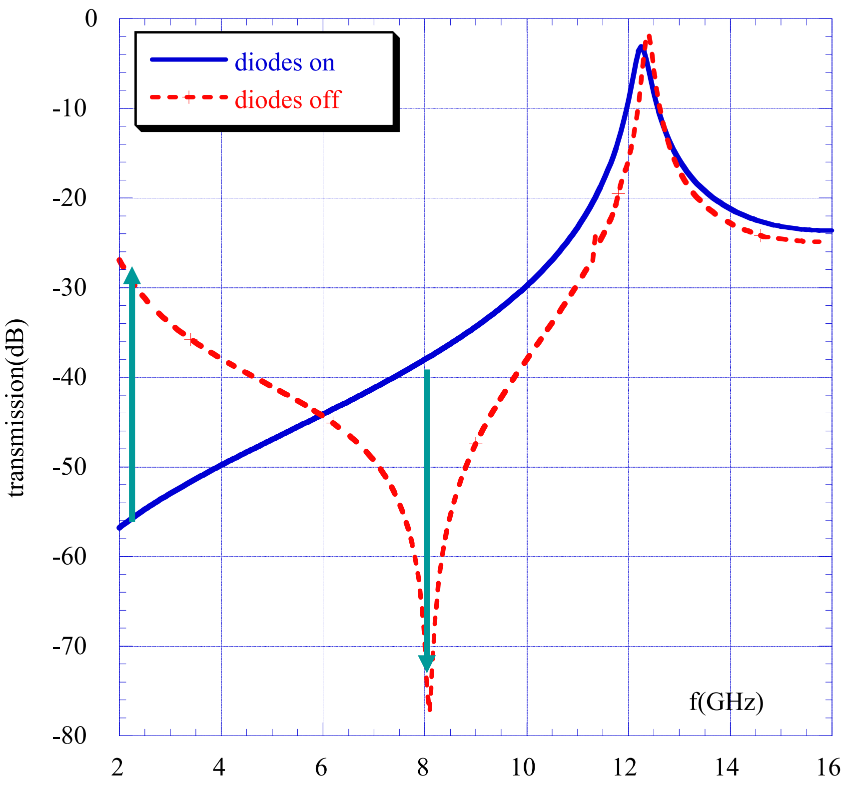


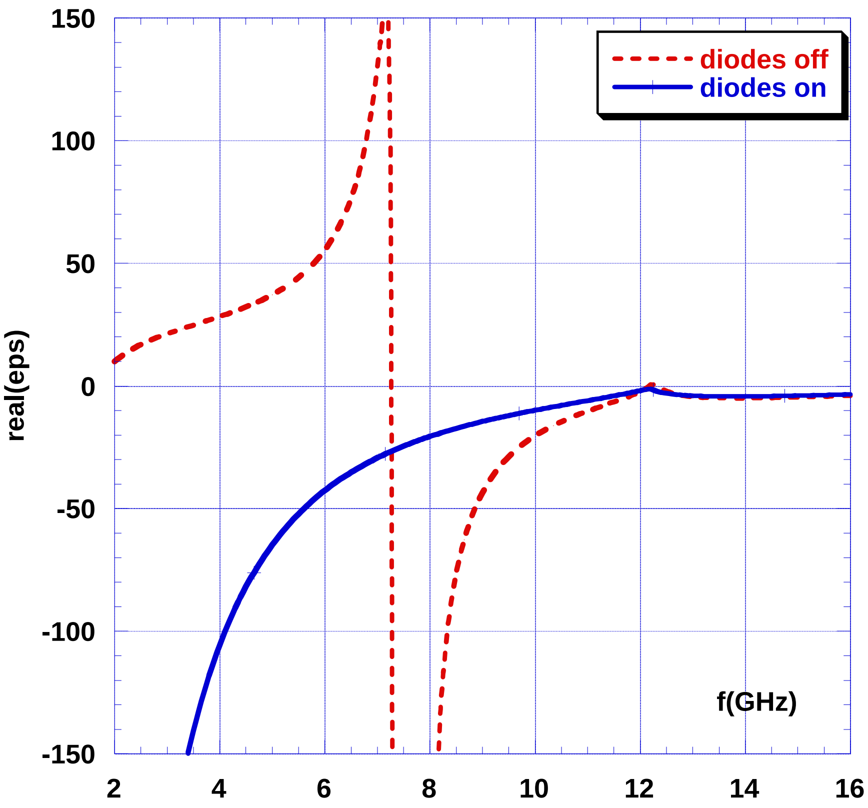


- The switching level is 15dB.
- The directivity of the antenna is unchanged.

From the wire lattice to the LHM

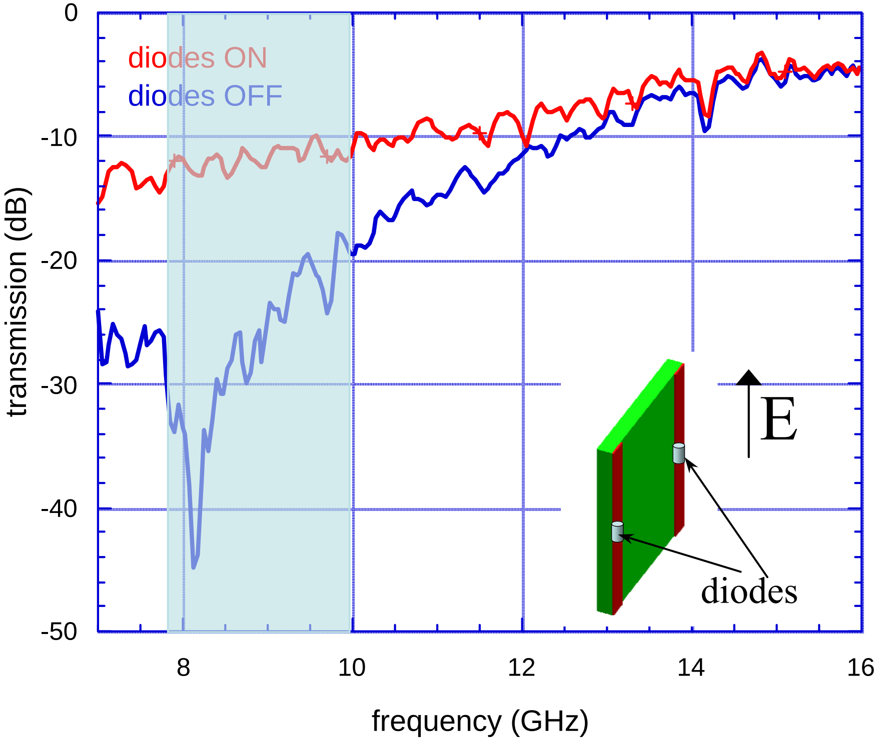
Control of the permittivity.

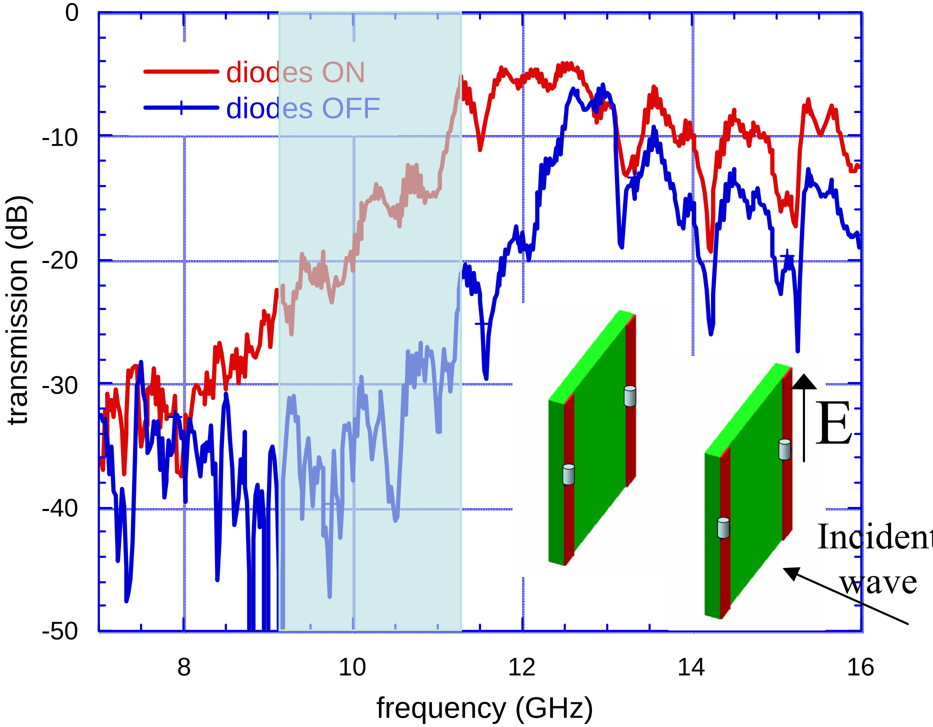




2 boards of metallic wires with PIN diodes: the switch of the transmission and the permittivity for the 2 states of the diodes.

Transmission of metallic stripes.

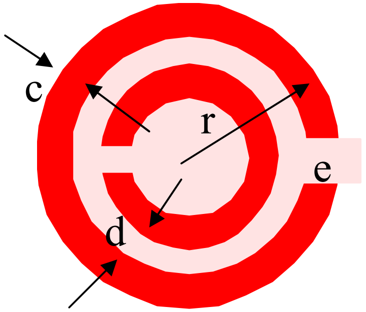


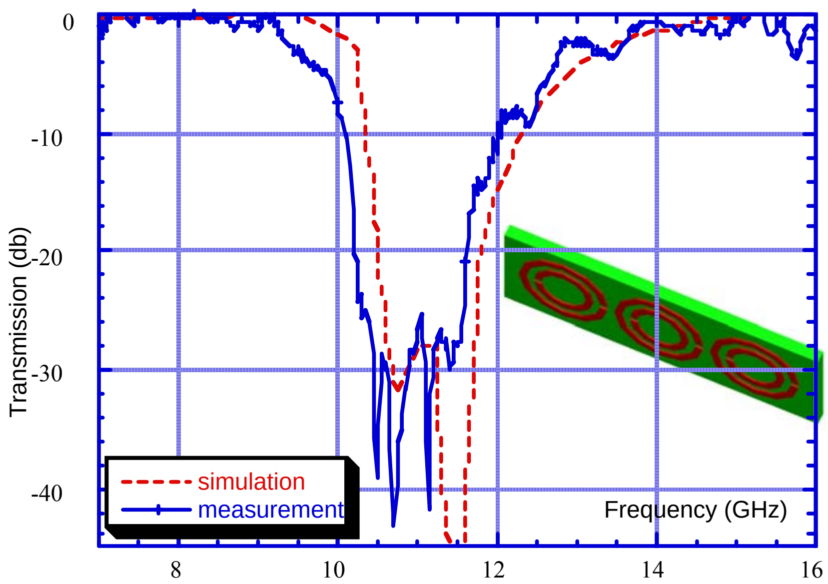


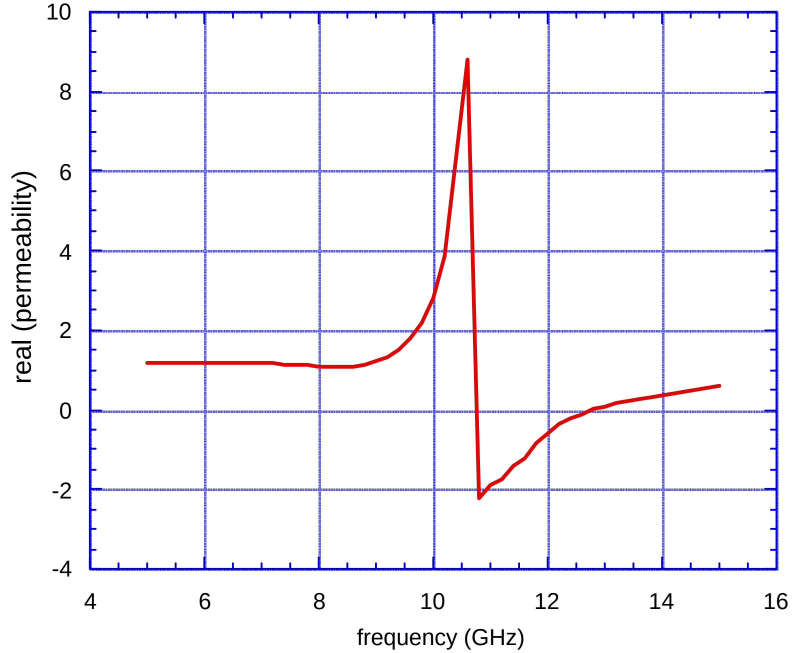
Comparison of the transmission through 1 and 2 boards of metallic wires with PIN diodes

Permeability of the Split Ring Resonators

- r = 1.5 mm, c=d=e=0.25mm.
- The permeability is negative at the beginning and the end of the rejection.



