# Development of metamaterials based antennas at ISL

Ronan Adam*, Vincent Jaeck, Mario Martinis, Loïc Bernard

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# Development of metamaterials based antennas at ISL



1. **Innovative HF communication systems based on metamaterials**
   - 1.1. General remarks, context & motivations
   - 1.2. Previous work
   - 1.3. Use of metamaterials to enhance the performances of compact phased array
   - 1.4. Metamaterials in cavities for the design of compact antennas

2. **Metamaterial inspired antennas for QR spectroscopy**
   - 2.1. QR spectroscopy
   - 2.2. Motivations
   - 2.3. Multimode antennas
   - 2.3. Theoretical studies
   - 2.4. Experimental results

# 1. Innovative HF communication systems based on metamaterials

## 1.1. General remarks, context & motivation

- Use of metamaterials to enhance the performances of communication systems embedded in projectiles and flying systems of high velocity

- Specific configurations for ISL applications :
  - Huge mechanical constraint (high-g hardened)
  - Small dimensions and close environement (cavity)

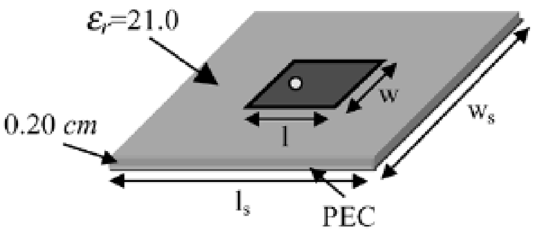
- Focus on antenna part : bandwidth enlargement , backward radiation reduction, size reduction, compact arrays …

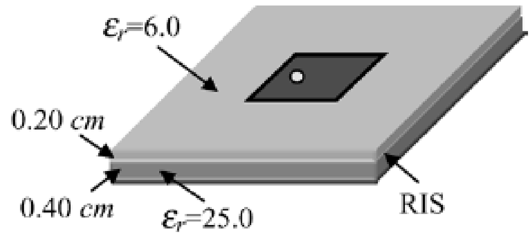
# 1. Innovative HF communication systems based on metamaterials

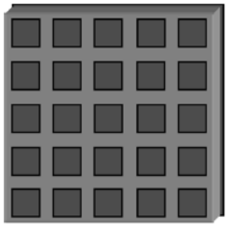
## 1.1. Previous work – Reminder on reactive impedance substrate (RIS)



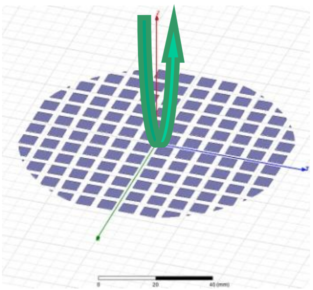
RIS : artificial surfaces introduced by Sarabandi [1]

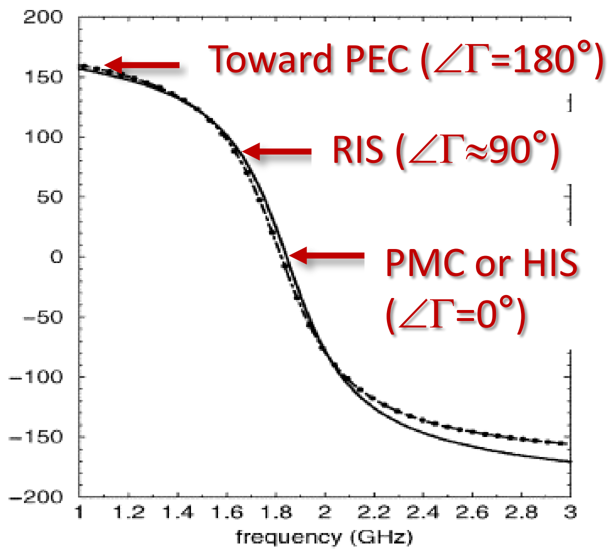


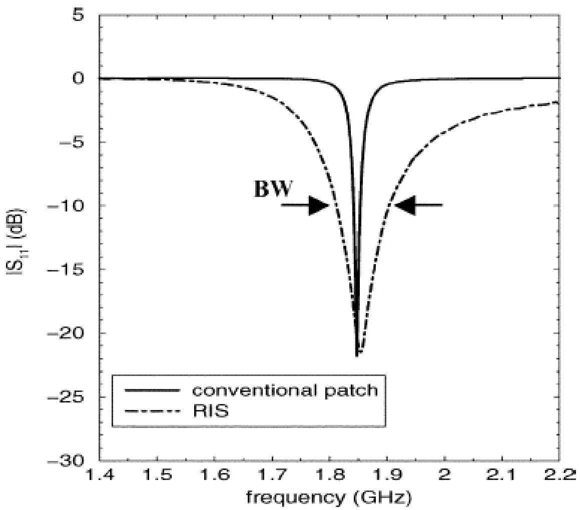



Plane wave illumination of the surface:






Significant $S_{11}$-BW enlargement of printed antennas

[1] H. Mosallaei and K. Sarabandi, "Antenna Miniaturization and Bandwidth Enhancement Using a Reactive Impedance Substrate",IEEE TAP vol. 52, NO. 9, Sept. 2004

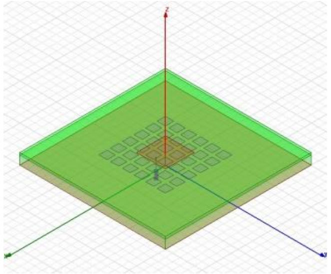
# 1. Innovative HF communication systems based on metamaterials

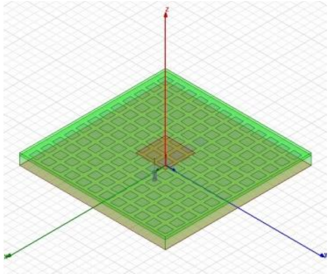
## 1.1. Previous work : Design of bandwidth-enlarged single patch antennas printed on RIS for telemetry applications at 2.3 GHz

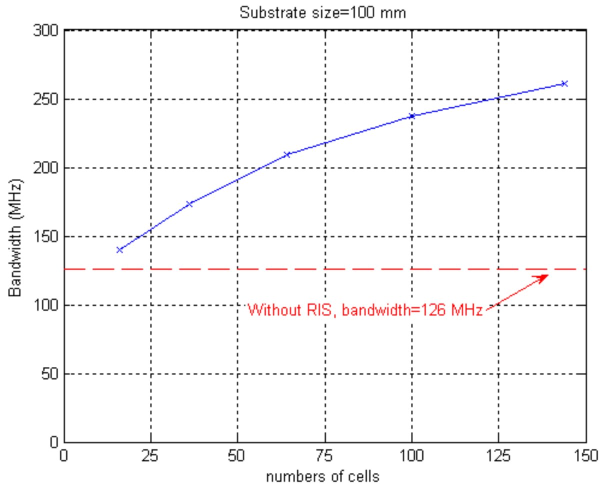


- **Linear polarization:**

Investigations on the influences of the number of unit-cells under the patch and on the lateral size of the antennas, in a RIS configuration (constant unit-cell period, in free-space)








For a given lateral size bandwidth increased with the number of cells

# 1. Innovative HF communication systems based on metamaterials

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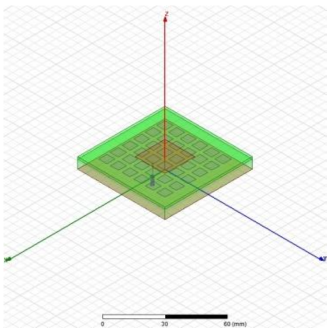
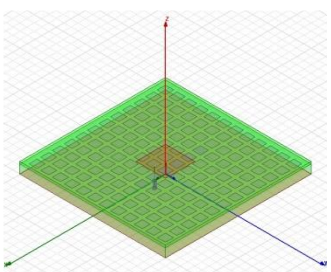
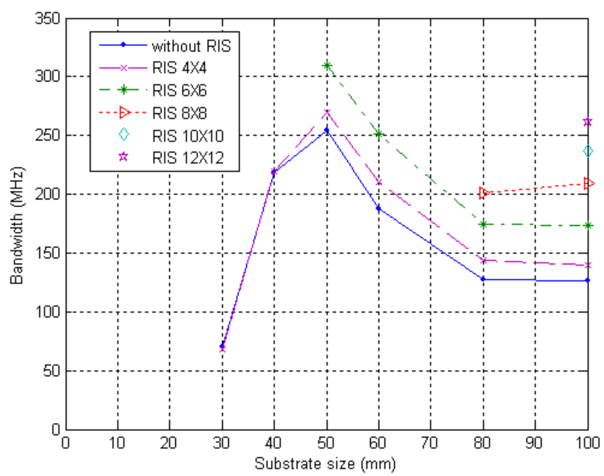







Strong impact on the bandwidth of the lateral size for a given number of cells!

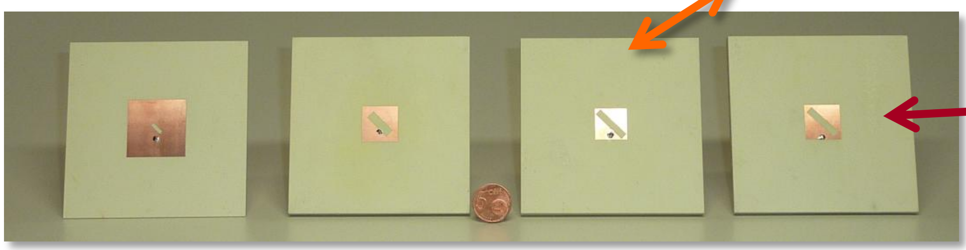
The ground plane acts as a second resonator and coupling effects with the patch are involved.

*C.Ren, L.Bernard et R.Sauleau, « Investigations and design of small-size printed antennas on a reactive impedance substrate », EUCAP 2010*

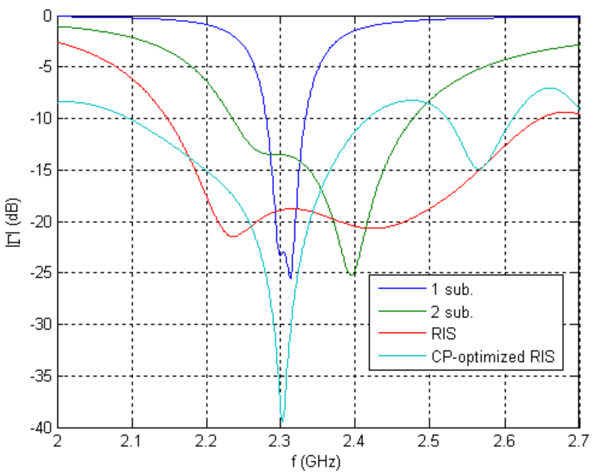
# 1. Innovative HF communication systems based on metamaterials

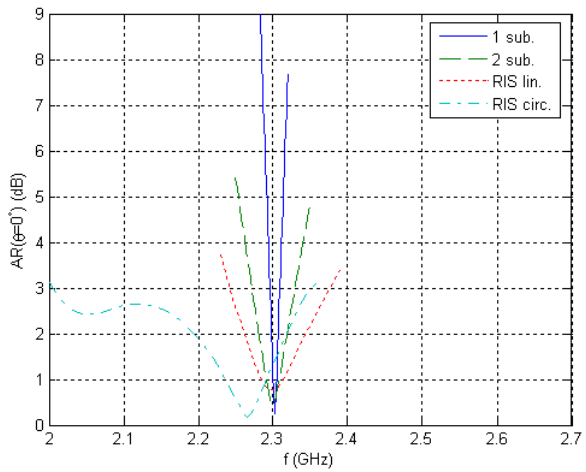
## 1.1. Previous work : Design of bandwidth-enlarged single patch antennas printed on RIS for telemetry applications at 2.3 GHz

- **Circular polarization:**








- CPBW x 6.1 (14.9% meas.)
- $S_{11}$BW x 1.3 (11.4% meas.)

Wideband antenna : 10.6% global Bandwidth (meas.)

