Développement et validation d'une métasurface acoustique orientable large bande composée de résonateurs électroacoustiques actifs

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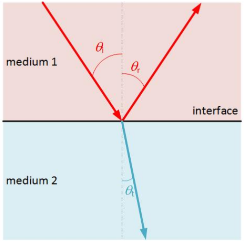
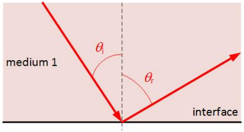
Acoustic metasurfaces

Principle :
Interfaces breaking the Snell-Descartes laws of refraction.

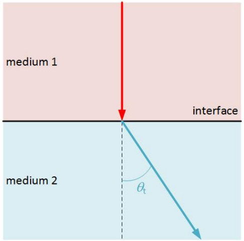
Snell-Descartes



Anomalous reflection

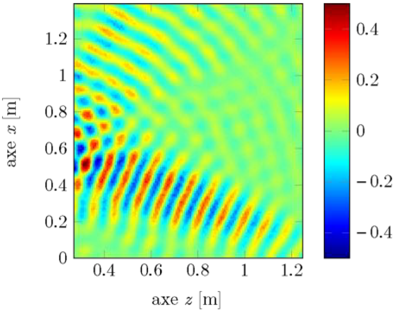


Anomalous transmission

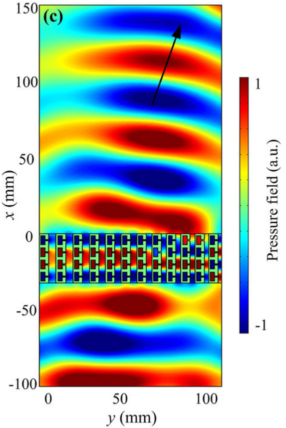


Acoustic metasurfaces

State of the art :



C. Faure et al, Applied Physics Letters 108, 064103 (2016)

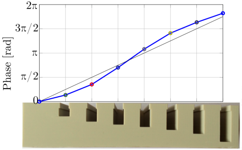


J. Lan et al, Scientific Reports 7, 10587 (2017)

Acoustic metasurfaces

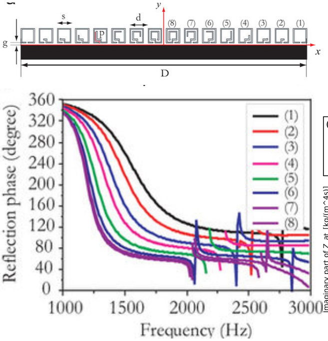
State of the art : Realizations

Helmholtz resonators



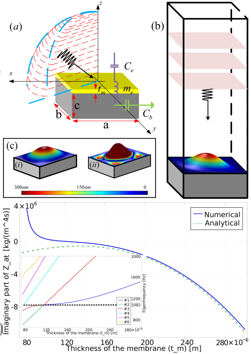
C. Faure et al, Applied Physics Letters 108, 064103 (2016)

Labyrinthine-path ("space coiling")



K. Song et al, Scientific Reports 94, 014302(2016)

Membrane resonators

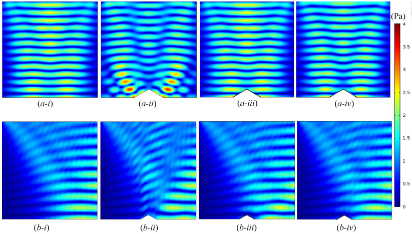


H. Esfahlani et al, Physical Review B 6, 32300 (2016)

Acoustic metasurfaces

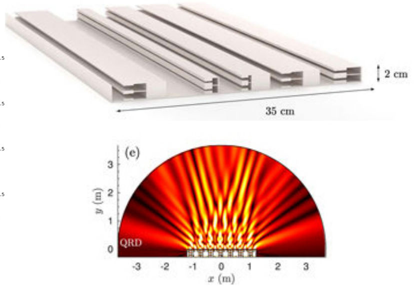
State of the art : Applications

Cloaking



H. Esfahlani et al, Physical Review B 6, 32300 (2016)

Sound diffusion



N. Jimenez et al, Scientific Reports 7, 5389 (2017)

Motivations

- Reconfigurability
  Passive designs only allow for fixed reflection (resp. transmission) characteristics.
  No possibility to reconfigure them on-the-fly.