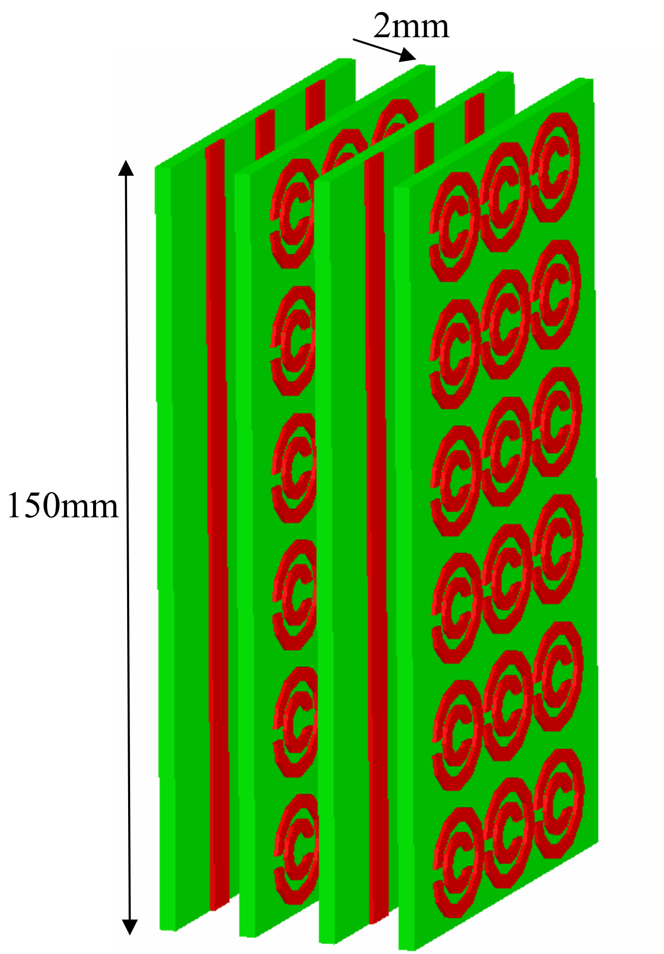




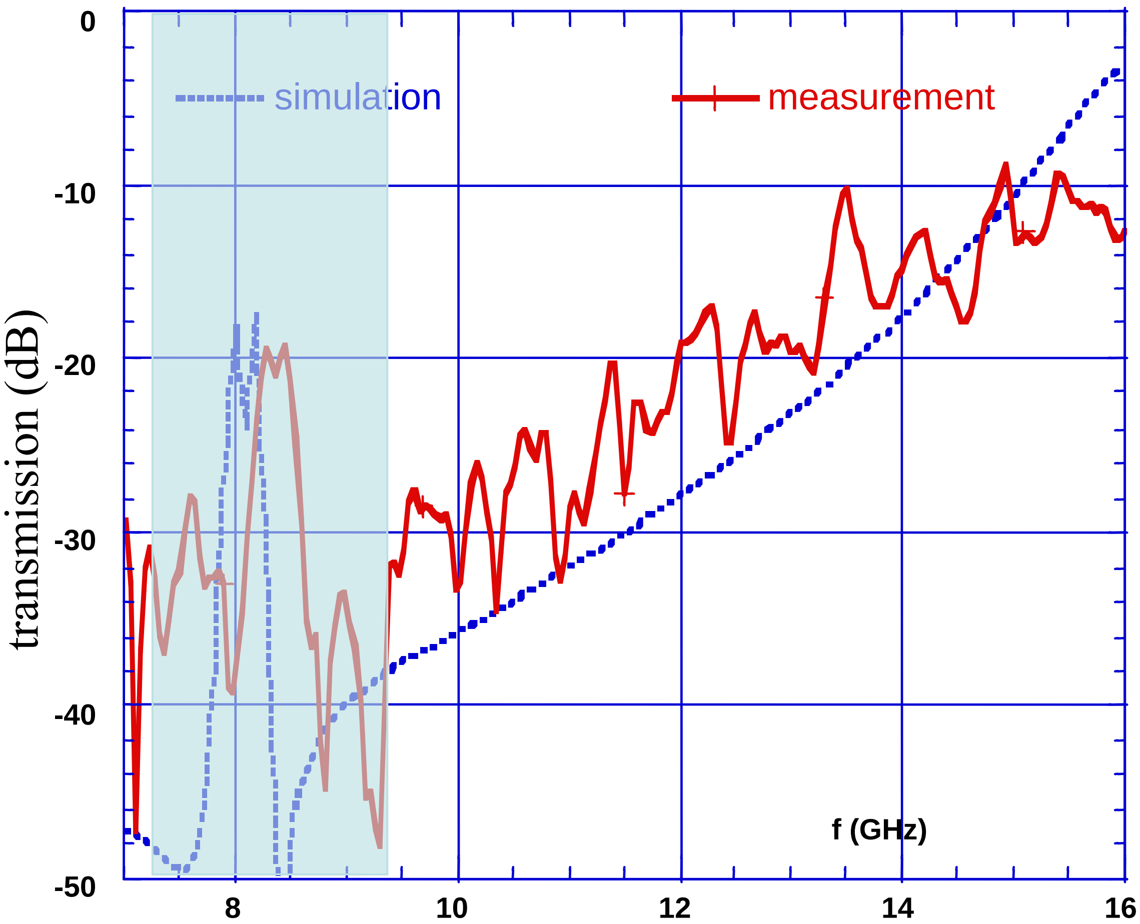
calculation for 1 disc

A first passive prototype

Transmission of the LHM: measurement and calculation

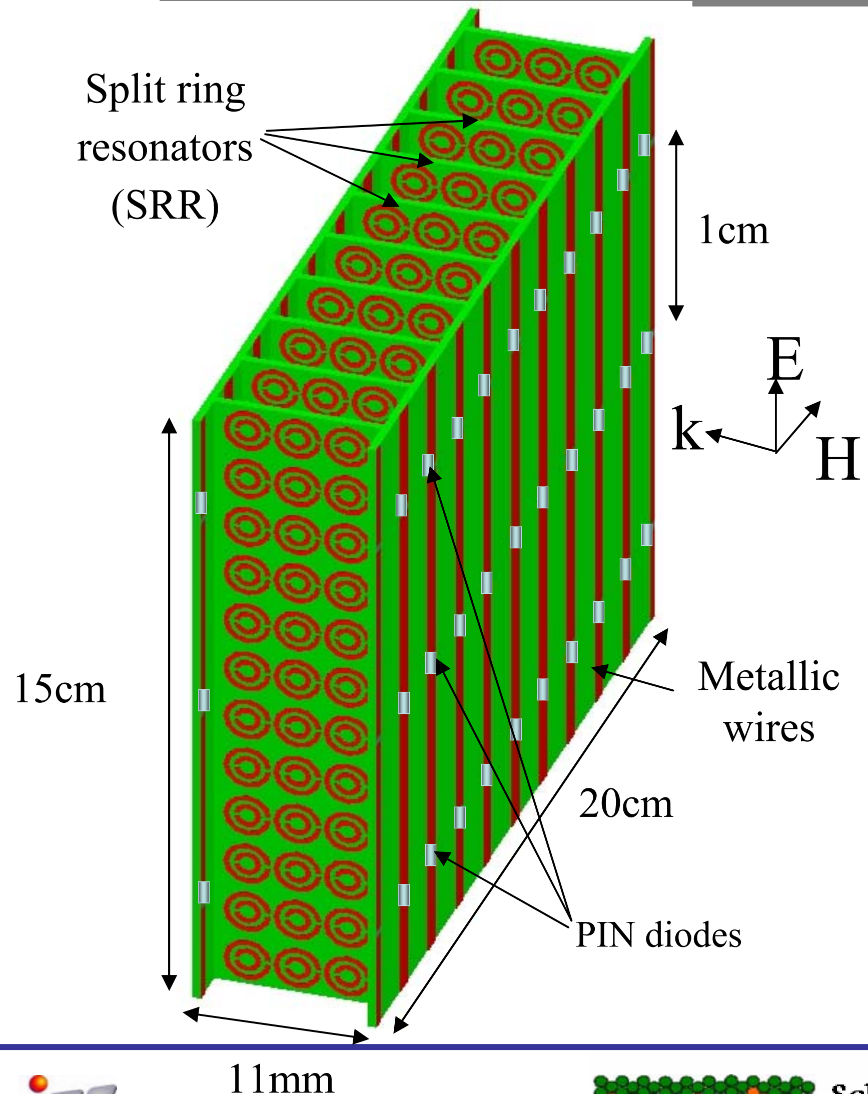


The first prototype.



Measurement of the whole controllable LHM

The whole metamaterial: the design.

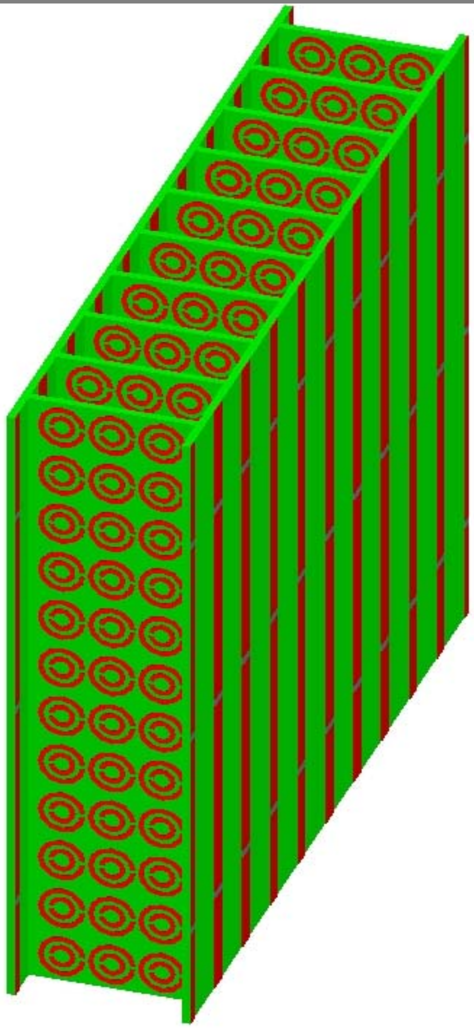


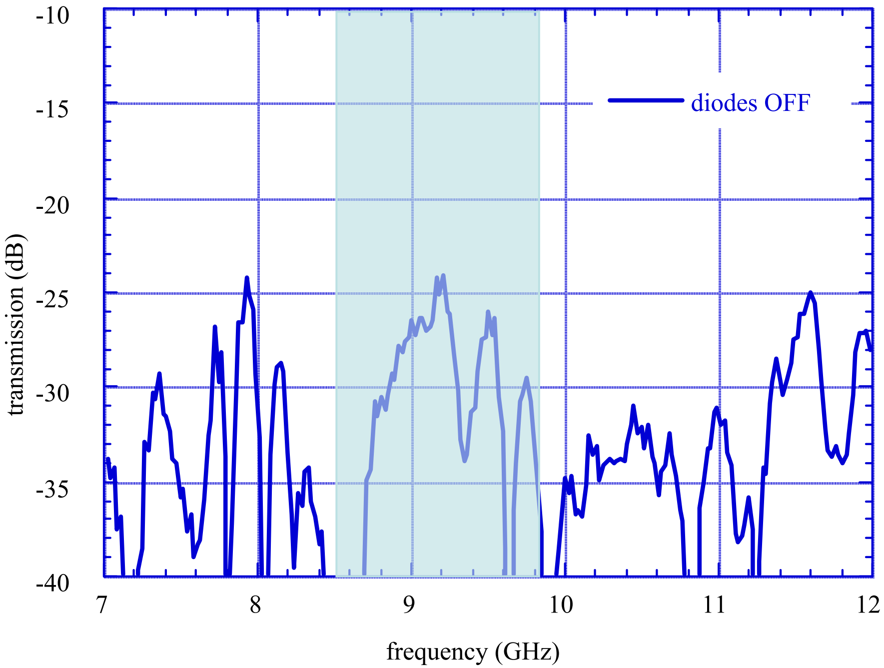
The whole structure is the association of 2 lattices:

a) **Lattice of wires with diodes:**
-2 parallel boards: height 150mm, width 200mm and thickness 0.4mm.
-Metallic wires of 1mm width spaced by 4mm.
-PIN diodes on these wires every 1cm.

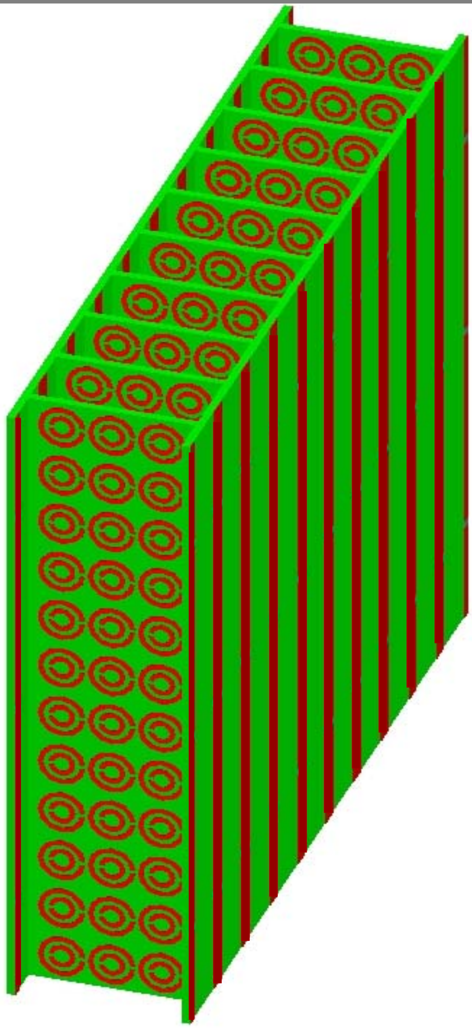
b) **Lattice of SRR**:
-Exterior diameter : 3mm and the interior one: 1.75mm.
-Discs spaced by 3.1mm (center to center).
-Boards spaced every 4mm.
-Boards' width: 11mm.

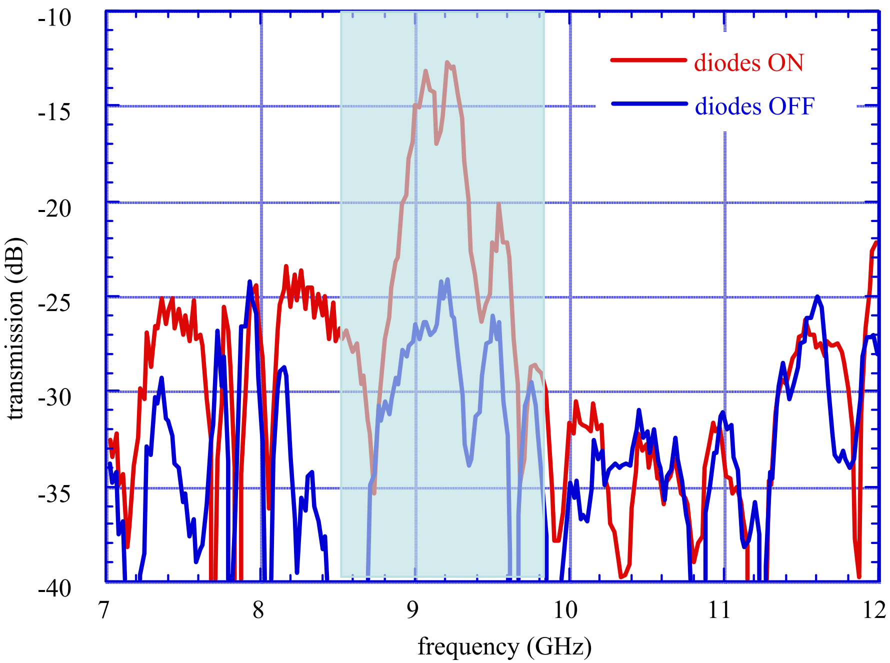
The whole controllable metamaterial: transmission





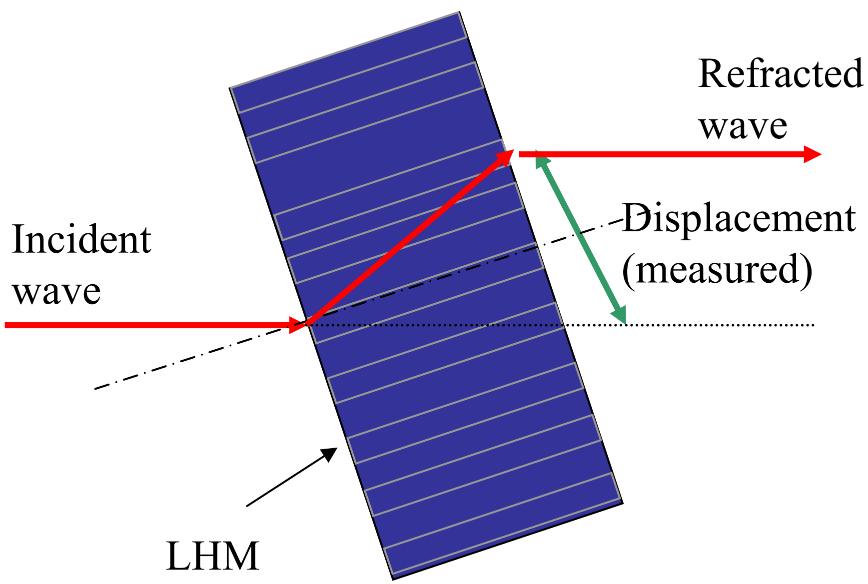
The whole controllable metamaterial: transmission

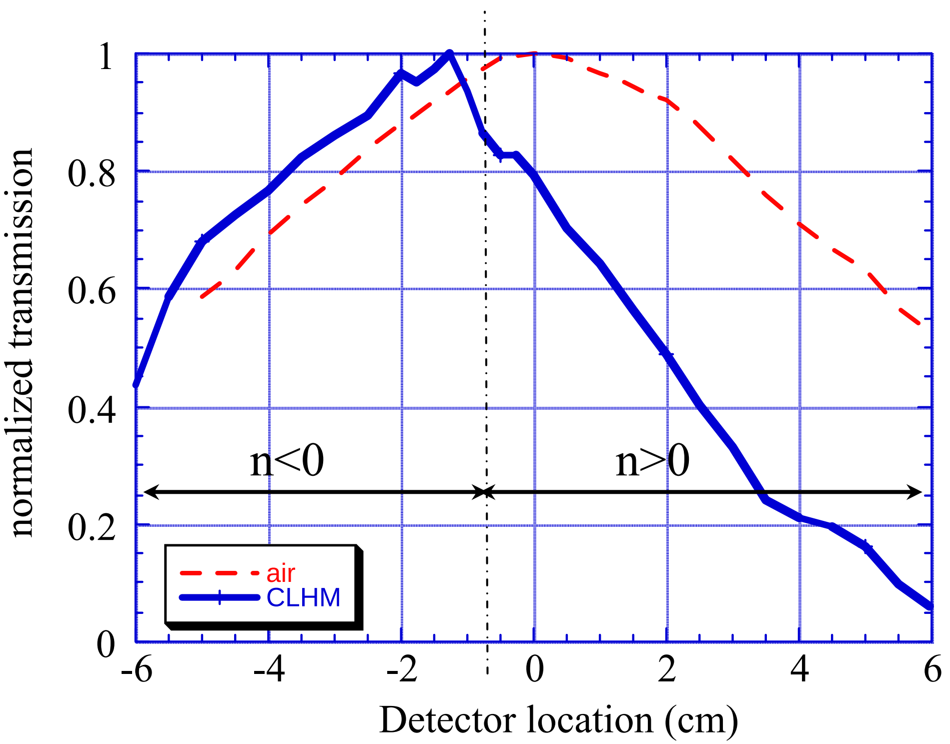




Switching between both states of the material
-Diodes OFF: reflective material.
-Diodes ON: left handed material.