*L. Bernard, G. Chertier, R. Sauleau, Wideband Circularly Polarized Patch Antennas on Reactive Impedance Substrates, IEEE AWPL, vol. 10, 2011*

# 1. Innovative HF communication systems based on metamaterials

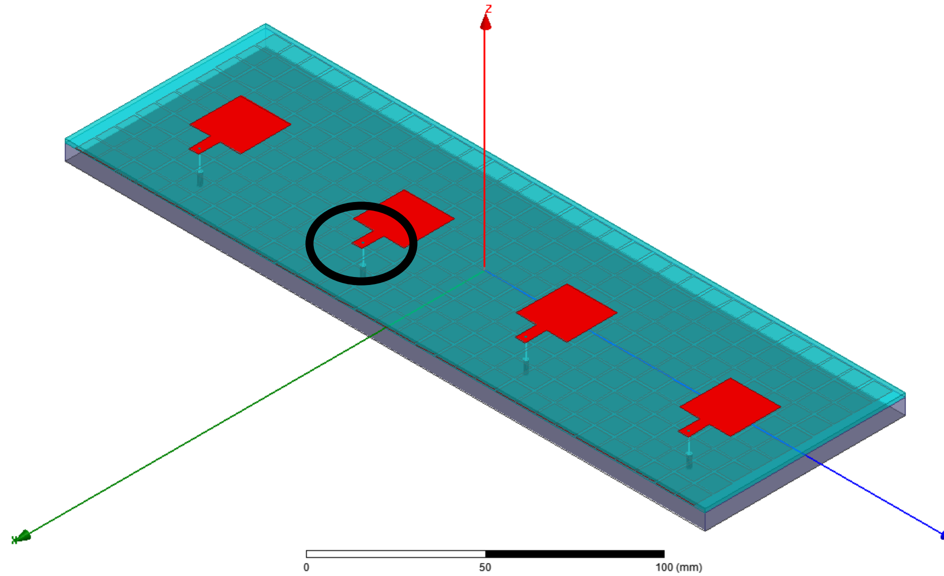
## 1.2. Use of metamaterials to enhance the performances of compact phased arrays

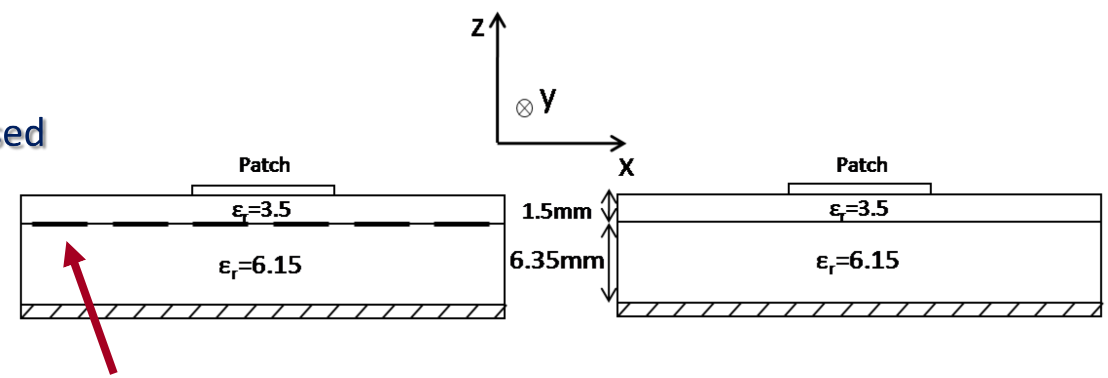


- Motivation of the present study:

Design of a printed antenna phased array with a BW of at least 300 MHz and a steerable beam on +/- 25°

- Use of RIS to enlarge the BW of a printed array?
- Mutual coupling not drastically increased?
- Can the beam still be steered?
- Are the performances of the phased array competitive over the whole enlarged BW?




With RIS

Without RIS

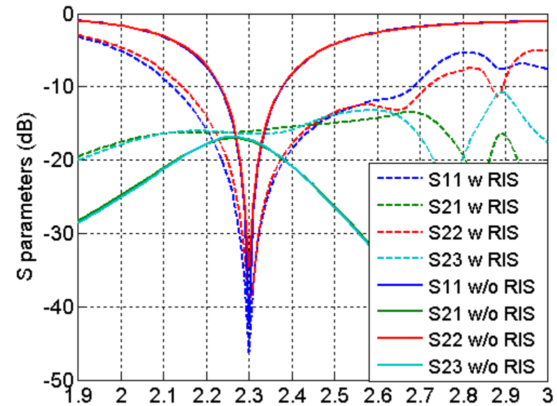
L. Bernard, V. Jaeck, "Investigations on bandwidth enhancement of low cost printed phased array with Reactive Impedance Substrates", IEEE International Symposium on Phased Array Systems & Technology 2013

# 1. Innovative HF communication systems based on metamaterials

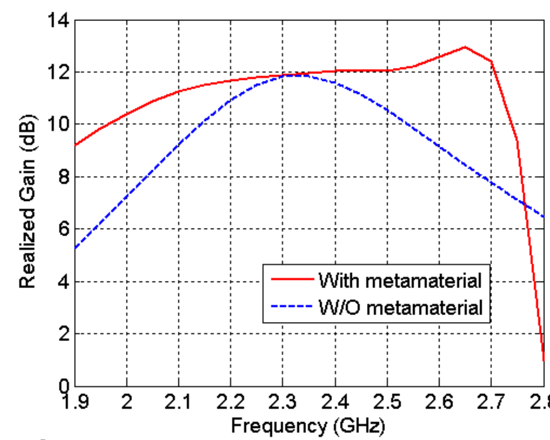
## 1.2. Use of metamaterials to enhance the performances of compact phased arrays

### Summary of the numerical simulations:

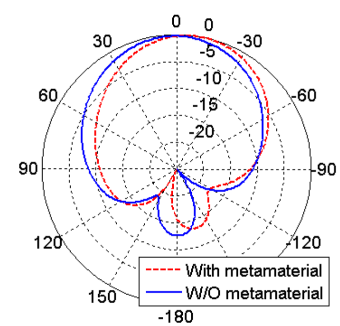
- $S_{ii}$ BW enlarged with the RIS for all considered spacing
- Mutual coupling increased for large spacing (but <-16dB)
- Mutual coupling decreased for small spacing

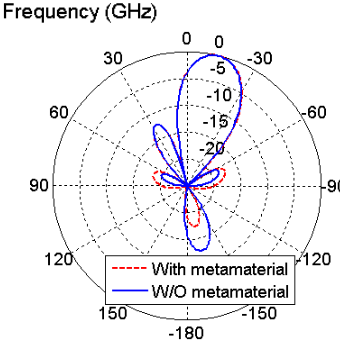



- The maximum of gain is similar for a given size
- The frequency band for gain higher than half of the maximum is wider with the RIS ($BW_{(Gain\text{-}3dB)}$)
- The gain is maintained high on a larger bandwidth
- The FTBR is larger in the cases of RIS
- Asymmetry of the radiation pattern in the E-plane in RIS cases (feeding line)



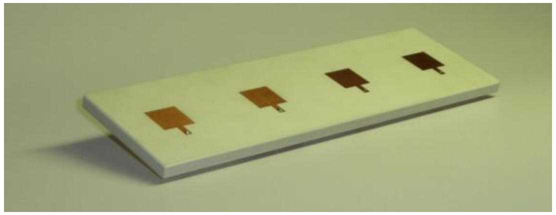

For all cases (with and without RIS), the beam is effectively steered for a progressive phase excitation of 45° (H-plane)



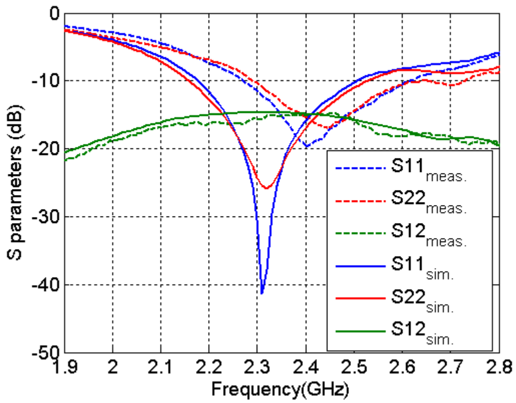
## 1.2. Use of metamaterials to enhance the performances of compact phased arrays

- **Measurement results:**



Overall dimensions:

- 80 mm of width (0.6 $\lambda_0$)
- 256 mm of length (2 $\lambda_0$)
- about 8 mm of thickness (lower than $\lambda_0/16$)




- Simulated $S_{11}$ BW of 150 MHz w/o RIS vs 320 MHz with RIS
- Frequency shift of 100 MHz
- Quite good agreement with numerical results
- Measured $S_{11}$ BW of 340 MHz
- Measured coupling $S_{12}$ lower than -15 dB

**The BW can be more than double by using RIS**

# 1. Innovative HF communication systems based on metamaterials

## 1.2. Use of metamaterials to enhance the performances of compact phased arrays

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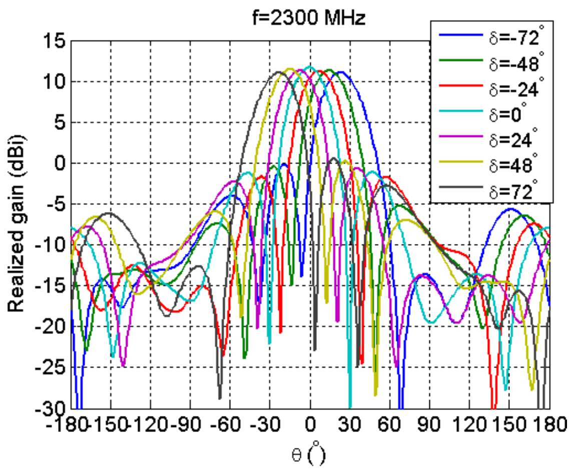
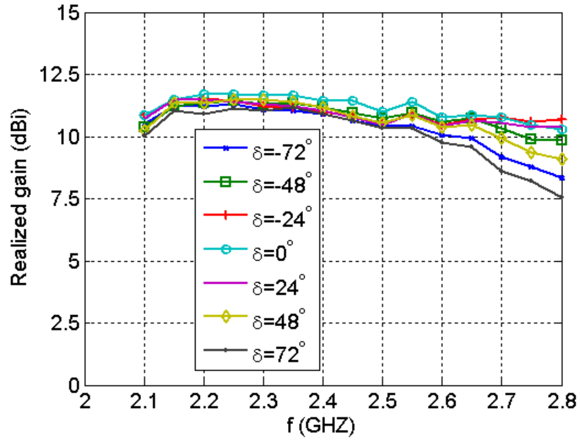
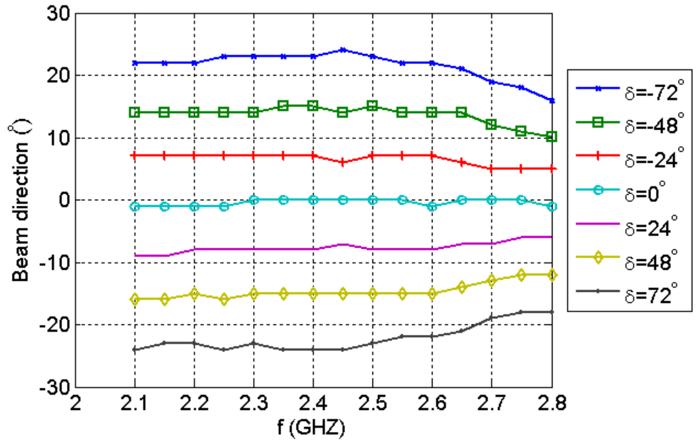



Gain remains high over[2100-2600] MHz




Beam direction quite stable over [2100-2600 MHz]

**Progressive phase excitation δ:**

- Maximum gain variation of 0.6dB
- FSLL <-10dB
- HPBW: [25-28]° in H-plane
- Scanning range: [-23;+23]°

# 1. Innovative HF communication systems based on metamaterials

## 1.3. Metamaterials in cavities for the design of compact antennas.

*PhD work of Mario MARTINIS With IETR*

**Is it possible to design very small antennas in a cavity with sufficient bandwidth?**

Integration of cavity-backed antenna (2.3 GHz) into projectile:

- Metallic environment
- Small dimensions
- Excited EM modes different from open-environment case
- Bandwidth enhancement by the means of metamaterials
- Aimed at the maximum achievable bandwidth with given cavity sizes.

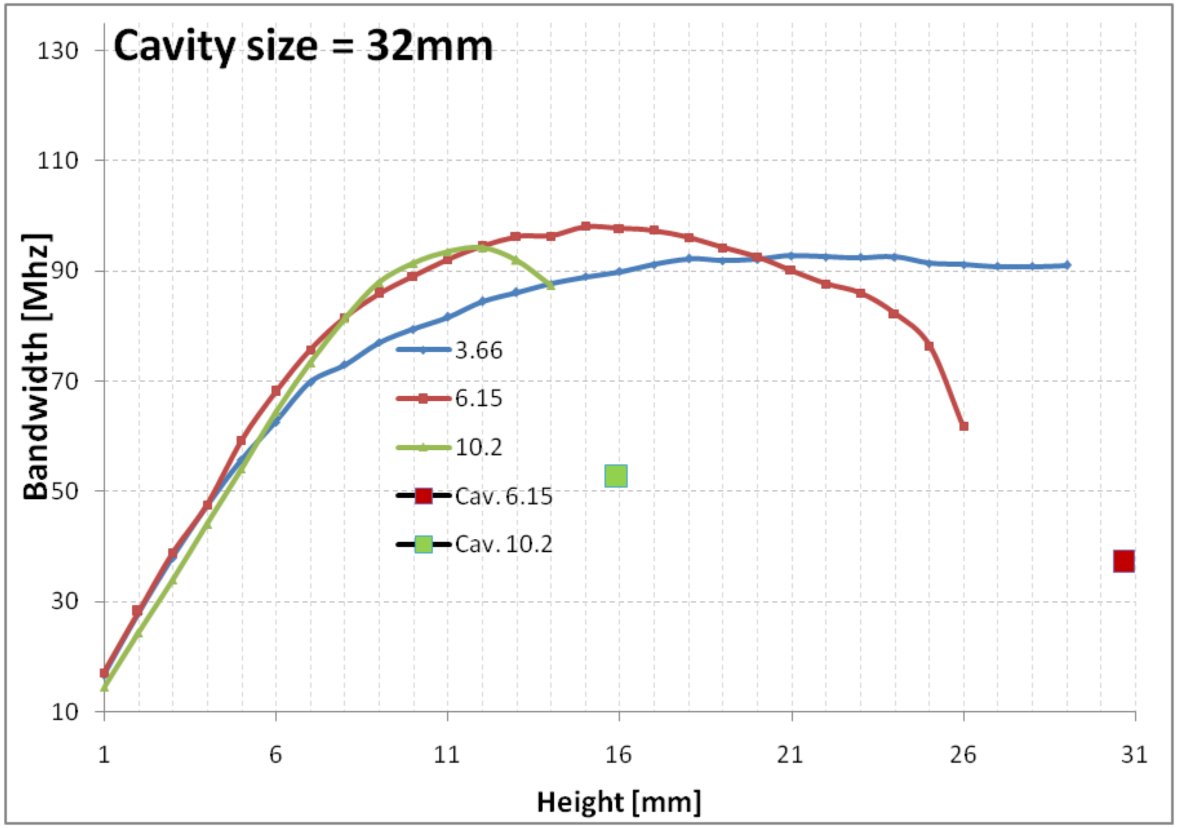
*M. Martinis, K. Mahdjoubi, R. Sauleau, S. Collardey, L. Bernard, "Bandwidth behavior of miniature rectangular cavity antennas" IEEE Conference on Antennas and Propagation in Wireless Communications 2013*

