





Subwavelength Absorbers and Metasurfaces

On the design of perfect absorbers and diffusers

Noé Jiménez[1], W. Huang[1], V. Pagneaux[1], T. Cox[2], V. Romero-García[1], J-P. Groby[1]

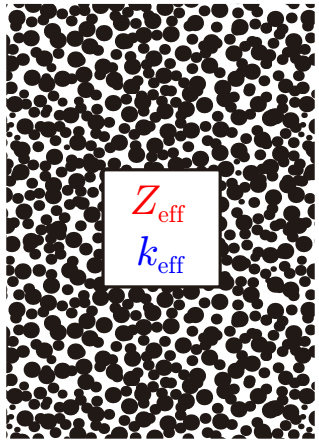
[1] LAUM, UMR CNRS-6613, France
[2] Acoustics Research Centre, University of Salford, UK

COST Action DENORMS Workshop, January 26, 2017, Rome

Introduction

Perfect absorption: rigid backed materials

- Acoustic material with:
  Characteristic impedance Z_{eff} and wavenumber k_{eff}

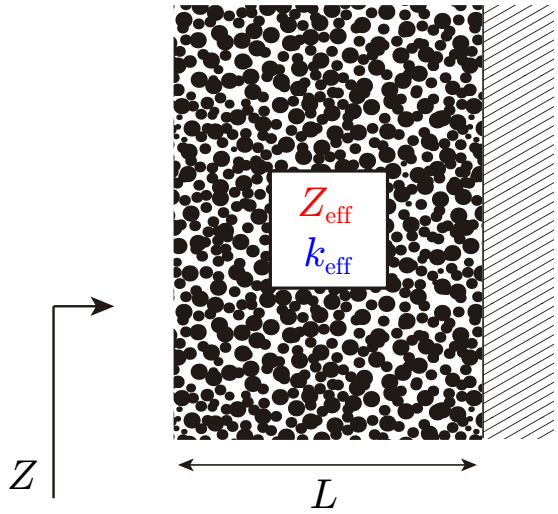


Introduction

Perfect absorption: rigid backed materials

- Acoustic material with:
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- Acoustic impedance for *rigid-backed*:

$$Z(\omega) = -iZ_{\text{eff}} \cot k_{\text{eff}} L$$



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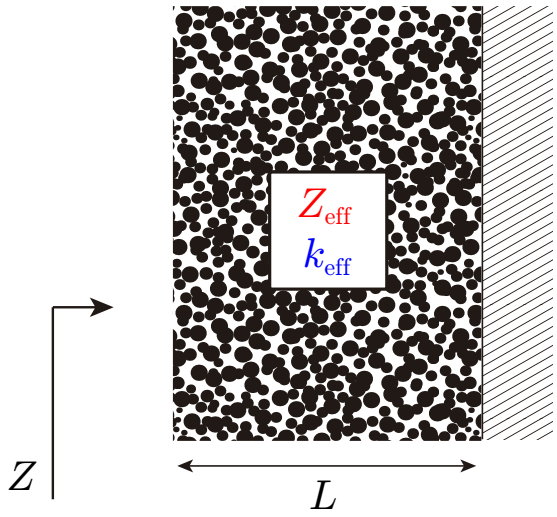
- Reflection:

$$R = \frac{Z(\omega)/Z_0 - 1}{Z(\omega)/Z_0 + 1}, \quad \alpha = 1 - |R^2|$$

- Perfect Absorption:

$$\alpha = 1 \quad \rightarrow \quad \begin{cases} \text{Re}(Z) = Z_0 \\ \text{Im}(Z) = 0 \end{cases}$$

  - Rigid backed problem: **Impedance matching conditions**



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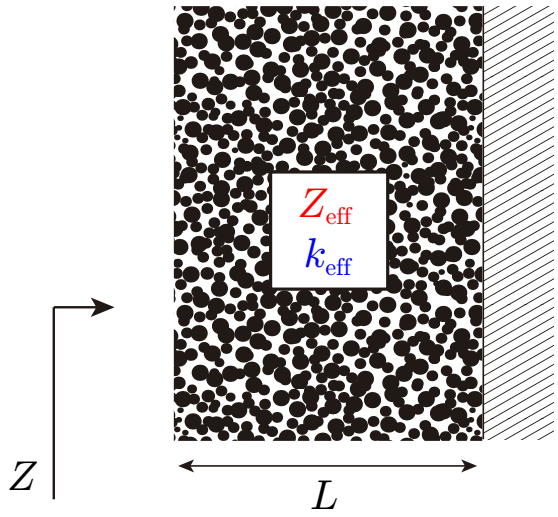
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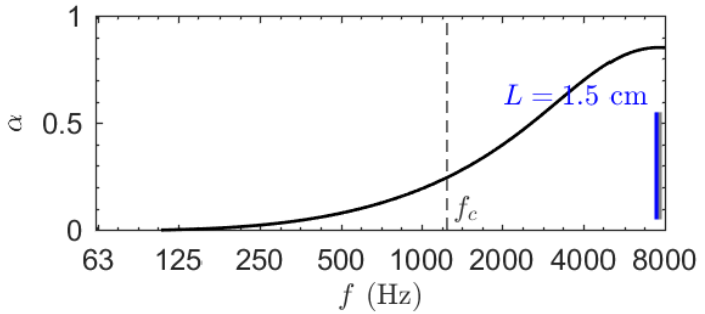
- **Which is the thinnest perfect-absorber we can built?**
  - $\text{Re}\, Z(\omega)$ is in general different from Z_{air}
  - $Z(\omega)$ is generally complex ▶ $\text{Im}(Z) = 0$ at resonance $L = \lambda_{\text{eff}}/4$

Introduction

Example: **Perfect absorption** in a rigid backed porous material

To down-shift the $\lambda/4$ resonance:

1. **Change the thickness**
   - Is it perfect absorption?

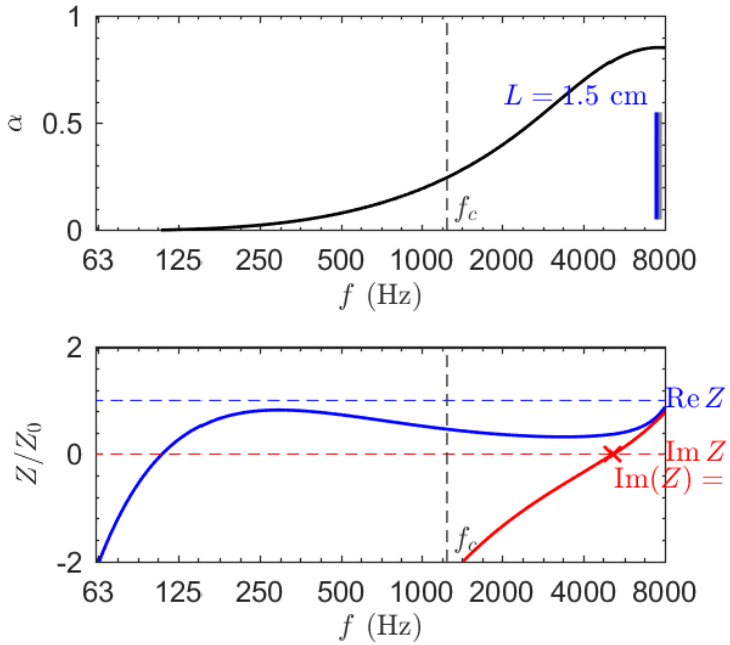


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Example: **Perfect absorption** in a rigid backed porous material

To down-shift the $\lambda/4$ resonance:

1. **Change the thickness**
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2. **Look at the impedance matching**
   - Phase matching can be achieved,
   - For thick panels the $\lambda/4$ resonance enters in the viscous regime



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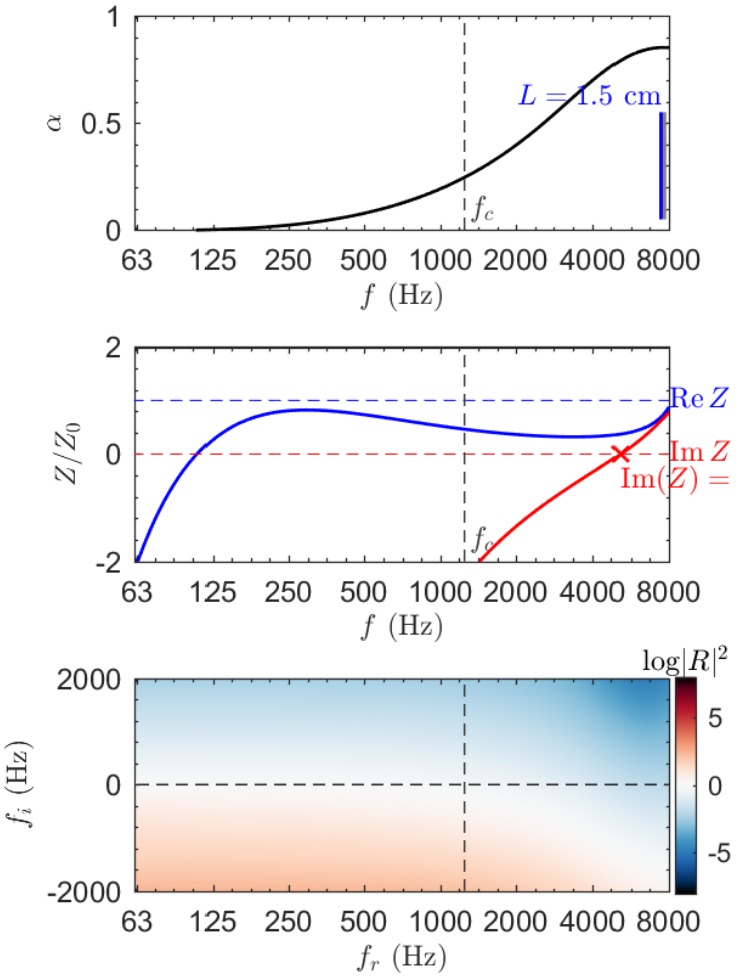
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2. **Look at the impedance matching**
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   - For thick panels the $\lambda/4$ resonance enters in the viscous regime
3. **Look at the scattering matrix:**

$$\boldsymbol{S} = \begin{bmatrix} T & R^{+} \\ R^{-} & T \end{bmatrix} \rightarrow \lambda_{1,2} = |R|$$

   - No scattering for $\lambda_{1,2} = 0$
   - Critical coupling condition
   - The eigenvalues $\lambda_{1,2}$ in the complex plane ...



Introduction

Perfect sub-wavelength absorbers

1. **Perfect absorption**:
   - The system must be critically coupled with the exterior medium
   - General case: $\lambda_{1,2} = 0$
   - Intrinsic losses compensate the energy leakage of the structure
   - Freedom to modify the intrinsic losses of the system

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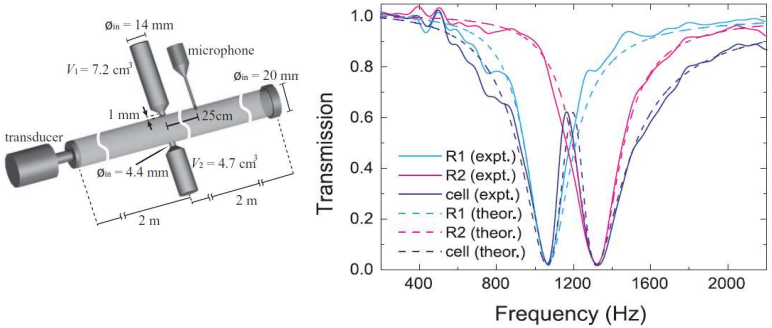
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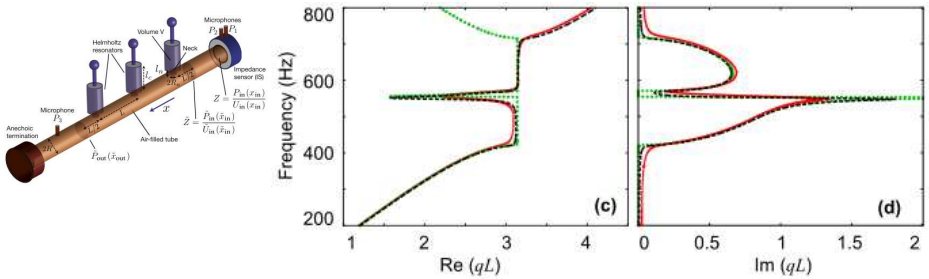
2. **Sub-wavelength resonance**:
   - Use Helmholtz resonators, coiled $\lambda/4$ resonators, membranes, bubbles ...
   - Design sub-wavelength resonators using slow sound metamaterials

Slow-sound absorbers

1 Use of slow sound to design sub-wavelength resonators



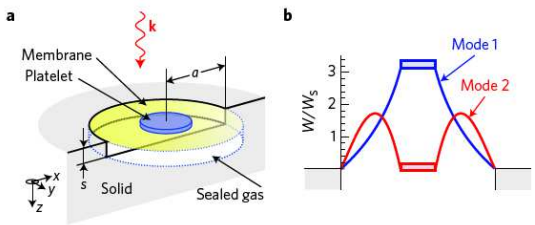
Phys. Rev. B 84, 064304 (2011)



New J. Phys. 16, 093017 (2014)

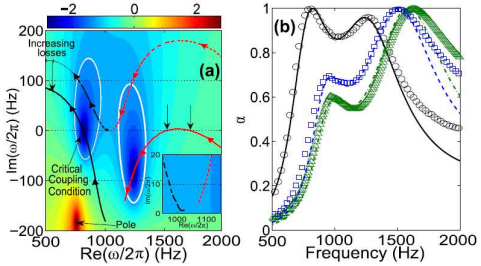
2 Critically coupled sub-wavelength resonators ▶ Reflection problems

▶ Membranes



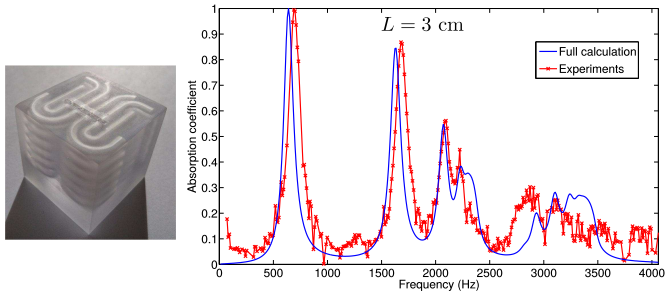
Nature Mat. 13, 813 (2014)

▶ Viscoelastic membranes



Scientific Rep. 15519 (2016)