Measurement of the negative refraction





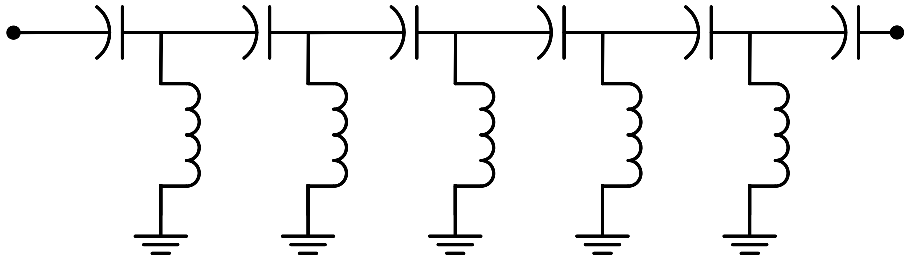
The refractive index equals -1.5

Active Variable Phase Metamaterial Cavity for Directive Antenna

1D and 2D metamaterials: an old but new concept ?

→ **L. Brillouin**, “Wave Propagation in Periodic Structures: Electric Filters and Crystal Lattices”, Mc Graw Hill, 1946

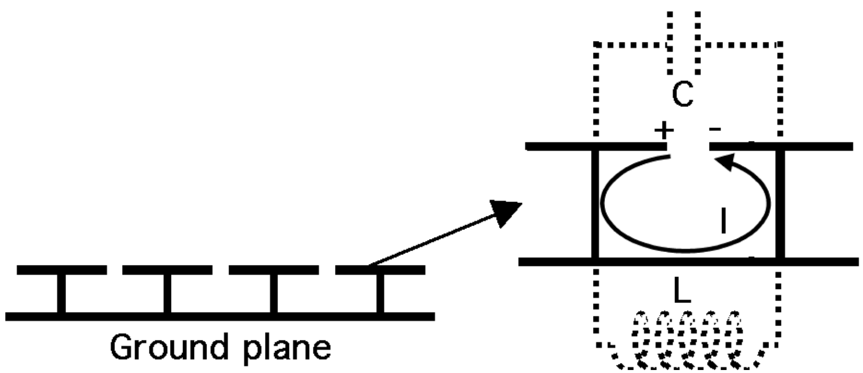
→ **J. R. Pierce**, Bell Labs, “Traveling-Wave Tubes”, D. Van Nostrand Company, 1950



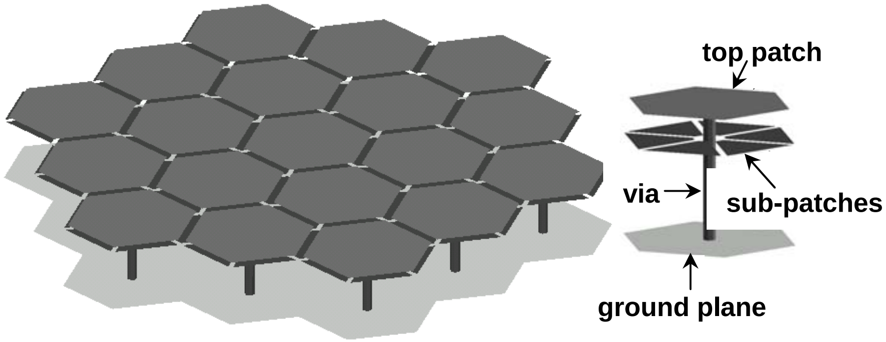
$$V_\phi \cdot V_g < 0$$

Use of metallic motifs with LC resonances

→ **D. Sievenpiper**, “High impedance electromagnetic surfaces”, PhD 1999



→ **C. Caloz et al.**, “Transmission line approach of left-handed …”, IEEE Trans. Antennas 2004



Goals

- Planar Directive Antenna in X band.
- Compactness (Thickness << $\lambda/4$).
- Reconfigurable antenna.

Fabry-Perot cavity antenna: operating principle…

Maximum power at boresight [1] ($\theta = 0$) is obtained when :

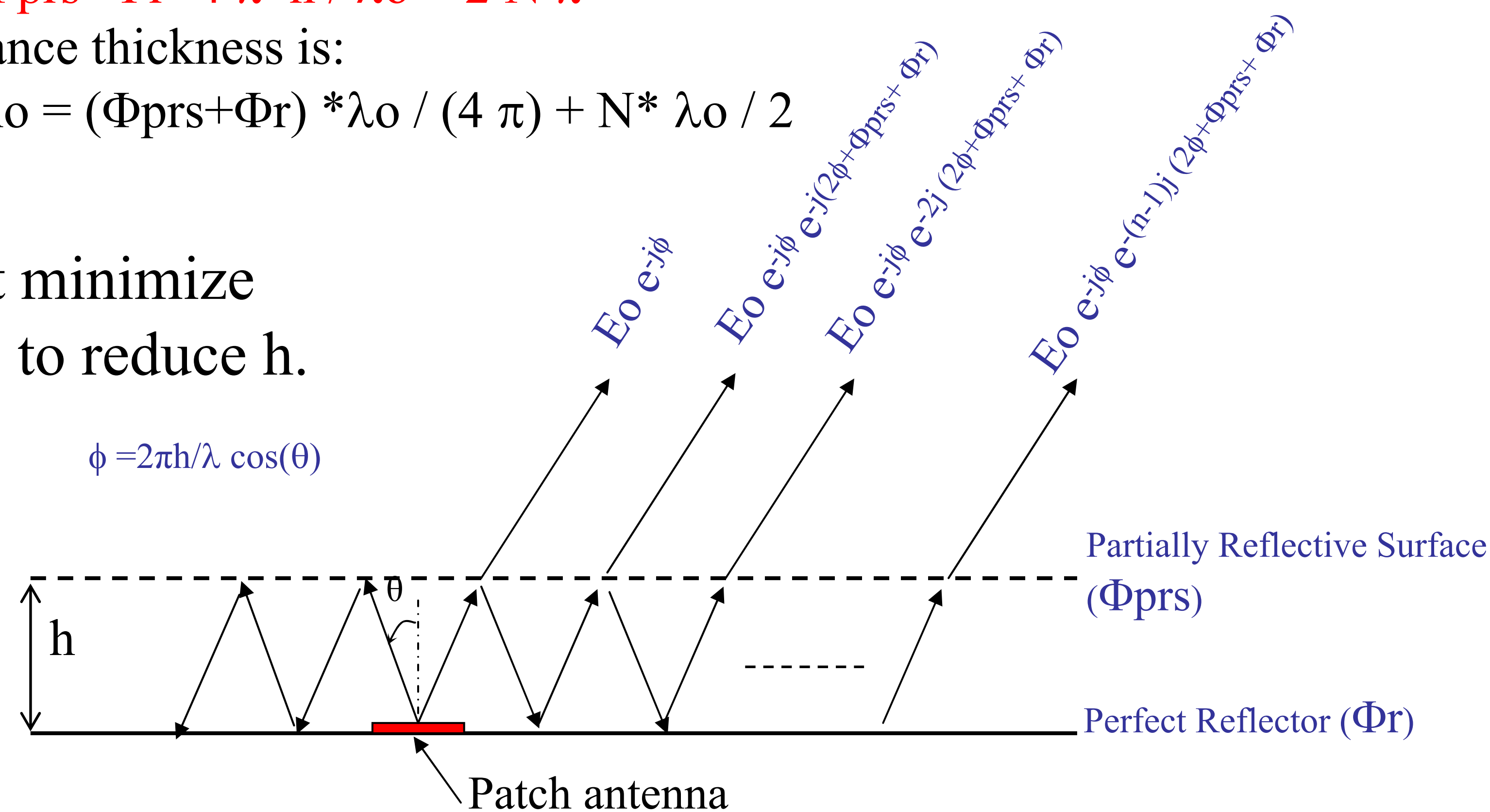
$$\Phi prs + \Phi r - 4\pi \; h / \lambda o = 2 N \pi$$

The resonance thickness is:

$$ho = (\Phi prs + \Phi r) * \lambda o / (4\pi) + N * \lambda o / 2$$

- We must minimize (Φprs+Φr) to reduce h.

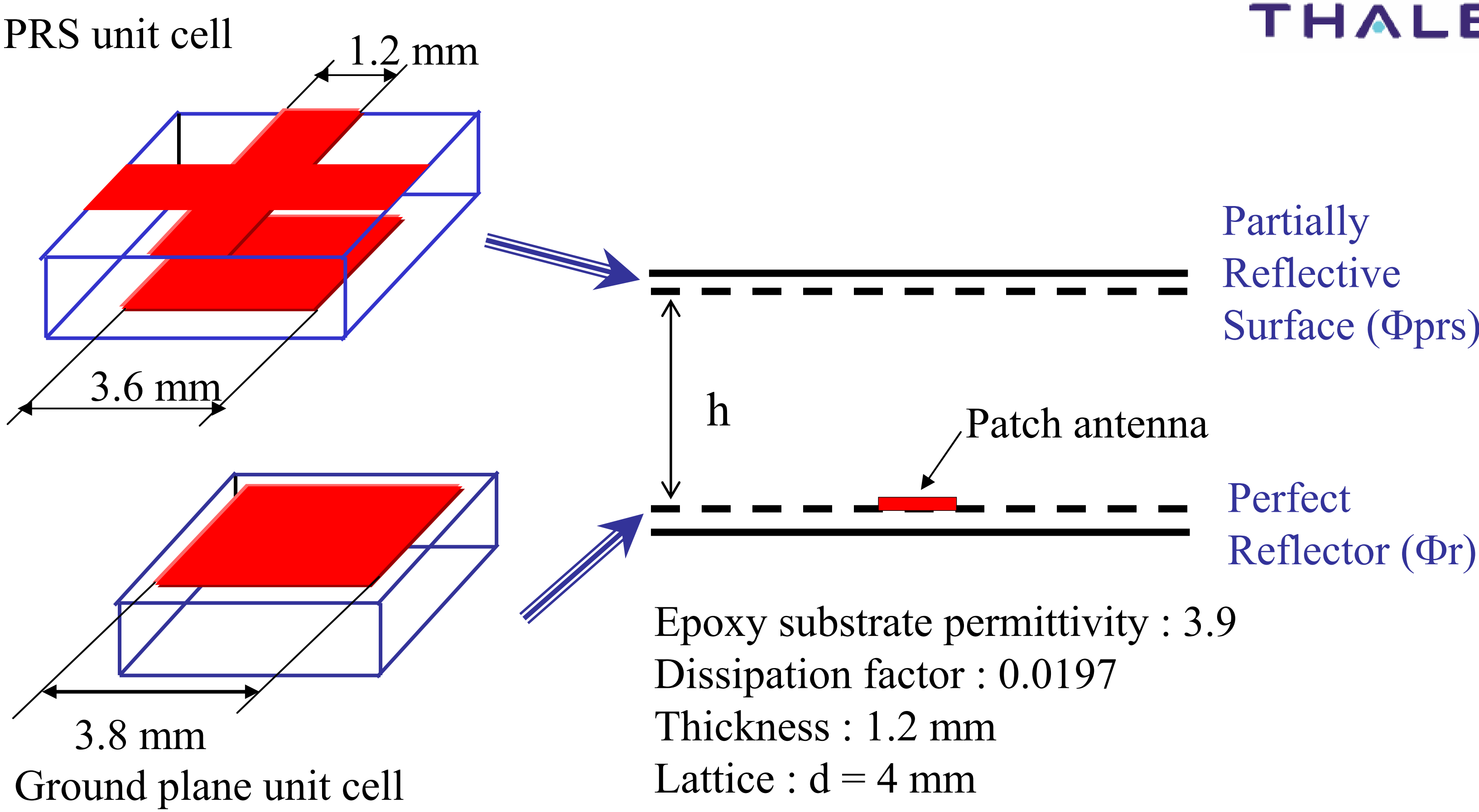
$\phi = 2\pi h/\lambda \cos(\theta)$



[1] G.V. Trentini, IRE Transactions on Antennas and Propagation, Vol 4, p. 666-671, oct. 1956.

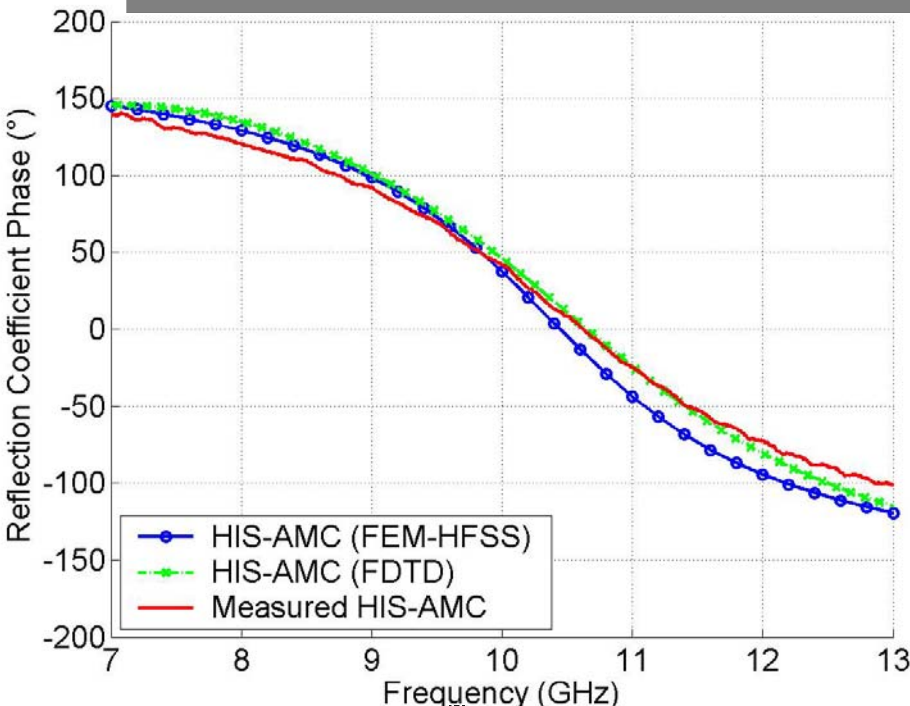
All-metamaterial-based Cavity Design

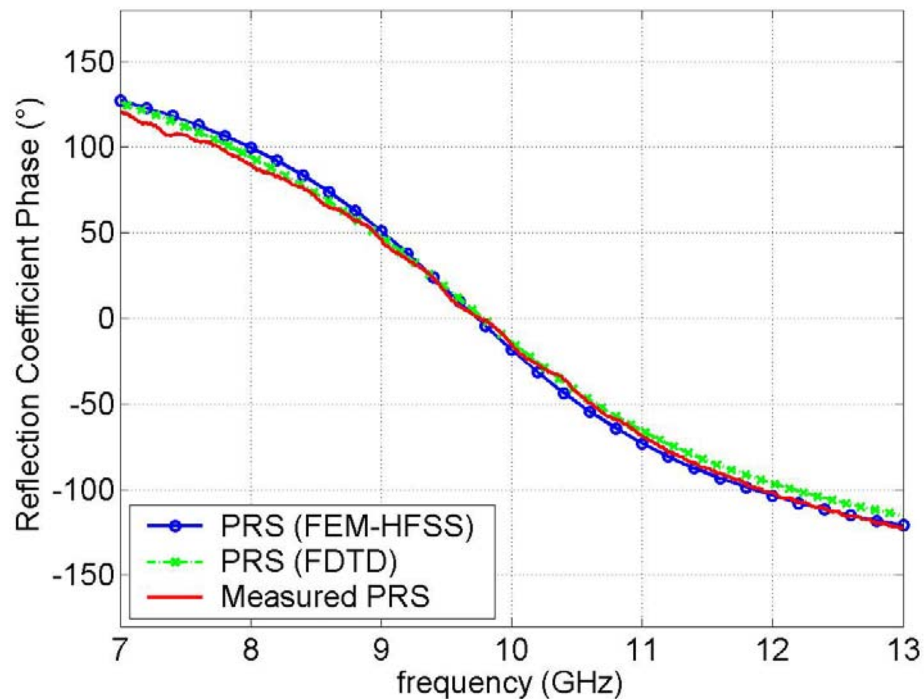
THALES

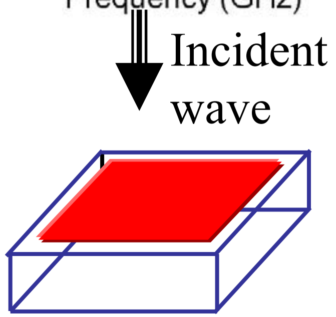


Epoxy substrate permittivity : 3.9
Dissipation factor : 0.0197
Thickness : 1.2 mm
Lattice : d = 4 mm