*M. Martinis, K. Mahdjoubi, R. Sauleau, S. Collardey, L. Bernard, "Bandwidth behavior of patch antennas enclosed in miniature circular cavities", accepted to EUCAP 2014 Conference*

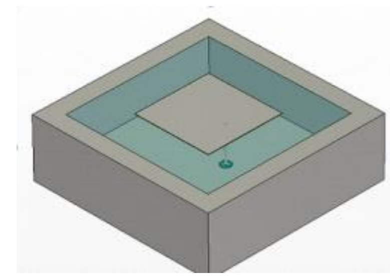
# 1. Innovative HF communication systems based on metamaterials

## 1.3. Metamaterials in cavities for the design of compact antennas.

- Extensive investigations on single patch in small cavity ($\approx\lambda_0/4$)
- Determination of maximum achievable bandwidth for given size (diameters and maximum thickness)




**Analytical calculations and full wave simulations**



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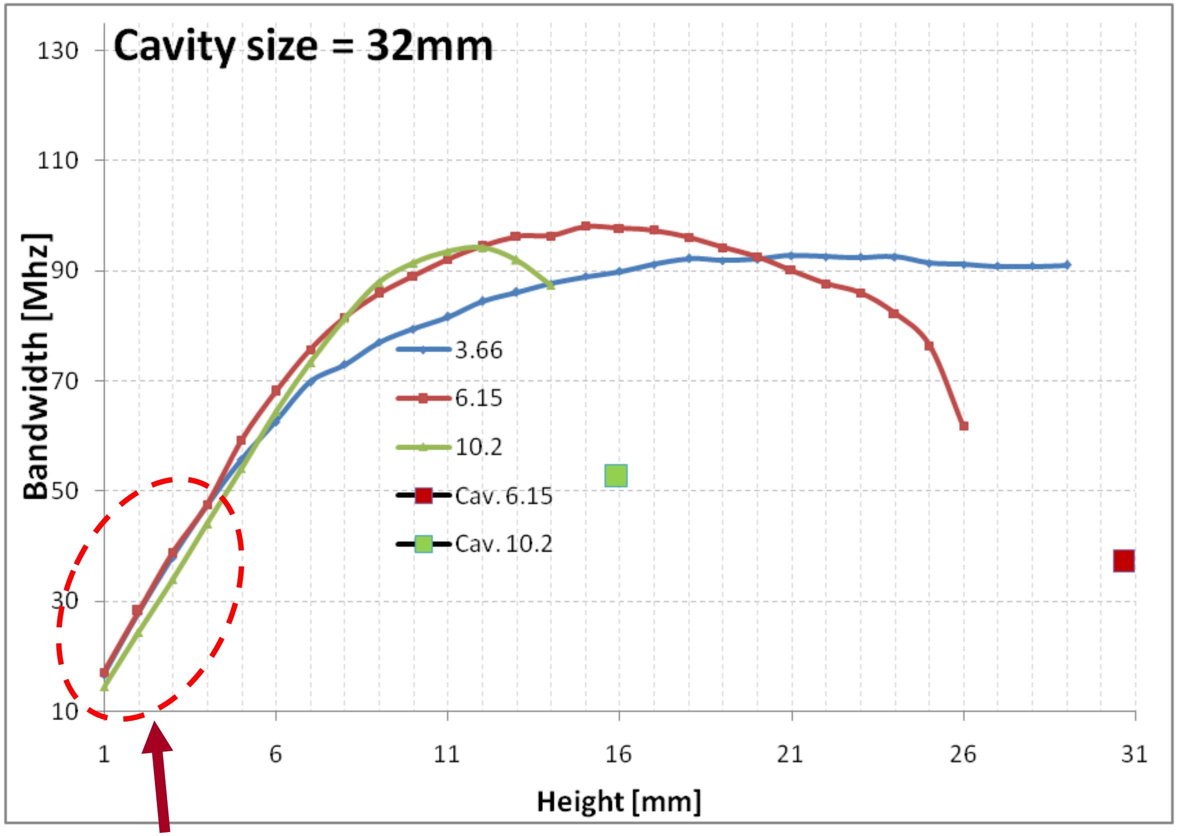
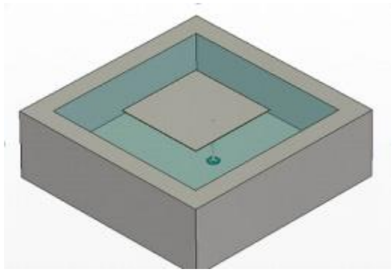



Classical patch antenna behaviour

**Analytical calculations and full wave simulations**



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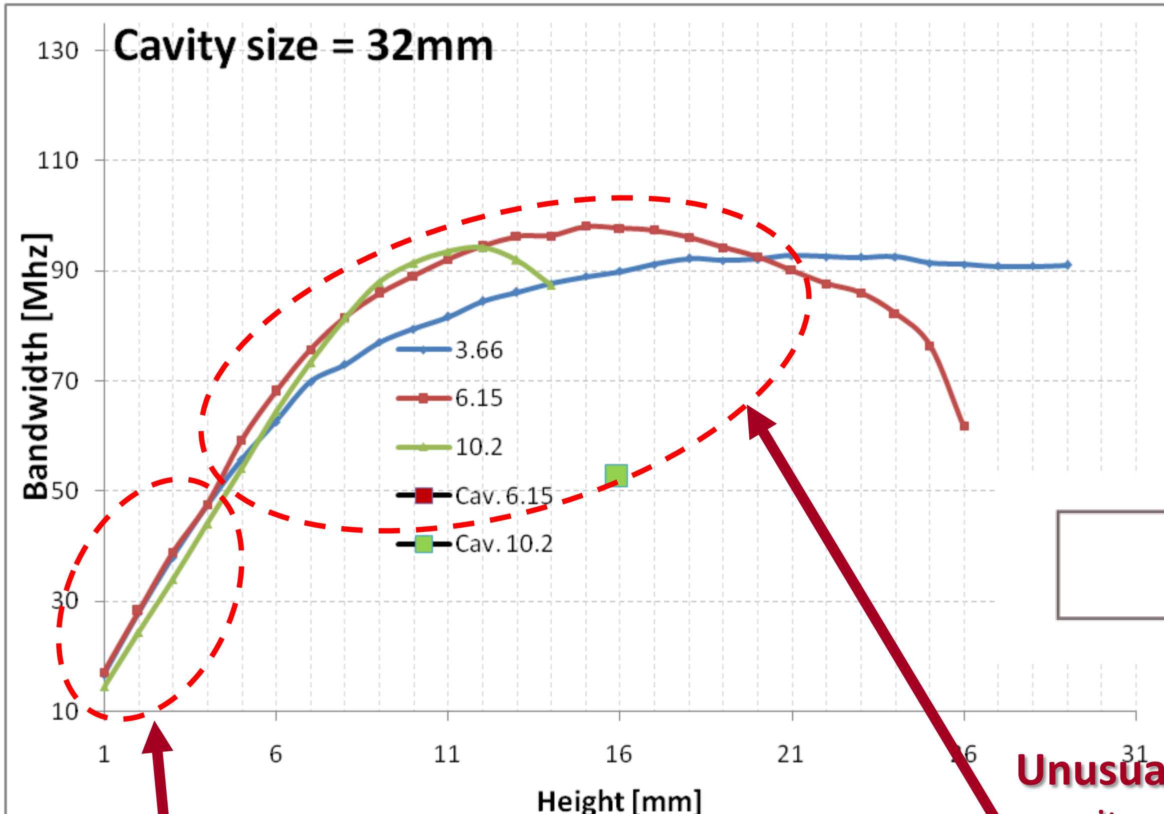


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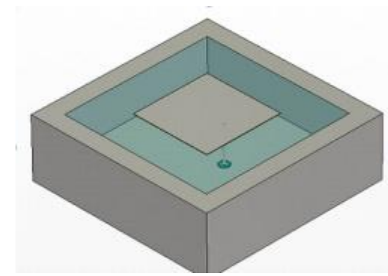

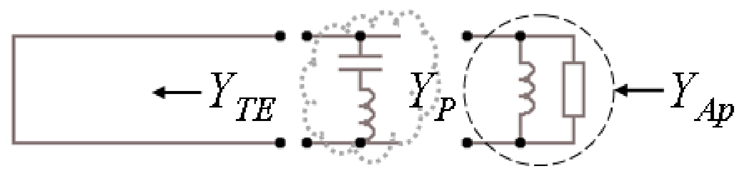


**Classical patch antenna behaviour**

**Unusual results**

- cavity acts as a waveguide
- bandwidth has a maximum

# 1. Innovative HF communication systems based on metamaterials

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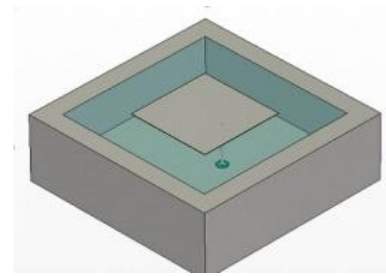

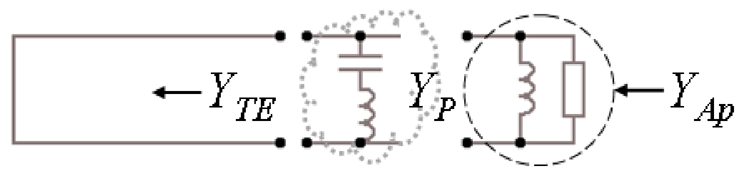


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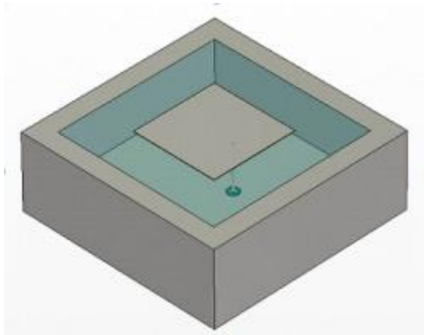
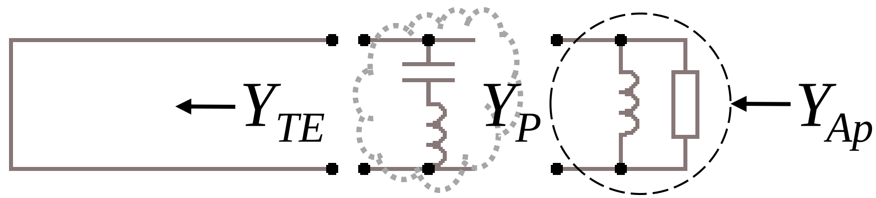
**Classical patch antenna behaviour**

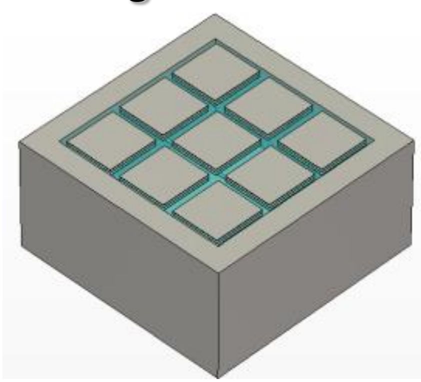
# 1. Innovative HF communication systems based on metamaterials

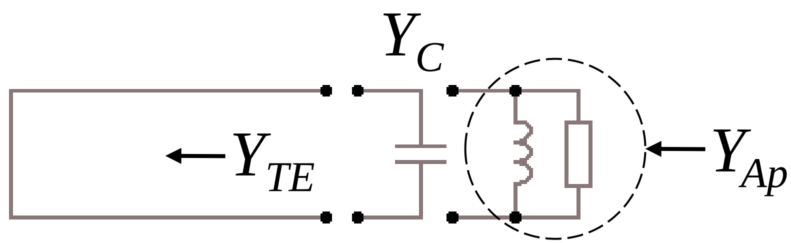
## 1.3. Metamaterials in cavities for the design of compact antennas.