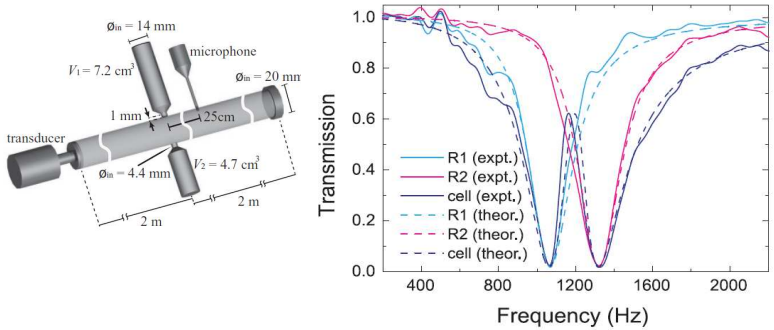
▶ QWR + slow-sound



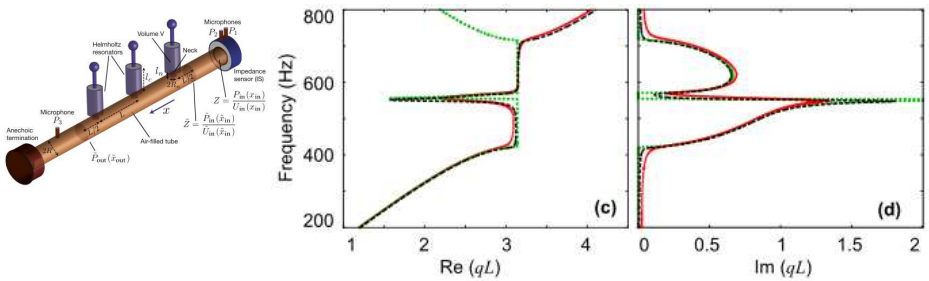
J. Acoust. Soc. Am. 139, 1660 (2016)

Slow-sound absorbers

1 Use of slow sound to design sub-wavelength resonators



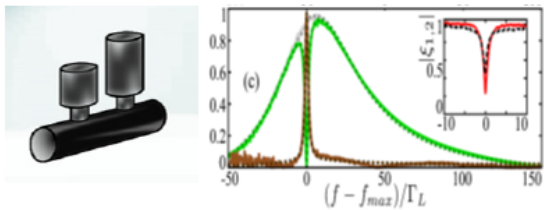
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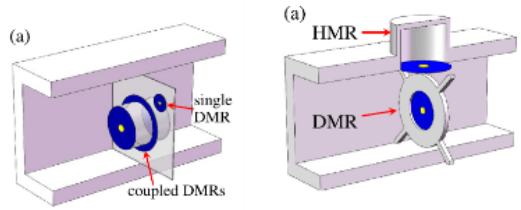
2 Critically coupled sub-wavelength resonators ▶ Transmission problems

- ▶ Double interacting HR



Appl. Phys. Lett. 107, 244102 (2015)

- ▶ Degenerate resonances



Appl. Phys. Lett. 107 104104 (2015)

- ▶ Can we design deep sub-wavelength perfect absorbers for both **reflection** and **transmission** problems?

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1 Reflection

2 Transmission

3 Metadiffusers

4 Conclusions

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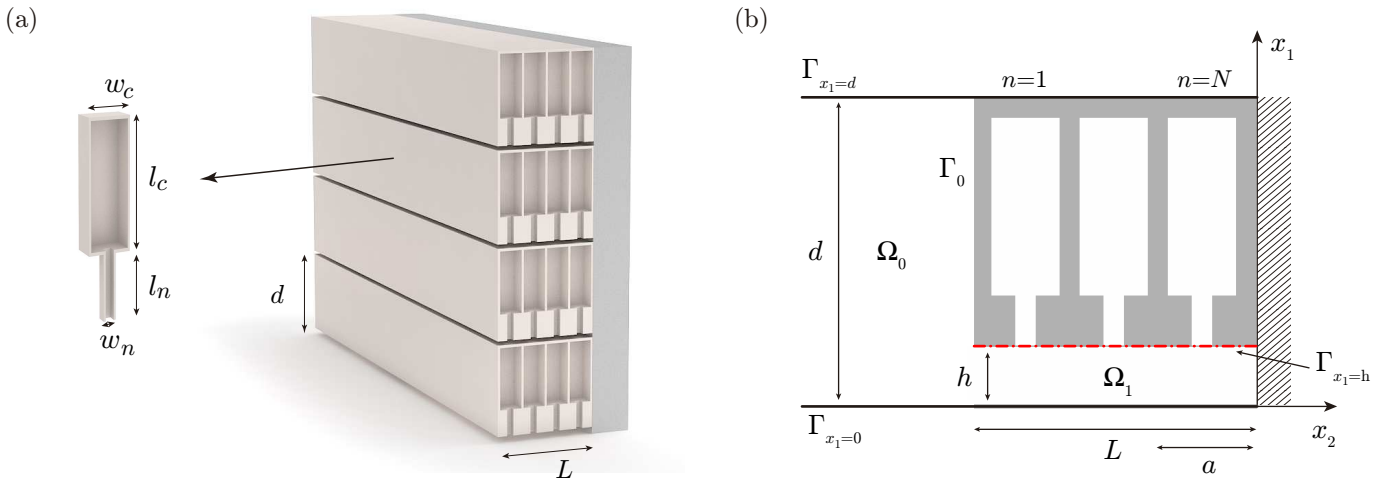
3 Metadiffusers

4 Conclusions

Ultra-thin metamaterial for perfect and quasi-omnidirectional sound absorption

Locally resonant metamaterial:

- Slotted panel loaded by an array of identical Helmholtz resonators [1]
- Thermo-viscous losses can be adjusted by tuning the geometry [2]
- Use **slow-sound** ▶ deep-subwavelength resonator
- Use **critical coupling** ▶ perfect absorption



▶ **What is the thinner perfect-absorber we can built?**

[1] N. Jiménez *et. al.* App Phys Lett 109(**12**) 121902 (2016)
[2] MR. Stinson, J Acoust Soc Am 89(**2**) 550 (1991)

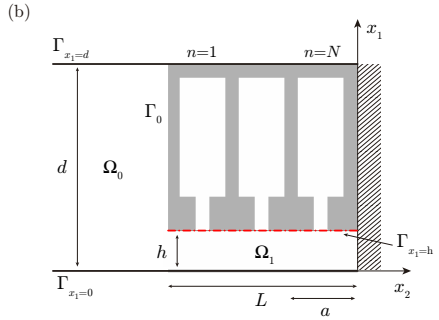
Solution of the problem

1. Modal expansion method (**MEM**):

Bloch waves, $k_{1q}^a = k_1^i + 2q\pi/d$ + modal expansion in the slit

$$p^{[0]} = \sum_{q\in\mathbb{Z}} \cos\frac{q\pi}{d}x_1 \left[A_q^i \delta_q^0 e^{-ik_{2q}^{[0]}(x_2-L)} + R_q e^{ik_{2q}^{[0]}(x_2-L)}\right],$$

$$p^{[1]} = \sum_{q\in\mathbb{Z}} A_q \cos\left(k_{2q}^{[1]}x_2\right)\cos\left(k_{1q}^{[1]}x_1\right),$$



- **Effective parameters** can be derived:

Where $\phi_t = h/d$ and $\phi_n = w_n^2/a^2$

$$\rho_{eff} = \frac{\rho_s}{\phi_t}, \quad \kappa_{eff} = \frac{\kappa_s}{\phi_t}\left[1 + \frac{\kappa_s\phi_n\left(v_c\kappa_n + v_n\kappa_c\right)}{\kappa_n h\left(S_n\kappa_c - v_c\rho_n l_n\omega^2\right)}\right]^{-1},$$

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Accounting for the radiation ("end") correction

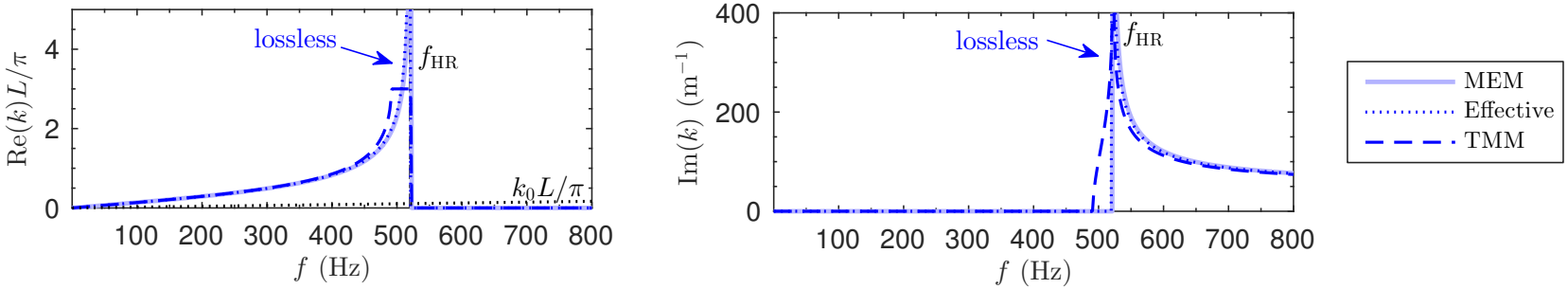
$$\boldsymbol{T} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} = M_{\Delta l}\left(M_s M_{\mathrm{HR}} M_s\right)^N, \text{ with } M_{\mathrm{HR}} = \begin{pmatrix} 1 & 0 \\ 1/Z_{\mathrm{HR}} & 1 \end{pmatrix},$$

3. Finite-Element method (**FEM**) Comsol Multiphysics®
4. **Experimental** validation in impedance tube

Dispersion relations in the slit

Lossless case:

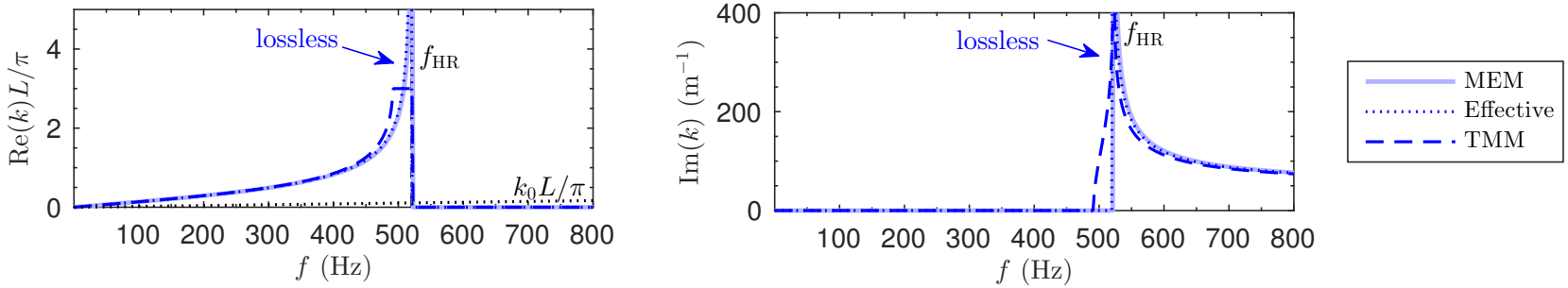
- Band-gap above the resonance of the HRs
- Highly dispersive propagation: slow-sound in the low frequency regime

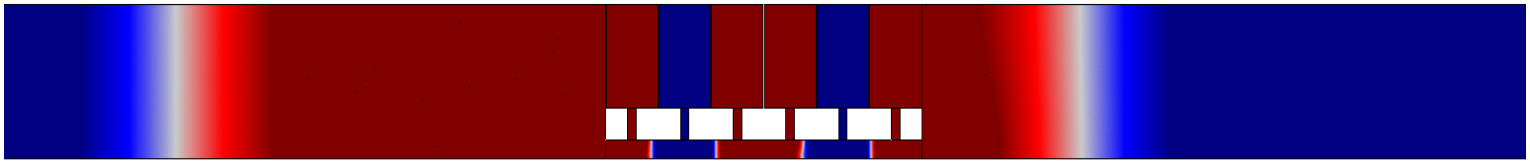


Dispersion relations in the slit

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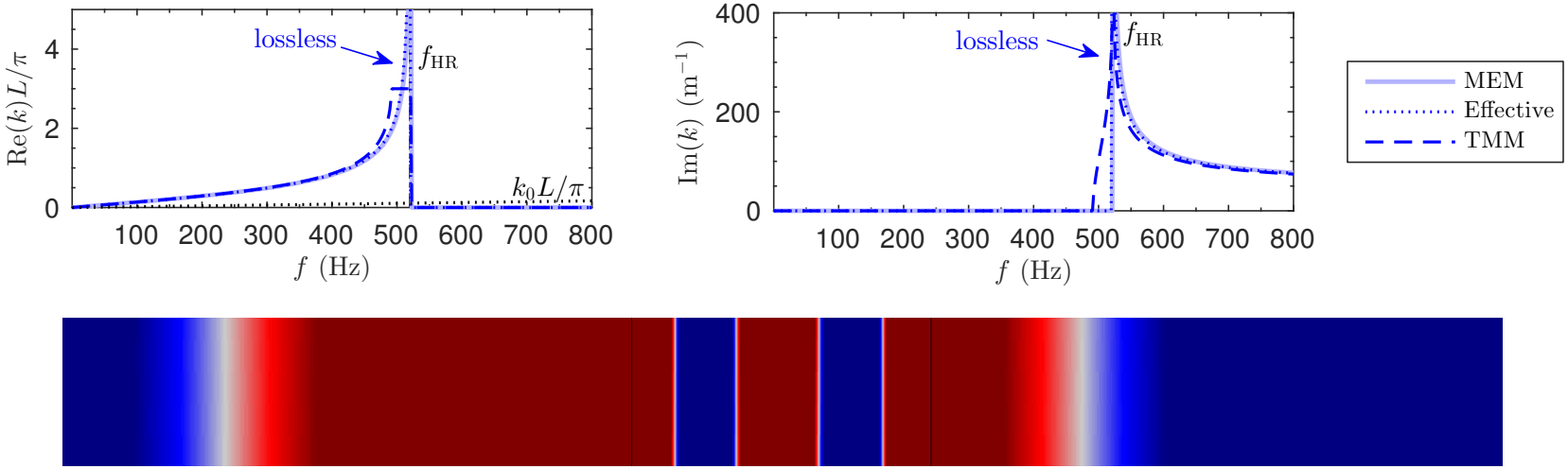




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Lossless case:

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- Cavity modes ($2k_{eff}L/\pi = 1, 3, \ldots$) are down-shifted in frequency
- **The slit behaves as a deep-subwavelength resonator**