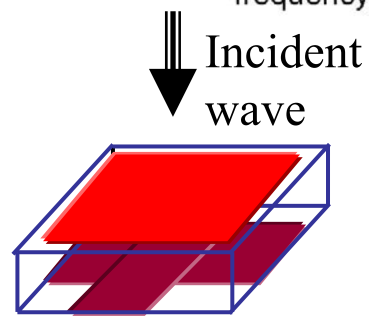
Normal Incidence Reflection Coefficients Phase





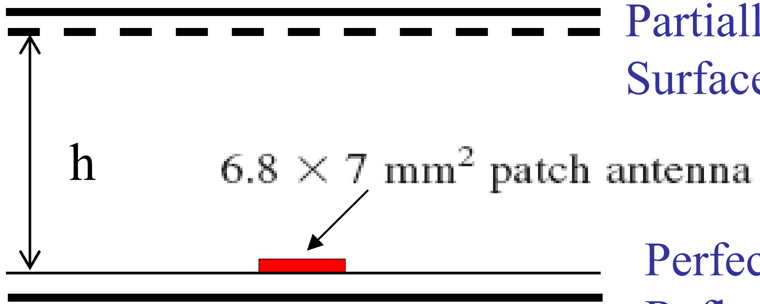


Ground plane unit cell



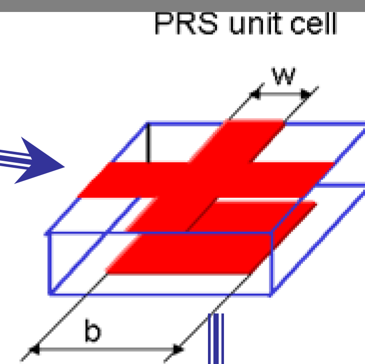
PRS unit cell

Composite metamaterial based subwavelength cavities

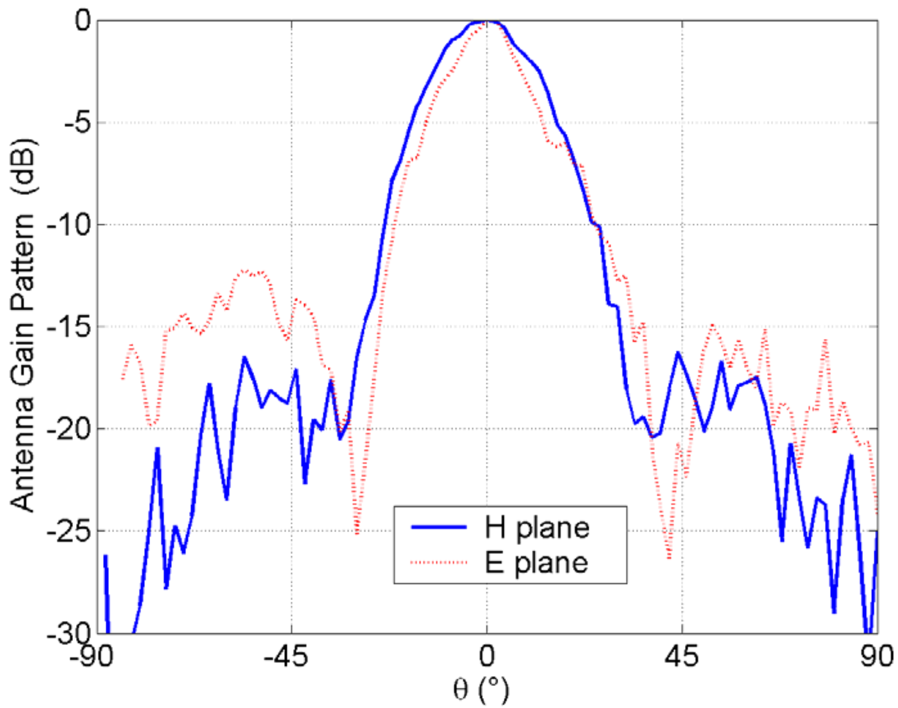


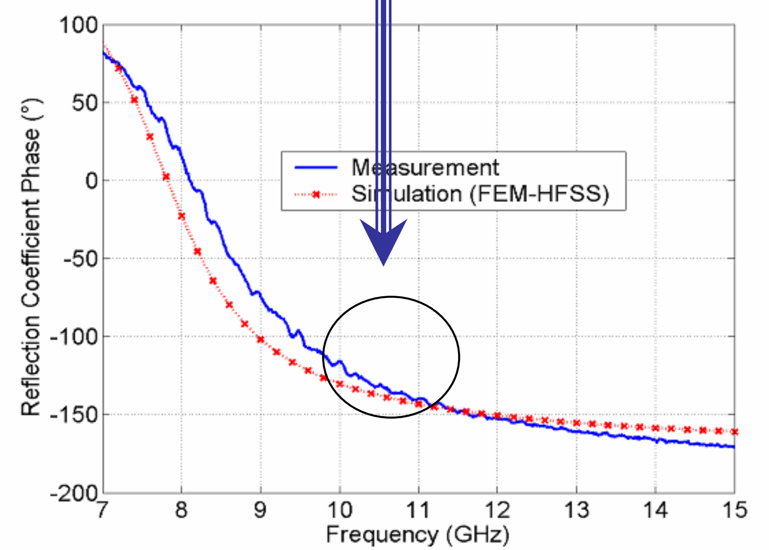
Partially Reflective Surface (Φprs)

Perfect Reflector (Φr)



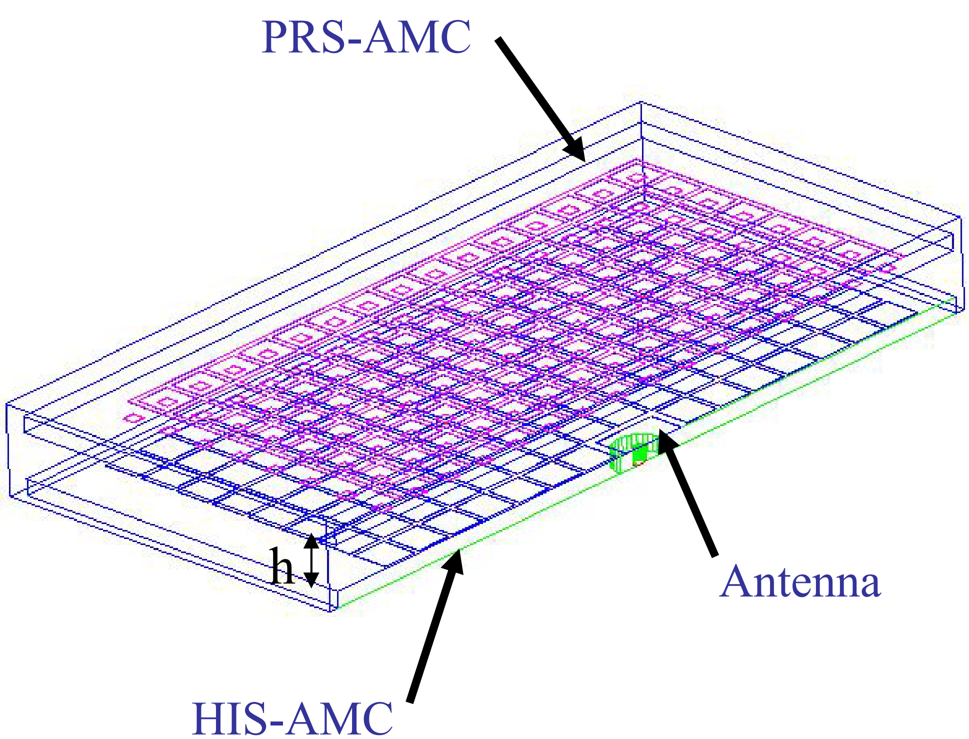
ε_r=3.9
δ=0.0197
h=1.2 mm
a=5 mm
b=4.8
w=2.2 mm

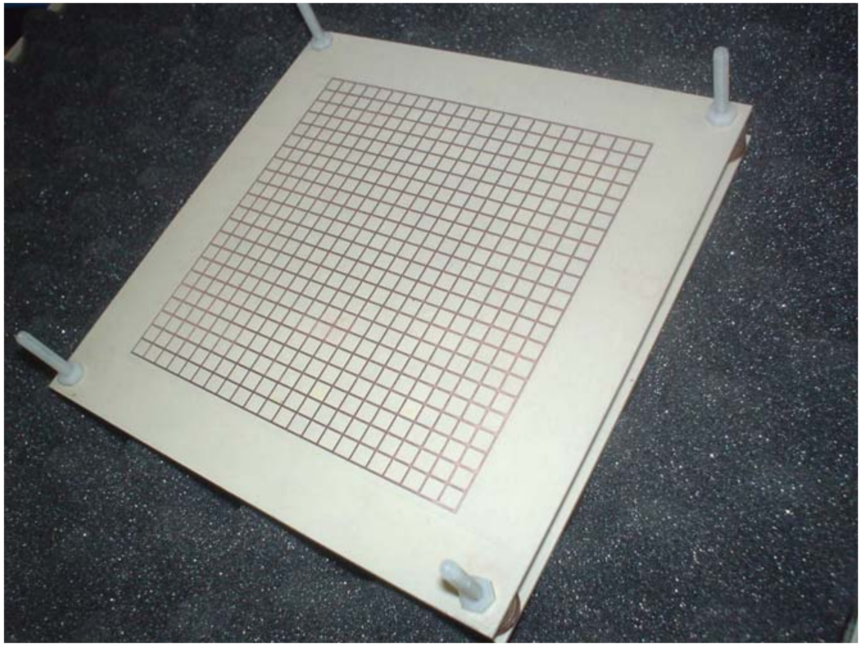




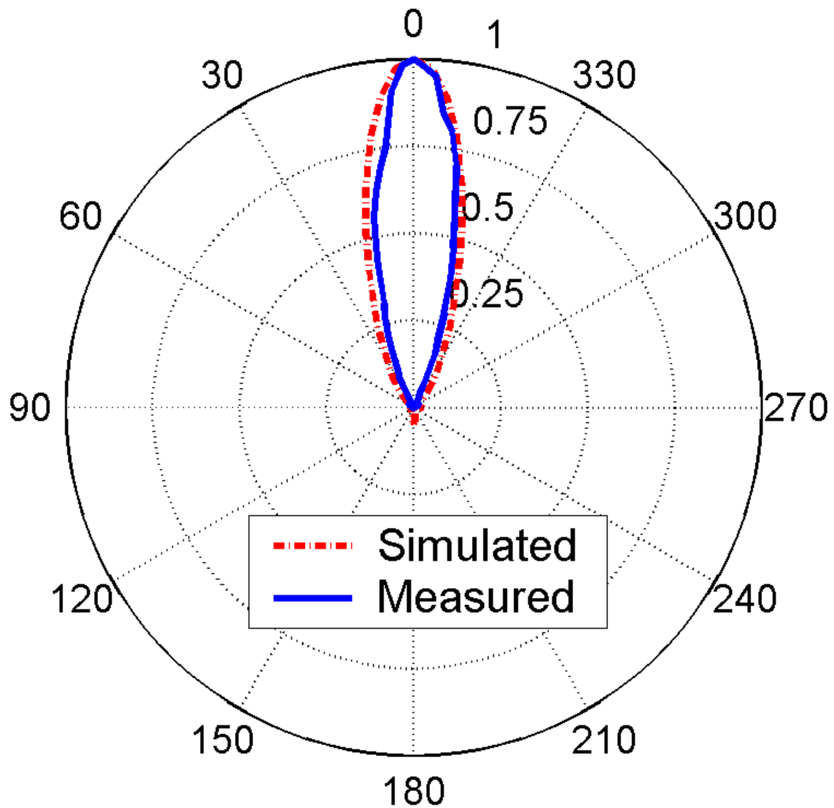
- Resonance thickness $h = \dfrac{\lambda}{30}$
- High directivity (22 dB)

The Fabry-Perot Cavity antenna: realization.