- Broadband properties
  The reported (passive) concepts rely on resonant behaviours (labyrinthine, Helmholtz resonators, membranes-based resonators, etc.).
  The achieved properties only hold around a prescribed frequency, with narrow-band efficiency.

- Lossless reflection (resp. transmission)
  Acoustic resonators generally yield a certain amount of losses, that lower the reflection (resp. transmission) efficiency.
  Difficulties to ensure total reflection (resp. transmission) on passive metasurface.

→ active concepts

Metasurface principle

Proposed geometry of Acoustic Metasurface (reflection)

2D arrangement of $M \times N$ small vibrating circular pistons of same radius r_d.

Subwavelength condition : $2r_d < \frac{\lambda}{10}$, where $\lambda = \frac{c_0}{2\pi f}$ is the wavelength and $c_0 = 343\text{m.s}^{-1}$ the sound celerity in the air.

$\rightarrow$ maximum radius of 34 mm up to 500 Hz.

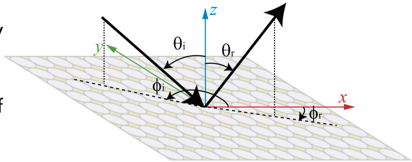
Each piston presents an individual reflection coefficient $\Gamma_{m,n}(f) = A^{mn}(f)e^{j\Psi^{mn}(f)}$.
Assuming $A^{mn}(f)$ is the same $\forall(m,n)$

Anomalous reflection condition :

Incident harmonic plane wave (frequency f)

Incident angle (θ_i, ϕ_i).

$\rightarrow$ Anomalous reflected angle (θ_r, ϕ_r) if (Generalized Snell-Descartes law) :

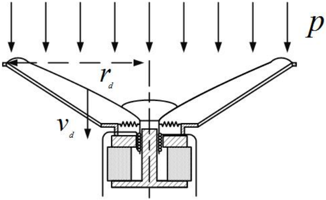


$$\Psi^{mn} = \psi_0 - \frac{2\pi f}{c_0}(2r_d)\left[m(\sin\theta_r\cos\phi_r + \sin\theta_i\cos\phi_i) - n(\sin\theta_r\sin\phi_r + \sin\theta_i\sin\phi_i)\right]$$

ψ_0 : phase reference over the metasurface (eg. central cell)

Membrane resonator unit-cell

Unit-cell : loudspeaker diaphragm (SDOF mechanical resonator)



Acoustic specific impedance :

$$Z_{as}(\omega) = \frac{1}{S_d}\left(j\omega M_{ms} + R_{ms} + \frac{1}{j\omega C_{ms}}\right)$$

M_{ms} : moving mass,

Rms : mechanical resistance,

Cms : mechanical compliance,

Sd : diaphragm area

Unit-cell size $\ll \lambda$

$\rightarrow$ reflection coefficient independent on (θ_i, ϕ_i) :

$$\Gamma(\omega) = \frac{(R_{ms} - S_d Z_c) + j\left(\omega M_{ms} - \frac{1}{\omega C_{ms}}\right)}{(R_{ms} + S_d Z_c) + j\left(\omega M_{ms} - \frac{1}{\omega C_{ms}}\right)} = \frac{-\left(\frac{f}{f_s}\right)^2 + j\left(\frac{f}{f_s}\right)\frac{1}{Q_s}(1 - \frac{1}{r_s}) + 1}{-\left(\frac{f}{f_s}\right)^2 + j\left(\frac{f}{f_s}\right)\frac{1}{Q_s}(1 + \frac{1}{r_s}) + 1}$$

$Z_c = \rho_0 c_0$ with $\rho_0 = 1.2\text{kg.m}^{-3}$

$$r_s = \frac{R_{ms}}{S_d Z_c}$$

$$f_s = \frac{1}{2\pi\sqrt{M_{ms} C_{ms}}}$$

$$Q_s = \frac{1}{R_{ms}}\sqrt{\frac{M_{ms}}{C_{ms}}}$$

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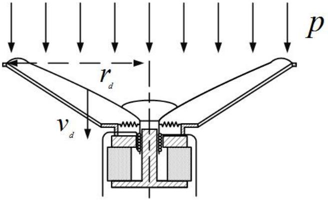

