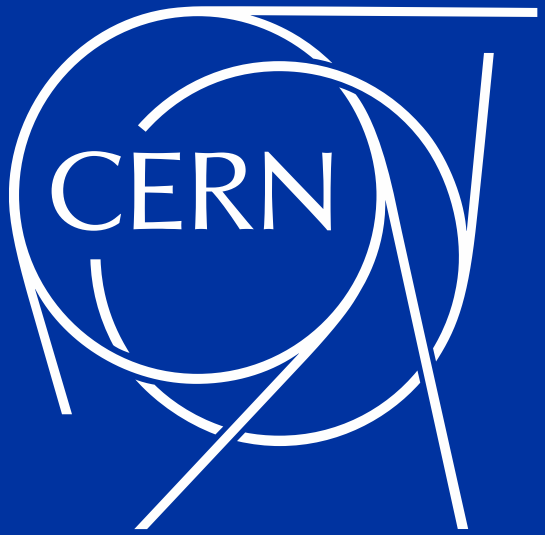

CERN

Metamaterials as Room Temperature Superconductors

Alessandro Danisi, Carlo Zannini

Special Thanks: Roberto Losito, Giovanni Rumolo, Leonardo Sito

Disclaimer

- The aim is to show a research which is on-going
  - https://www.nature.com/articles/s41598-023-29966-2
- Objective is to approach superconductive-like properties
- Very high electrical conductivity at room temperature
- This aim is investigated with the use of metamaterials
- Although the presentation title is appealing, we are not re-creating superconductors at room temperature

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- The idea
- Analytical model: the metaconductive transition
- A simple design equation
- Experimental Proof of Concept

Possible application for sustainable accelerators

Metamaterials

μετά = “to go beyond”

“Structures and composite materials that either mimic known material responses or qualitatively have new, physically realizable response functions that do not occur or may not be readily available in nature.”

Nader Engheta & Richard W. Ziolkowski
“Metamaterials: Physics, Engineering and Explorations”
IEEE & Wiley Interscience Press, 2006

Material characteristics

μ

ENG Materials: artificially realizable (& plasmas)

$\varepsilon < 0, \mu > 0$

$\varepsilon > 0, \mu > 0$

ε

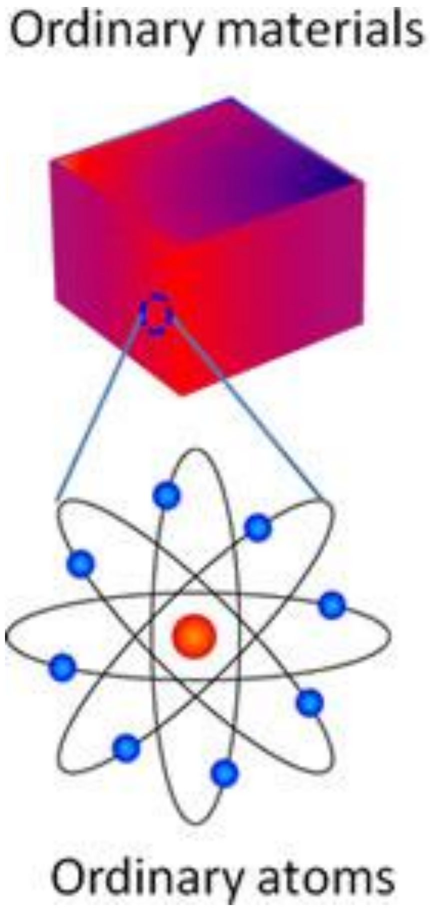
DNG Materials: artificially realizable (not found in nature)

$\varepsilon < 0, \mu < 0$

MNG Materials: artificially realizable (not found in nature)

$\varepsilon > 0, \mu < 0$

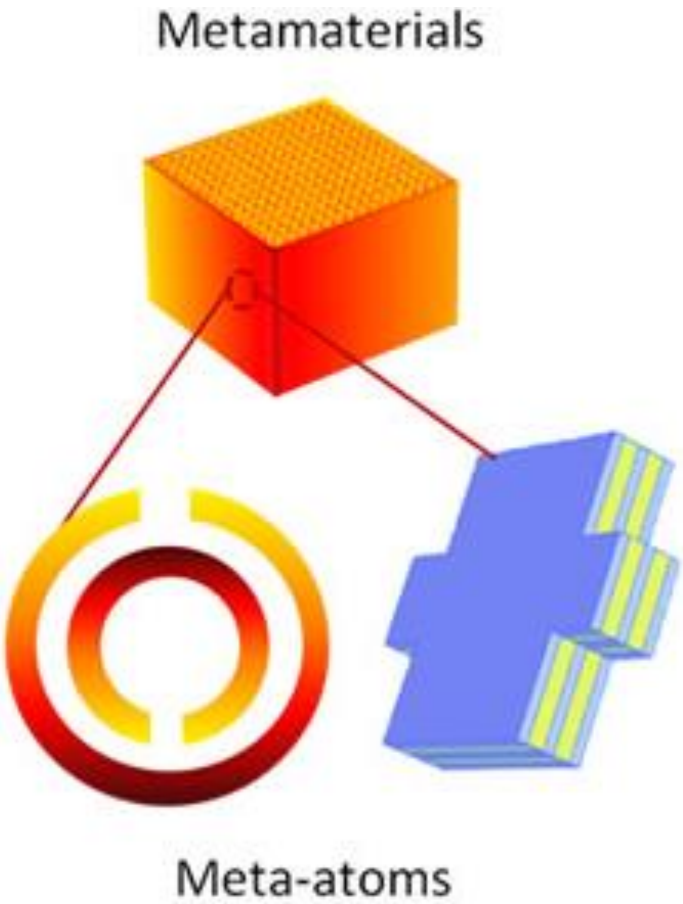
How to produce a metamaterial?



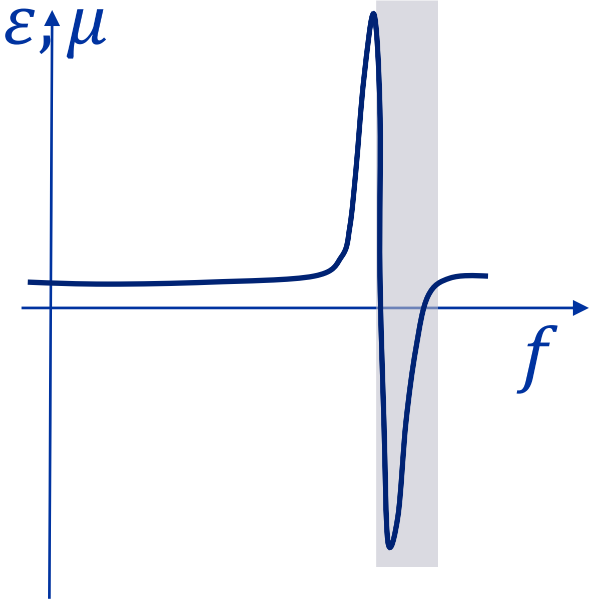
Atoms, their organization in domains and polarizations give the electromagnetic properties.