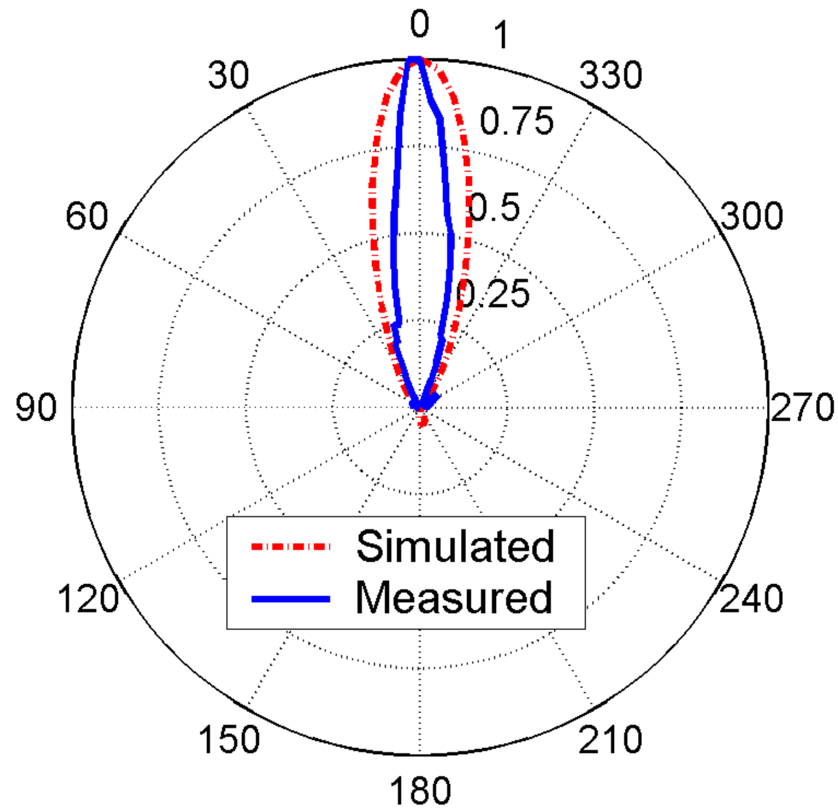




Optimized Metamaterial-based Cavity Radiation Patterns



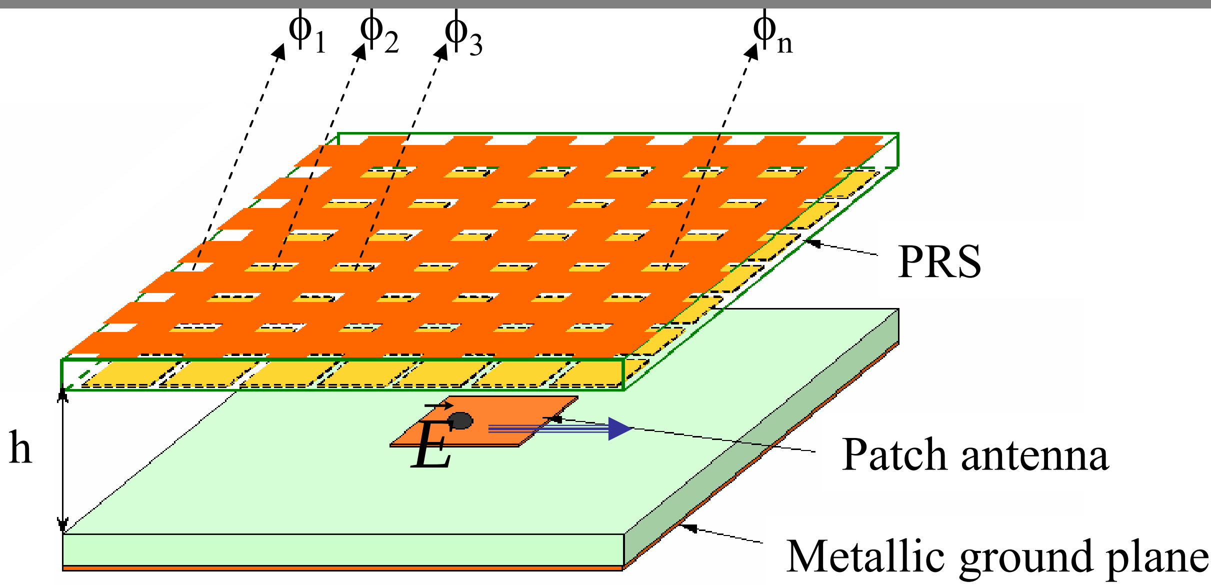
H Plane

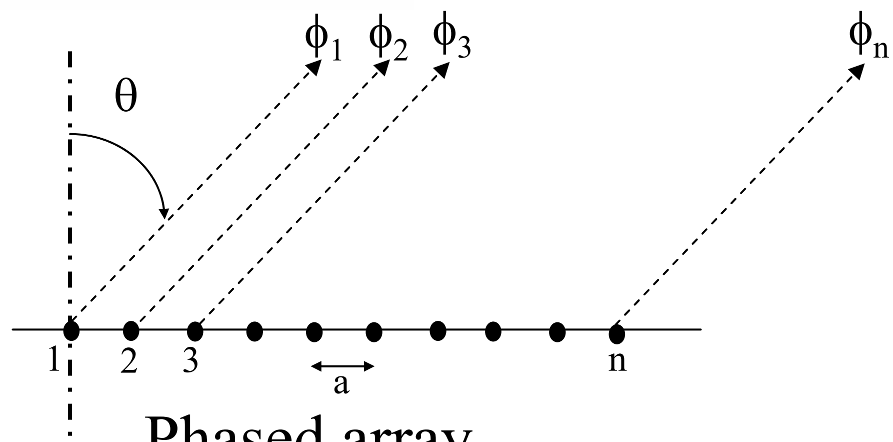


E Plane

Radiation patterns of the Resonant mode at 9.7 GHz for h=1 mm

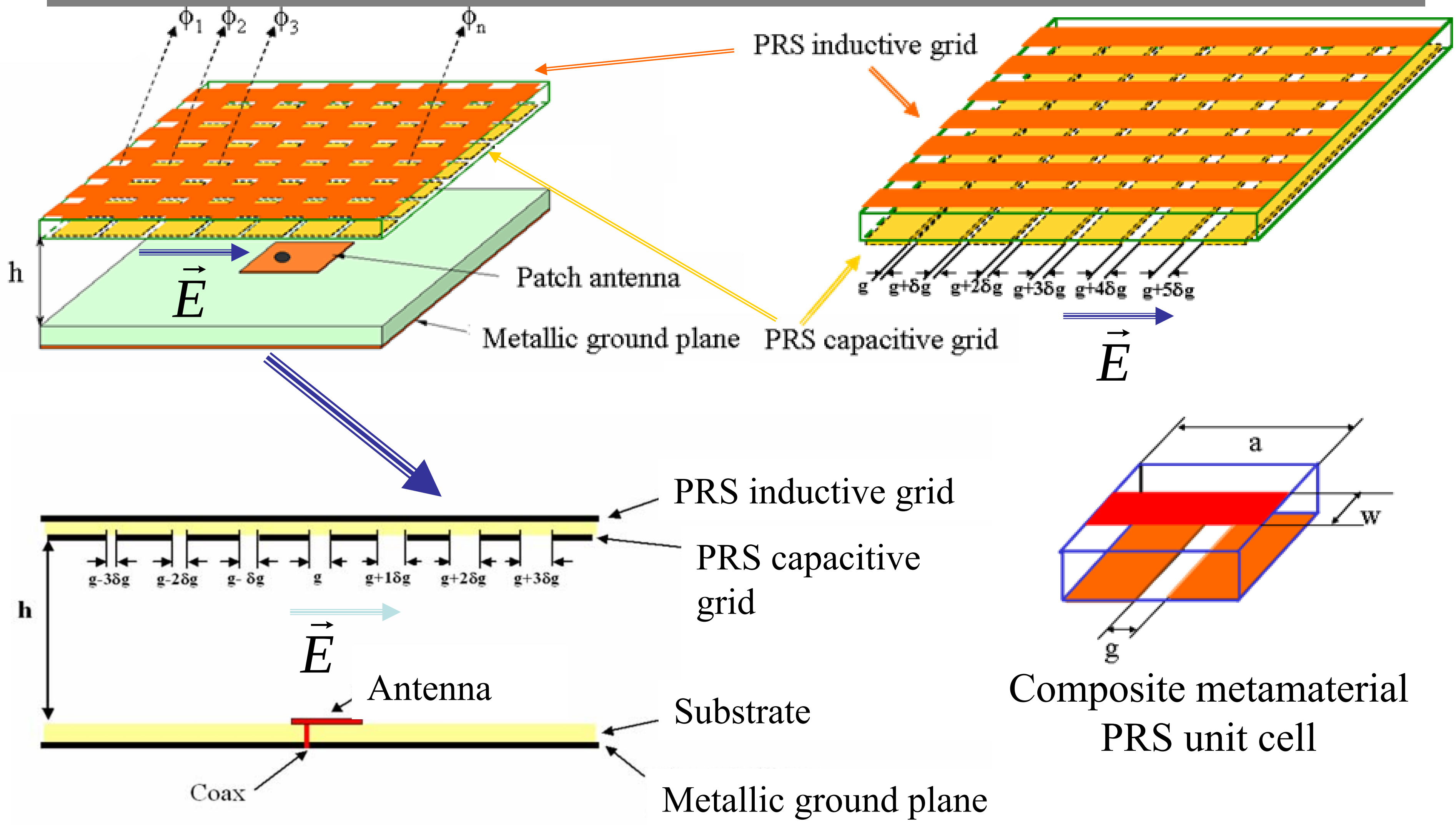
Steerable Metamaterial-based cavity operating principle



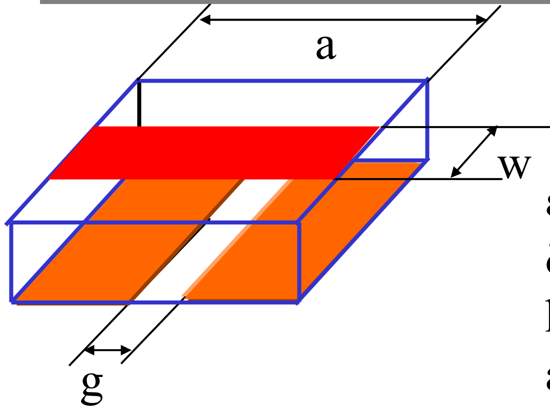


Phased array

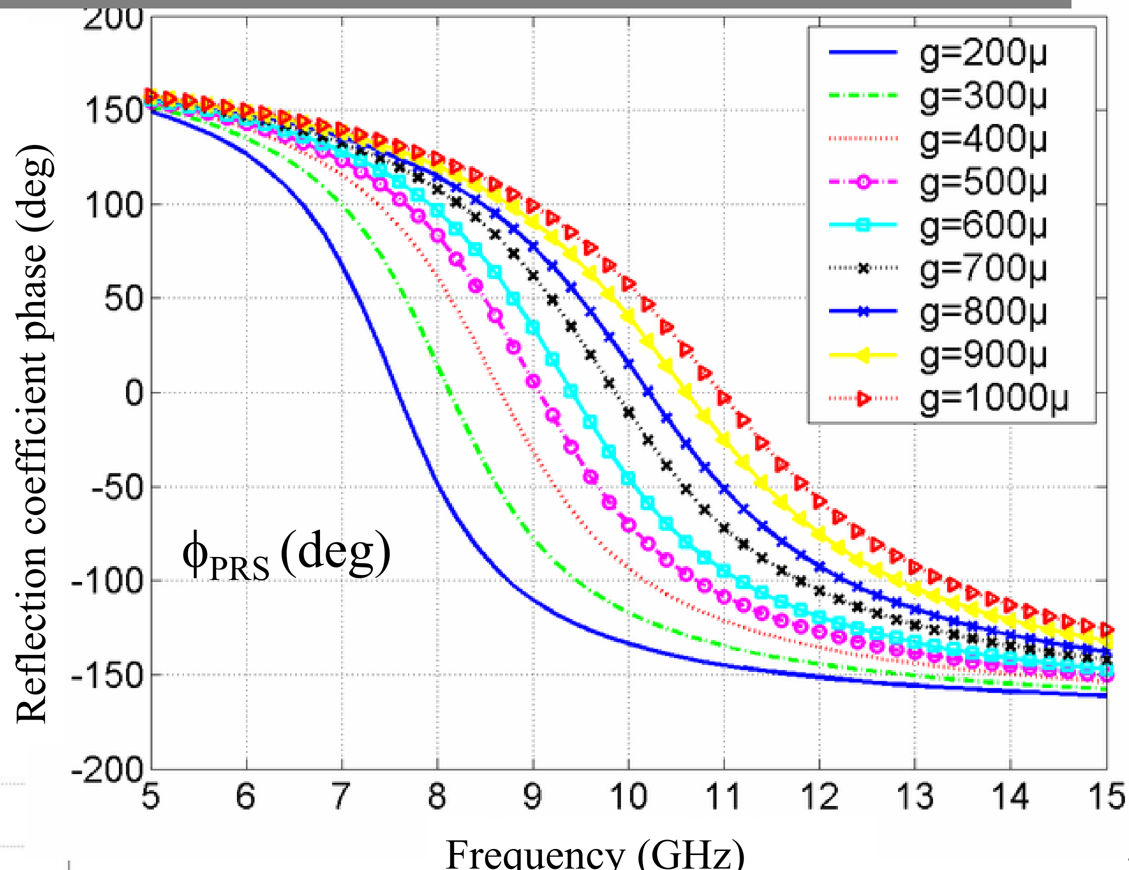
One dimensional composite metamaterial PRS conception

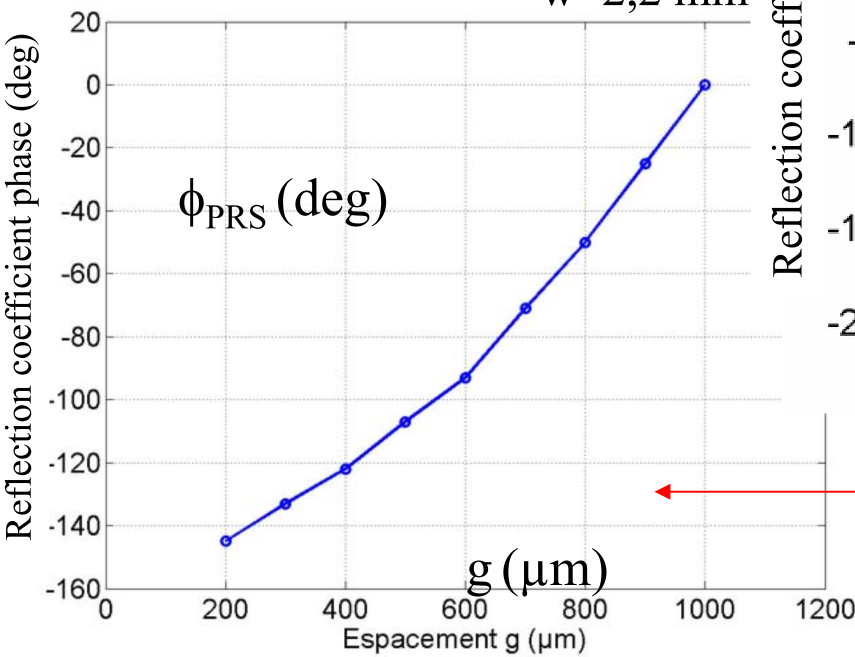


Composite metamaterial PRS Analysis



ε_r=3.9
δ=0.0197
h=1,2 mm
a=5 mm
w=2,2 mm

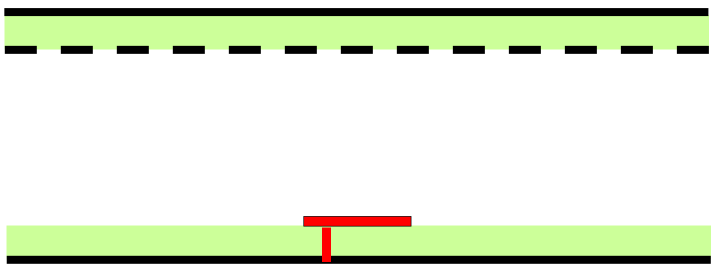




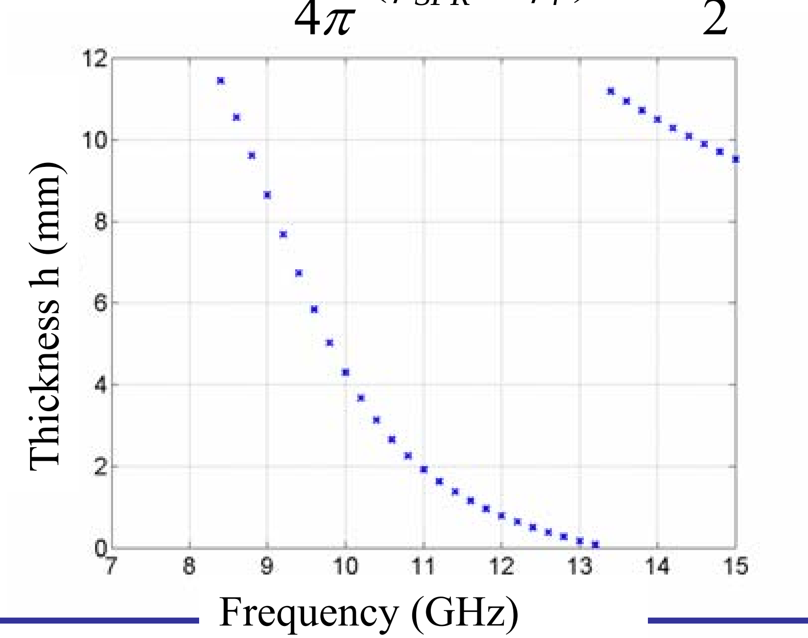
Reflection phase variation as a function of ***g*** at 11 GHz