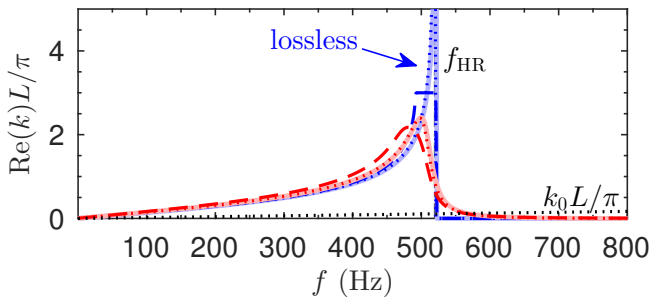
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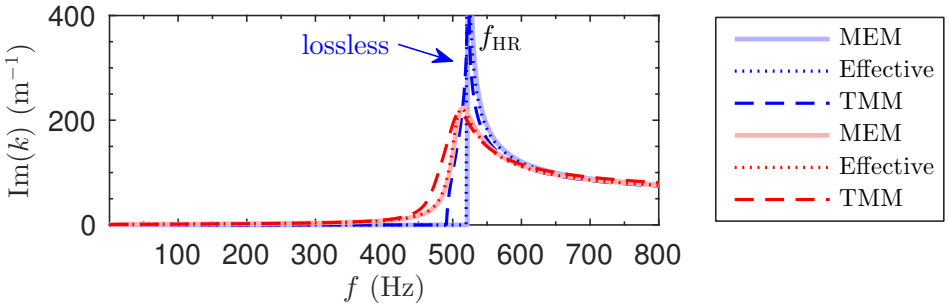
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Lossy case:

- Dissipation limits the minimum slow-sound value
- Tune the losses to compensate the leakage of the structure
- **Critical coupling**

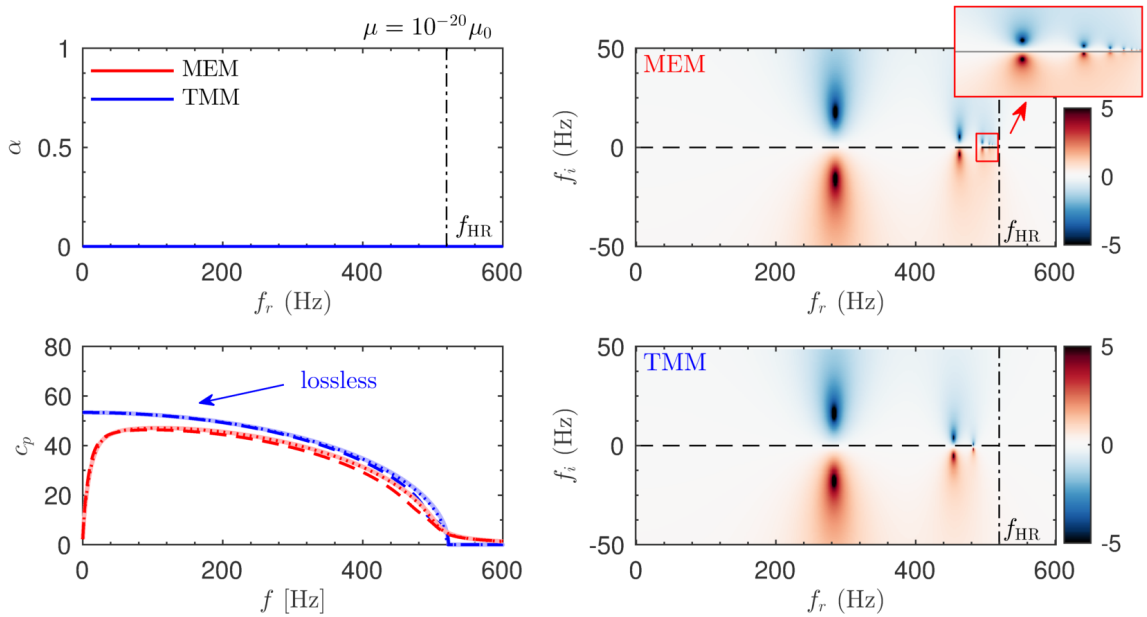




Critical coupling

Panel with $N = 3$ resonators: *complex frequency plane representation of the eigenvalues of the scattering matrix*

- **TMM**: N resonances ▶ n peaks of absorption
- **MEM**: ∞ resonances ▶ overestimate absorption near the band-gap

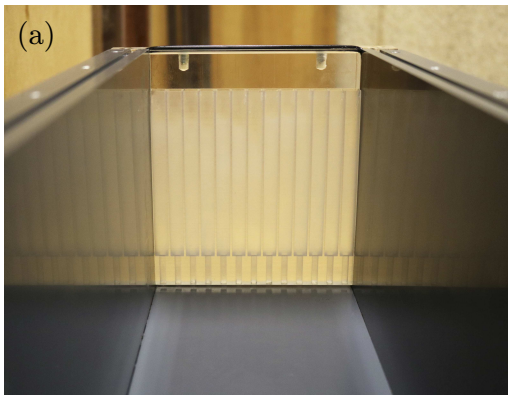


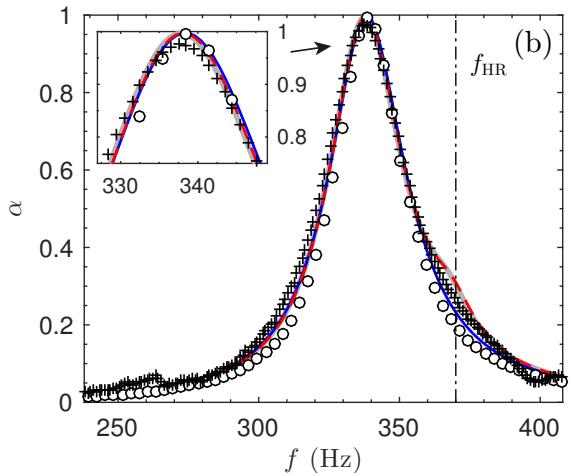
- Which is the **thinner perfect-absorber** we can build?

Ultra-thin panel

- Use optimization to design deep-subwavelength absorber, $f = 350$ Hz
- Experimental validation of a 3D printed panel
- Thickness $L = \lambda/86$, ($L = 1$ cm) (around $\lambda/100$ with thinner walls)







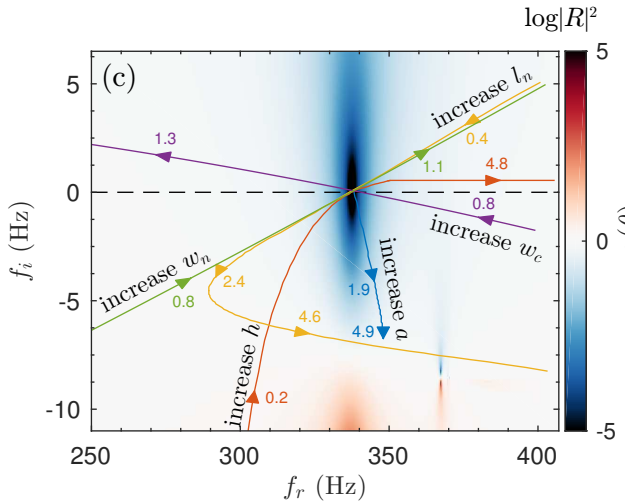
- Is the absorption really perfect?

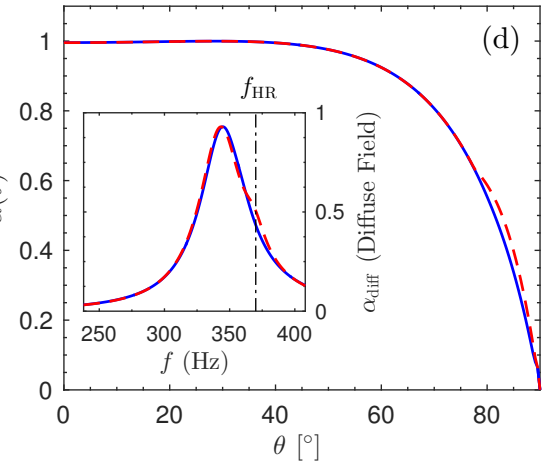
Perfect and quasi-omnidirectional sound absorption

- *Is the structure critically coupled?*
  Check the trajectory of the zero when geometry changes

- *How it behaves at oblique incidence angles?*
  Deep sub-wavelength feature leads to quasi-omnidirectional behaviour







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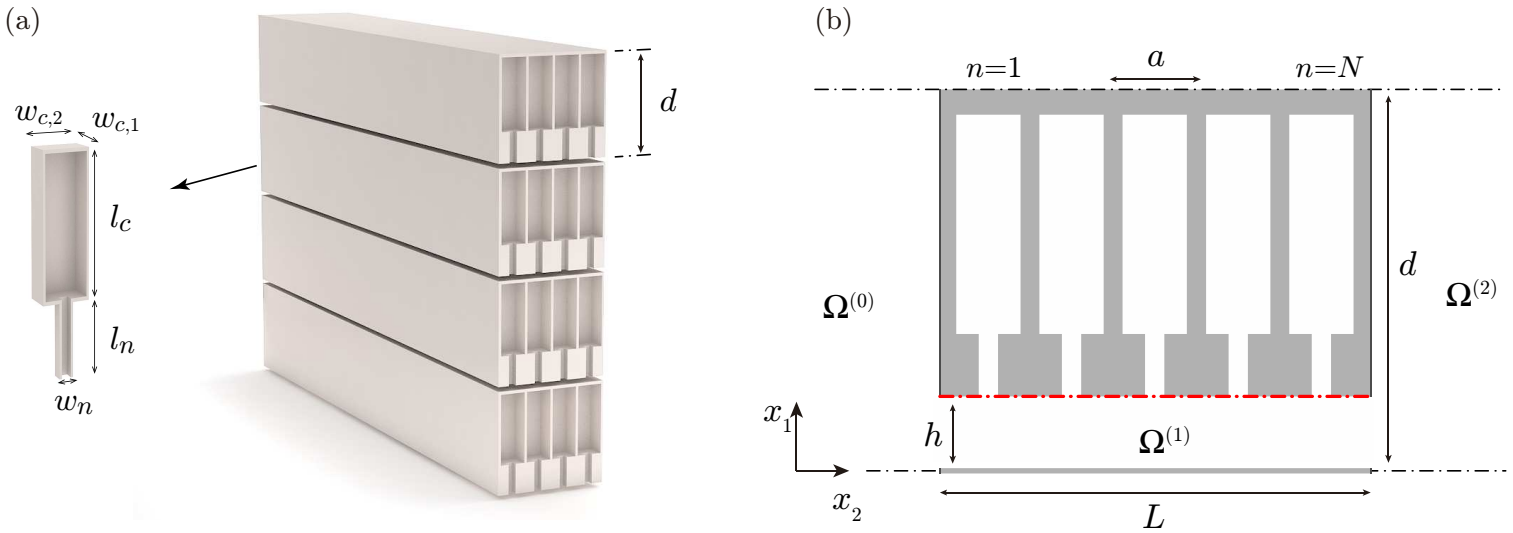
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Configuration

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- Explore the limits of absorption in sub-wavelength panels in transmission using monopolar resonators [1]

[1] Jiménez *et al.*, Physical Review B 95, 014205 (2017)

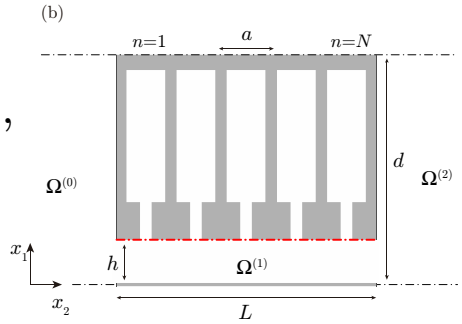
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$$p^{[2]}(\boldsymbol{x}) = \sum_{q\in\mathbb{Z}} T_q e^{\mathrm{i}k_{1q}^a x_1 - \mathrm{i}k_{2q}^a x_2} \ .$$



- **Effective parameters** can be derived:

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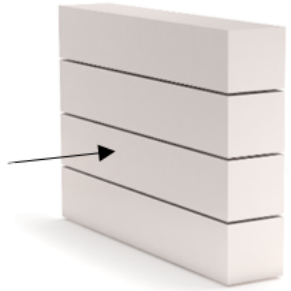
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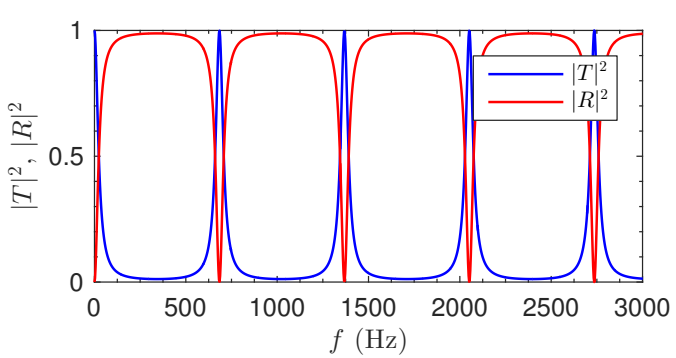
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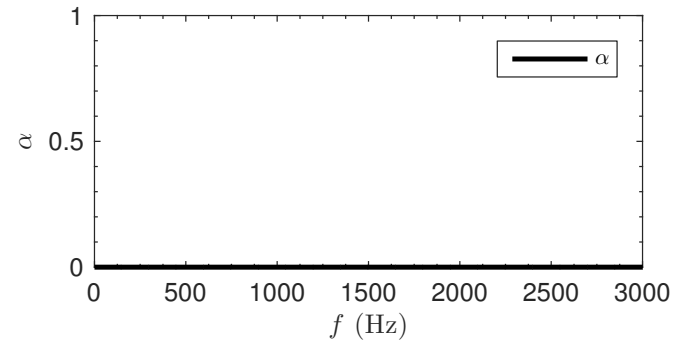
Simple slit

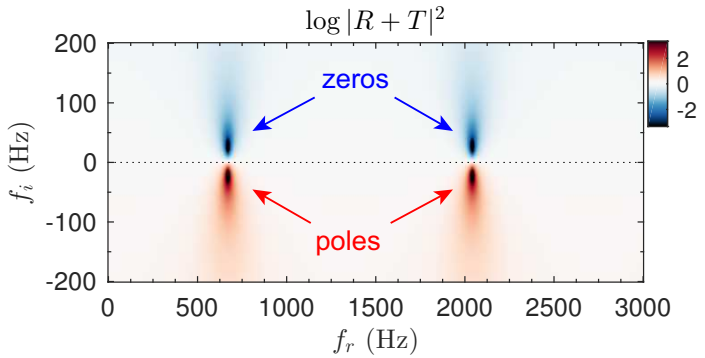
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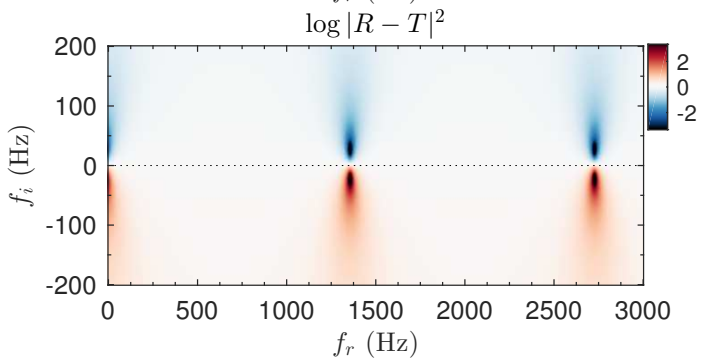