New design





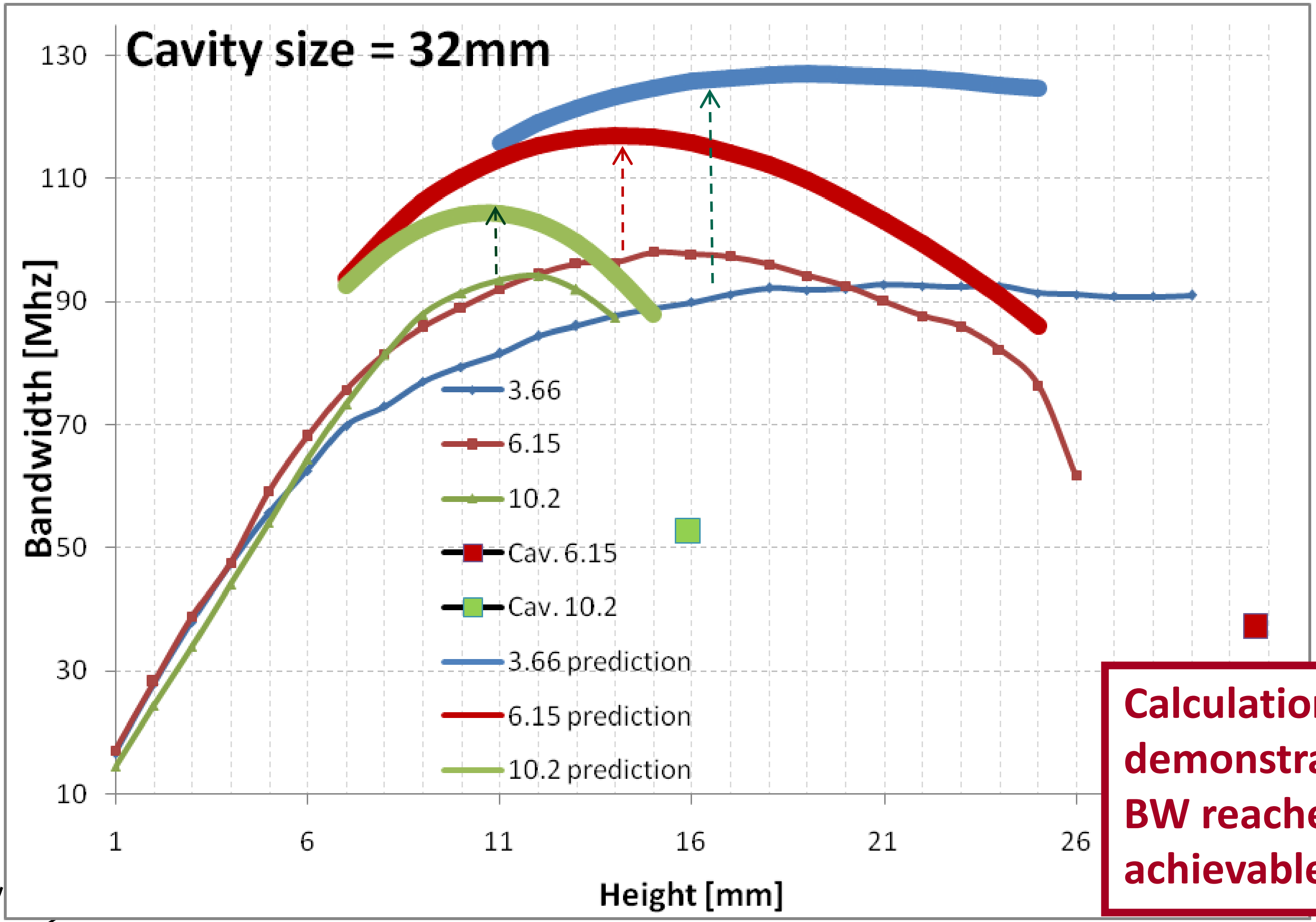

Capacitance in the model can be realised with a metasurface made of small patches

# 1. Innovative HF communication systems based on metamaterials

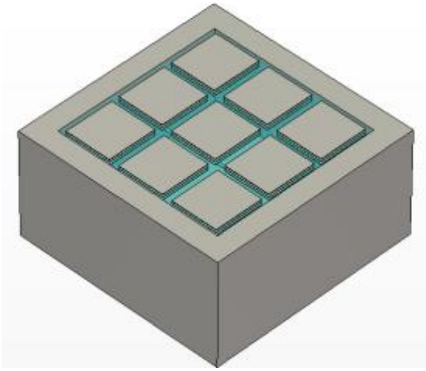
## 1.3. Metamaterials in cavities for the design of compact antennas.



Simulation and calculated results:




**Improvement compared to patch antennas in all cases**



**Calculation in progress for demonstration that the RIS-BW reaches the maximum achievable value**

## 2. Metamaterial inspired antennas for QR spectroscopy

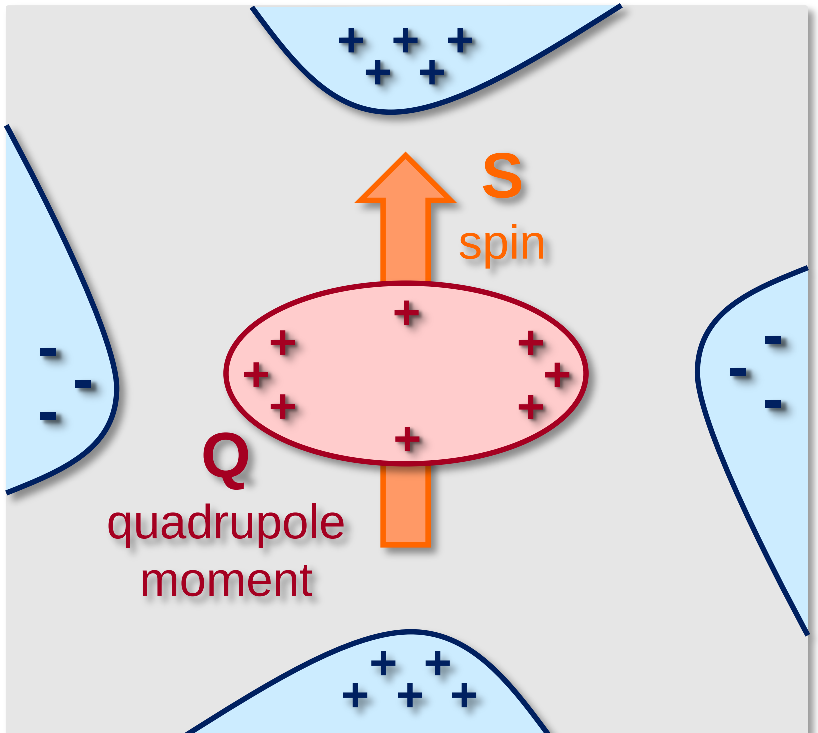


*R. Adam , T. Schunck, L. Merlat, "Multimode Antennas for Nuclear Quadrupole Resonance Detection of Explosives", in Proc. EUCDE, Roma, March 2013.*

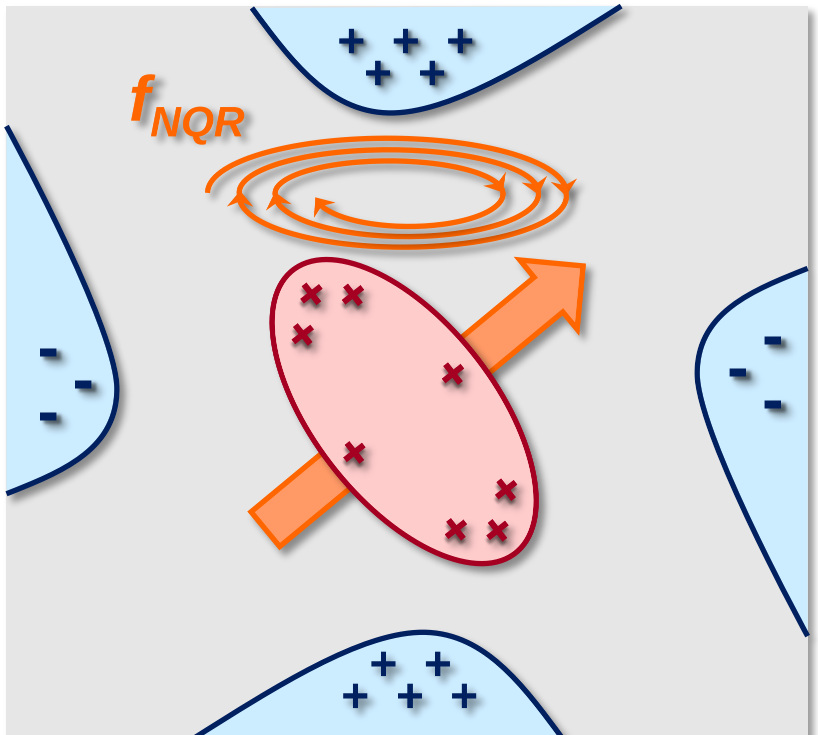
# Quadrupole Resonance Spectroscopy

- Magnetic resonance spectroscopy technique operating in the low RF range
- Quadrupole moment / electric field gradient interaction






Equilibrium




External RF magnetic field pulse

# NQR Applications

- Forensic
- Counterfeit chemicals identification
- Medicine authentification
- Detection of concealed illicit substances, explosives

conphirmer

SEVENTH FRAMEWORK PROGRAMME

**Development of a scanning device at checkpoint for the detection of concealed explosives (TNT, RDX and PETN)**

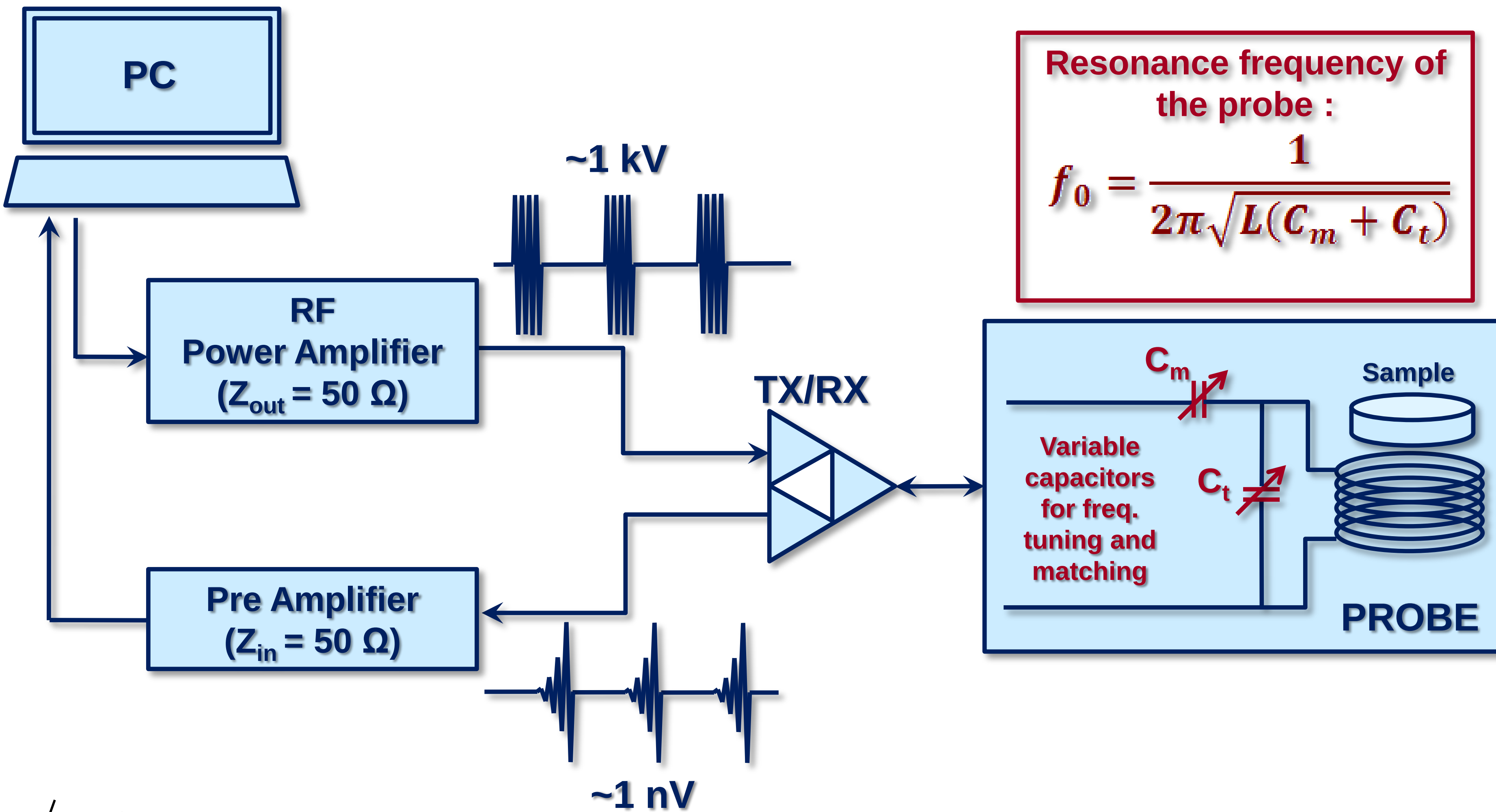
# NQR multimode antennas for single side detection