Unit-cell size « λ

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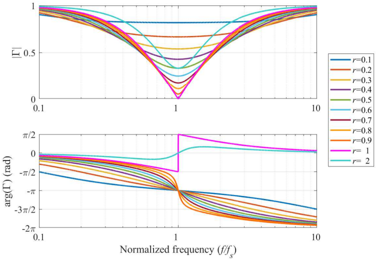
Fixed $Q_s = 1$



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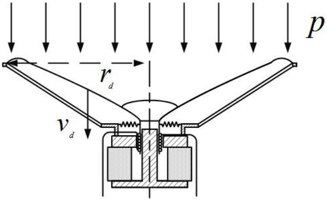

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Unit-cell size « λ

→ reflection coefficient independent on (θ_i, ϕ_i) :

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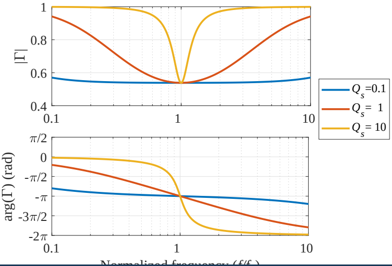
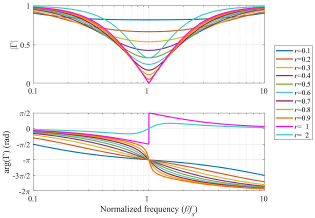
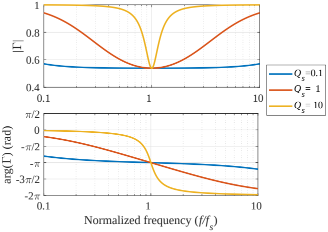
Fixed $r_s = 1/3$



(passive) design guidelines





In order to ensure desired reflection properties still hold over a significant frequency bandwidth around the natural frequency of the loudspeaker, we need to set the resistance and quality factor of the (passive) loudspeaker diaphragm.

It yields :

$r_s \in [0.3 - 0.6] \rightarrow R_{ms} \approx \frac{S_d Z_c}{2}$

$Q_s \in [1 - 10]$

Selected loudspeaker : MONACOR SPX-30M

Parameter	Symblol	Value	Unit
Effective piston area	S_d	32	cm^2
Effective piston radius	r_d	32	cm
Mechanical mass	M_{ms}	3.17	g
Mechanical resistance	R_{ms}	0.75	$N.s.m^{-1}$
Mechanical compliance (with enclosure)	C_{mc}	184.10^{-6}	$m.N^{-1}$
Force factor	$B\ell$	3.67	N/A
Resonance frequency	f_s	208	Hz
Loss factor	r_s	0.57	
Quality factor	Q_s	5.5	

Metasurface design strategy

Question : how to impose desired reflection phases Ψ^{mn} at resonance frequency f_s ?

Metasurface design strategy

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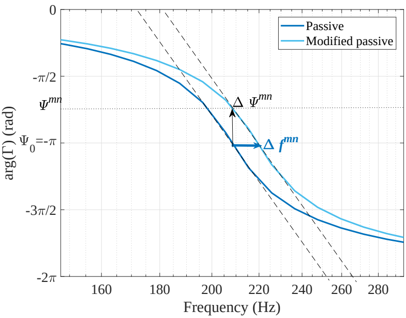
Reflection phase linearly decreases with frequency, turning (almost) from 0 to -2π over a given frequency band (at least one octave around f_s).
If Q_s and r_s are preserved on all unit-cells, a simple resonance shift Δf^{mn} allows assigning prescribed reflection phases Ψ^{mn}.



Target acoustic impedance :

$$Z_{at}^{mn}(\omega) = \frac{1}{S_d}\left(j\omega\mu_M^{mn}M_{ms} + \mu_R R_{ms} + \frac{1}{j\omega\mu_C^{mn}C_{ms}}\right)$$

with

- $Q_s = 6$
- $\mu_R = r_s = \frac{1}{3}$

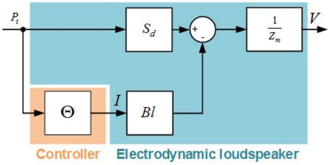
And the control parameters :