- Fabry-Pérot modes: perfect transmission / reflection
- Two eigenvalues $\lambda_{1,2}$
- Zeros of $|R-T|$ and $|R+T|$ are staggered in frequency







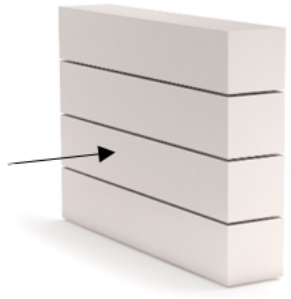


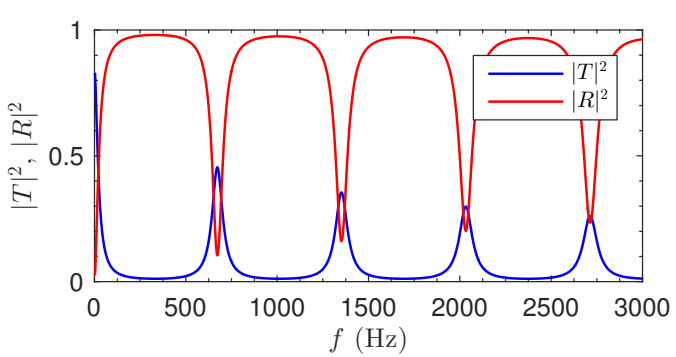
Slit: $h = 3.8$ mm, $L = 25$ cm, $d = 15$ cm

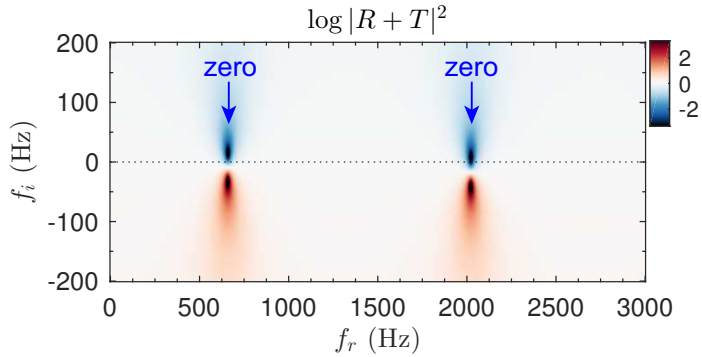
Simple slit

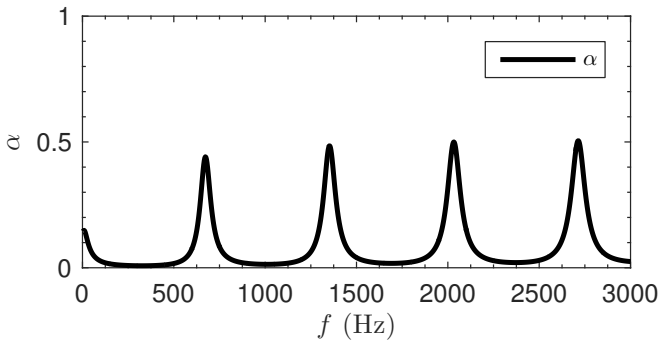
Introduce thermoviscous losses:

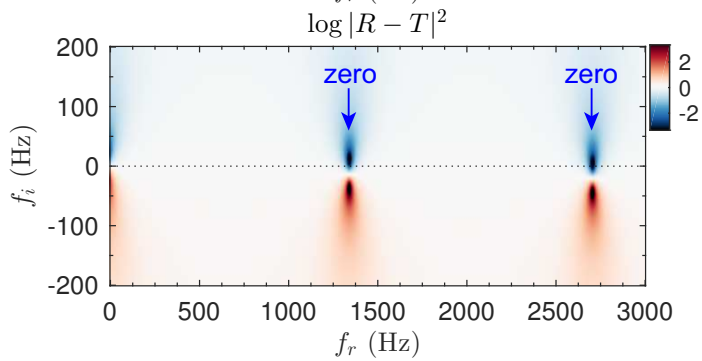
- Absorption at Fabry-Prot resonances
- Zeros of $|R-T|$ and $|R+T|$ are staggered in frequency $\alpha = (\alpha_{\text{sym}} + \alpha_{\text{asym}})/2$, so $\alpha_{\max} \geq 0.5$









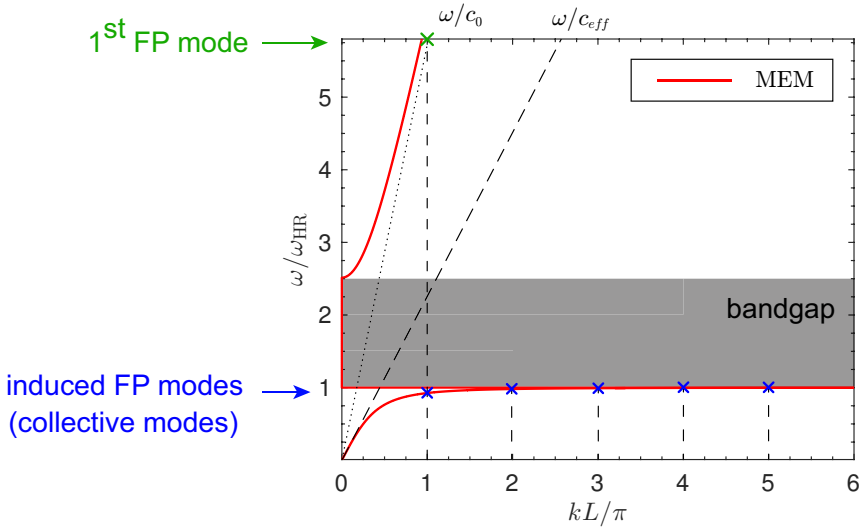


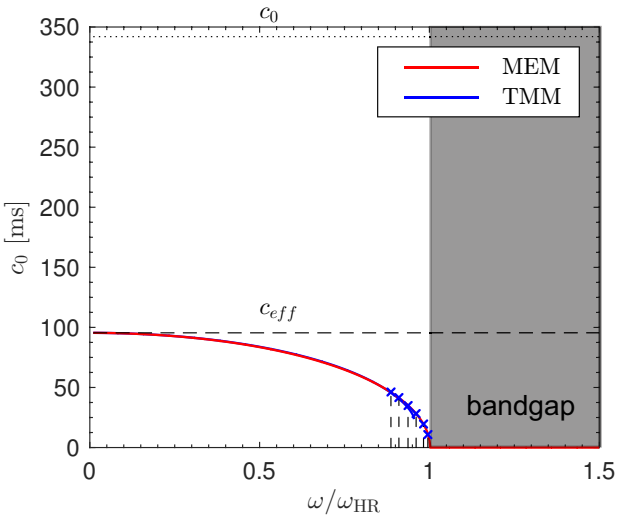
- Use slow sound to accumulate the resonances for sound absorption

Introduce Resonators

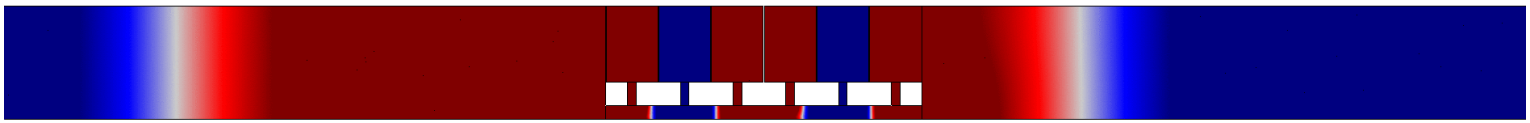


- **Strong dispersion:** *resonances accumulate* below ω_{HR}
  - ▶ Low frequency Fabry-Pérot ▶ collective modes of the resonators





- **Slow sound:** The slit becomes a *deep-subwavelength resonator*:



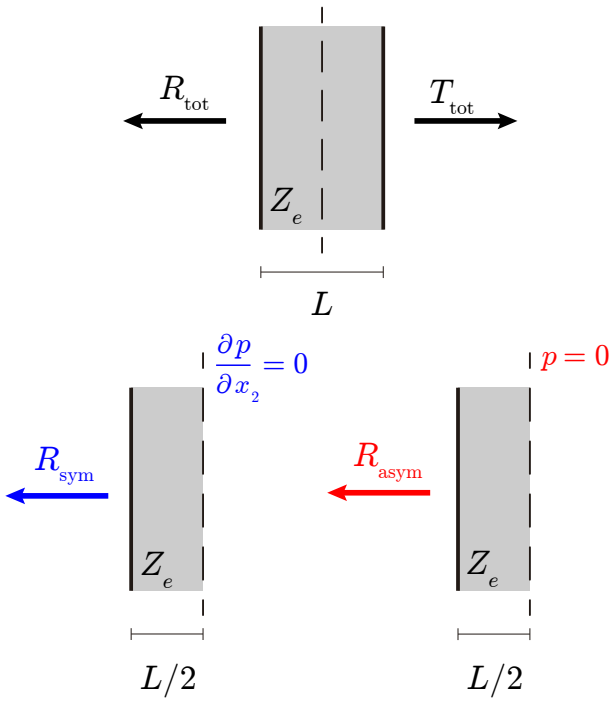
Case a): Large number of resonators

Slab of equivalente material

1. For symmetric system $R^+ = R^-$ the **Scattering matrix** leads to

$$\boldsymbol{S} = \begin{bmatrix} T & R^+ \\ R^- & T \end{bmatrix} \rightarrow \lambda_{1,2} = \begin{cases} |R+T| = |R_{\text{sym}}| \\ |R-T| = |R_{\text{asym}}| \end{cases}$$

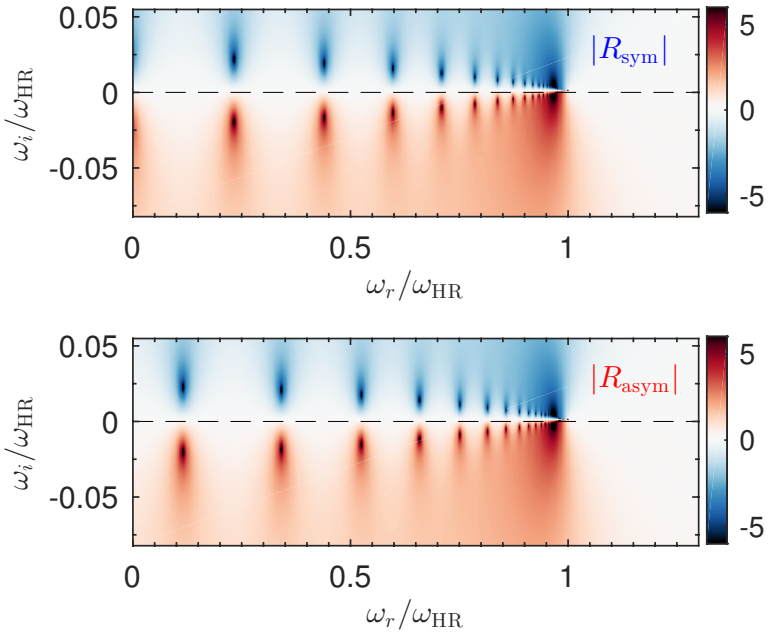
2. Decompose the problem: symmetric and anti-symmetric



Case a): Large number of resonators

Slab of equivalente material

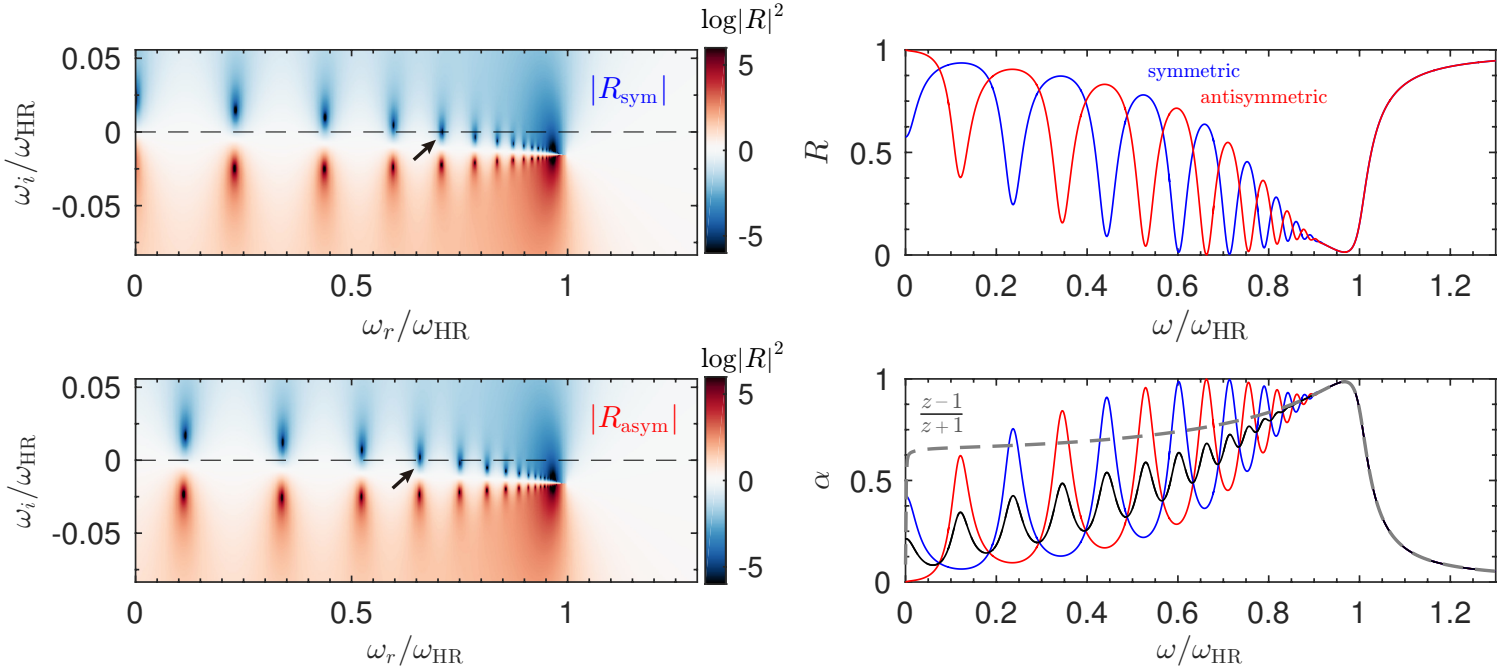
3 Accumulation of resonances, **lossless case** ($N = 30$)



Case a): Large number of resonators

Slab of equivalente material

4 Accumulation of resonances, **lossy case** ($N = 30$)



5 Accumulation point corresponds to impedance matching condition,
- **Perfect absorption is impossible** because $\mathrm{Im}(Z_{\mathrm{eff}}) \neq 0$ and $R_{\mathrm{sym}} \neq R_{\mathrm{asym}}$