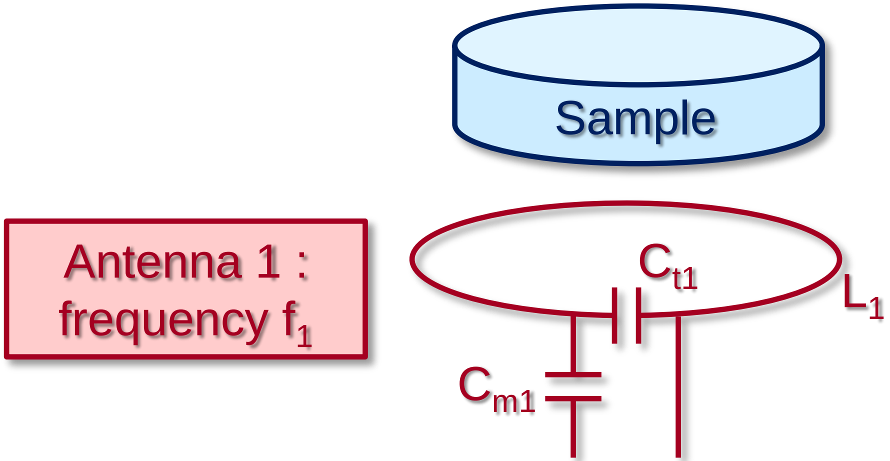
- **Motivations :**
  - Simultaneous detection of different substances
  - Decrease of the false alarm rate, and/or of the operation time
  - Circular polarization : detection enhancement (+21% in SNR)

- **Requirements :**
  - Signals close to the thermal noise. Narrow selective band receiver mandatory : resonant antenna
  - Power efficiency at the transmitter, lowest noise floor at the receiver : matched antenna
  - Noise (RF interference) resilient

# NQR Detection Scheme



# Double-frequency Antenna



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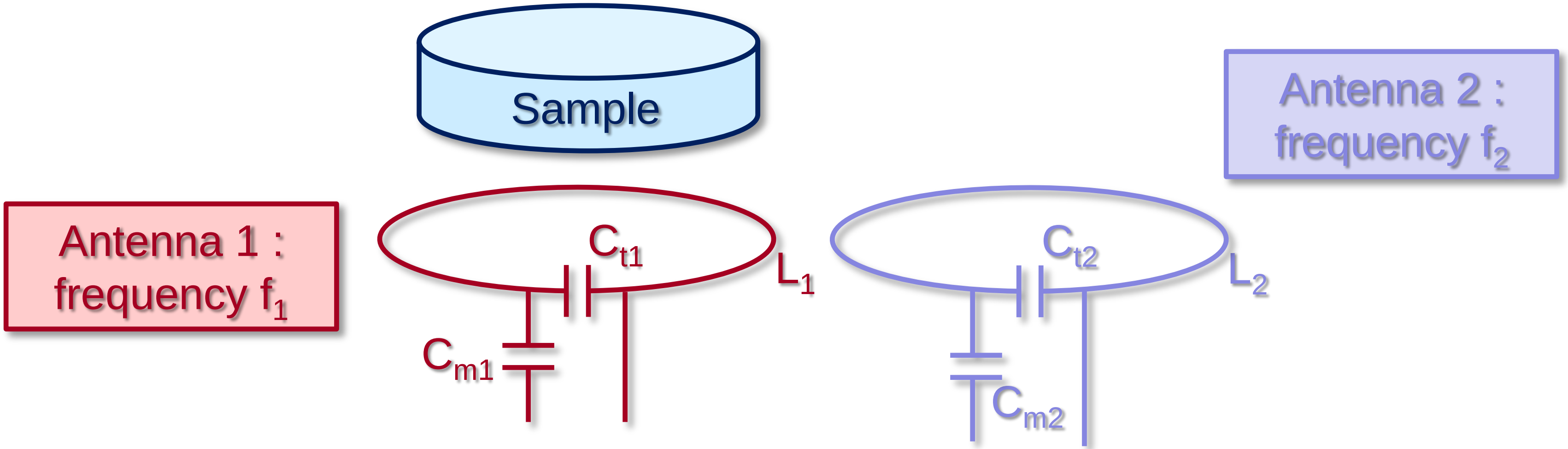

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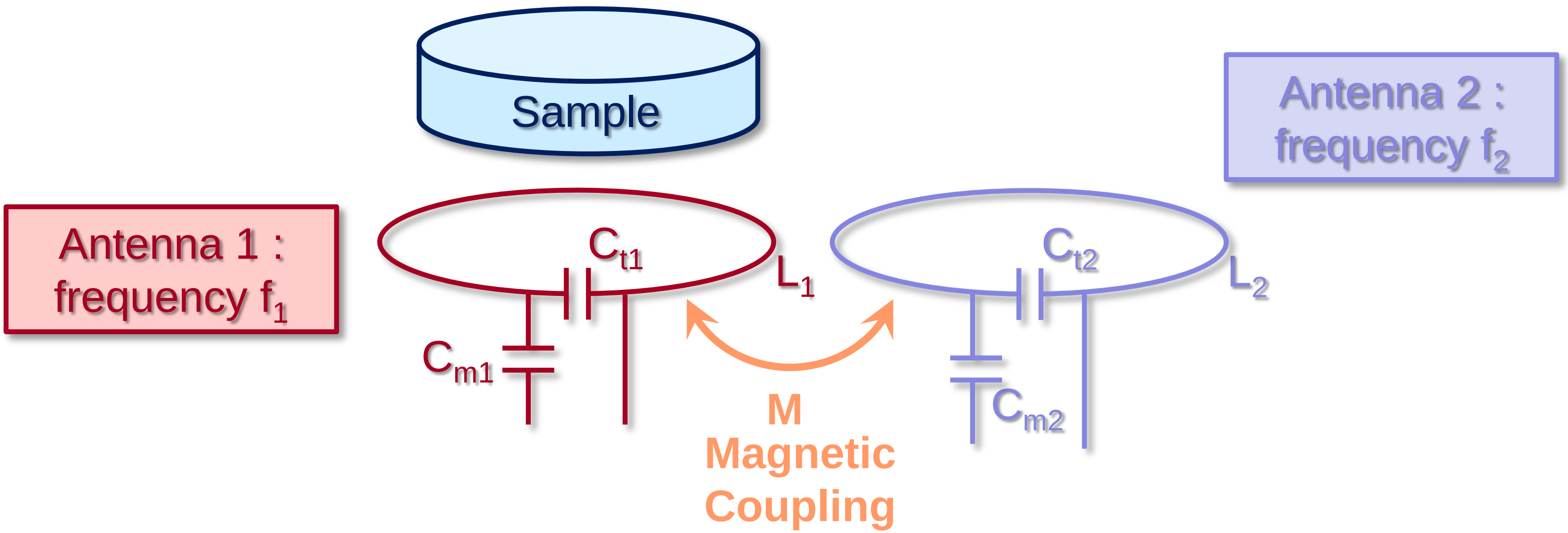

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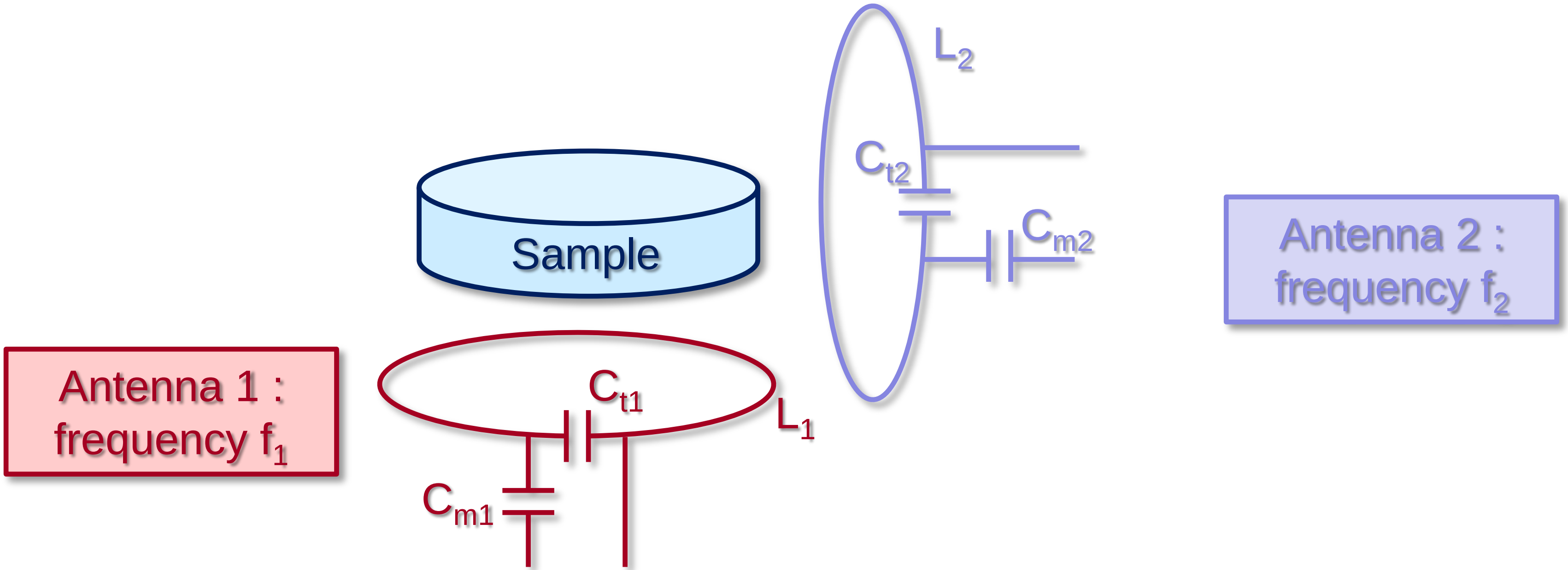
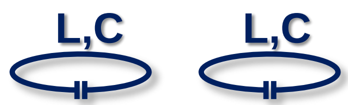



- Cancelation of the magnetic coupling : perpendicular antennas
- Complex geometry : planar structures are impossible
- Limited to 3 frequencies

# Set of sub-wavelength resonant loops



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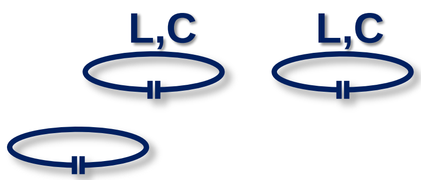

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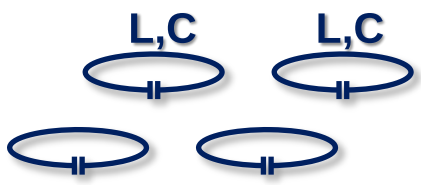
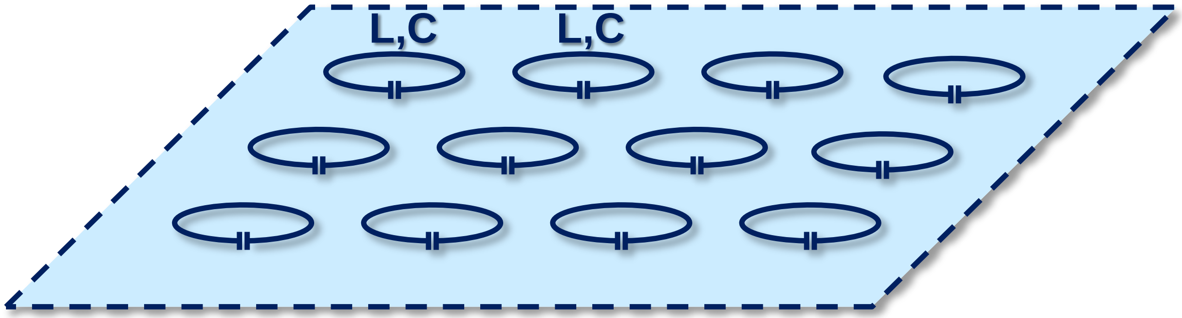
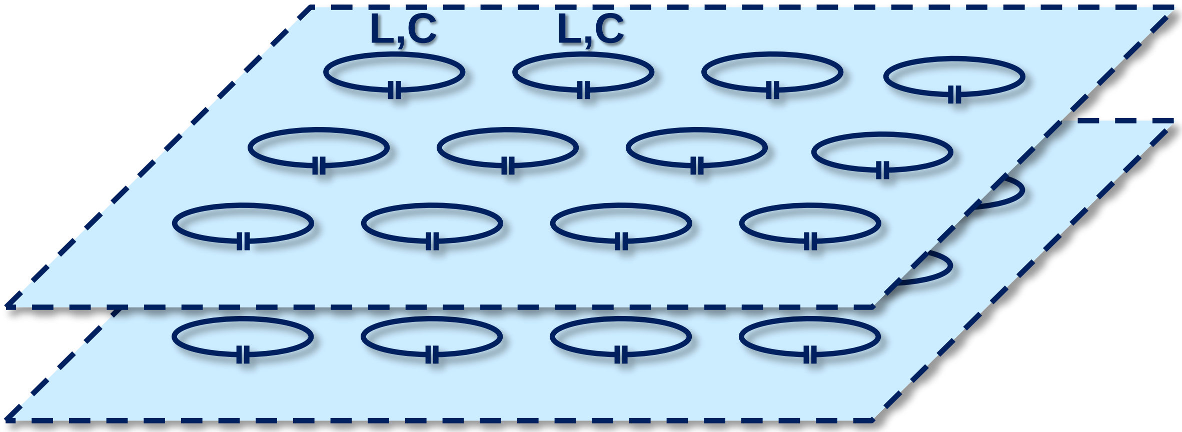