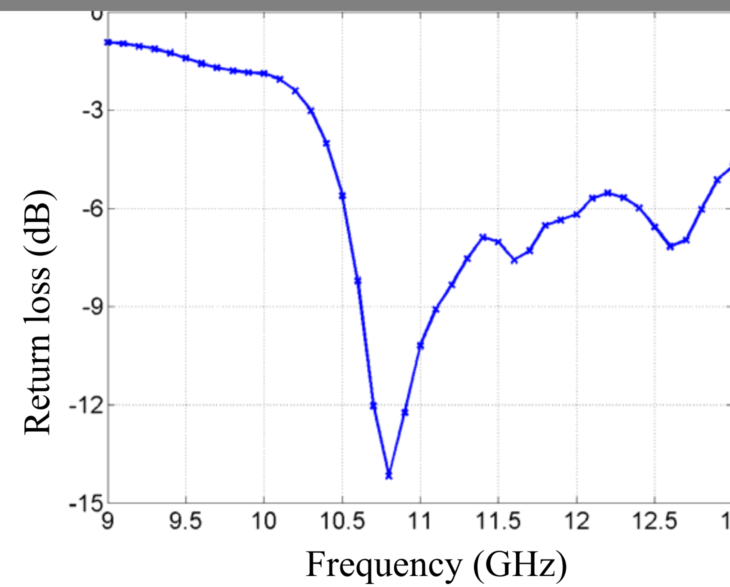
Metamaterial-based subwavelength cavity analysis

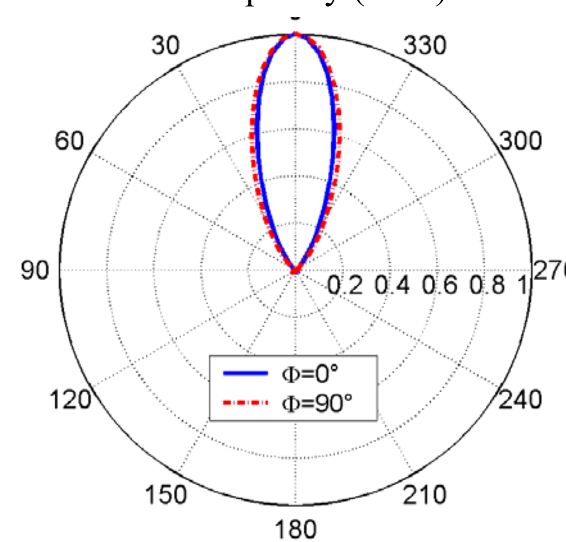
g=600 μm, h=2 mm



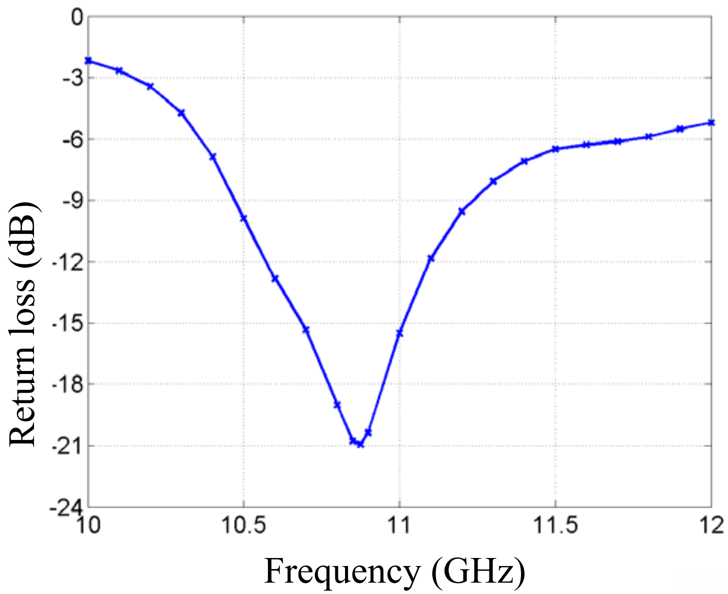
$$h = \frac{\lambda}{4\pi}(\phi_{SPR} + \phi_r) \pm N\frac{\lambda}{2}$$

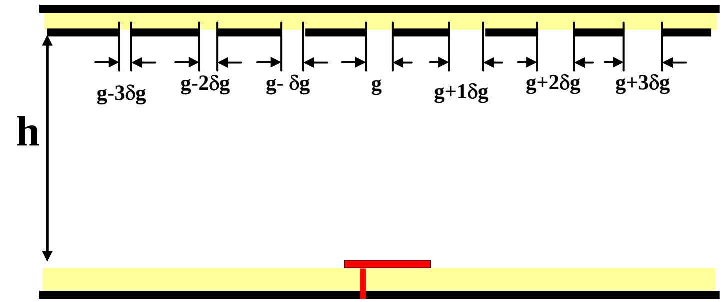




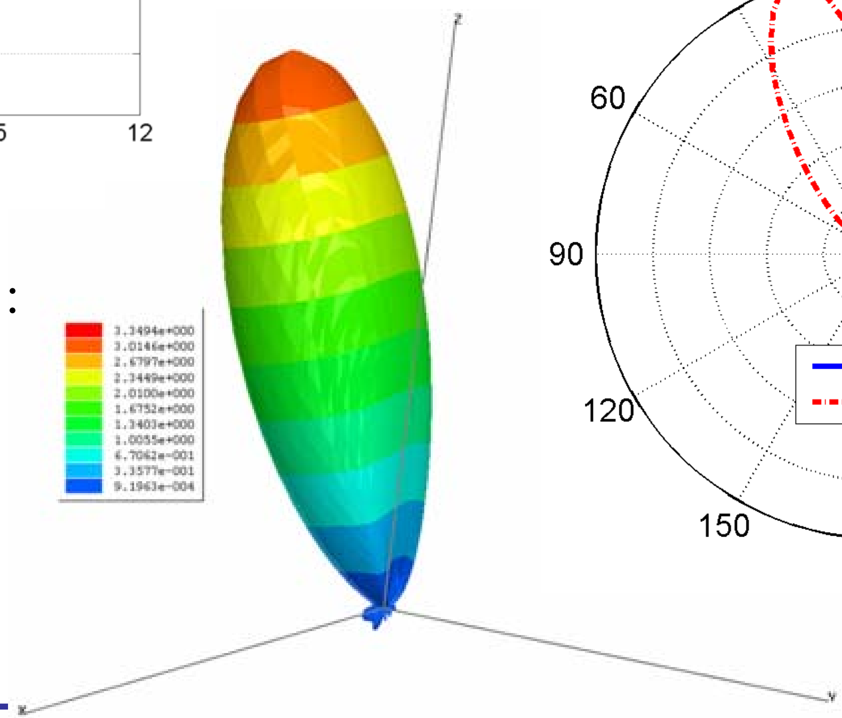


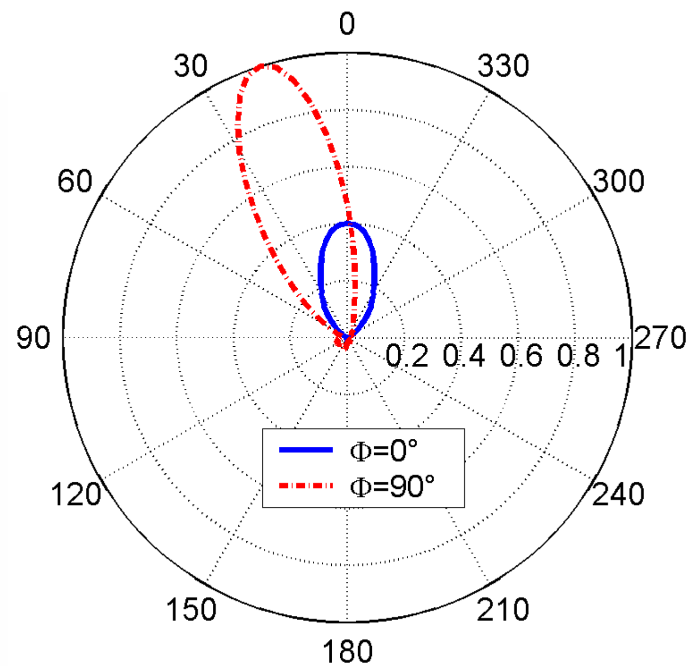
Metallic gap width variation effect



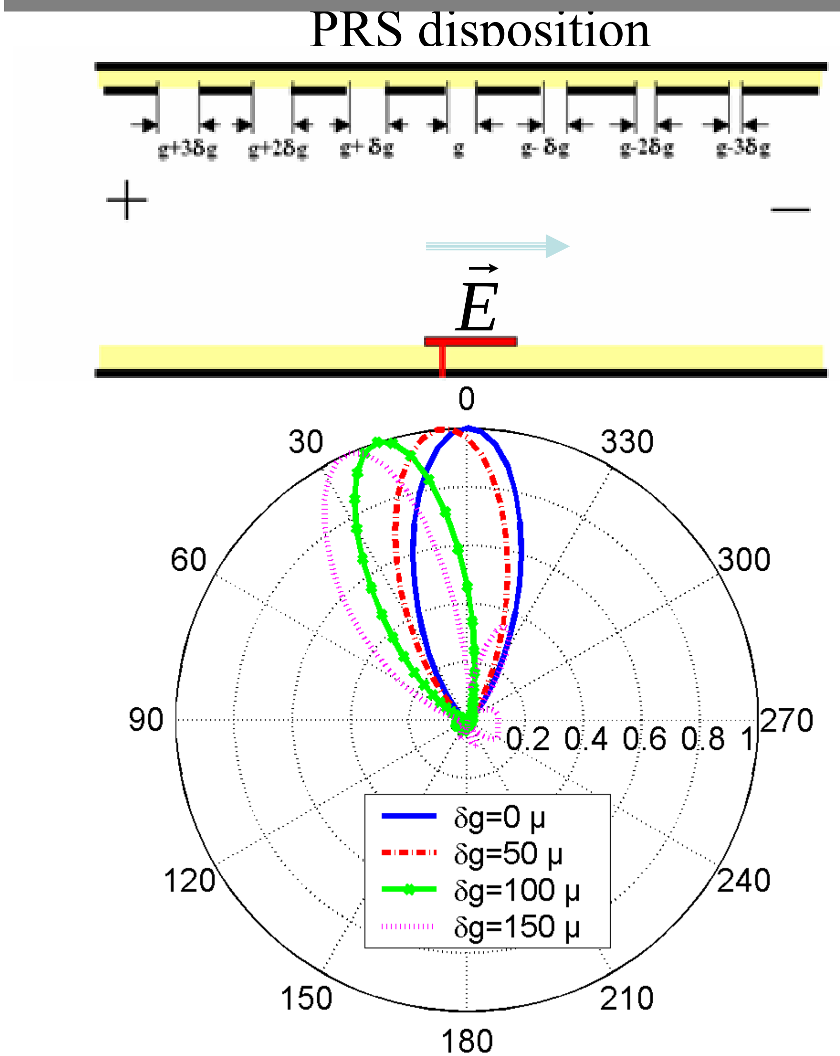


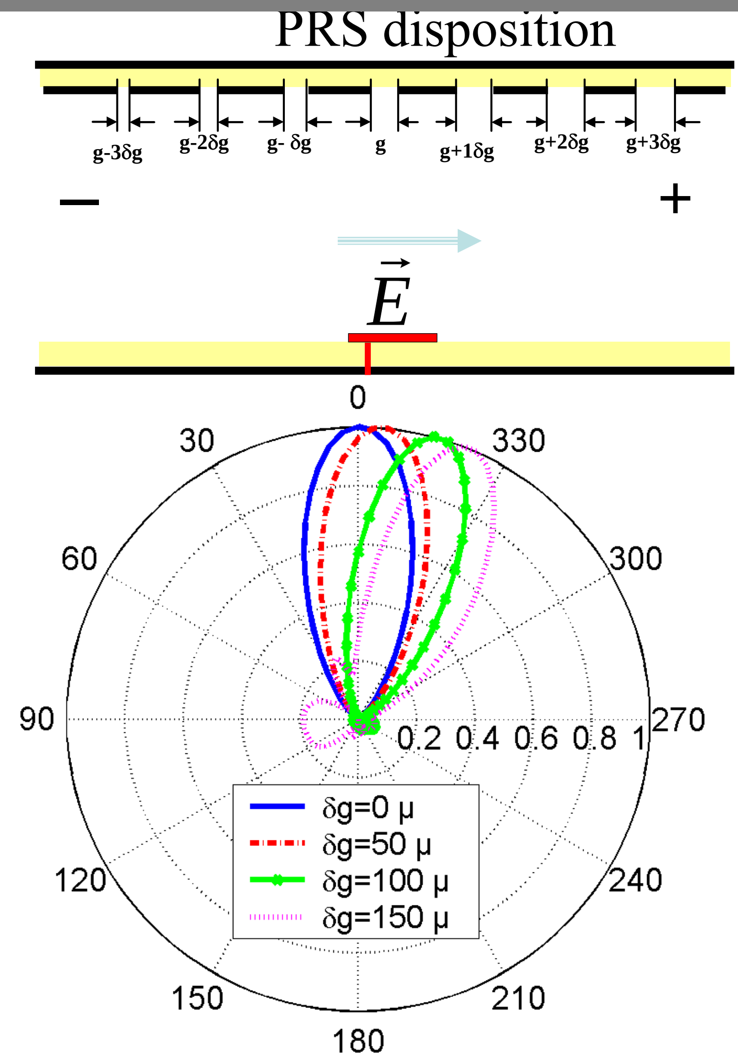
Metamaterial-based cavity :
g=600 µm, δg=100 µm
and h=2 mm