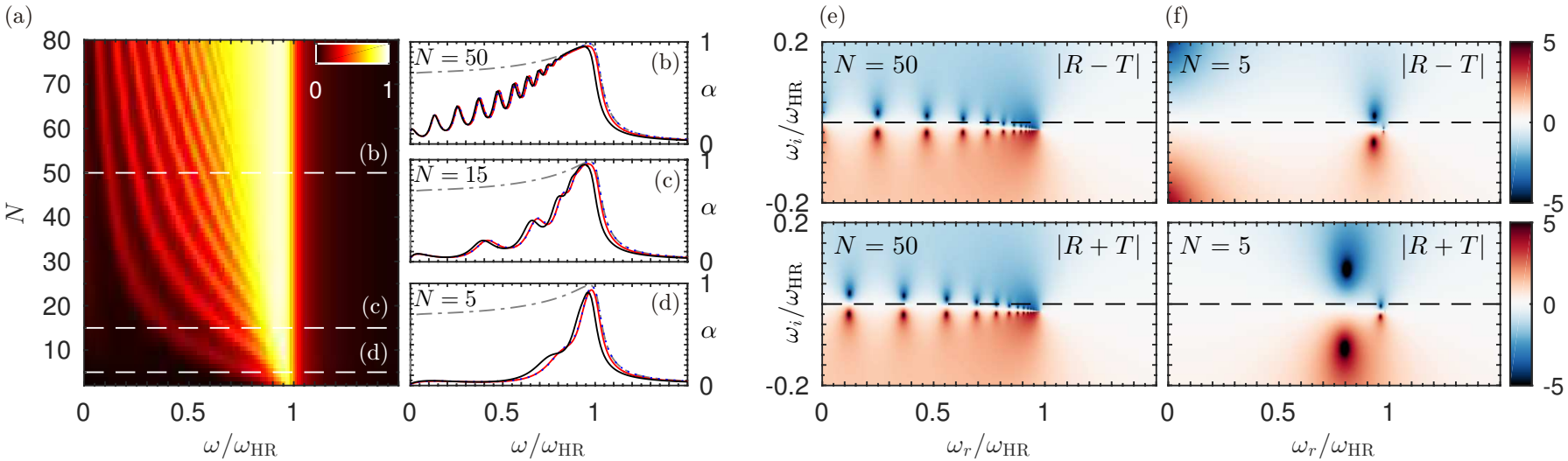
6 Accumulation point: $T \approx 0$ (entrance of the band gap) and $R \approx 0$ (Fabry-Pérot)
- Due to strong dispersion, ***quasi*-perfect absorption is observed**

Case b): Finite number of resonators

Looking for subwavelength thickness structures...

How thin can be the material?

- The number of resonances is equal to the number of resonators
  - Discreteness **reduce the accumulation** of resonances!
- Compromise between absorption and number of resonators
  - Even with $N = 10$ resonators *quasi*-perfect absorption is observed

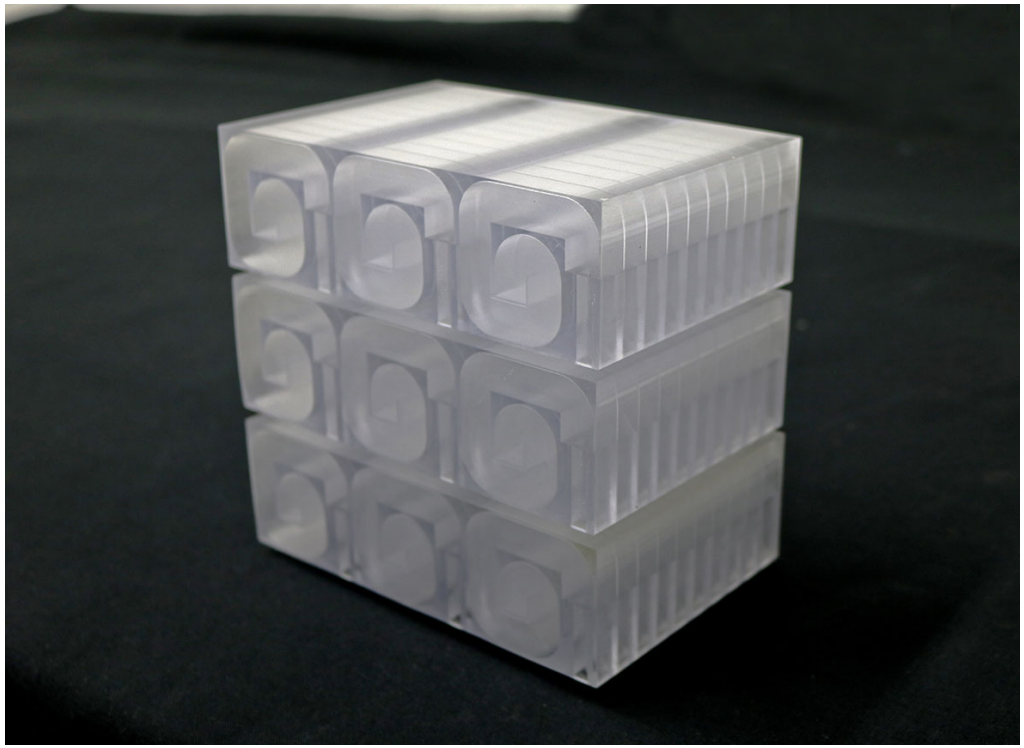


- **Modes still staggered but strong dispersion stretches them below** ω_{HR}

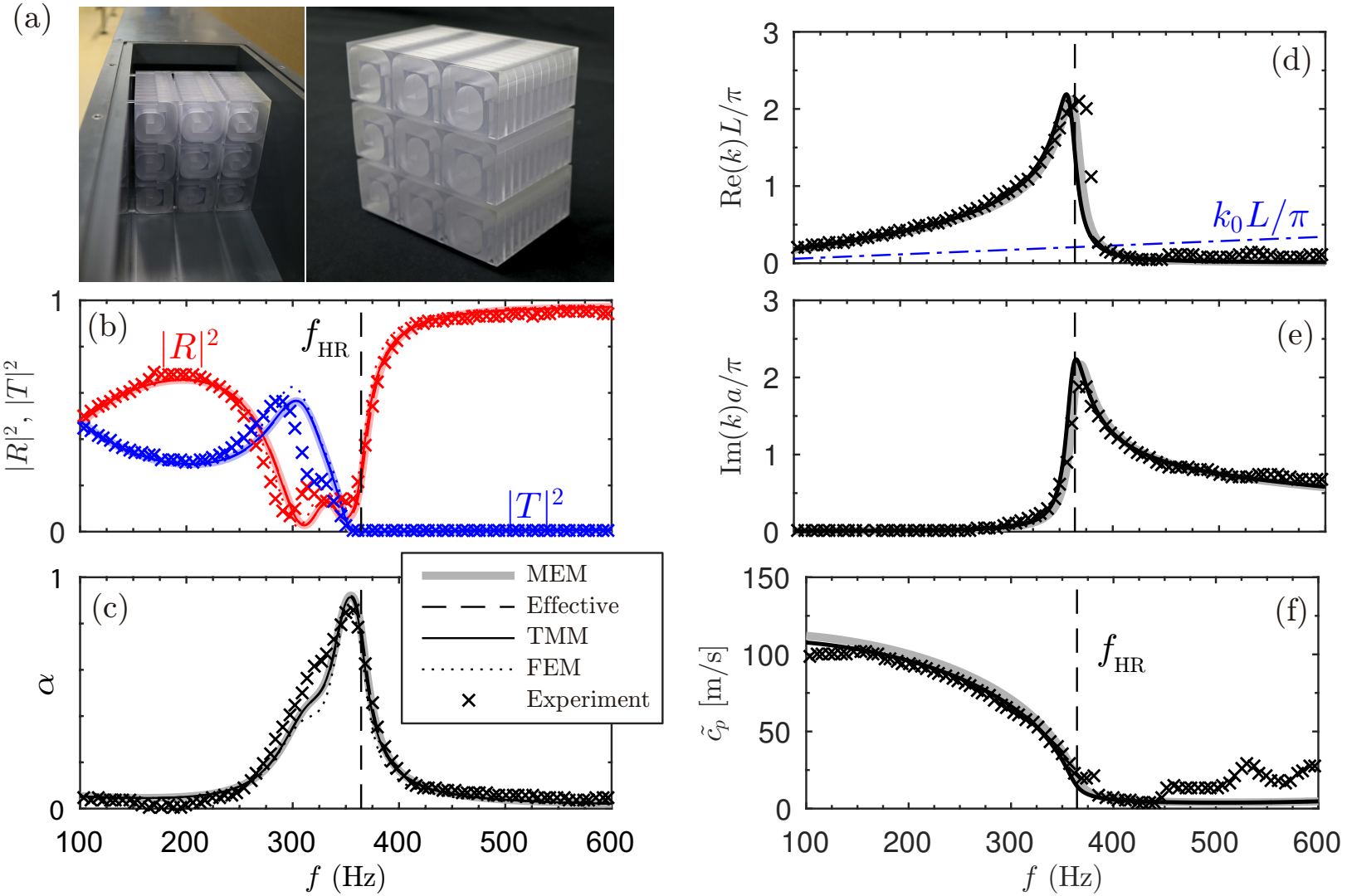
Experimental results

Sub-wavelength sample design:

- Optimize geometry using TMM
- Constrained thickness: $L = \lambda/10$, $d = \lambda/20$, $N = 10$
- 3D printing: stereolithography using photosensitive epoxy polymer



Experimental results



Accumulation can be used to obtain quasi-perfect absorption [1]

How to obtain perfect absorption in transmission?

Approaches:

1. **Deeper subwavelength** monopolar resonators
   - Bubbles, membranes, ...
2. Combinations of **monopolar and dipolar** resonances
   - Degenerate resonators [2]
3. Only monopolar? use **non-identical resonators** [3]
   - Break the symmetry using double-interacting resonators
   - Broadband absorption: rainbow trapping absorbers

[1] PRB 95 014205 (2017)

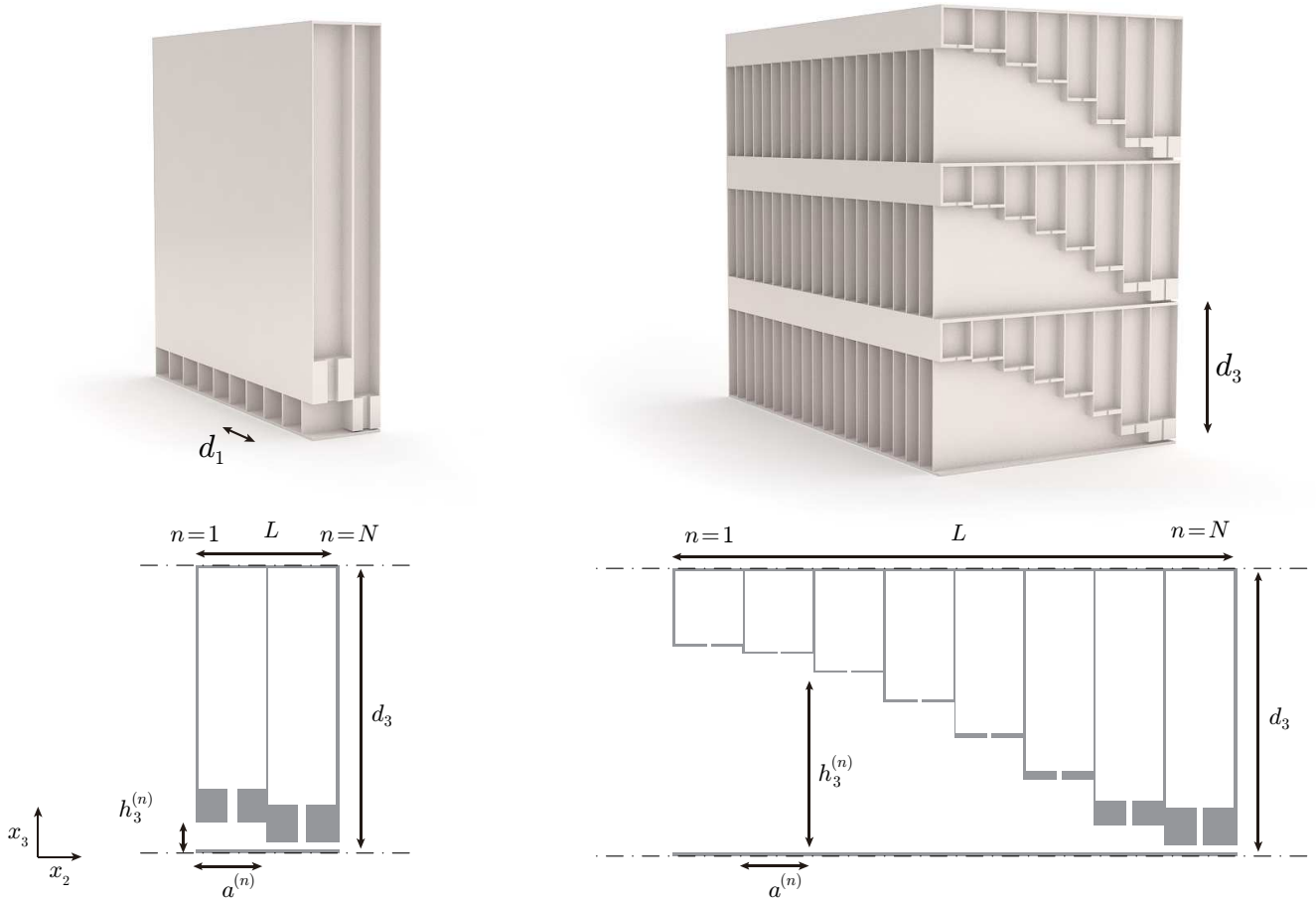
[2] APL 107 104104 (2015)

[3] APL 107 244102 (2015)

Rainbow-trapping absorbers

Broadband and perfect sound absorption in transmission [1]

- Subwavelength Asymmetric Panel
- Rainbow Trapping Absorber



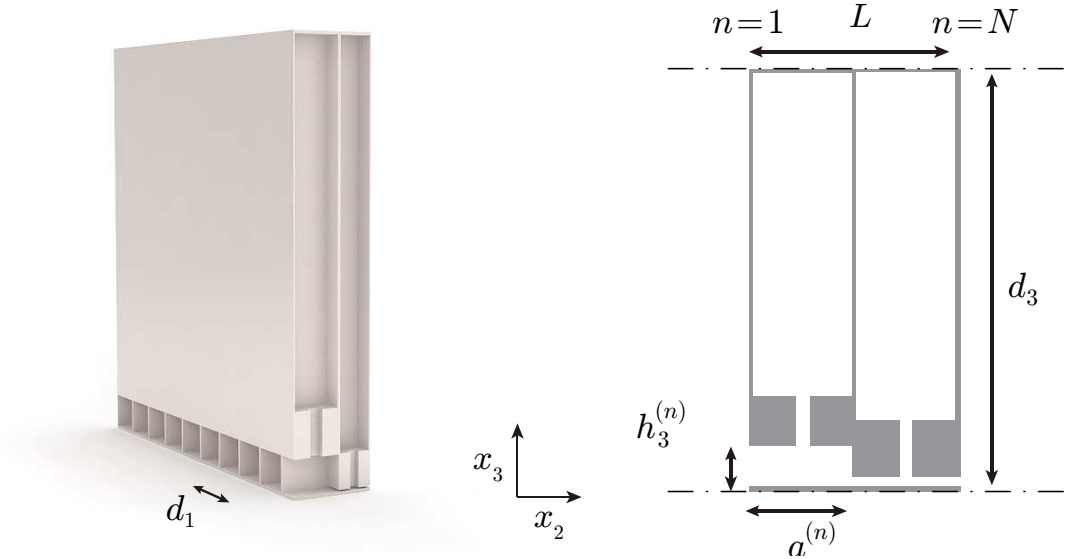
[1] Jiménez et. al. 2017 (Submitted draft)