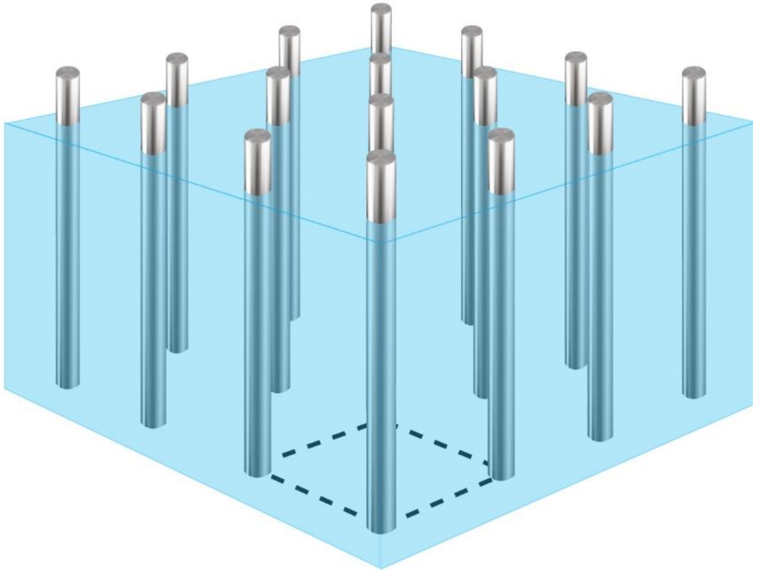
“Engineer” the material such that at certain frequencies (wavelengths) it is seen as made of “meta-atoms”.

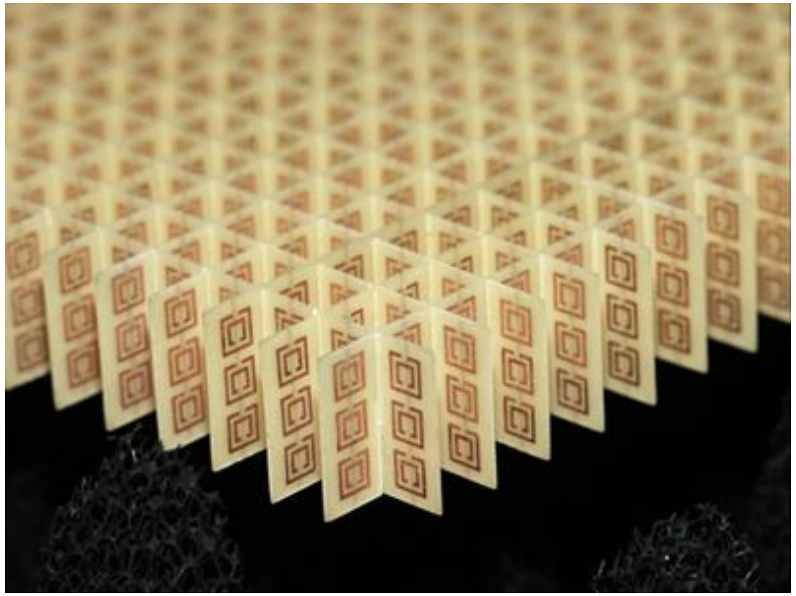
The “meta-atoms” can be engineered so as to give desired electromagnetic properties.



ENG or MNG metamaterial







Conductive inclusions in low-ε substrates

Anisotropic material

Equivalent ε depends on concentration, $\varepsilon_{sub}, \sigma_{incl}$, orientation. ε will be a tensor.

Conductive inclusions in high-ε substrates

Anisotropic material

Equivalent μ depends on concentration, $\varepsilon_{sub}, \sigma_{incl}$, orientation. μ will be a tensor.

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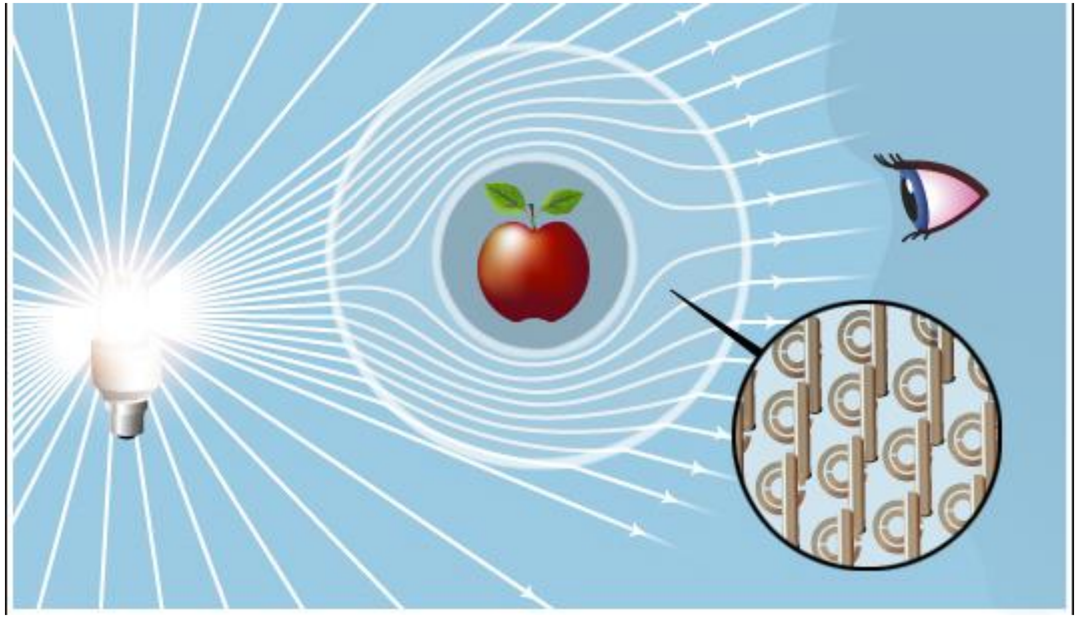
The idea

Using optical metamaterials one could make surrounding objects invisible to light.



Metamaterials are masking the object and changing its properties

Analogously, can we use metamaterials to mask a material and improve its conductivity properties beyond normal capabilities?