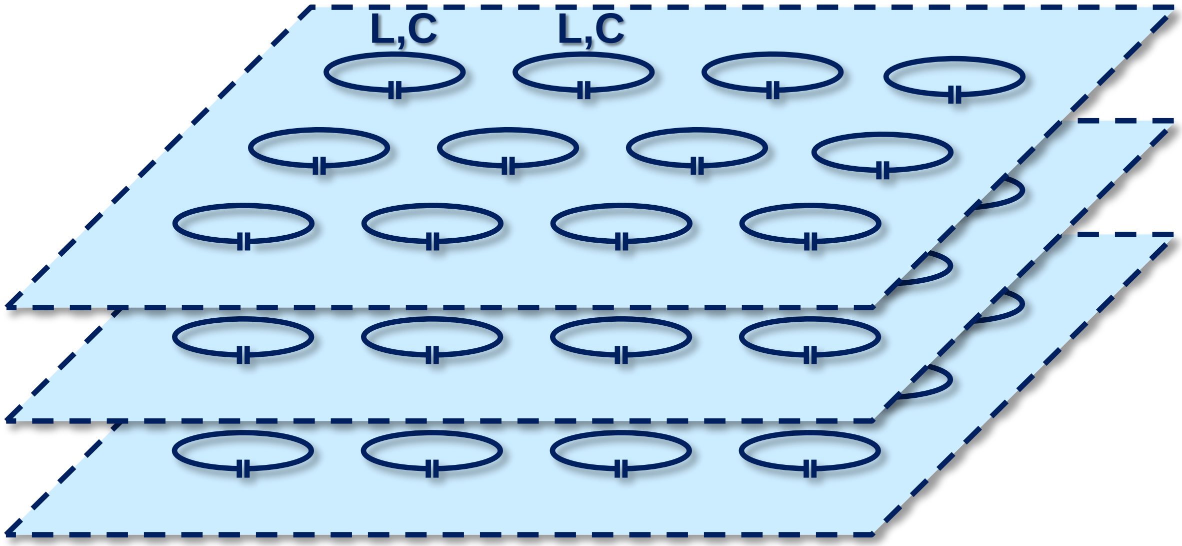
# Set of sub-wavelength resonant loops



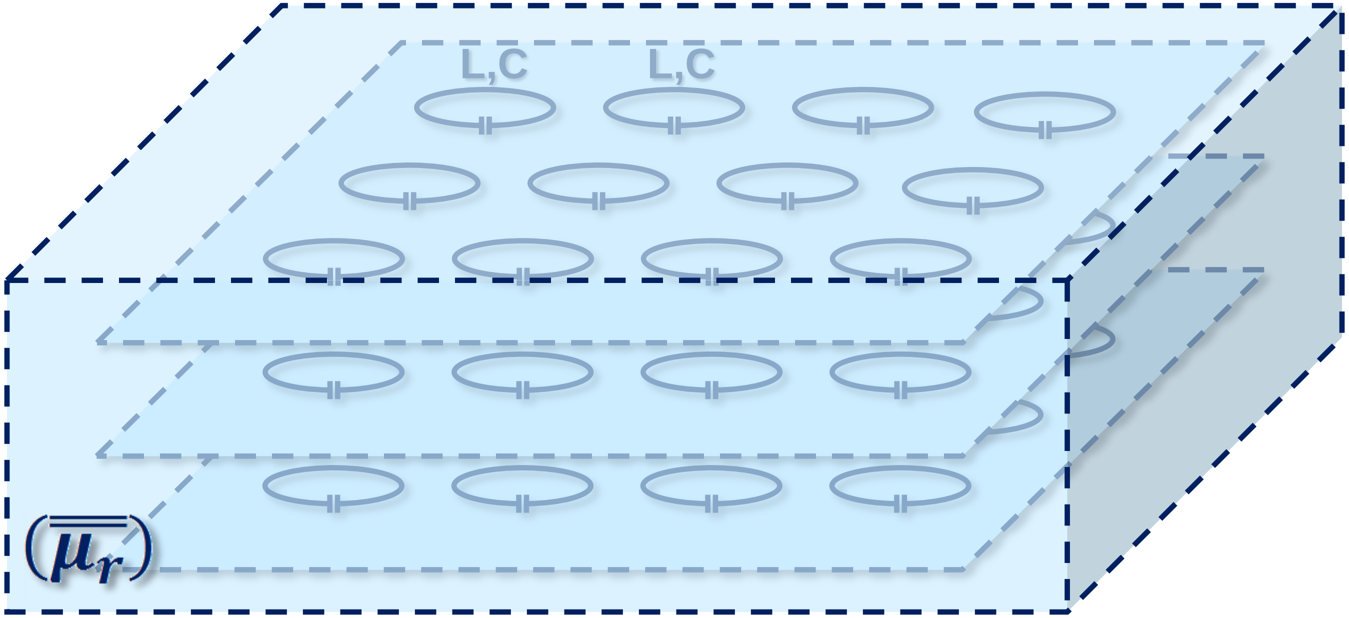
# Set of sub-wavelength resonant loops



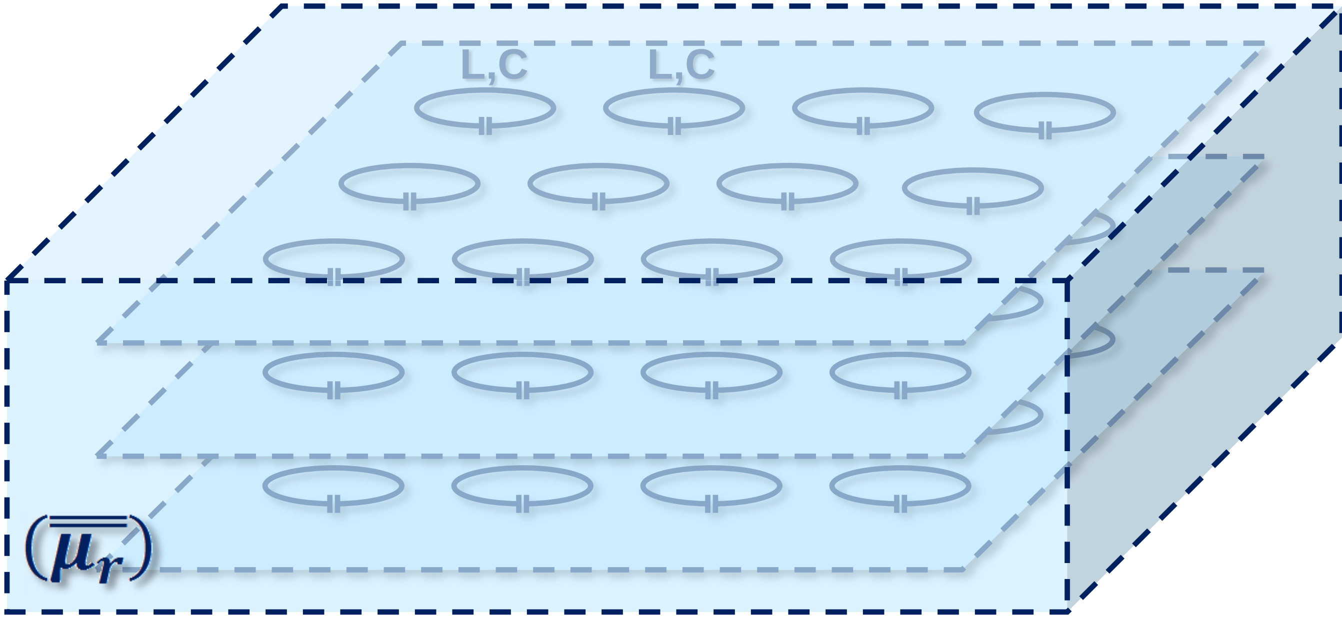
# Set of sub-wavelength resonant loops

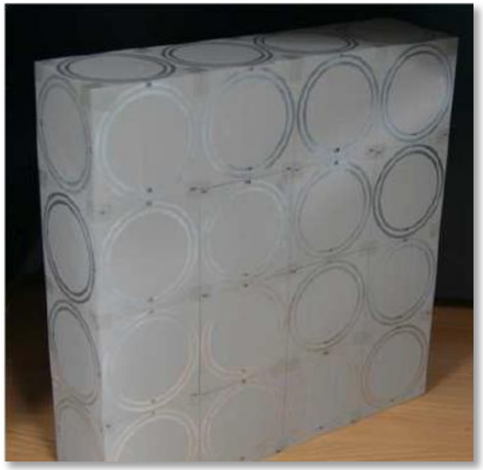


# Metamaterial



# Metamaterial

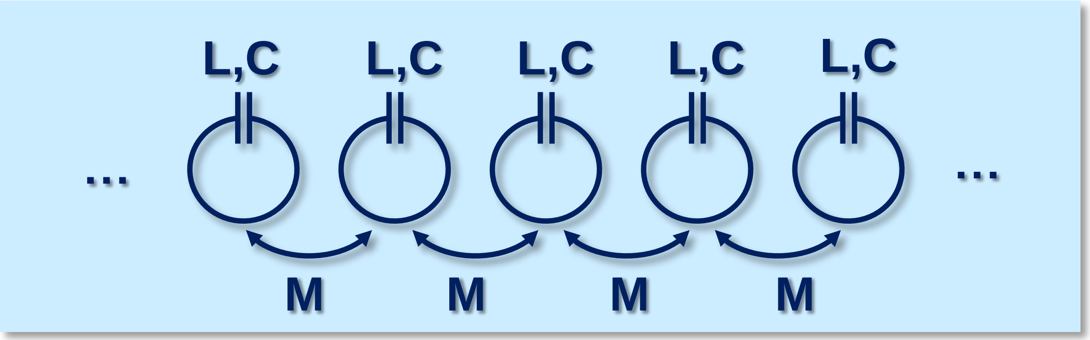


PIER Vol. 106, pp. 33-47, 2010

Metamaterial made of Split Ring Resonators (SRR) : Enables negative permeability

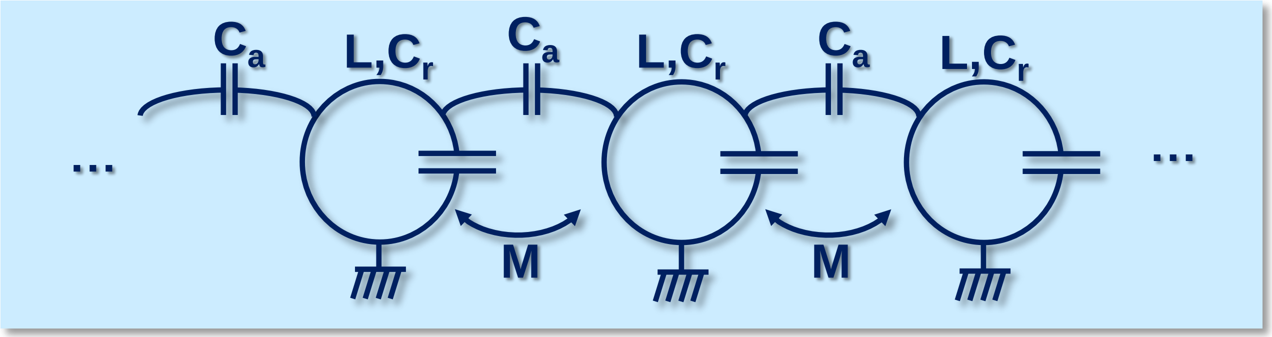
# 1-D Metamaterial




A travelling wave can propagate along an array of magnetically coupled SRR : magneto-inductive wave

Slow wave structure : $\lambda_g << c/f$ ⇨ Enables small resonant "antenna"