Subwavelength asymmetric panel

Panel with $N = 2$ resonators

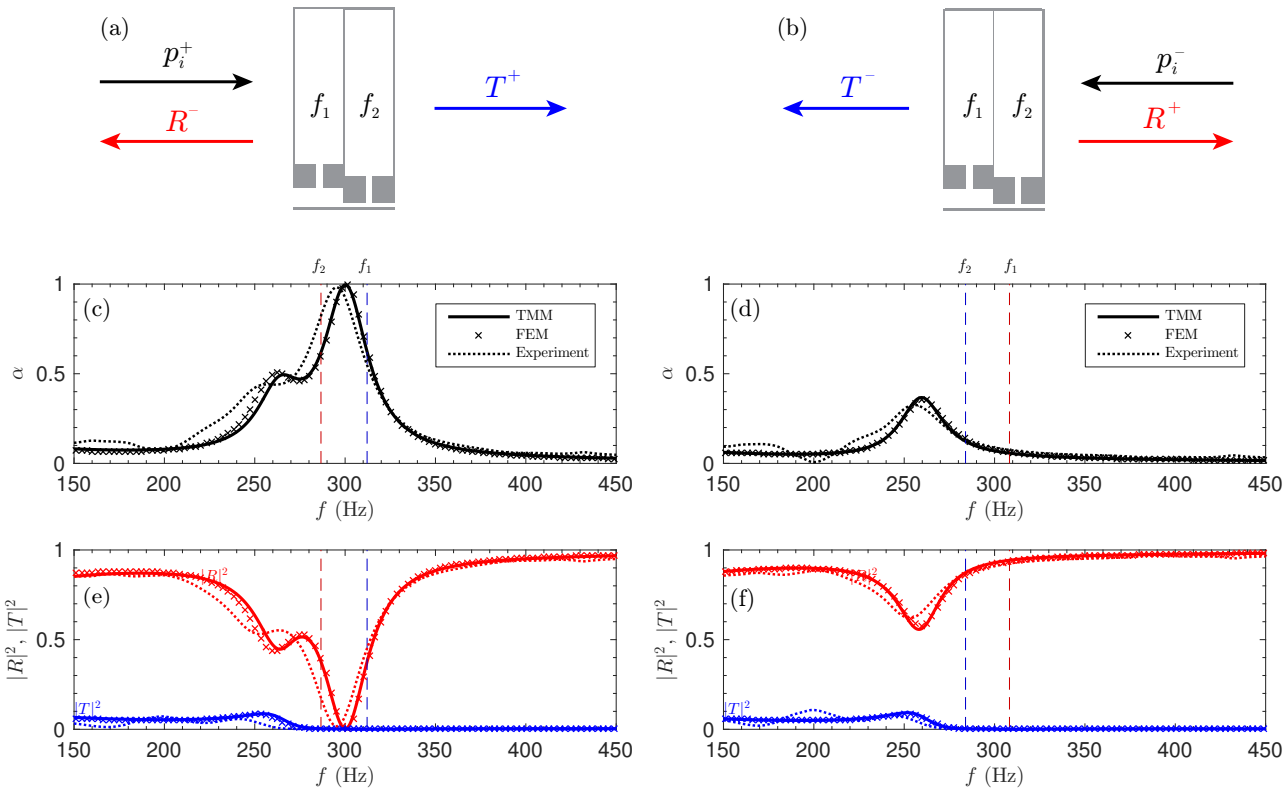
1. **Inner** resonator:
   - Lower resonance frequency
   - Creates a band-gap around its resonance
   - **Transmission** vanishes: it acts as a rigid wall

2. **Outer** resonator:
   - Higher resonance frequency
   - Critically couples the **reflection** problem



Subwavelength asymmetric panel

- Forward and backward propagation

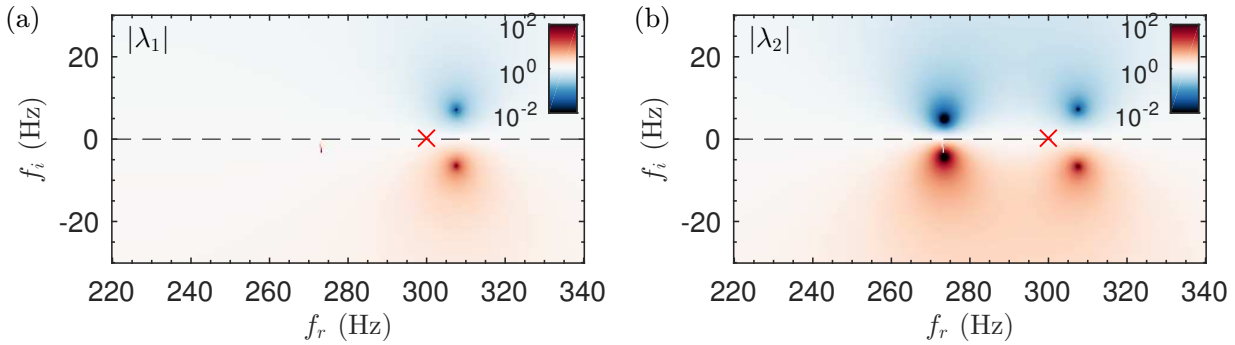


- Asymmetric reciprocal system ▶ absorption becomes unidirectional
- Perfect absorption for a panel of thickness $L = \lambda/40$ ($L = 2.5$ cm)

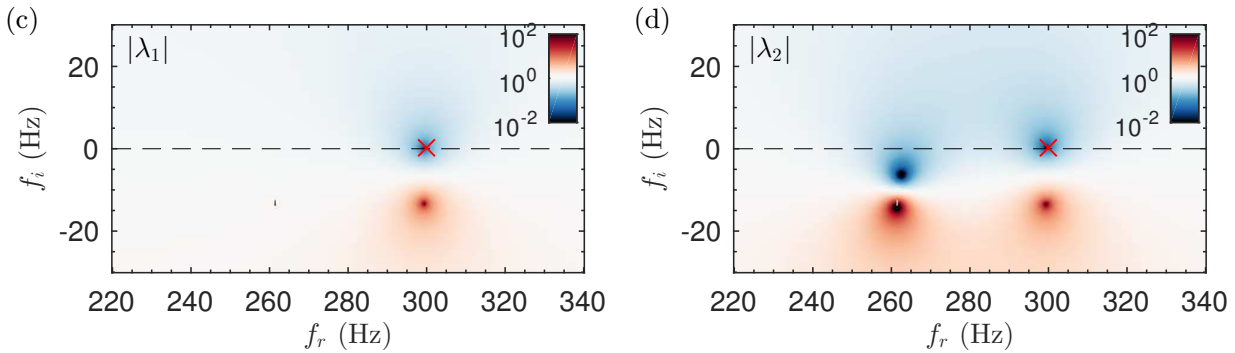
Subwavelength asymmetric panel

Complex frequency plane representation of $\lambda_{1,2}$

- **Lossless case:** $N = 2$ resonances



- **Lossy case:** tune the losses to critically couple the system
  - Perfect absorption occurs when both eigenvalues vanish
  - Place the zeros at the real axis

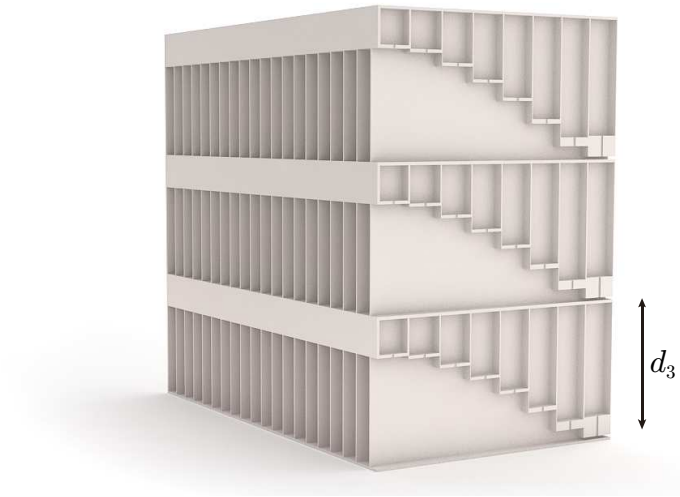


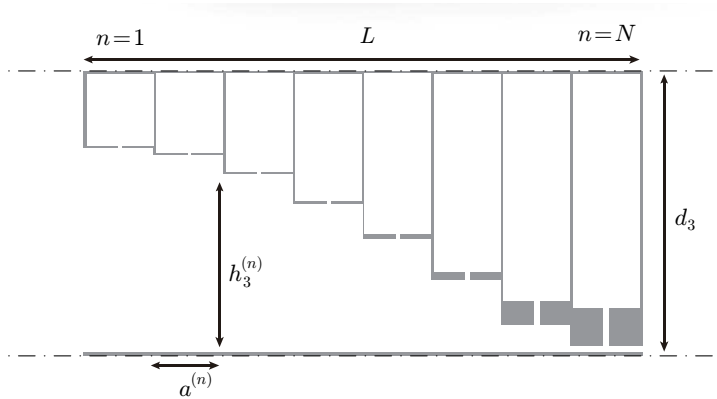
Rainbow trapping absorber

Same idea than in the asymmetric panel, but in cascade:

1. Resonator n:
   - Lower resonance frequency: $\omega_n < \omega_{n-1}$
   - Creates a band-gap around its resonance
   - Transmission vanishes

2. Resonator $n-1$:
   - Higher resonance frequency: : $\omega_n < \omega_{n-1}$
   - Critically couples the structure at frequency ω_{n-1}

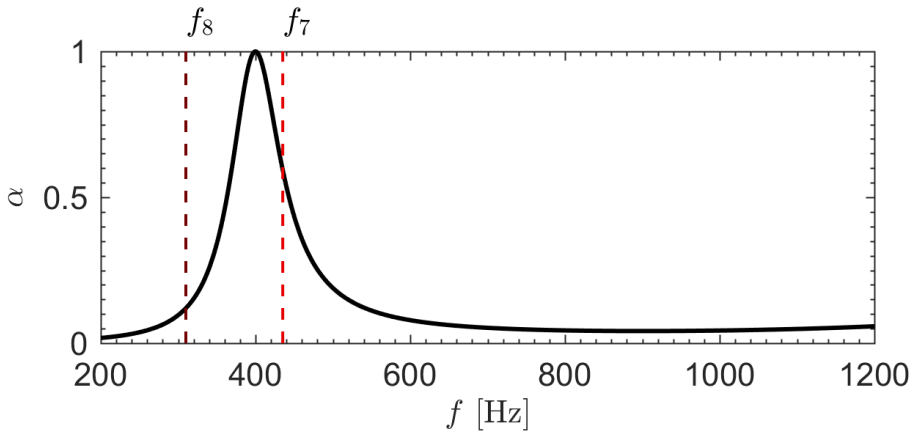


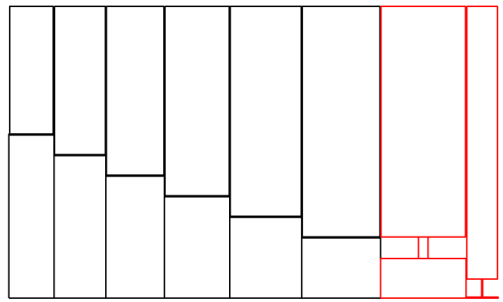


Rainbow trapping absorber

Broadband and perfect asymmetric absorption:

- Overlapping of $N-1=8$ peaks of perfect absorption
- Panel of thickness $L=\lambda/12$ ($L=10$ cm)