- $\frac{f_s + \Delta f^{mn}}{f_s} = \frac{1}{\sqrt{\mu_M^{mn}\mu_C^{mn}}}$
- $\mu_C^{mn} = \frac{1}{2\pi Z_c S_d C_{ms} Q_s}\frac{1}{(f_s + \Delta f^{mn})\mu_R}$
- $\mu_M^{mn} = \frac{Z_c Q_s S_d}{2\pi C_{ms}}\frac{\mu_R}{(f_s + \Delta f^{mn})}$

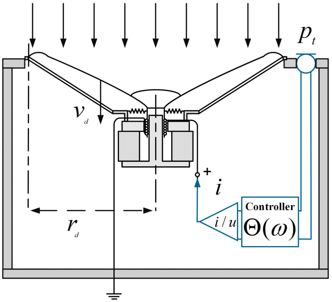
Electroacoustic resonator

Electroacoustic resonator principle

Specific feedforward control :
Microphone-based feedforward control,
through voltage-controlled current amplifier



$$Z_{ms}.V = P_t\left(S_d - B\ell\Theta\right)$$



The effective specific acoustic impedance at the diaphragm then reads :

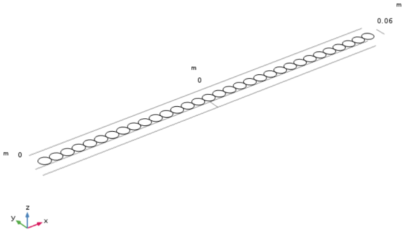
$$Z_a(\omega) = \frac{P_t(\omega)}{V(\omega)} = \frac{Z_{ms}(\omega)}{S_d - B\ell\Theta(\omega)}$$

Strategy : to achieve a target specific acoustic impedance $Z_{at}^{mn}(\omega)$:

$$\Theta^{mn}(\omega) = \frac{S_d Z_{at}^{mn}(\omega) - Z_{ms}(\omega)}{B\ell Z_{at}^{mn}(\omega)}$$

Studied Active Metasurface geometry

To simplify the design, we will only consider a row of the 2D metasurface, made of M=32 unit-cells ($\phi_i = \phi_r = 0$rad)



The mth unit-cell reflection phase, at f_0 shall be :

$$\Psi^m(f0) = \Psi_0 - m\frac{2\pi f_0}{c_0}(2r_d)(\sin\theta_r + \sin\theta_i)$$

with $\Psi_0 = \Psi^{M/2+1}(f_0) = -\pi$

Active metasurface design

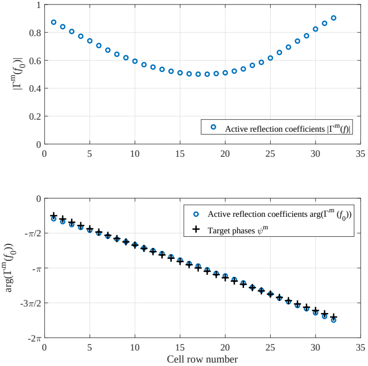
1. choice of the target reflected angle θ_r for a given incident angle θ_i (at central frequency f_0) ;
2. definition of the reflection phase grating $\psi^m(f_0)$ over the metasurface of lattice constant $2r_d$ according to $\Psi^m(f0) = \Psi_0 - m\dfrac{2\pi f_0}{c_0}(2r_d)(\sin\theta_r + \sin\theta_i)$;
3. definition of the reflection phase reference at the $(\mathrm{M}/2{+}1)^{\mathrm{th}}$ cell such as $\arg(\Gamma^{\mathrm{M}/2+1}(f_0)) = -\pi$;
4. identification of the resonance shift $\Delta f^m = f_0 - f^m$ for each cell over the metasurface, so that $\arg(\Gamma^{\mathrm{M}/2+1}(f^m)) = \psi^m$;
5. identification of the control parameters μ_M^m, μ_C^m achieving such resonance shift (with constant $\mu_R = 1/3$) :
   - $\mu_C^m = \dfrac{1}{2\pi Z_c S_d C_{ms} Q_s}\dfrac{1}{(f_0 + \Delta f^m)\mu_R}$
   - $\mu_M^m = \dfrac{Z_c Q_s S_d}{2\pi C_{ms}}\dfrac{\mu_R}{(f_0 + \Delta f^m)}$
6. modification of the acoustic impedance of the m^{th} cell with the controller

$$\Theta_t^m(\omega) = \frac{S_d}{B\ell}\,\frac{(j\omega)^2 M_{ms}\left(\mu_M^m - 1\right) + j\omega(\mu_R S_d Z_c - R_{ms}) + \left(\frac{1-\mu_C^m}{\mu_C^m C_{ms}}\right)}{(j\omega)^2\mu_M^m M_{ms} + j\omega\mu_R S_d Z_c + \frac{1}{\mu_C^m C_{ms}}}.$$

Assessment of the achieved reflection coefficients

Let's consider the case where $\theta_i = -\dfrac{\pi}{4}$ and $\theta_r = \dfrac{\pi}{3}$, and a metasurface composed of 32 unit-cells.