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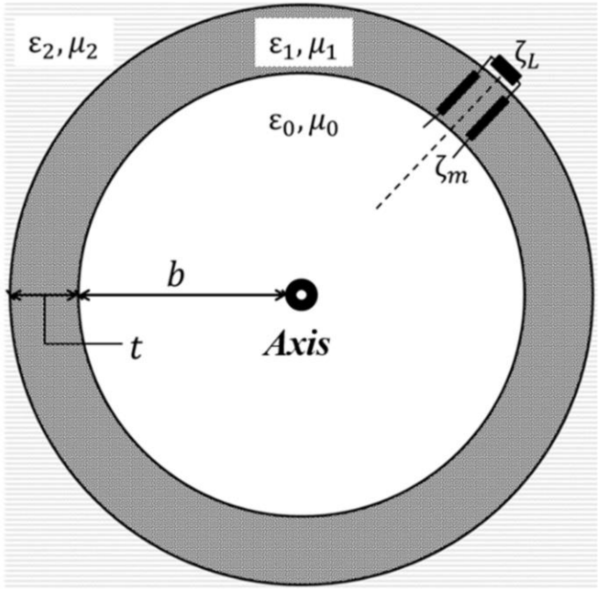
Analytical model: the metaconductive transition



$$|\varepsilon_1 \mu_1| \gg \varepsilon_0 \mu_0$$

$$\delta \ll b$$

$$t \ll b$$

$$\zeta_L = \frac{1+j}{\sigma_2 \delta}$$

$$\zeta_1 = \sqrt{\mu_1/\varepsilon_1}$$

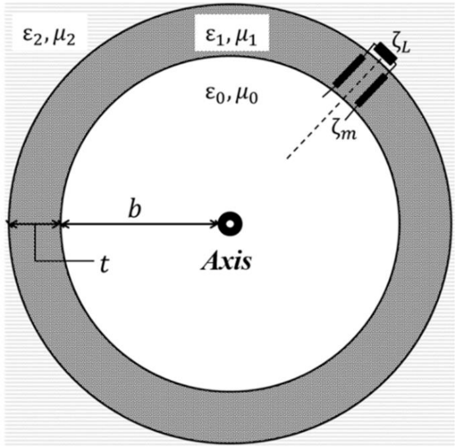
$$k_1 = \omega\sqrt{\mu_1 \varepsilon_1}$$

Surface impedance seen by the propagating wave

$$\zeta_m = \zeta_1 \cdot \frac{\zeta_L + j\zeta_1 \tan k_1 t}{\zeta_1 + j\zeta_L \tan k_1 t}$$

Analytical model: the metaconductive transition

$$\zeta_m = \zeta_1 \cdot \frac{\zeta_L + j\zeta_1 \tan k_1 t}{\zeta_1 + j\zeta_L \tan k_1 t}$$



$$k_1 t = \beta - j\alpha$$

$$\tan(\beta - j\alpha) = \frac{\tan\beta - j\tanh\alpha}{1 + j\tan\beta\tanh\alpha}$$

$$\zeta_L = a + ja$$

$$\zeta_1 = b' + jb''$$

$$\boxed{Re\{\zeta_m\} = \frac{\left(b'^2 + b''^2\right)\cdot N_1}{D} + \frac{\left(b'^2 - b''^2 + 2b'b''\right)\cdot N_2}{D} + \frac{\left(b'^3 + b'b''^2\right)\cdot N_3}{D} + \frac{\left(b''^3 + b'^2 b''\right)\cdot N_4}{D} + \frac{N_5}{D}}$$

Analytical model: the metaconductive transition

$$Re\{\zeta_m\} = \frac{\left(b'^2 + b''^2\right)\cdot N_1}{D} + \frac{\left(b'^2 - b''^2 + 2b'b''\right)\cdot N_2}{D} + \frac{\left(b'^3 + b'b''^2\right)\cdot N_3}{D} + \frac{\left(b''^3 + b'^2 b''\right)\cdot N_4}{D} + \frac{N_5}{D}$$

$$D = \left|b' - b'' \tan\beta \tanh\alpha - a(\tan\beta - \tanh\alpha) + j\left[a(\tan\beta + \tanh\alpha) + b' \tan\beta \tanh\alpha + b''\right]\right|^2$$

$$N_1 = a\left[1 + (\tan\beta)^2(\tanh\alpha)^2\right] + b' \tanh\alpha - b'' \tan\beta$$