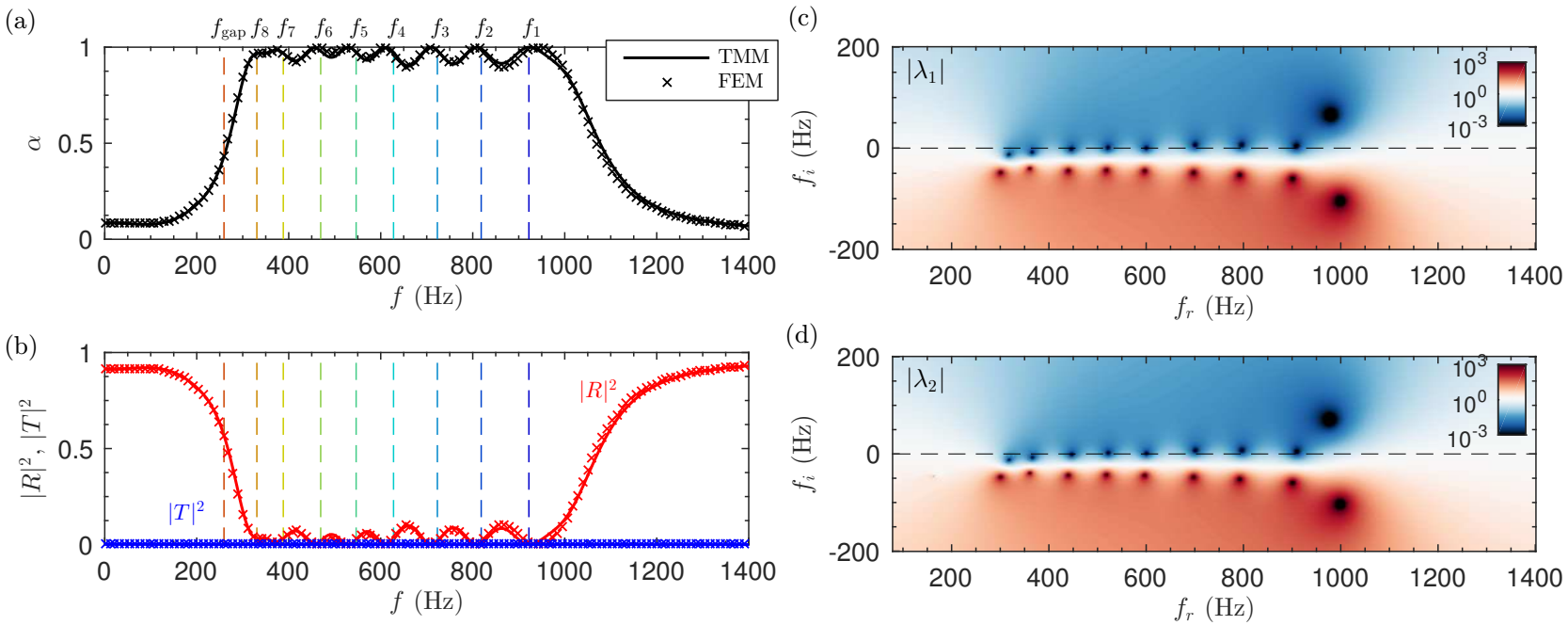




Rainbow trapping absorber

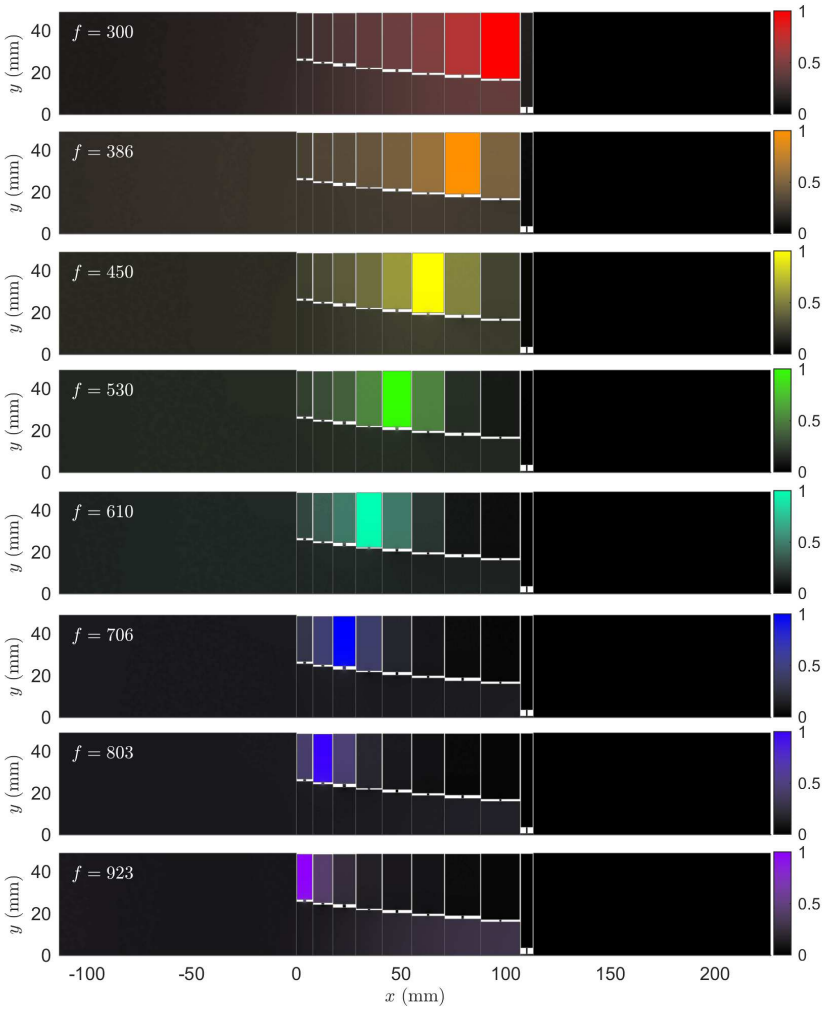
Broadband and perfect asymmetric absorption:

- Overlapping of $N - 1 = 8$ peaks of perfect absorption
- Panel of thickness $L = \lambda/12$ ($L = 10$ cm)
- Experimental constraints: 3D printer precision 0.1 mm step



Rainbow trapping absorber

- Waves are slowed-down into the structure
- For each frequency, energy is localized in each resonator
- Slit section changes with depth: impedance matching
- Frequency range: 1.5 octaves



Index

1 Reflection

2 Transmission

3 Metadiffusers

4 Conclusions

Metadiffusers

Far-field polar pressure distribution:

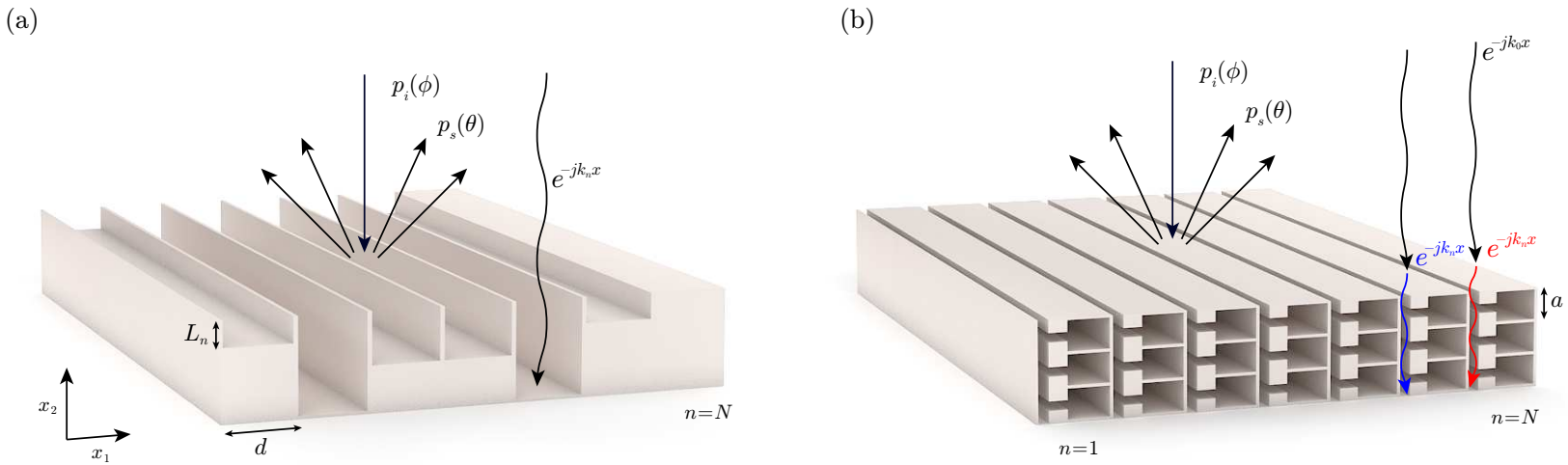
- **Sound diffusers**: uniform polar scattering
- **Fraunhofer-Fourier integral**: the scattered pressure in the far-field is essentially a Fourier transform of the reflected field along the surface:

$$p_s(\theta) = \int_{-b}^{b} R(x) e^{jkx \sin\theta} dx$$

- Structures whose its reflection coefficient distribution have an uniform magnitude Fourier transform will present good **sound diffusion**

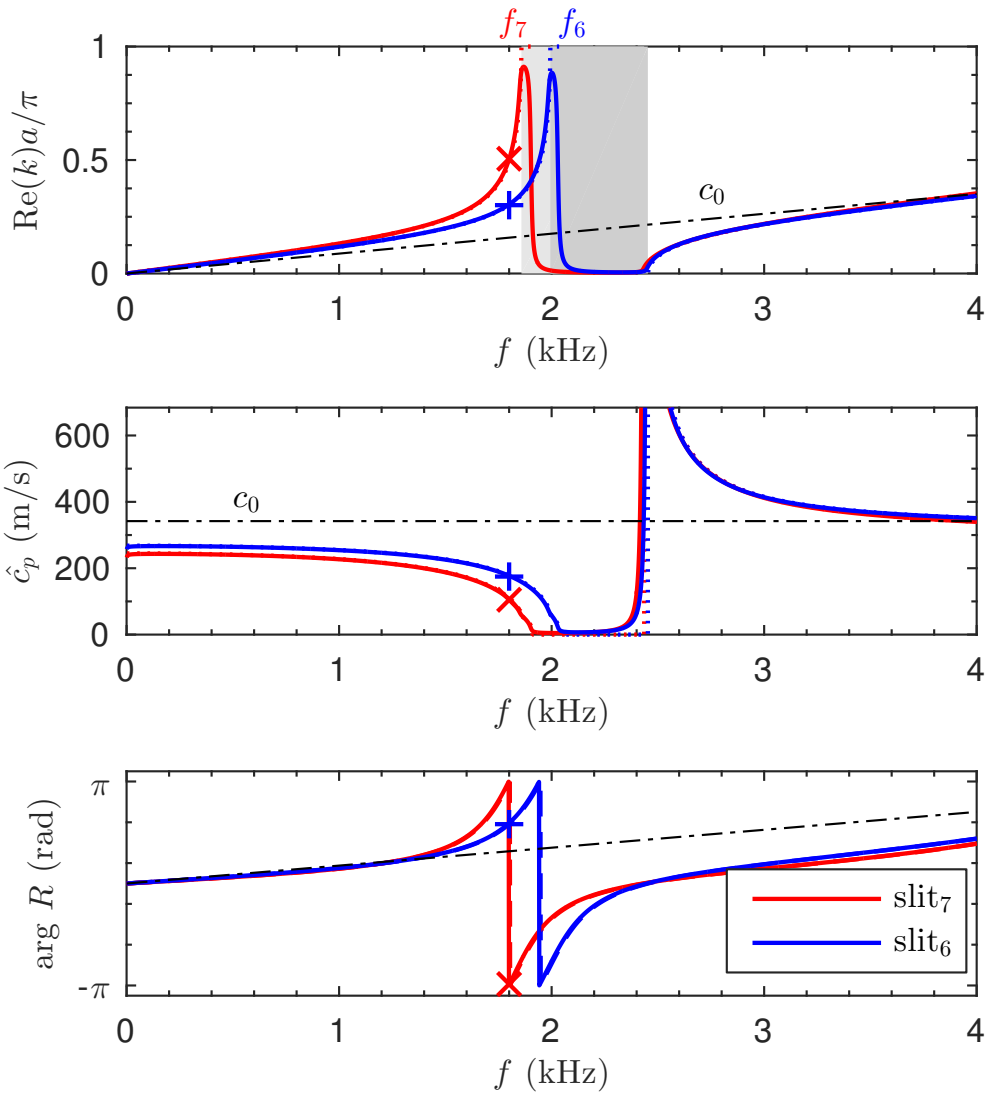
Metadiffusers

- **Phase grating diffuser (Schroeder)**
  - The reflection coefficient is tuned using QWRs
  - Phase inversion $R = e^{i\pi}$ ▶ $L = \lambda_0/4$
- **Metadiffusers**
  - Use slow-sound to tune the reflection coefficient of a thin panel
  - Phase inversion $R = e^{i\pi}$ ▶ $L = \lambda_{eff}/4$



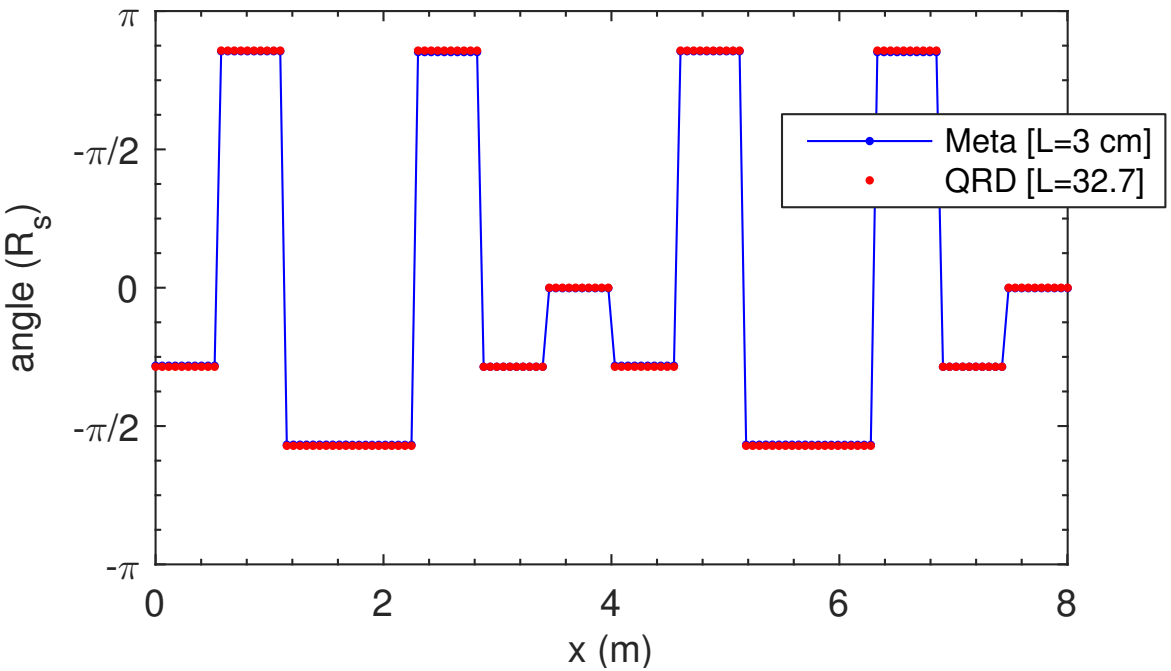
Tuning the reflection phase using dispersion

- Two slits: A and B
- Introduce strong dispersion
- Tune reflection coefficient phase



Phase sequences with flat Fourier spectrum

1. **Quadratic residue diffusers (QRD)**
   - $s_n = n^2 \mathrm{mod} N$
   - Tune each slit to the QRD reflection sequence