Beam steering

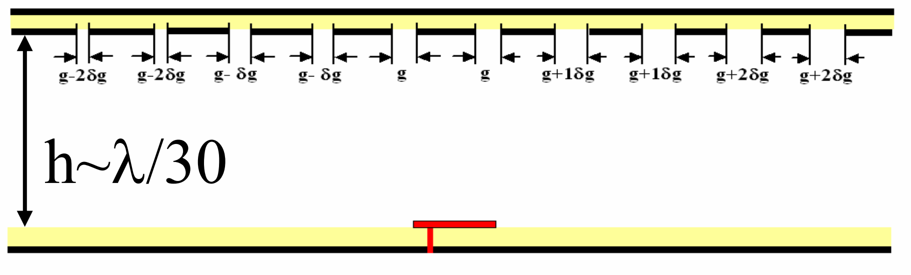


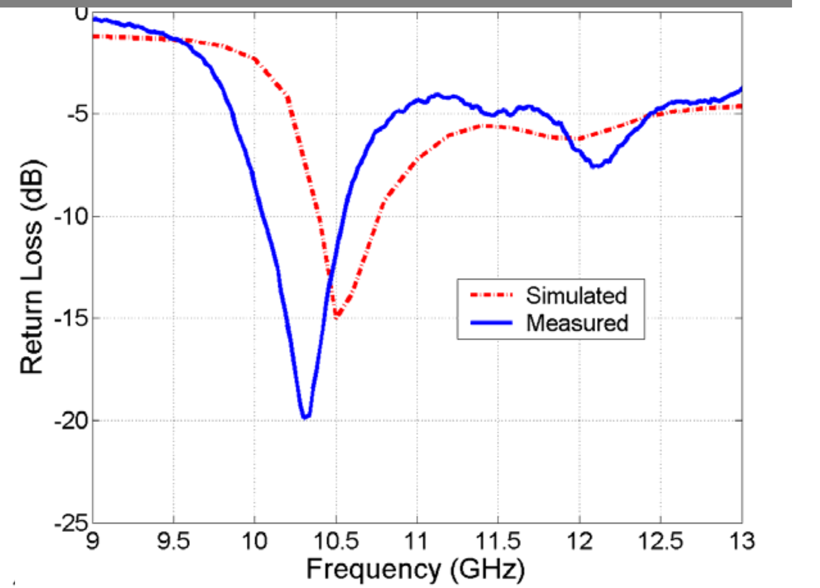


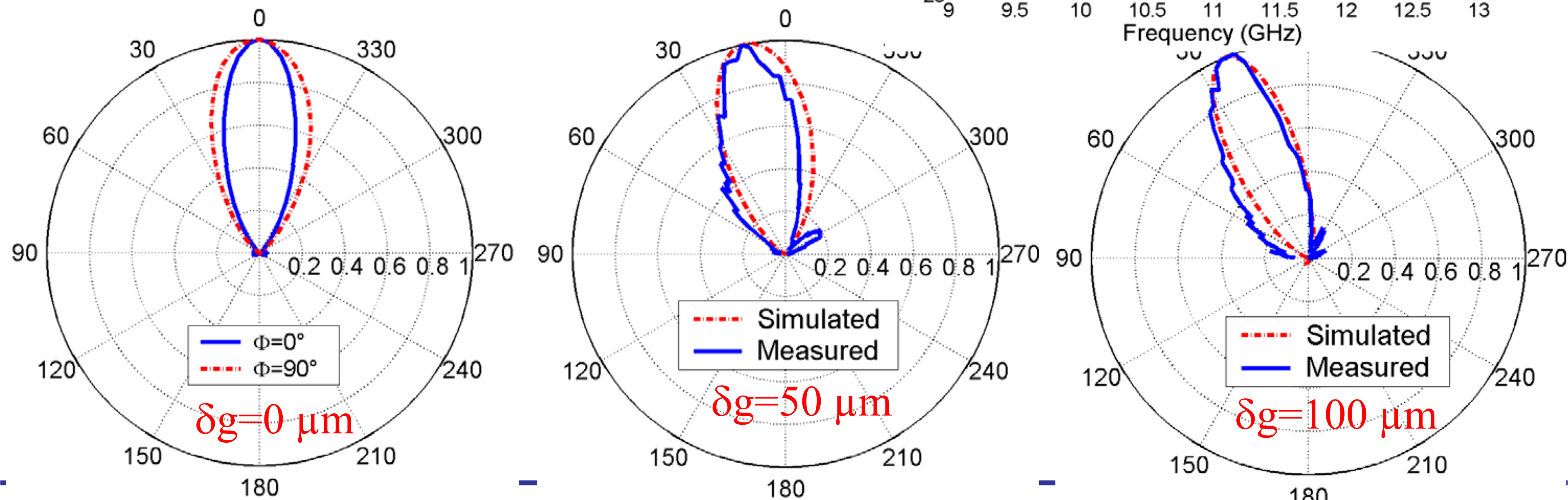
Beam steering by equivalent capacitance variation

Realization and characterization

Metamaterial-based cavity :
g=400 µm, h=1 mm.

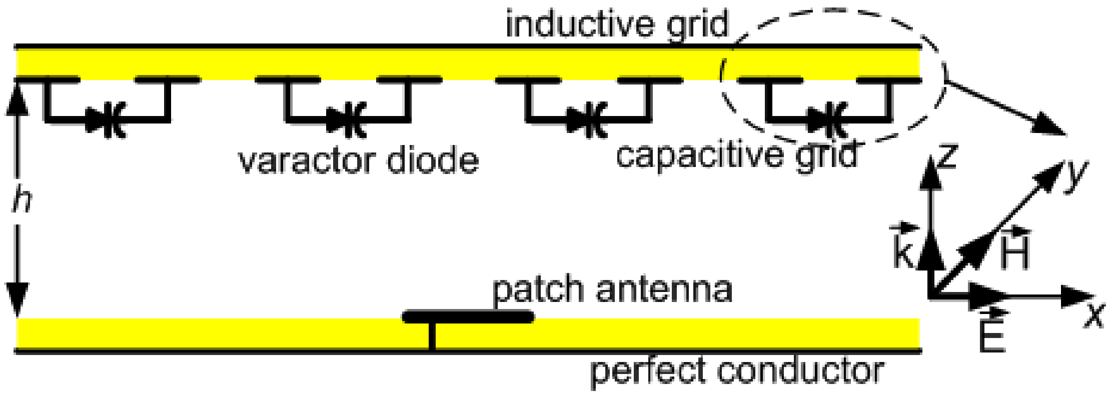


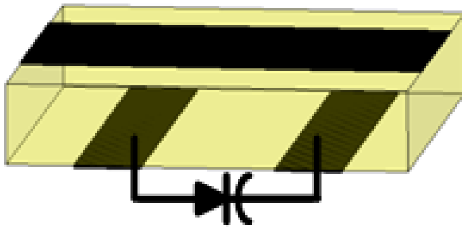


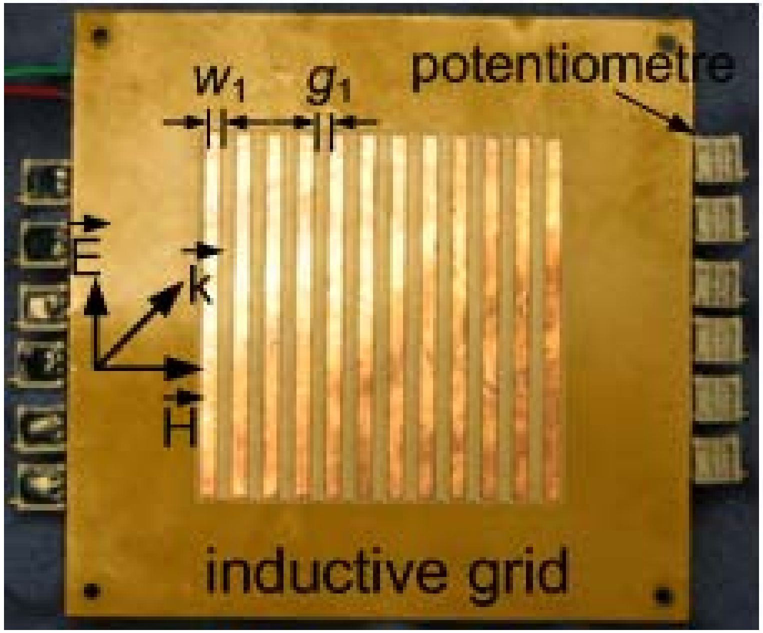


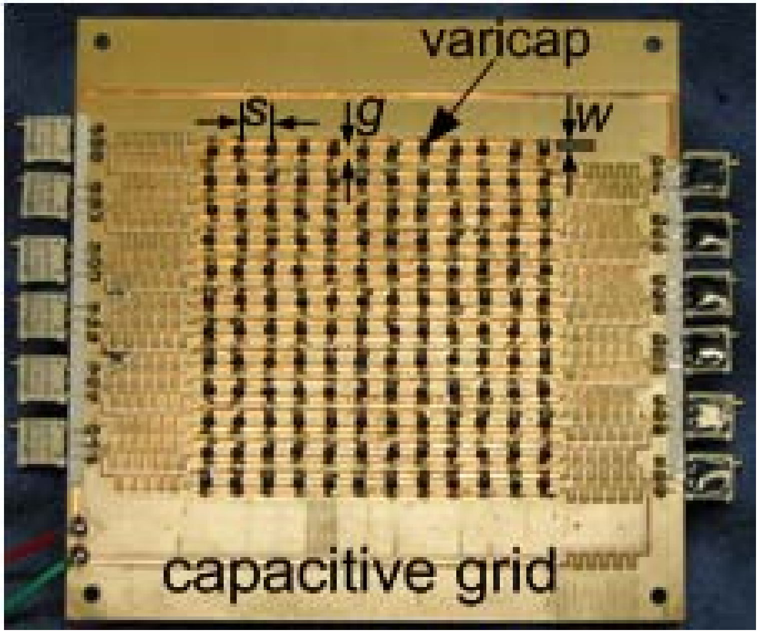
Active Metamaterial Antennas

Active Metamaterial-based Cavity Antenna

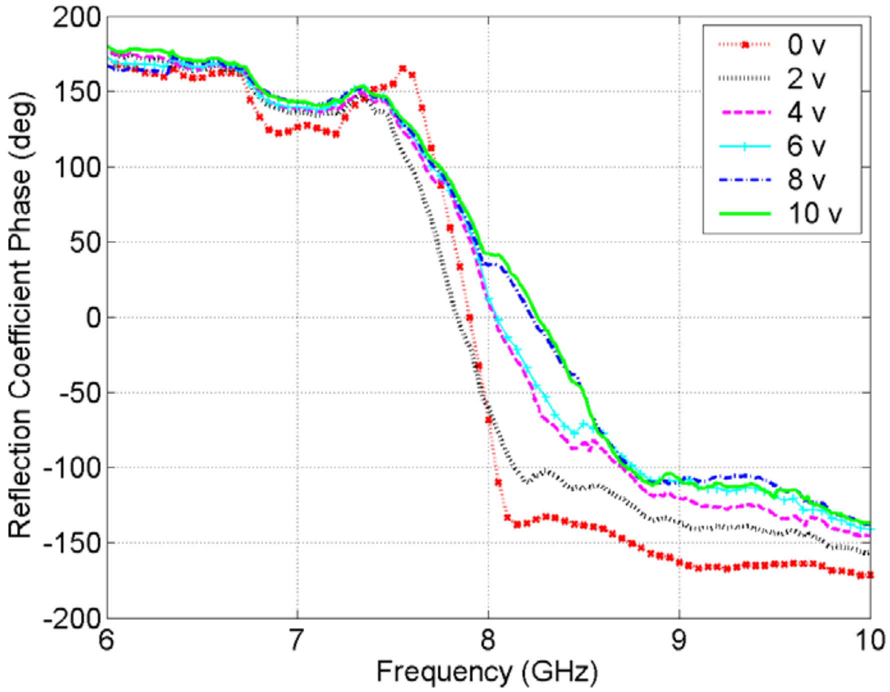


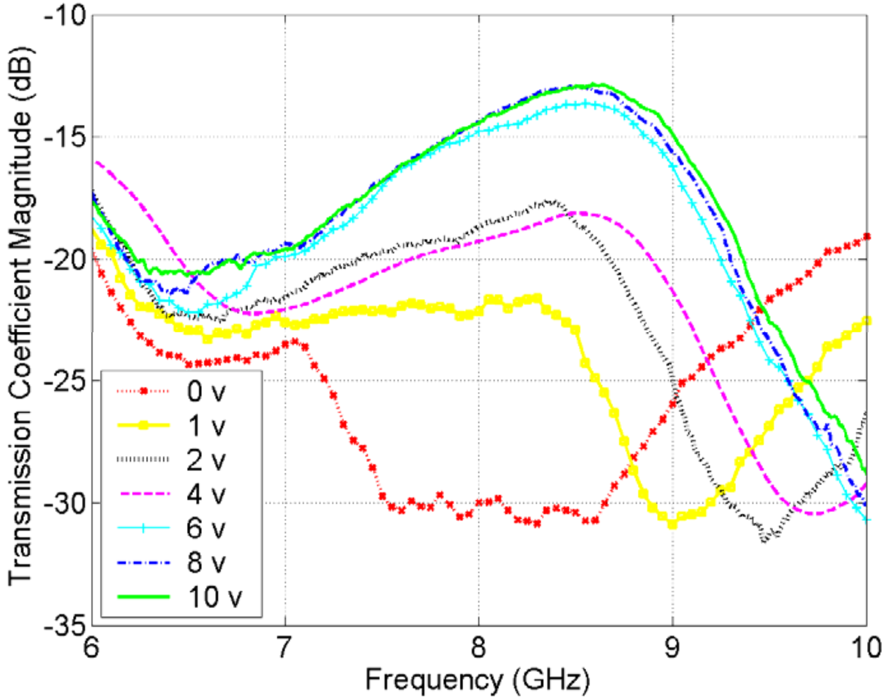




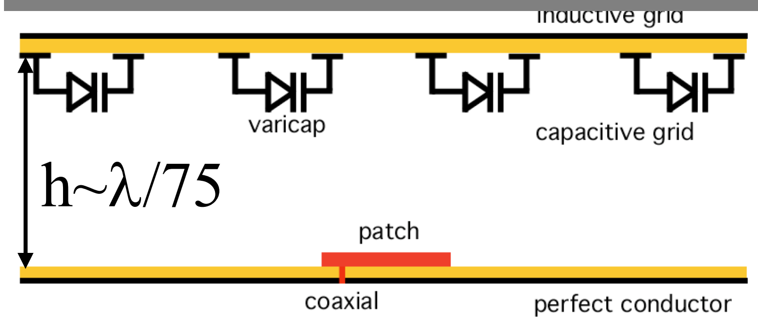


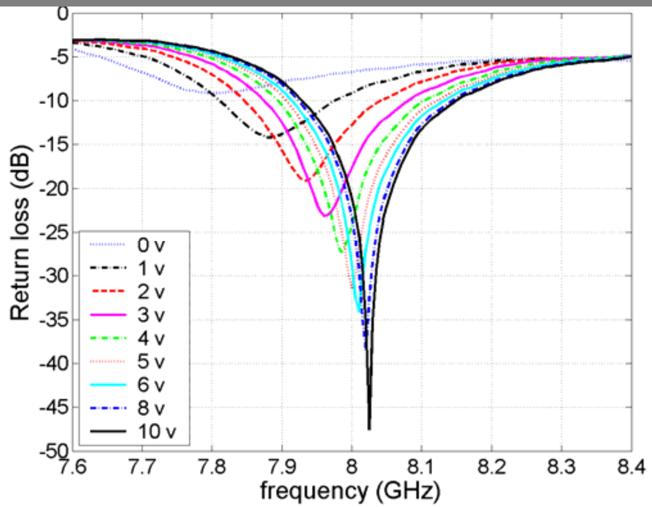
Phase and transmission control.



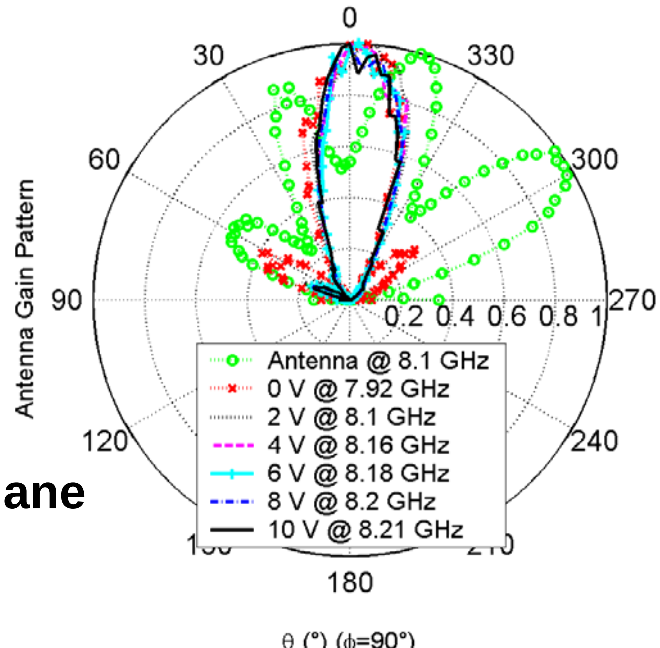


First operating mode: resonance frequency control.