$$N_2 = a\left[(\tan\beta)^2 + (\tanh\alpha)^2\right]$$

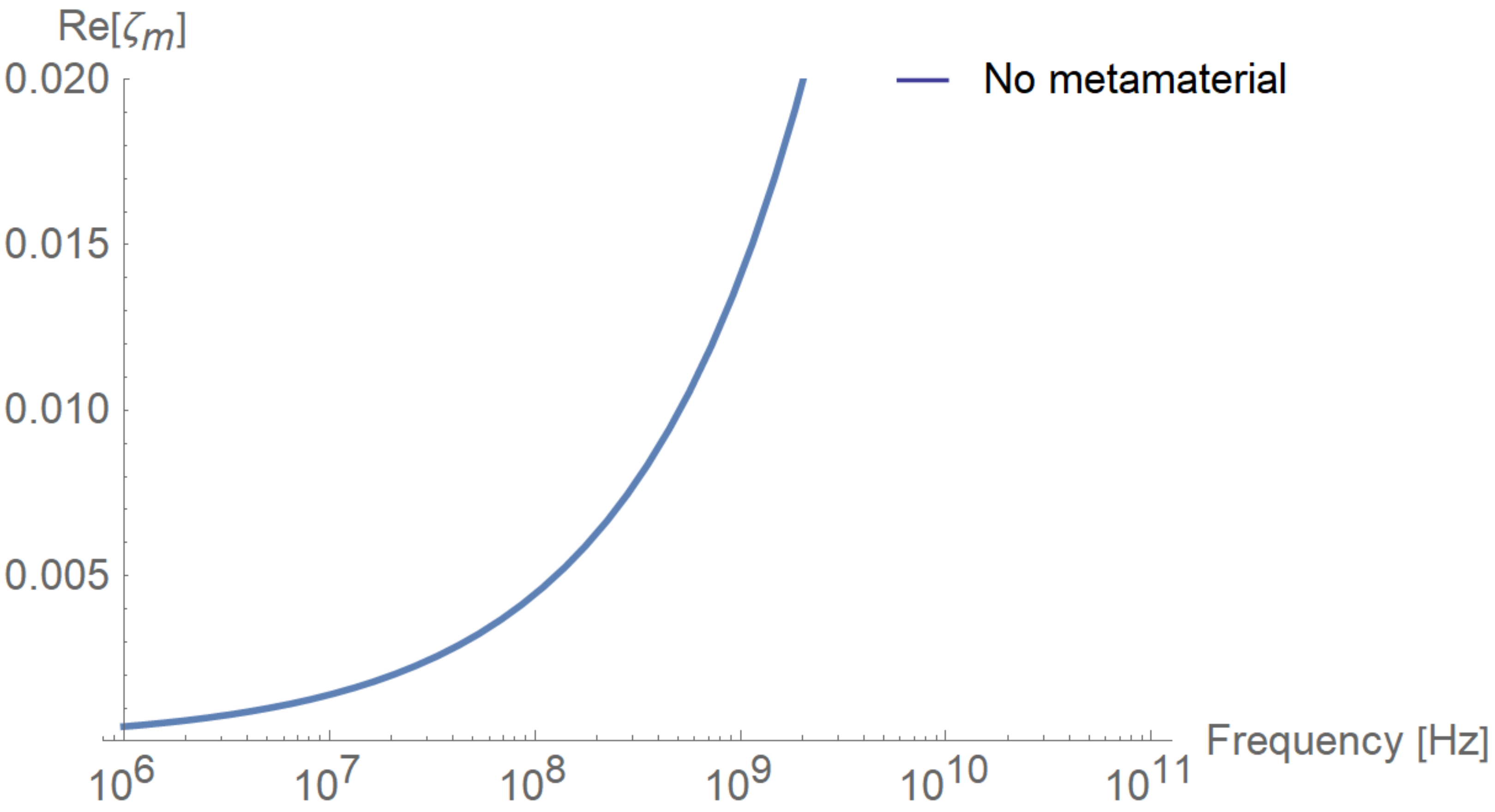
$$N_3 = \tanh\alpha(\tan\beta)^2$$

$$N_4 = \tan\beta(\tanh\alpha)^2$$

$$N_5 = 2a^2 b' \tanh\alpha\left[1 + (\tan\beta)^2\right] + 2a^2 b'' \tan\beta\left[1 - (\tanh\alpha)^2\right]$$

Analytical model: the metaconductive transition

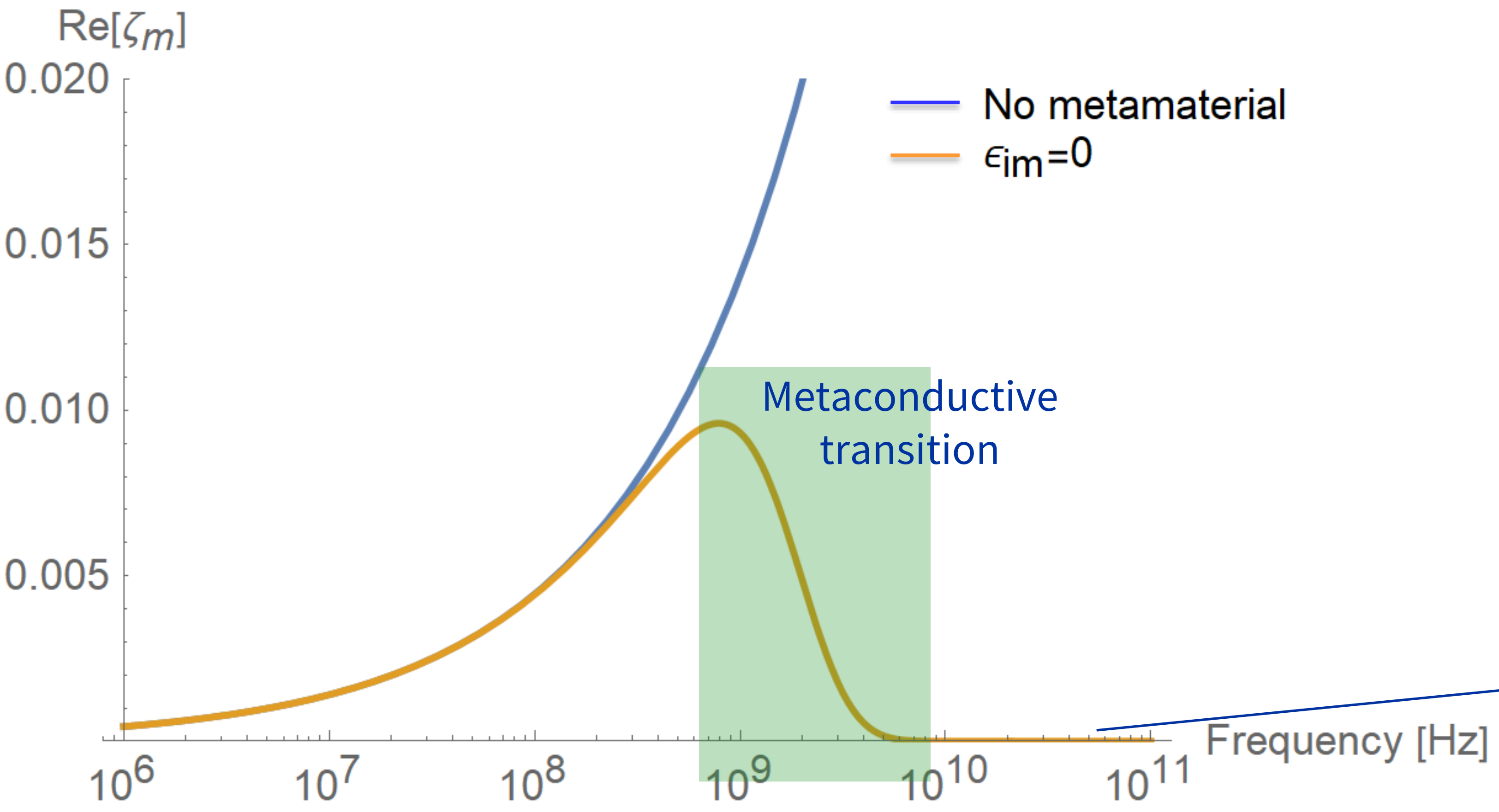
$$Re\{\zeta_m\} = \frac{\left(b'^2 + b''^2\right)\cdot N_1}{D} + \frac{\left(b'^2 - b''^2 + 2b'b''\right)\cdot N_2}{D} + \frac{\left(b'^3 + b'b''^2\right)\cdot N_3}{D} + \frac{\left(b''^3 + b'^2 b''\right)\cdot N_4}{D} + \frac{N_5}{D}$$



Parameter	Value
Metal conductivity	$2 \cdot 10^7$ S/m
Metamaterial type	ENG (Negative electrical permittivity)
ε_{r1}	-10 (lossless case); $-10 + j10^{-4}$ (lossy case) $-10 + j10^{-5}$ (lossy case)
μ_{r1}	1
Metamaterial layer thickness	10 mm