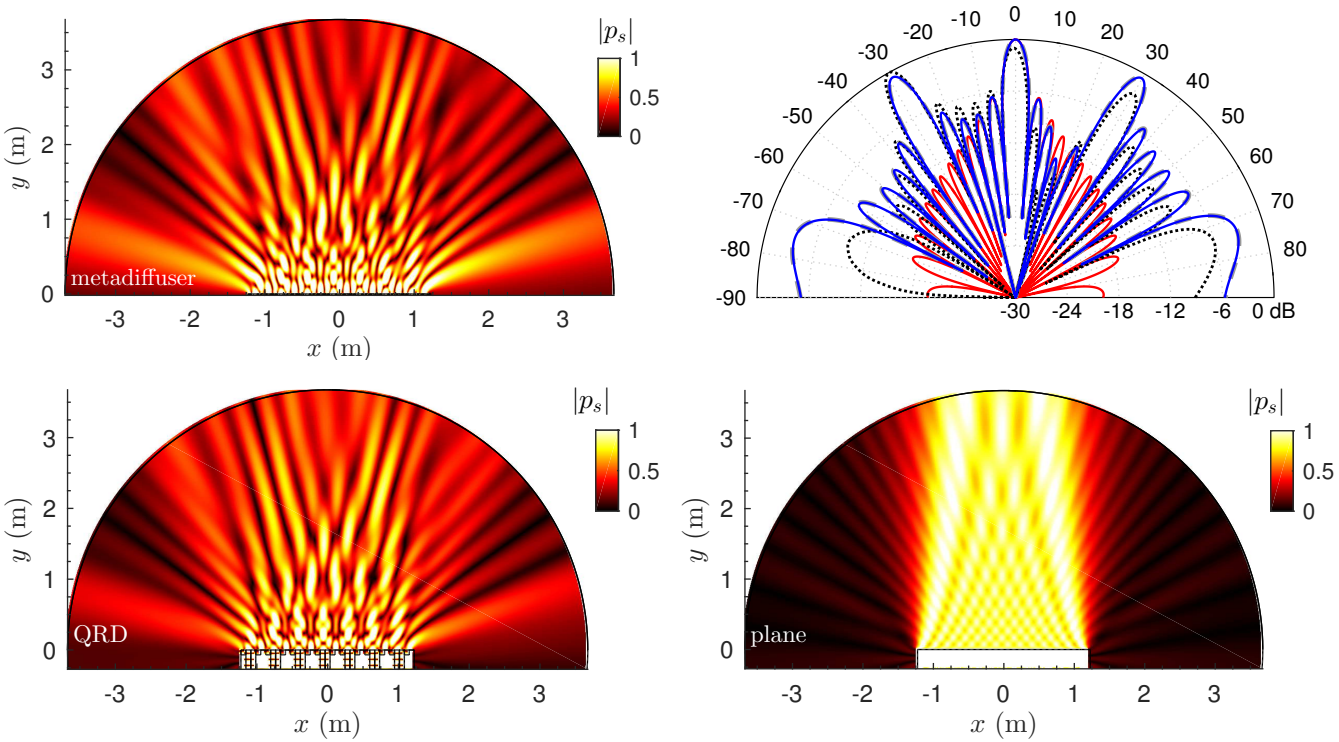


- QR-metadiffuser - $N = 5$ - $f = 500$ Hz - $L_{\mathrm{meta}} = \lambda/34$

Phase sequences with flat Fourier spectrum

1 Quadratic residue diffusers (QRD)

- $s_n = n^2 \mathrm{mod} N$
- Tune each slit to the QRD reflection sequence

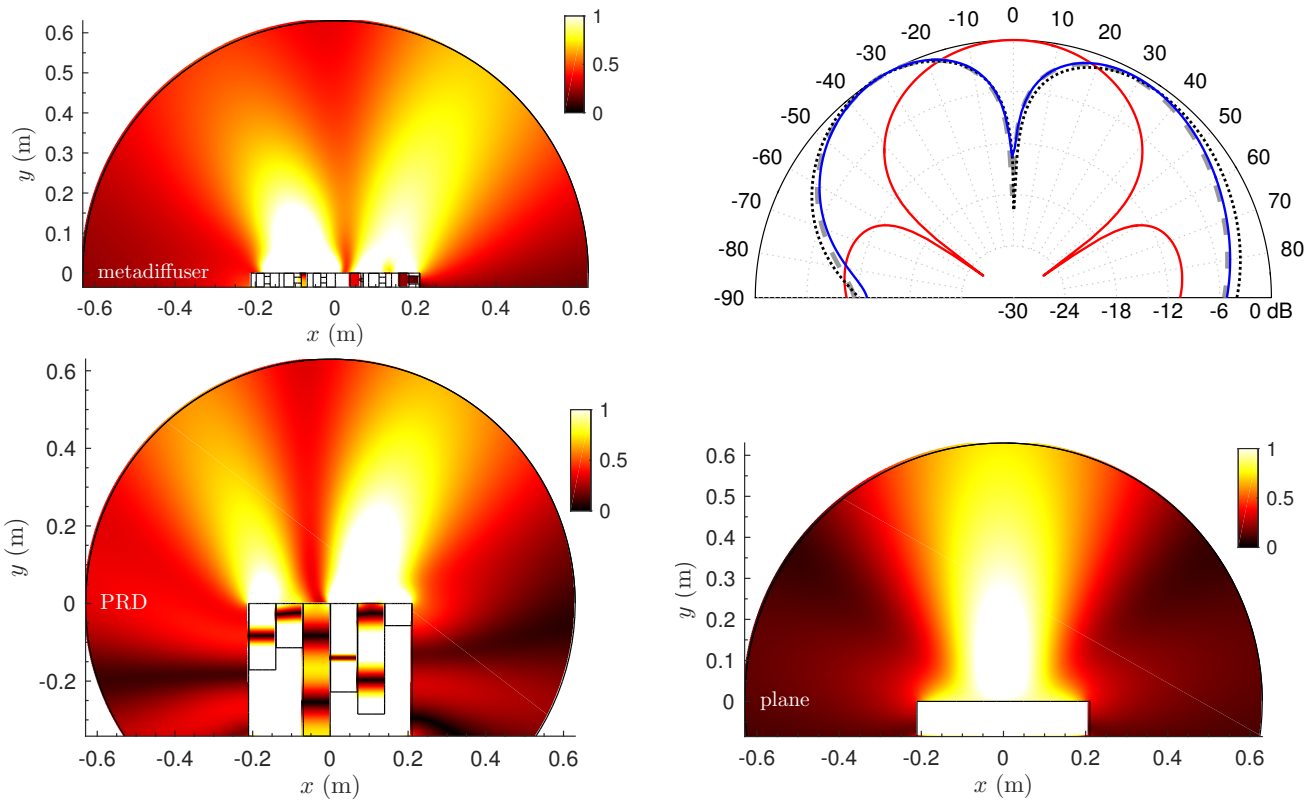


- QR-metadiffuser
- $N = 5$
- $f = 500$ Hz
- $L_{\mathrm{meta}} = \lambda/34$

Phase sequences with flat Fourier spectrum

2 Primitive root diffusers (PRD)

- $s_n = r^n \mathrm{mod} P$, with P a prime and r the primitive root of P
- Tune each slit to the PRD reflection sequence

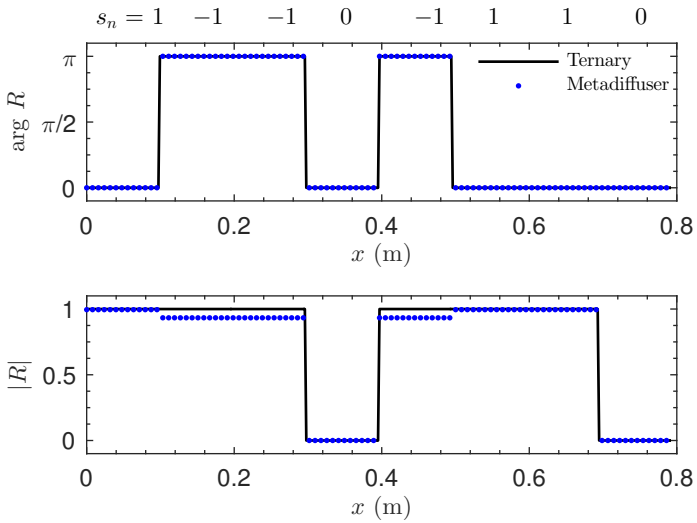


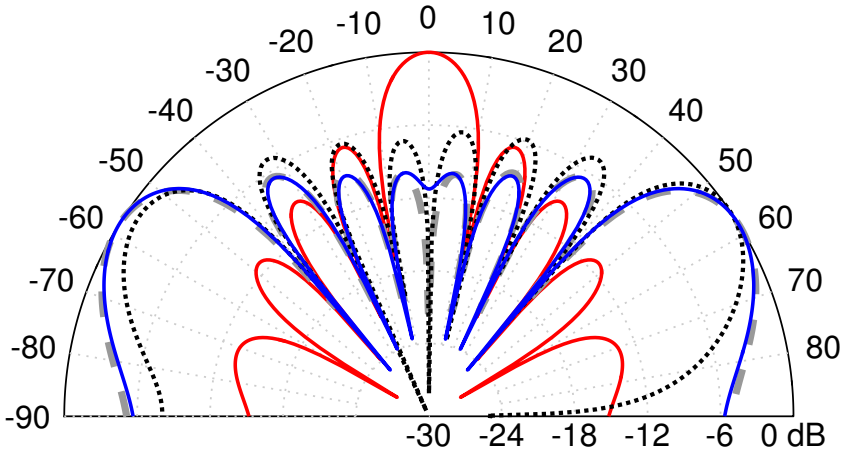
- PR-metadiffuser ▶ $P = 7$ ▶ $f = 500$ Hz ▶ $L_{\mathrm{meta}} = \lambda/20$

Phase sequences with flat Fourier spectrum

3 Ternary sequences

- Sequence composed by [1, -1, 0]
  “1” : Perfect reflector
  “-1” : Inverted phase
  “0” : Perfect absorber
- Only 2 different slits
- $L_{\text{meta}} = \lambda/20$

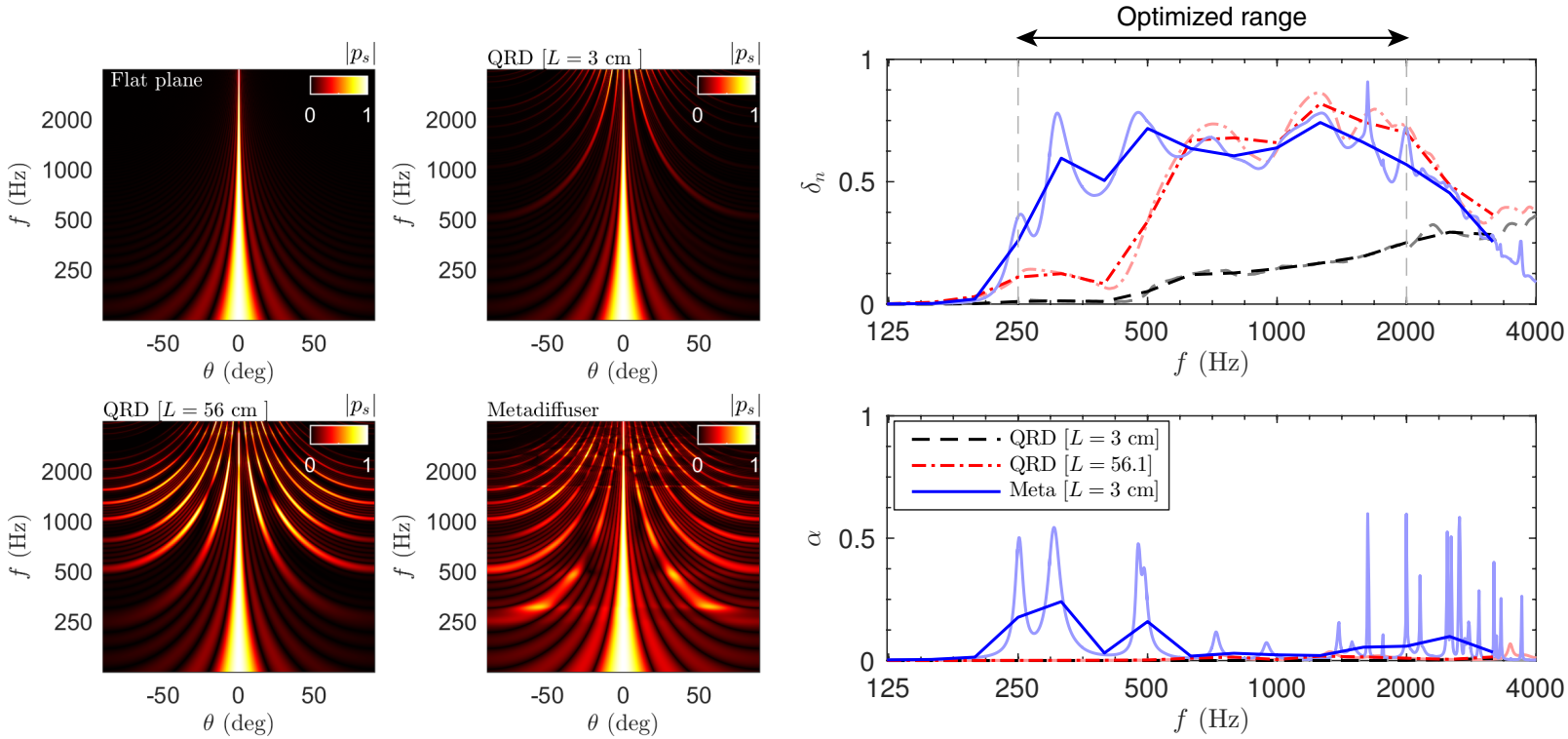




Subwavelength metadiffusers

4 Optimal broadband diffusers

- Optimize diffusion coefficient: Mix perfect absorption / phase sequence
- Metadiffuser $L = 3$ cm ▶ best performance than QRD diffuser of $L = 56$ cm
- $L_{\text{meta}} = \lambda/45$ (20 times thinner than QRD), for 4 octaves!



- $N = 11, N_{\text{HR}} = 2$

Conclusions

1. Deep-subwavelength perfect **absorbers**
   - Reflection: ultra-thin panel ▶ $L = \lambda/86$
   - Transmission: subwavelength asymmetric panel ▶ $L = \lambda/40$
   - Broadband transmission: rainbow trapping absorber ▶ $L = \lambda/12$

Conclusions

1. Deep-subwavelength perfect **absorbers**
   - Reflection: ultra-thin panel ▶ $L = \lambda/86$
   - Transmission: subwavelength asymmetric panel ▶ $L = \lambda/40$
   - Broadband transmission: rainbow trapping absorber ▶ $L = \lambda/12$

2. Deep-subwavelength **metadiffusers**
   - QRD, PRD ▶ $L \approx \lambda/30$
   - Ternary sequences using perfect absorbers ▶ $L = \lambda/10$
   - Broadband metadiffusers ▶ $L = \lambda/45$
   - STSM: COST Action DENORMS short term stay mission (1.5 month)

Conclusions

1. Deep-subwavelength perfect **absorbers**
   - Reflection: ultra-thin panel ▶ $L = \lambda/86$
   - Transmission: subwavelength asymmetric panel ▶ $L = \lambda/40$
   - Broadband transmission: rainbow trapping absorber ▶ $L = \lambda/12$

2. Deep-subwavelength **metadiffusers**
   - QRD, PRD ▶ $L \approx \lambda/30$
   - Ternary sequences using perfect absorbers ▶ $L = \lambda/10$
   - Broadband metadiffusers ▶ $L = \lambda/45$
   - STSM: COST Action DENORMS short term stay mission (1.5 month)

3. **Metamaterials** using Helmholtz resonators and slow-sound
   - Versatile: broad range of problems
   - Based HR: age duration / harsh environment
   - Void and open: lightweight, transparent to light and air flux
   - Degree of freedom: multifunctional optimization, structural, thermal, aesthetics
   - Construction: complex 3D structures...

Project funded by theMetaudible ANR project ANR-13-BS09-0003



Thanks for your attention!

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V. Romero-García[1], J-P. Groby[1]

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[2] Acoustics Research Centre, University of Salford, UK