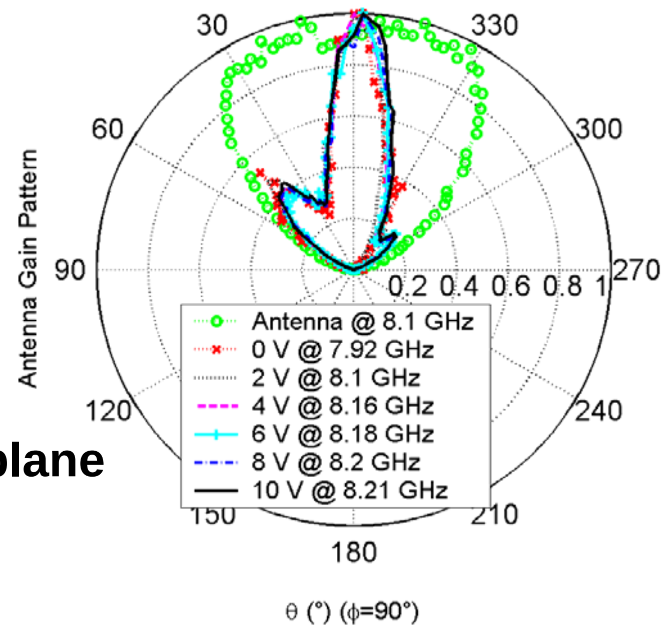




- Electronic frequency control of the cavity resonant mode



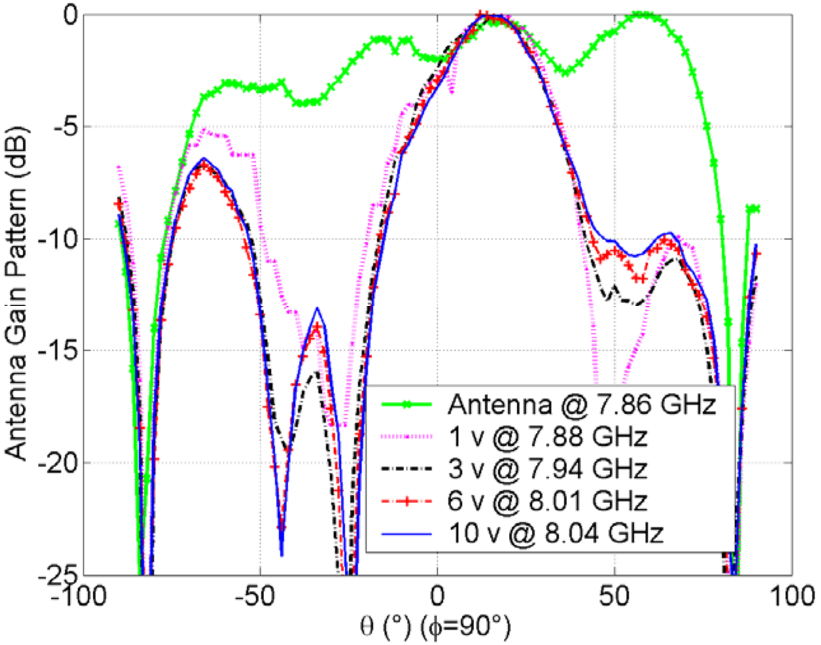
E plane



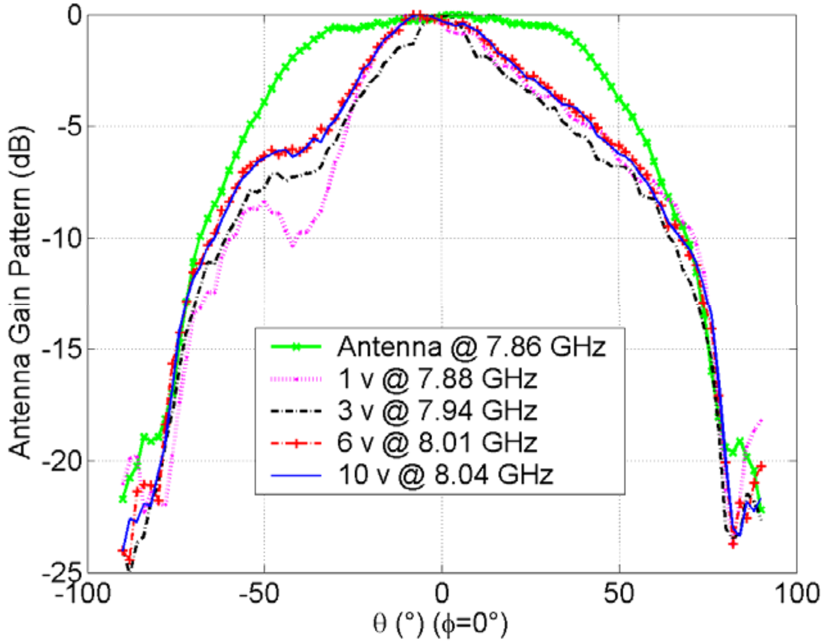
H plane

- Antenna directivity increase

Measured diagram pattern



E-plane (ϕ = 90°)



H-plane (ϕ = 0°)

The directivity is improved with the presence of metamaterial

Conclusions for the controllable photonic crystals

✓These kind of materials can be applied as spatial filters or frequential filters

✓Can be conformable

✓Many industrial applications in Telecommunications and Aeronautics

✓But: huge size at the low frequencies

✓Solution: the use of metamaterials

Conclusions about the radome

Conclusions:

- Simulations and realization of passive prototypes.
- Simulated switching of 27dB at 10GHz.
- Measured switching of 24dB at 9.3GHz.
- The switching does not alter the directivity of the antenna.

Perspectives:

- Simulations with active elements represented by an equivalent electrical circuit. (PIN diodes and/or photoconductors).
- The realization of active prototypes is underway.
- Test of the active structure in a real aeronautical radome (ATR 42).

Conclusions on metamaterial + antenna

Conclusions

- Antenna directivity enhancement and compactness due to the composite metamaterial PRS based cavity

- Passive adjustable steering beam subwavelength cavity antenna.

- Active antenna:
- 1st mode: Electronic frequency control of the cavity resonance.
- 2nd mode: Electronic steering beam subwavelength antenna.

Perspectives

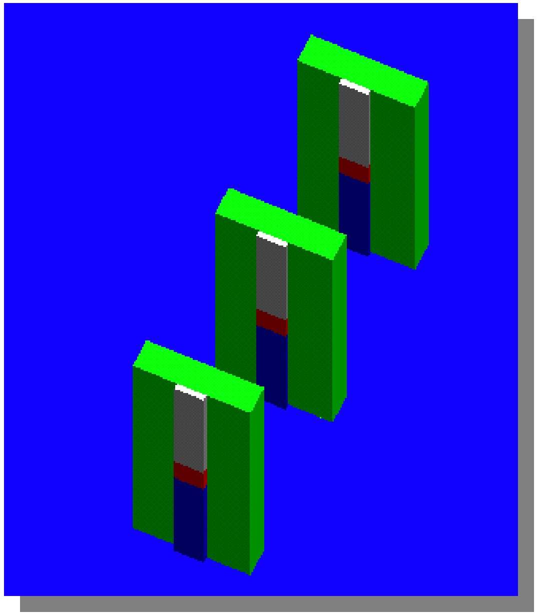
- Conformal active antenna.

Perspectives

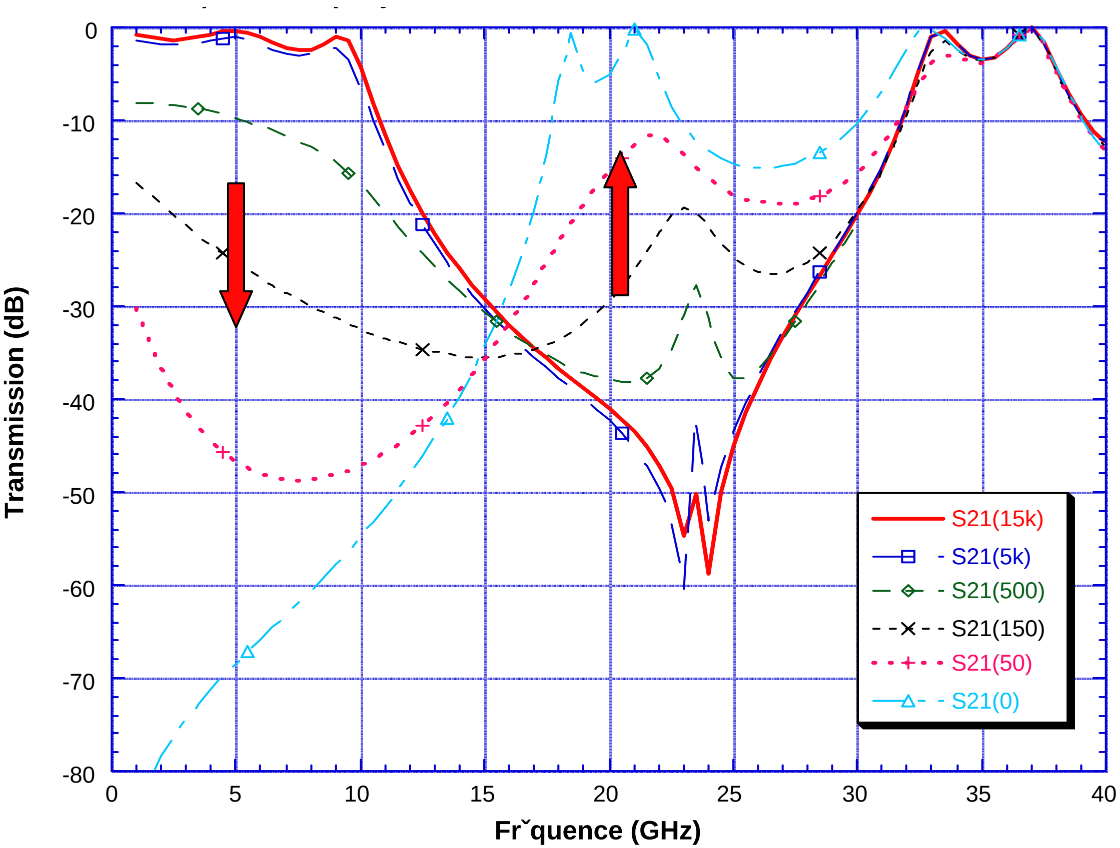
$\varepsilon<0$ $\mu<0$ LHM	→	$\varepsilon<0$ $\mu>0$ evanescent mode	
$\varepsilon<<0$ $\mu<0$ LHM with no transmission	→	$\varepsilon\sim-1$ $\mu\sim-1$ LHM	
$\varepsilon<0$ $\mu<0$ LHM	→	$\varepsilon>0$ $\mu>0$ RHM	
$\varepsilon<0$ $\mu<<0$ LHM with no transmission	→	$\varepsilon>0$ $\mu<0$ evanescent mode	

Many thanks for your attention!

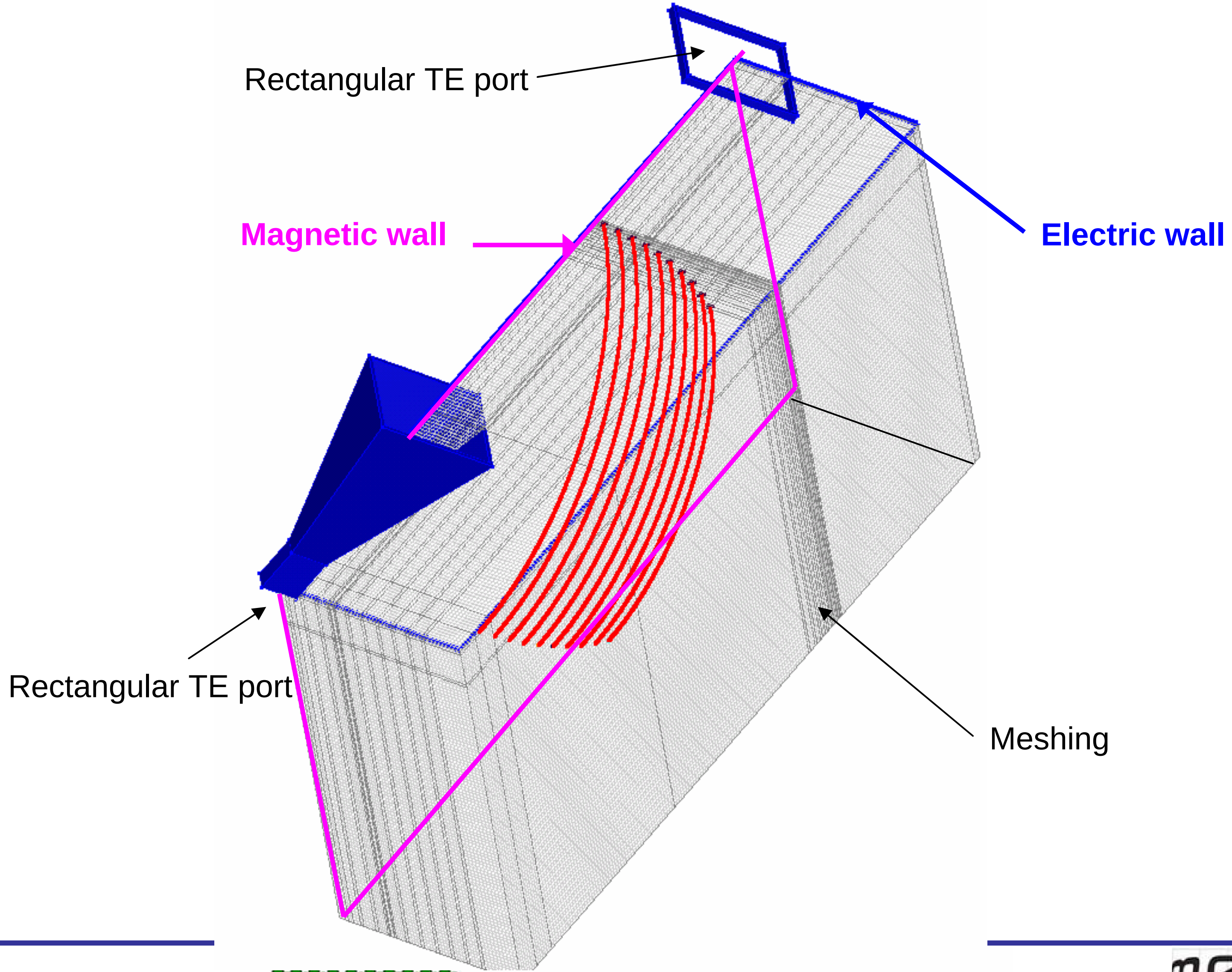
Active EBG structures with variable resistors.



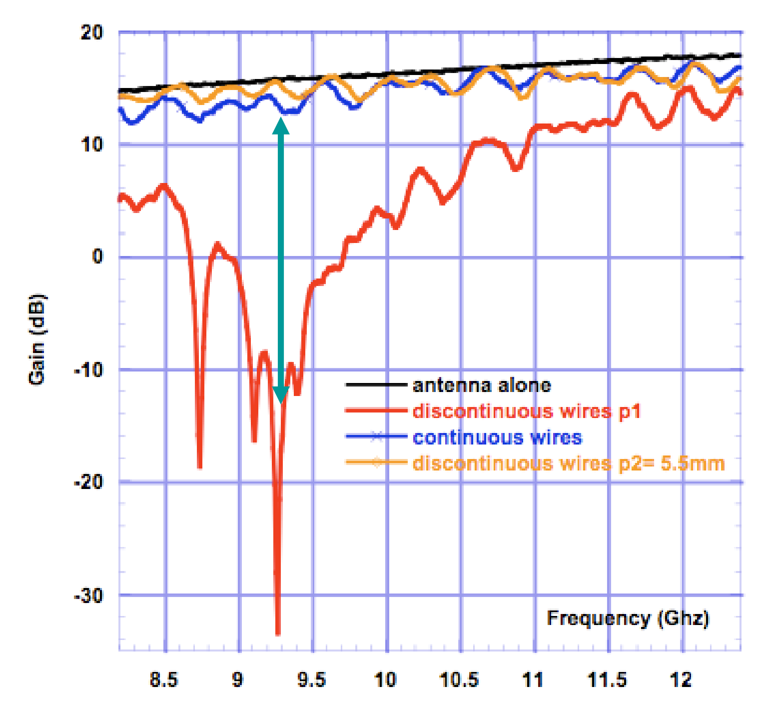
3 layers of metallic wires with variable resistors.



•Transmission of a planar EBG structure made of metallic wires incorporating variable resistors.
•The red arrows show the evolution of the allowed and forbidden frequency bands when the values of the resistors are reduced.


Rectangular TE port
Magnetic wall
Electric wall
Rectangular TE port
Meshing

Spherical and controllable radome
1st prototype and measurements



EADS