Analytical model: the metaconductive transition

$$Re\{\zeta_m\} = \frac{\left(b'^2 + b''^2\right)\cdot N_1}{D} + \frac{\left(b'^2 - b''^2 + 2b'b''\right)\cdot N_2}{D} + \frac{\left(b'^3 + b'b''^2\right)\cdot N_3}{D} + \frac{\left(b''^3 + b'^2 b''\right)\cdot N_4}{D} + \frac{N_5}{D}$$



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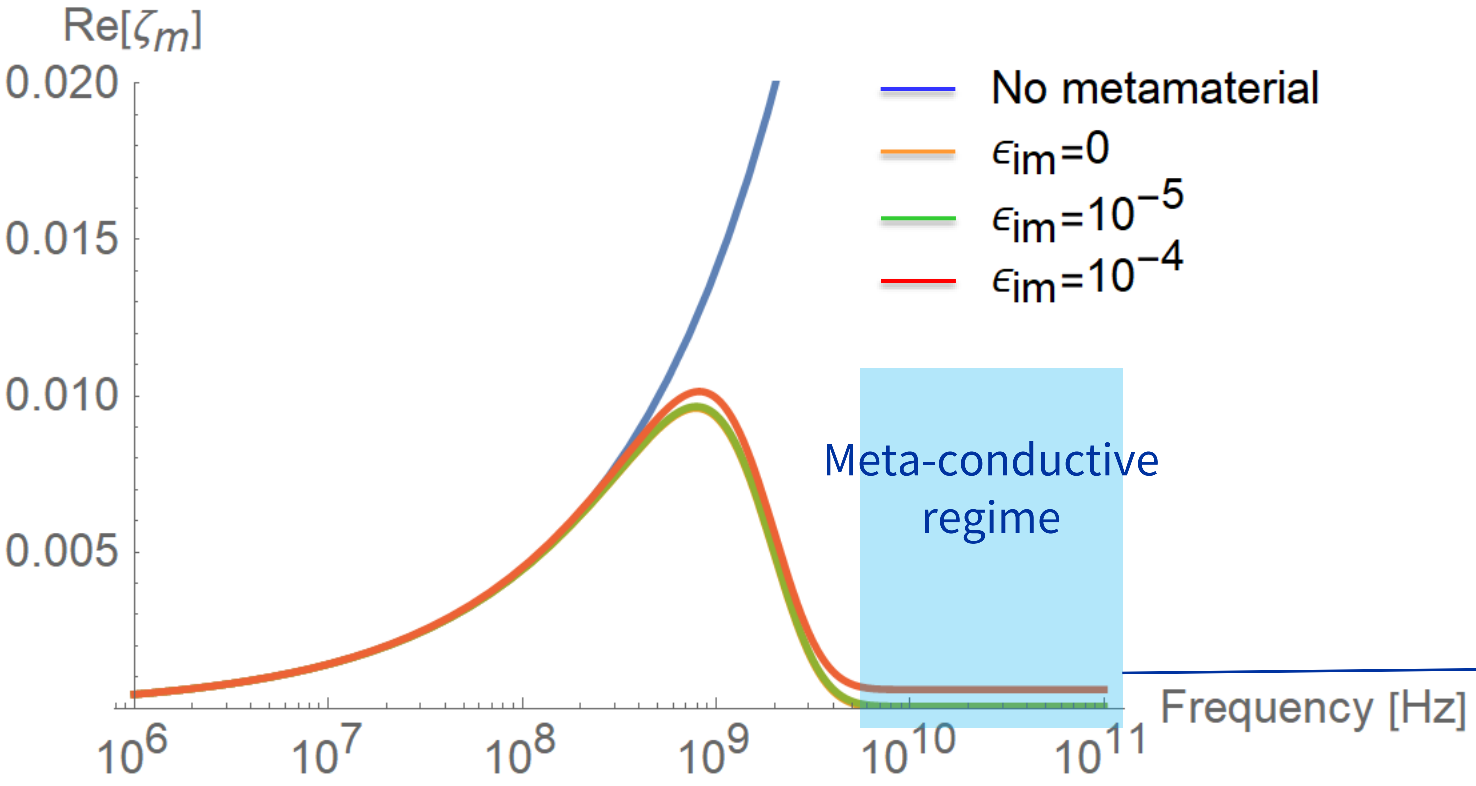
$\mathrm{Re}[\zeta_m] = 0$

Analytical model: the metaconductive transition

$$Re\{\zeta_m\} = \frac{\left(b'^2 + b''^2\right)\cdot N_1}{D} + \frac{\left(b'^2 - b''^2 + 2b'b''\right)\cdot N_2}{D} + \frac{\left(b'^3 + b'b''^2\right)\cdot N_3}{D} + \frac{\left(b''^3 + b'^2 b''\right)\cdot N_4}{D} + \frac{N_5}{D}$$



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μ_{r1}	1
Metamaterial layer thickness	10 mm

$$\mathrm{Re}[\zeta_m] = b'$$

The wall material has been masked and its conductivity been brought to superconductive-like values

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A simple design equation

$$\boxed{Re\{\zeta_m\} = \frac{\left(b'^2 + b''^2\right)\cdot N_1}{D} + \frac{\left(b'^2 - b''^2 + 2b'b''\right)\cdot N_2}{D} + \frac{\left(b'^3 + b'b''^2\right)\cdot N_3}{D} + \frac{\left(b''^3 + b'^2 b''\right)\cdot N_4}{D} + \frac{N_5}{D}}$$