The target reflection phase, at $f_0 = 343Hz$ ($> f_s$), over the 32 unit-cells are :



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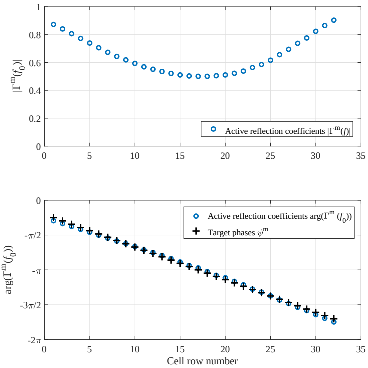
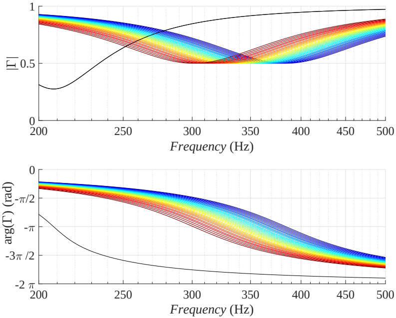
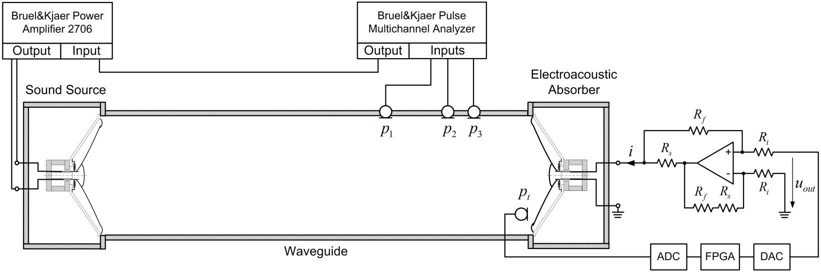


Corresponding reflection coefficient $\Gamma^m(f)$ with corresponding values of μ_M^m and μ_C^m :



Assessment of the achieved reflection coefficients

These settings are achieved experimentally on a MONACOR SPX-30M loudspeaker, and the reflection coefficient for each control case is assessed in an impedance tube :



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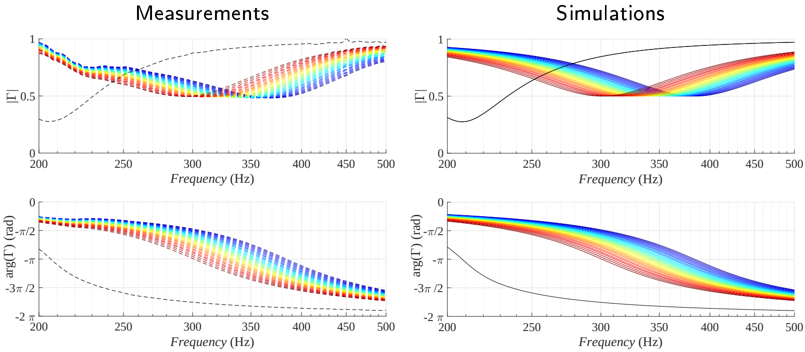
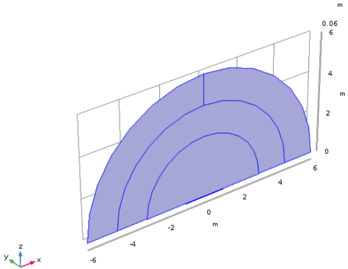
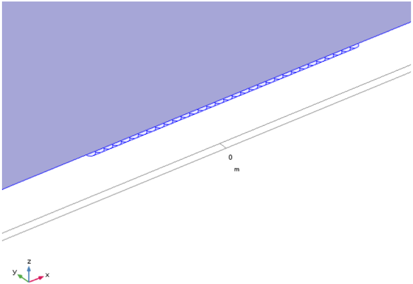