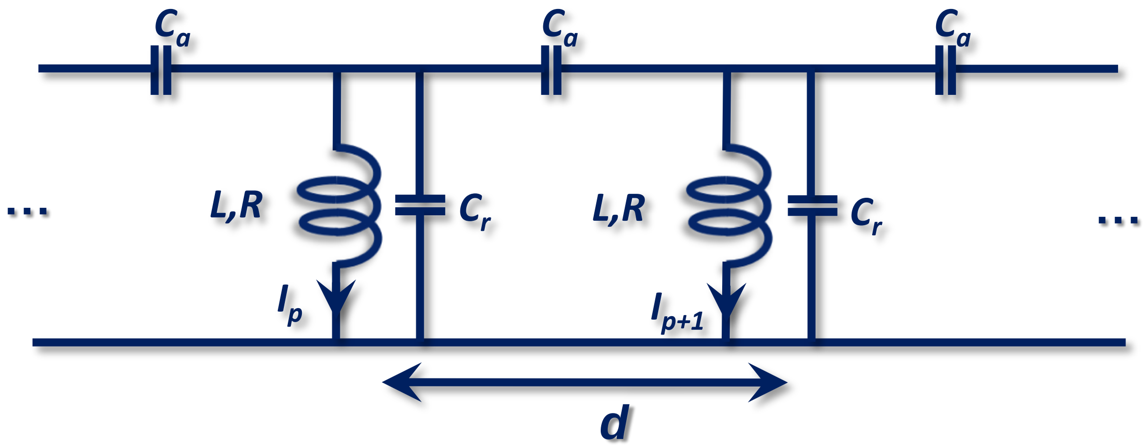
# New proposed structure



# Theoretical Model



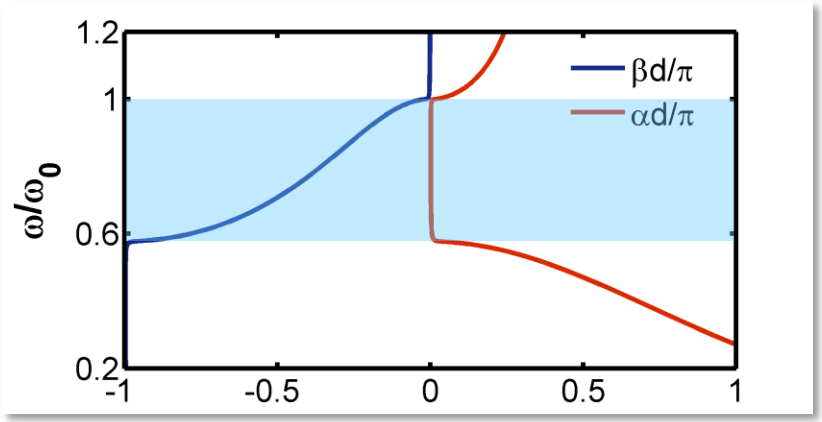
## Equivalent lumped element model :




$$I_p = I_0 \exp(-jnkd) \qquad k = \beta - j\alpha$$

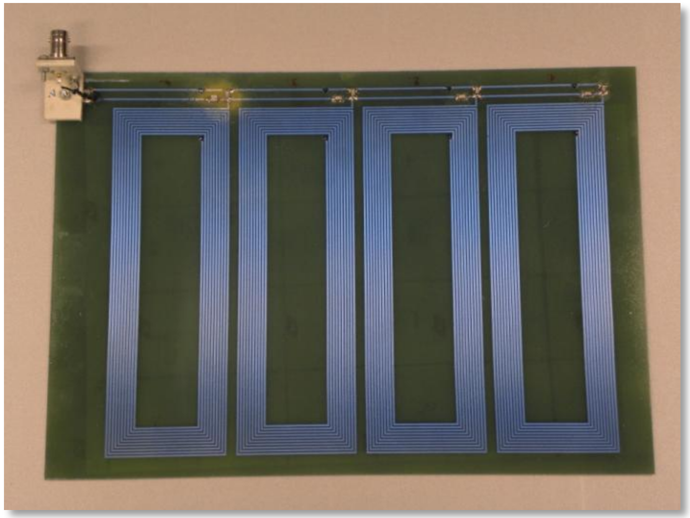
Dispersion relation :

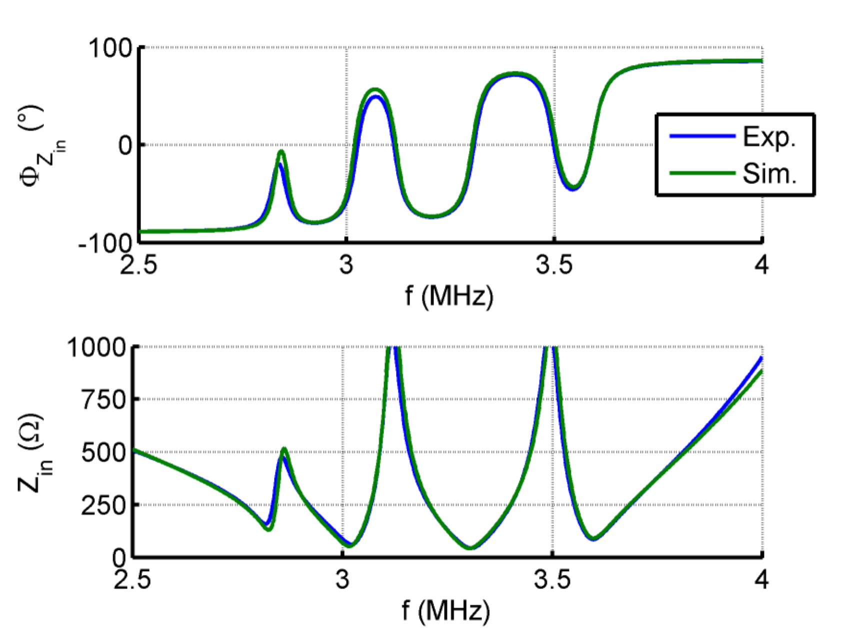
$$\cosh(kd) = 1 + \frac{1}{2\chi}\left(1 - \frac{\omega_0^2}{\omega^2}\frac{1+\frac{j}{Q}}{1-\frac{1}{Q^2}}\right)$$




$$\omega_0 = \frac{1}{\sqrt{LC_r}} \qquad Q = \frac{L\omega}{R} \qquad \chi = C_a/C_r$$

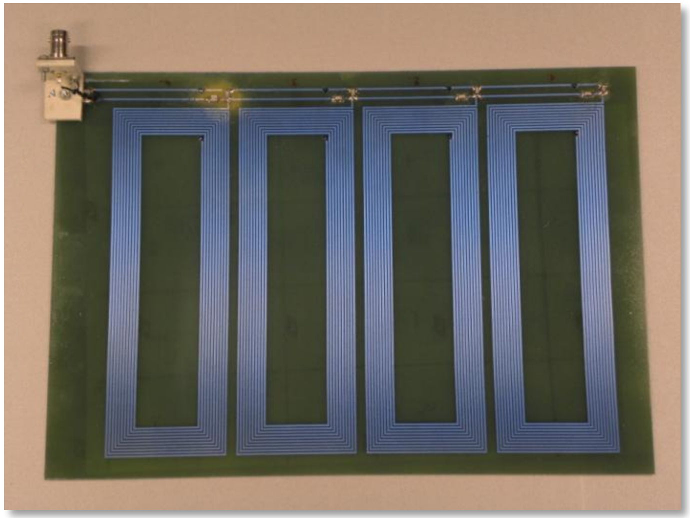
# Multimode antenna for the detection of HMT, $NaNO_2$ and SMZ

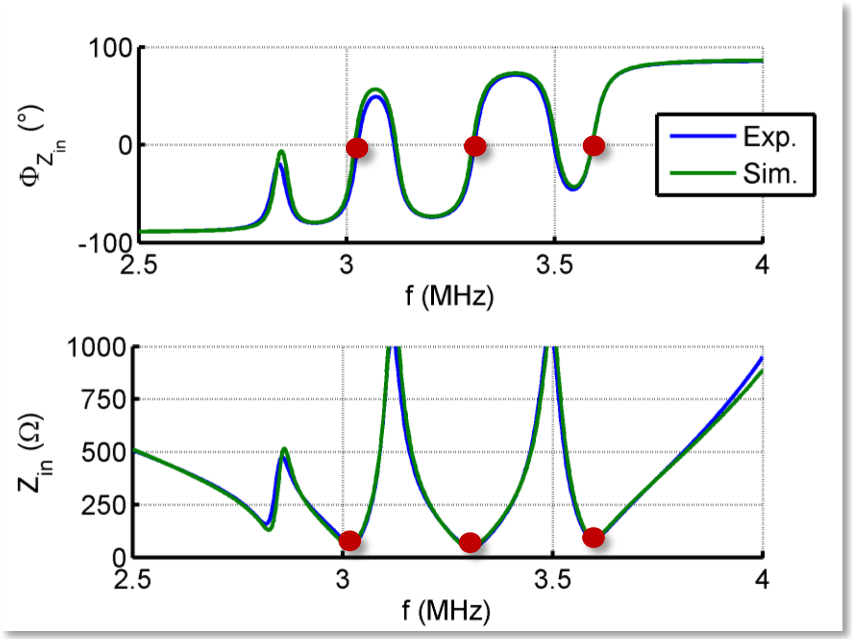





- **Antenna specifications :**
  - 30 cm x 20 cm
  - 4 resonators
  - 10 turns spirals
  - $C_r$=110 pF and $C_a$=1.5 pF
  - Q factor ≈ 50

# Multimode antenna for the detection of HMT, $NaNO_2$ and SMZ






0°

50Ω

3.1 MHz SMZ

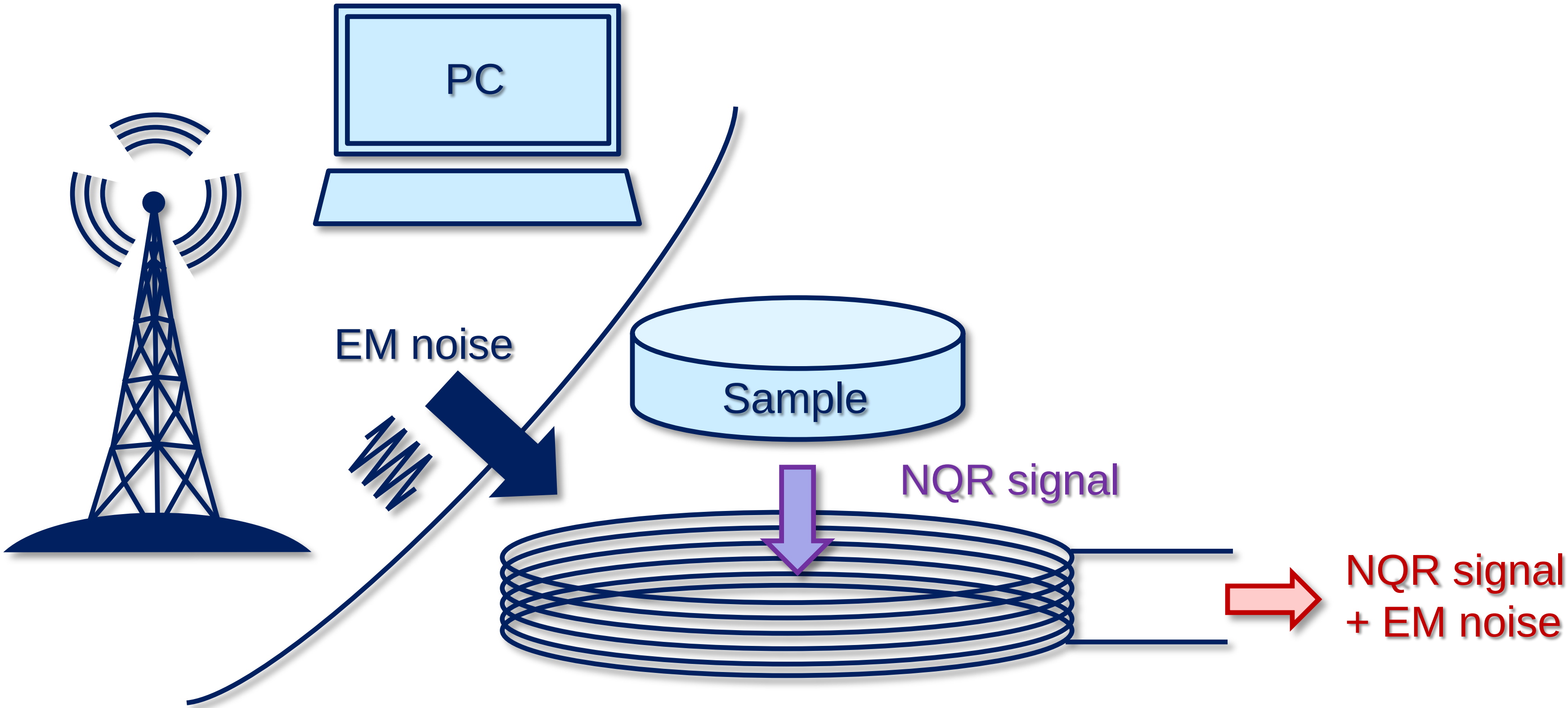
3.3 MHz HMT

3.6 MHz $NaNO_2$

- **Antenna specifications :**
  - 30 cm x 20 cm
  - 4 resonators
  - 10 turns spirals
  - $C_r$=110 pF and $C_a$=1.5 pF
  - Q factor ≈ 50