Lossless metamaterial

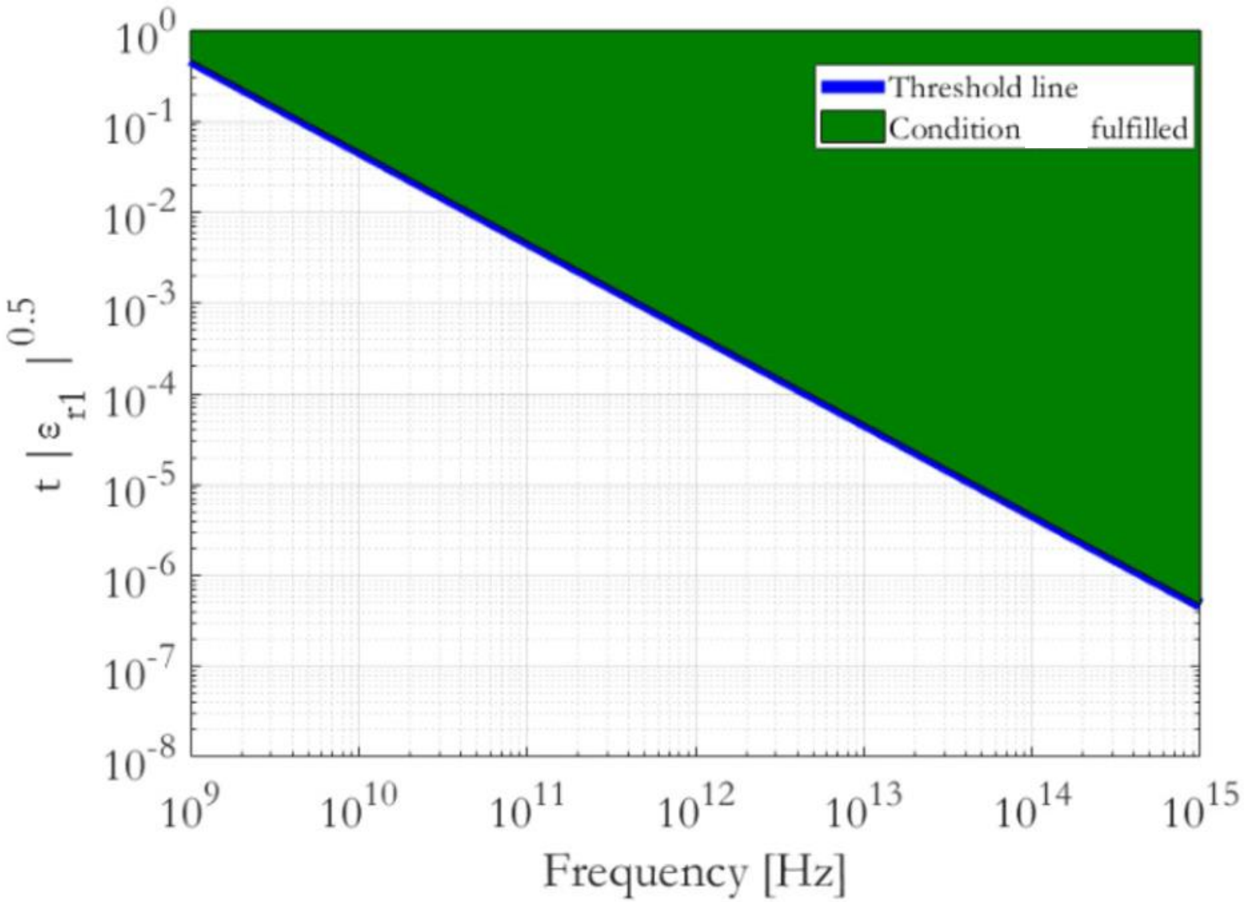
$$Re\{\zeta_m\} = \zeta_1 \cdot \frac{A\left[1 + (\tan k_1 t)^2\right]}{(A - \tan k_1 t)^2 + (\tan k_1 t)^2} \qquad A = \sigma_2 \delta \zeta_1$$

$$Re\{\zeta_m\} = 0 \Longrightarrow \tan(k_1 t) = j \Longrightarrow \tanh(|k_1 t|) = 1 \xrightarrow{\text{Practically satisfied}} |k_1 t| \geq 10$$

Simple design equation for metaconductive surfaces

$$\boxed{t\sqrt{|\varepsilon_{r1}|} \geq \frac{10c}{\omega_0 \sqrt{|\mu_{r1}|}}}$$

A simple design equation



$$\boxed{t\sqrt{|\varepsilon_{r1}|} \geq \frac{10c}{\omega_0\sqrt{|\mu_{r1}|}}}$$

Knowing the frequency at which the metamaterial should operate one can estimate the required thickness and properties of the metamaterial

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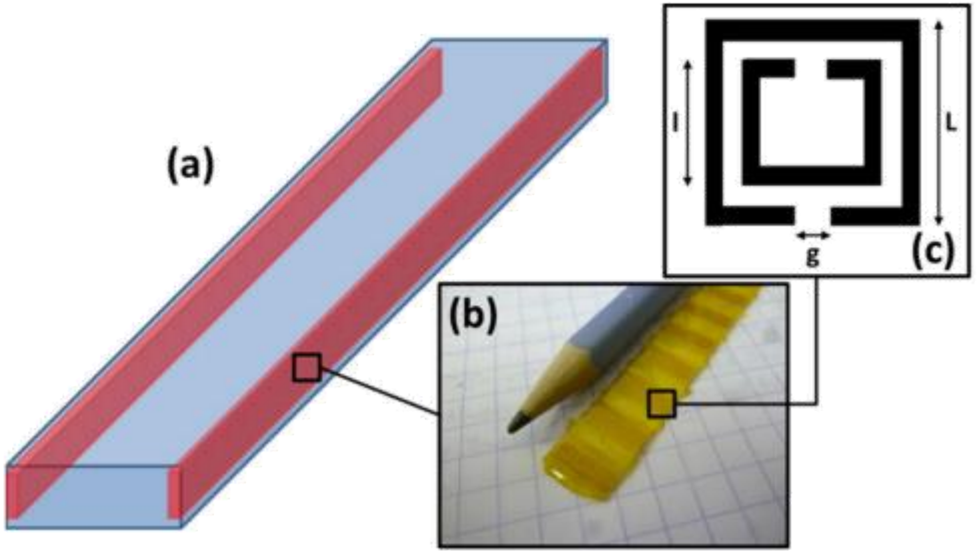
Proof of concept

First experiment was set using a WR284 rectangular waveguide as a cavity.

Waveguide is closed on a short on both sides, but with a tiny antenna on one side.

Frequency bandwidth between 2.6 and 3.8 GHz.

Measurement of unloaded Q of cavity modes were done.



L = 5.4 mm, l = 3.4 mm, g = 1 mm.