Simulation setting

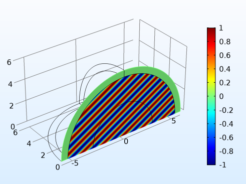
The active metasurface simulation is performed with COMSOL Multiphysics with the Acoustics Module :

- 3D space dimension
- Background plane wave condition, with $\theta_i = -\frac{\pi}{4}$
- cylindrical acoustic domain of radius 6 m, including 1.2m of PML, and a height of $2r_d$=6.4 cm
- 32 unit-cells modelled as Acoustic Impedances with μ_M^m,μ_R and μ_C^m.
- all other surfaces are modelled as "Sound Hard Boundary" (including the two delimiting *xoz* planes)
- Meshing : maximum element size = $\lambda/6$ at 500 Hz.





Sound pressure fields

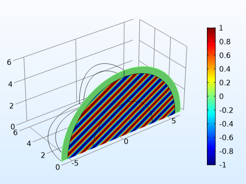


Two simulations cases :

$$\theta_i = -\frac{\pi}{4} \text{ and } \theta_r = \frac{\pi}{3}$$

$$\theta_i = -\frac{\pi}{4} \text{ and } \theta_r = 0 \text{ rad.}$$

Sound pressure fields



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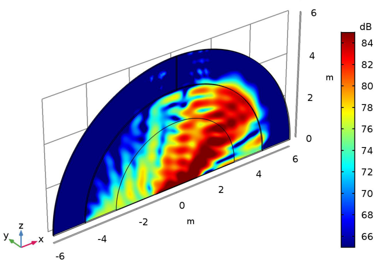

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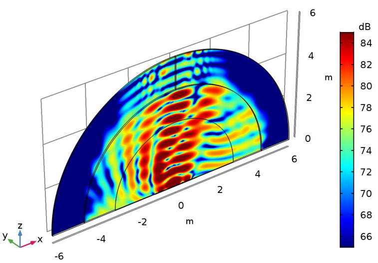
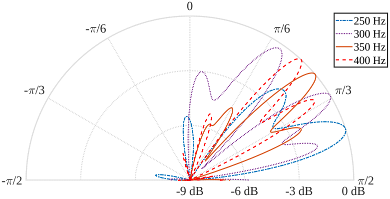


Directivities

Two simulations cases :

$\theta_i = -\frac{\pi}{4}$ and $\theta_r = \frac{\pi}{3}$



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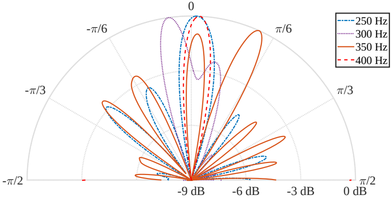

Conclusions

- Active Electroacoustic Resonators allow steering reflected wavefronts in a prescribed manner
- Effective at a central frequency, with relative bandwidth extension (up to one octave)
- Reflected coefficient higher than 0.5
- However, it is not yet possible to scan the full range of reflection phases ($[-2\pi - 0]$)

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Toward wideband steerable acoustic metasurfaces with arrays of active electroacoustic resonators

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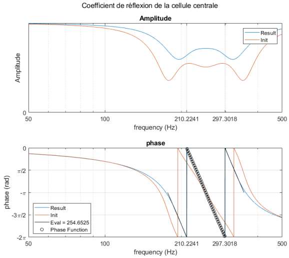
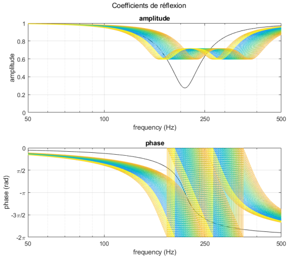
[2]*Laboratory of Wave Engineering (LWE), Ecole Polytechnique Fédérale de Lausanne (EPFL), Station 11, CH-1015 Lausanne, Switzerland*

Perspectives

- Toward broadband reflection properties :
  Design Multiple Degrees of Freedom Electroacoustic Resonators (MDOF, instead of SDOF)





- Realization of an experimental (1D or 2D) prototype for validation of the reflection properties.
- Lowering the losses should allow practical application of the concept.