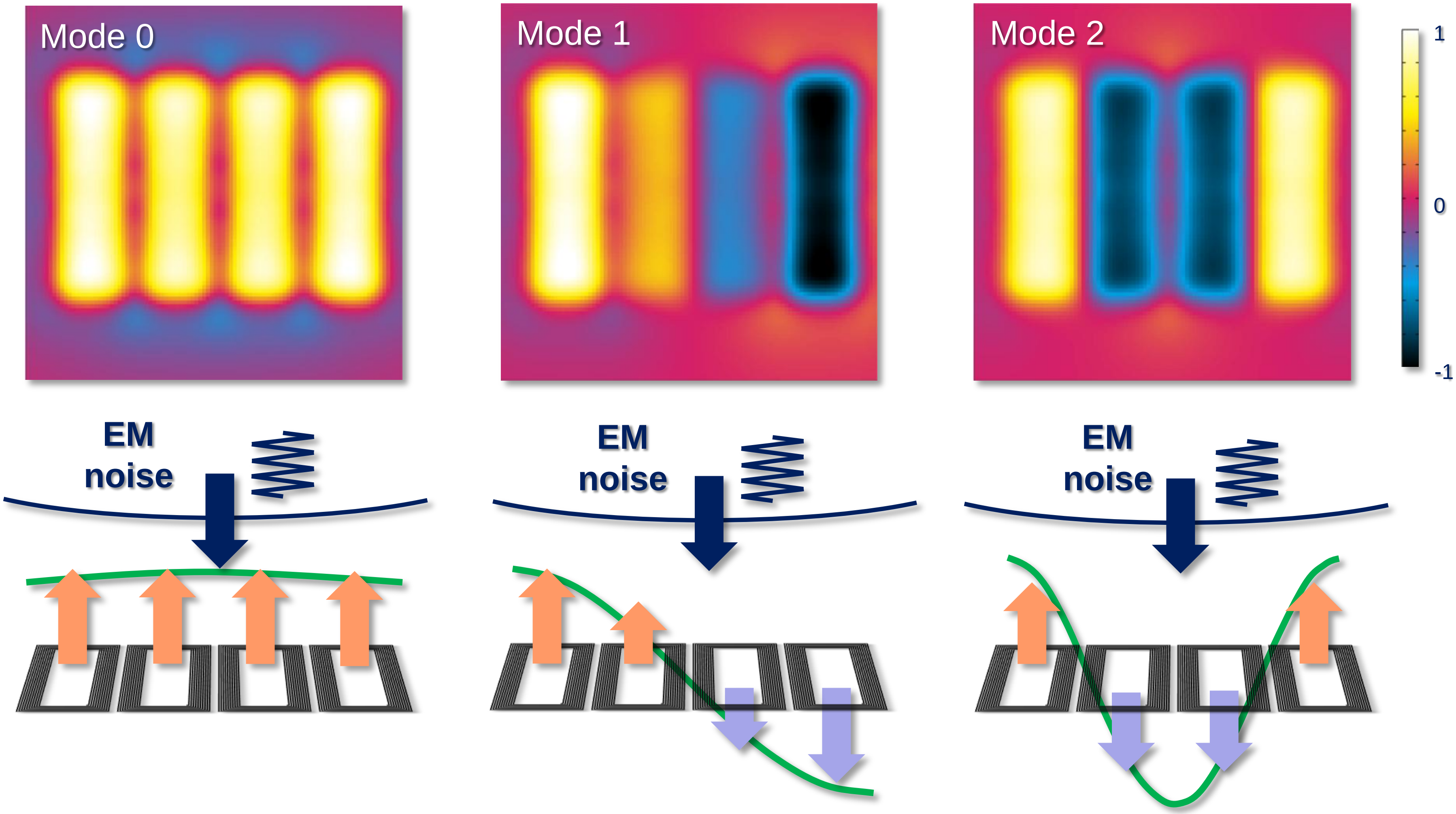
# Electromagnetic noise






**Low SNR : long operation time & poor sensibility**

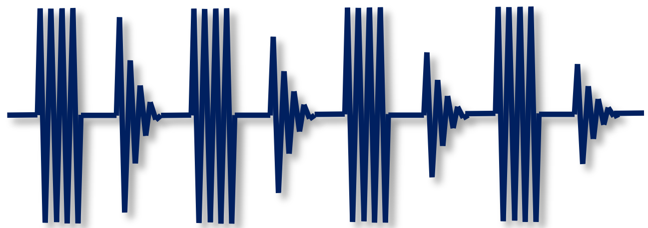
# Noise resilient antenna




**Self shielded antenna for upper modes**

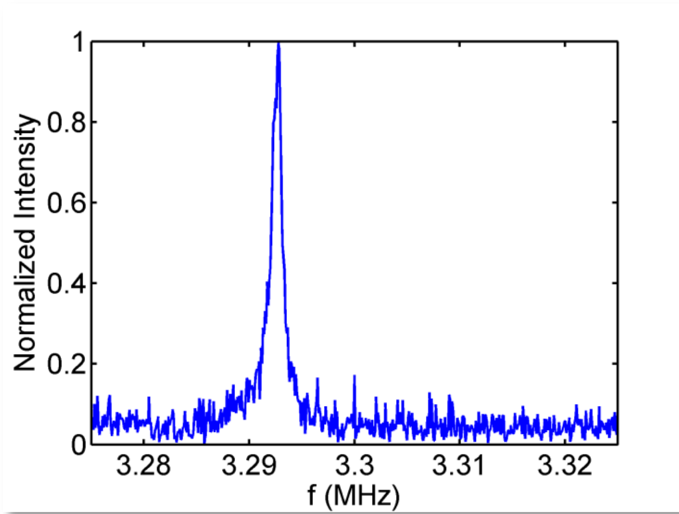
# Experimental Results



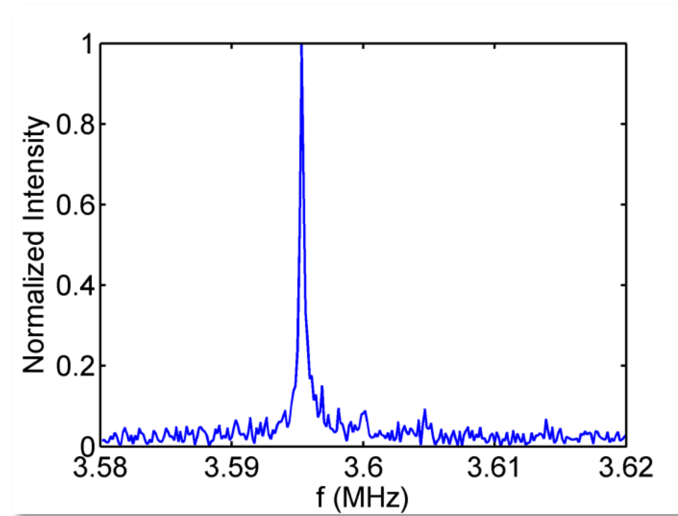


Steady State Free Precession (SSFP)

HMT Spectra




$NaN0_2$ Spectra

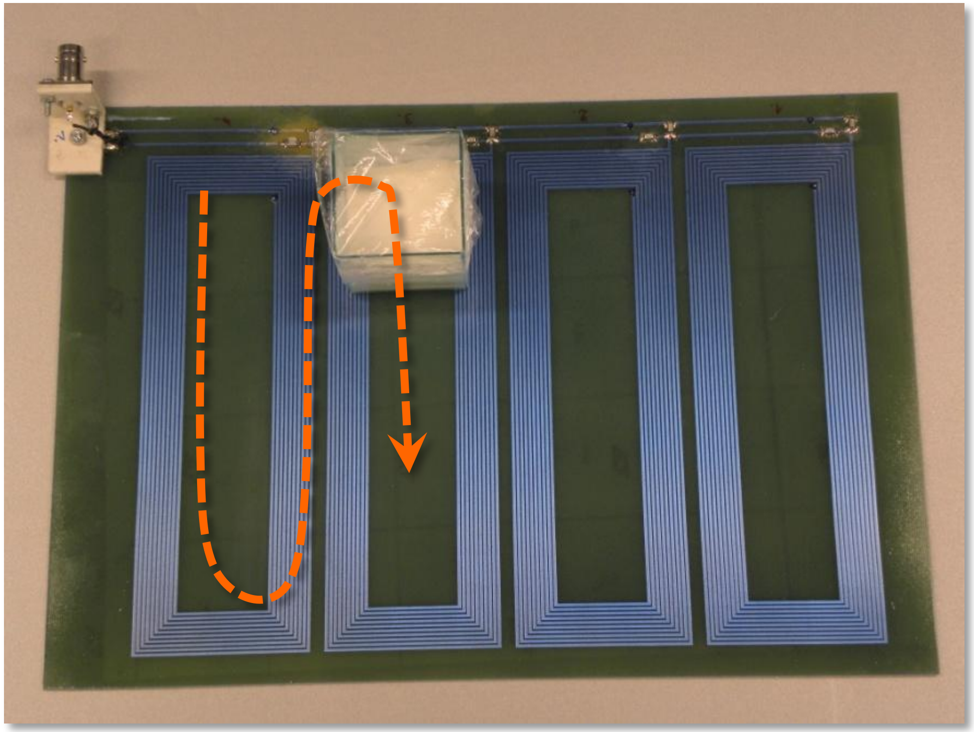



- **SNR > 10 for 50g of substance**
- **Detection of less than 5g**
- **Without any RF interferences mitigation**

# Experimental Results



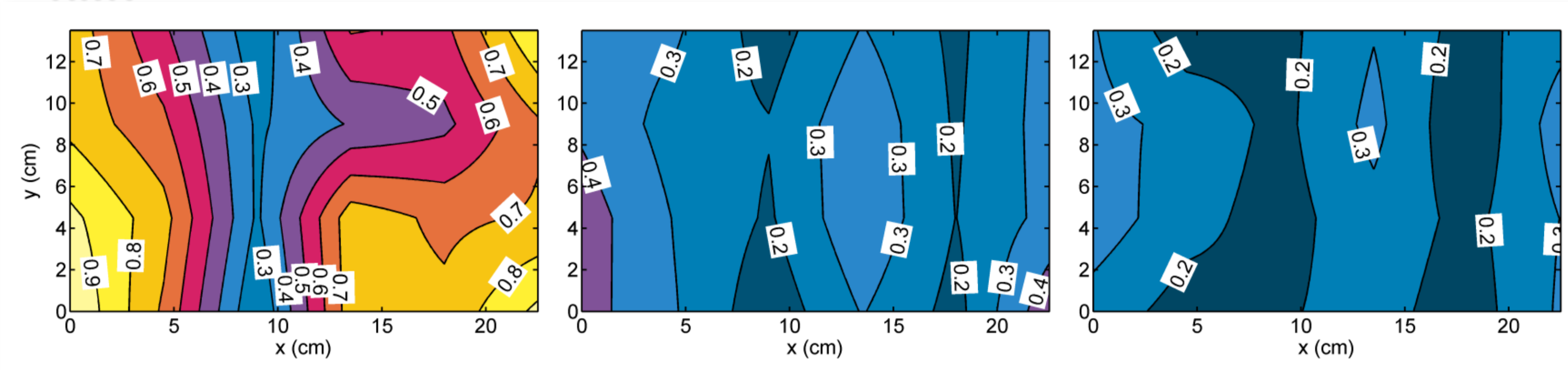
**SNR Maps :** 4.5cmx4.5cm box with 40g of HMT or $NaN0_2$



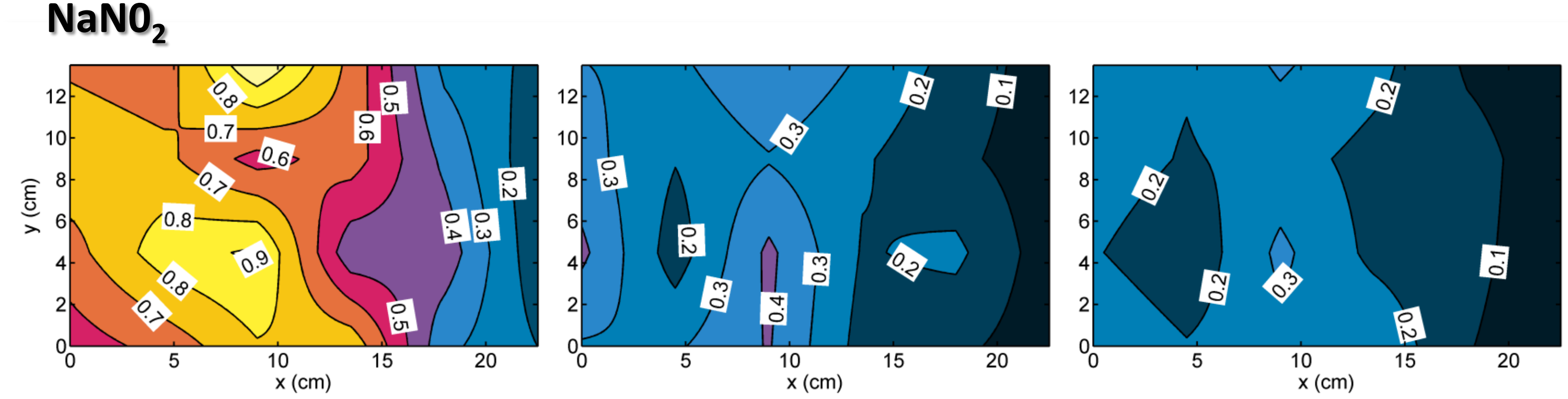
# Experimental Results

## Normalized SNR maps

### HMT




### $NaNO_2$




**z=0 mm** **7 mm** **10 mm**

# Conclusion and outlook



## 1. Innovative HF communication systems based on metamaterials

- RIS intensively investigated at ISL, both for LP and CP
- Meta-materials can effectively enhance the performances of printed antennas
- Designs of BW enhanced patch antennas ("medium" size)
- Designs of compact phased array with enhanced gain-BW
- Designs of small antennas in cavity, toward the maximum achievable BW with the given size

⇨ Antennas in very small cavities could be designed (work in progress) for instrumentation of projectiles with smaller calibers than today.

## 2. QR spectroscopy

- Increased number of resonant frequencies
- Enhanced sensibility and detection range : negative μ metamaterial lens