$$Q = Q_L\,(1 + 2g)$$

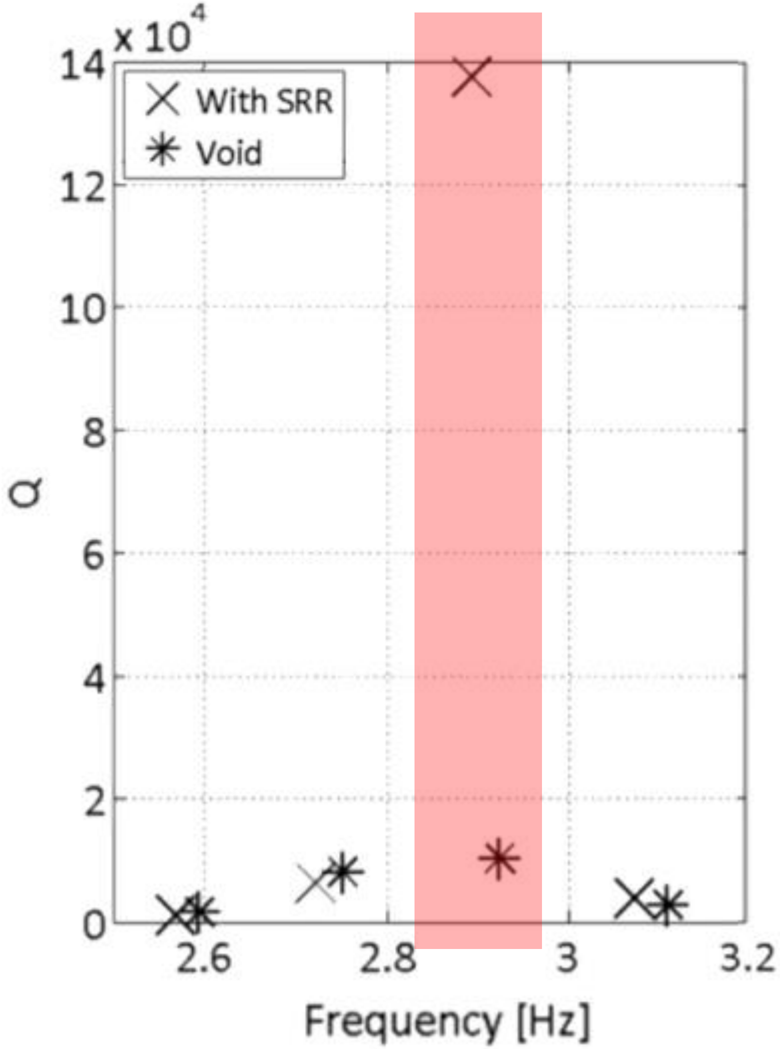
Proof of concept

Results show increase of Q value for 1 mode.

Increase of Q is about 1 order of magnitude.

In terms of equivalent electrical conductivity*, this corresponds to an increase of about 2 orders of magnitude.

Proof of concept is in agreement with theoretical model, predicting decrease of transported surface impedance.



PhD project on metamaterials started on 2023, L. Sito BE-ABP

On-going work: Controlled production and experimental characterization of electromagnetic metamaterials which will allow further experimental exploration of the metaconductive regime

*equivalent conductivity seen by the electromagnetic field, dependent on the transported impedance at the metamaterial-air interface.

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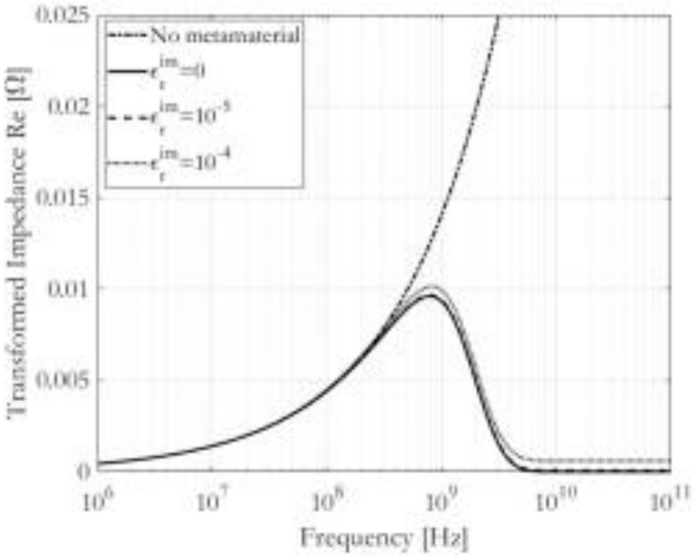
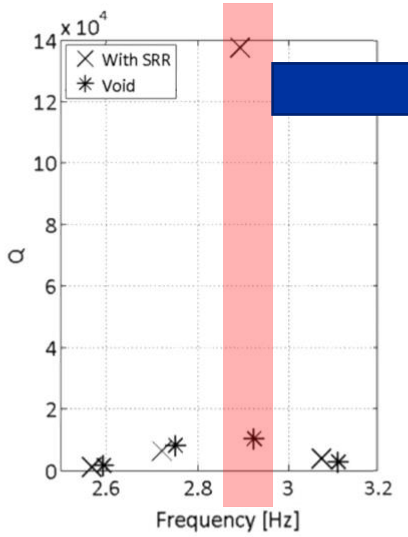
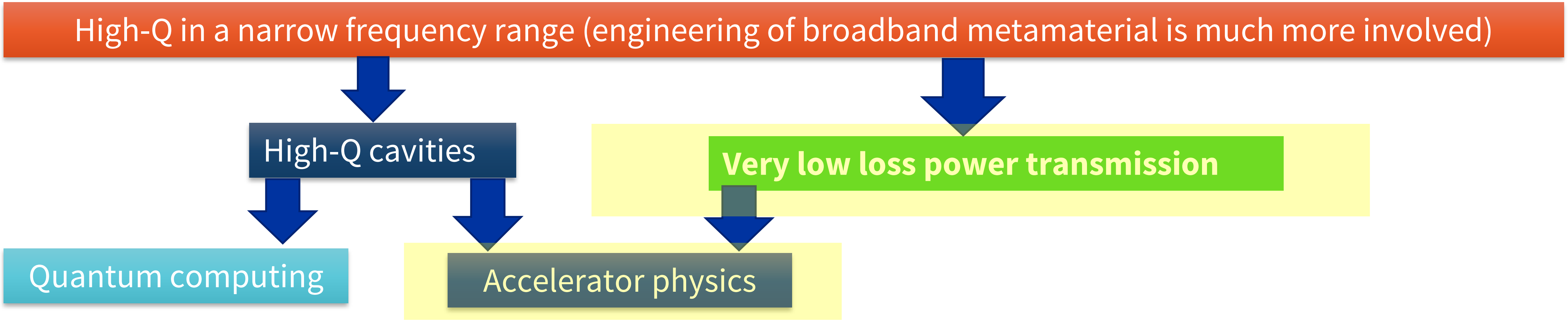
Possible applications for sustainable accelerators





Reduction of transmission power losses of one order of magnitude with respect to Copper waveguides

Factor 100 on conductivity ($\sigma_{eq} \approx 6 \times 10^9$)
Significantly higher than Copper electrical conductivity at cryogenic temperatures



High-Q in a narrow frequency range (engineering of broadband metamaterial is much more involved)

High-Q cavities

Very low loss power transmission

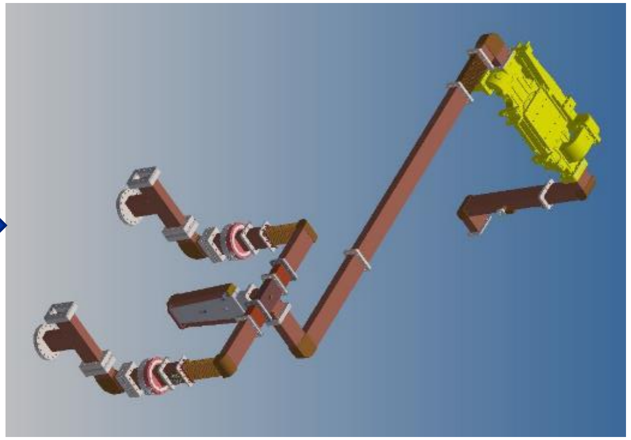
Quantum computing

Accelerator physics

Possible applications for sustainable accelerators

Very low loss power transmission

Where?



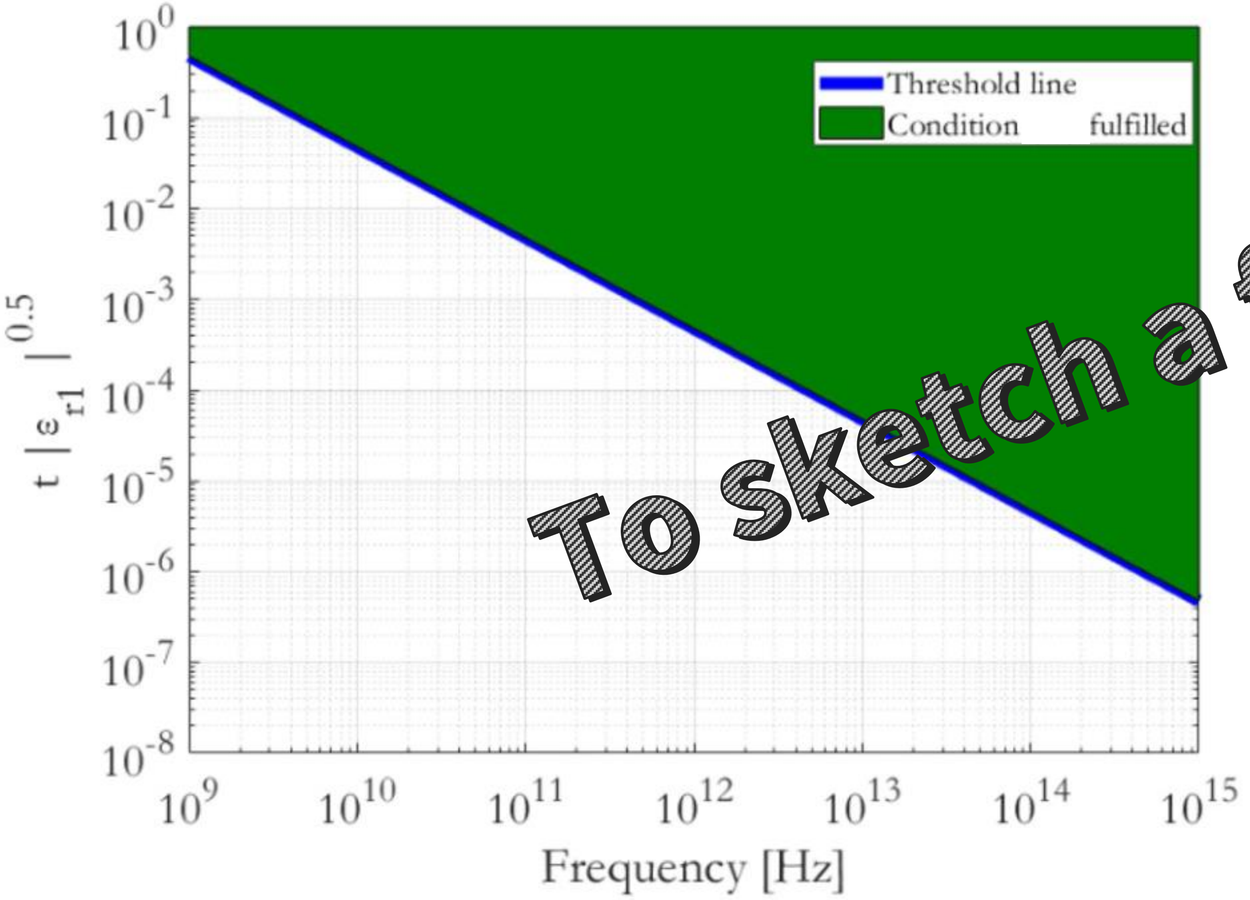
- Feeding waveguides for future colliders can be 100s meters long (or more)
- RF losses on these feeding WGs can be high and bring to energy inefficiency
- Metamaterials have shown the possibility to investigate on insertions to significantly reduce RF losses

Metamaterials can be studied as a future option for feeding WGs

Improved accelerator's sustainability

Possible applications for sustainable accelerators

A practical example



To sketch a first idea

$$t\sqrt{|\varepsilon_{r1}|} \geq \frac{10c}{\omega_0\sqrt{|\mu_{r1}|}}$$

$f_0 = 12\ \mathrm{GHz}$

$t\sqrt{|\epsilon_r|} \geq 0.04$

$t = 5\ \mathrm{mm}, \quad \epsilon_r = -64$

These values are needed to be well above the metaconductive transition. Might be fulfilled even with much lower t, ϵ_r if operational frequency is admitted to be closer to the metaconductive transition

Conclusions

- ❑ **Metamaterials are interesting composite materials showing negative constitutive parameters.**
- ❑ **Insertions of metamaterials have been analytically modelled with a transmission-line equivalence.**
- ❑ **They have shown to dramatically reduce the surface impedance of a conductor, when applied on the same, above a transition frequency.**
- ❑ **A first proof of concept has shown positive results.**
- ❑ **Possible applications in accelerators include: high-Q cavities, very low loss propagation in waveguides.**
- ❑ **Sustainability of accelerators could be significantly improved with adequate research on employment of metamaterials for RF waveguides, with the aim to drastically reduce power consumption**

Ongoing works / Plans for the near future:

- Controlled design, fine-tuning and production of metamaterials.
  - Focus on substrate materials (AlN, Al2O3) and compatibility for high power and vacuum.
  - Experimental validation of the engineered metamaterial properties.
- Investigation on accelerator physics applications
  - Very low loss power transmission waveguides
  - High-Q cavities (interesting also for quantum computing)
  - Beam-Coupling Impedance mitigation

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Metamaterial disclaimer

"Passive metamaterials […] are anyway made from usual materials like metals or dielectrics. On the microscopic level, the stored energy is the EM field energy in the substrate and inclusions. This energy is strictly a **non-negative** function. The energy stored in a sample of the effective medium is the average of the corresponding microscopic quantities, and there is no reason to expect that […] the effective material will store negative energy"

S. A. Tetryakov, S. I. Maslovski
"Veselago Materials: what is possible and impossible about the dispersion of the constitutive parameters"
IEEE Antenna & Propagation Magazine, vol. 49, no. 1, Feb. 2007.