





Perfect and broadband sound absorption based in Rainbow Trapping phenomena for transmission problems

Noé Jiménez[1,*], V. Romero-García[1], V. Pagneux[1] and J-P. Groby[1]

[1] Laboratoire d'Acoustique de la Université du Maine, UMR CNRS-6613 (France)
[*] *Now at*: Instituto de Instrumentación para Imagen Molecular (i3M), CSIC - UPV (Spain)

5th SAPEM, December 6, 2017, Le Mans (France)

Introduction

Goal: to design **Subwavelength perfect absorbers**

1. **Perfect absorbers**:
   - System must be critically coupled with the exterior media
   - In general: $\lambda_{1,2} = 0$
   - Intrinsic losses of the material exactly compensate the leakage of the structure
   - We need some degree of freedom to tune the losses of the system

Introduction

Goal: to design **Subwavelength perfect absorbers**

1. **Perfect absorbers**:
   - System must be critically coupled with the exterior media
   - In general: $\lambda_{1,2} = 0$
   - Intrinsic losses of the material exactly compensate the leakage of the structure
   - We need some degree of freedom to tune the losses of the system

2. **Subwavelength resonance**:
   - Use of subwavelength resonators: QWR, space coiling, Helmholtz, elastic plates and membranes, bubbles ...
   - Design of subwavelength resonating structures using metamaterials

Introduction

Scattering matrix:

- Relates the incoming and outgoing waves

$$\mathbf{S} = \begin{bmatrix} T & R^- \\ R^+ & T \end{bmatrix}. \tag{1}$$

- Perfect absorption is achieved when no waves are scattered by the structure
  - Eigenvalues of the scattering matrix

$$\lambda_{1,2} = T \pm \sqrt{R^+ R^-}, \tag{2}$$

- **Both eigenvalues of the $\mathbf{S}$-matrix should vanish**
  - If both eigenvalues are zero, we observe at least PA in one direction

- From which direction are waves perfectly absorbed?
  - Eigenvectors corresponding to λ_1 and λ_2

$$\vec{v}_1 = \left[R^-, -\sqrt{R^+ R^-}\right], \quad \vec{v}_2 = \left[\sqrt{R^+ R^-}, R^+\right], \tag{3}$$

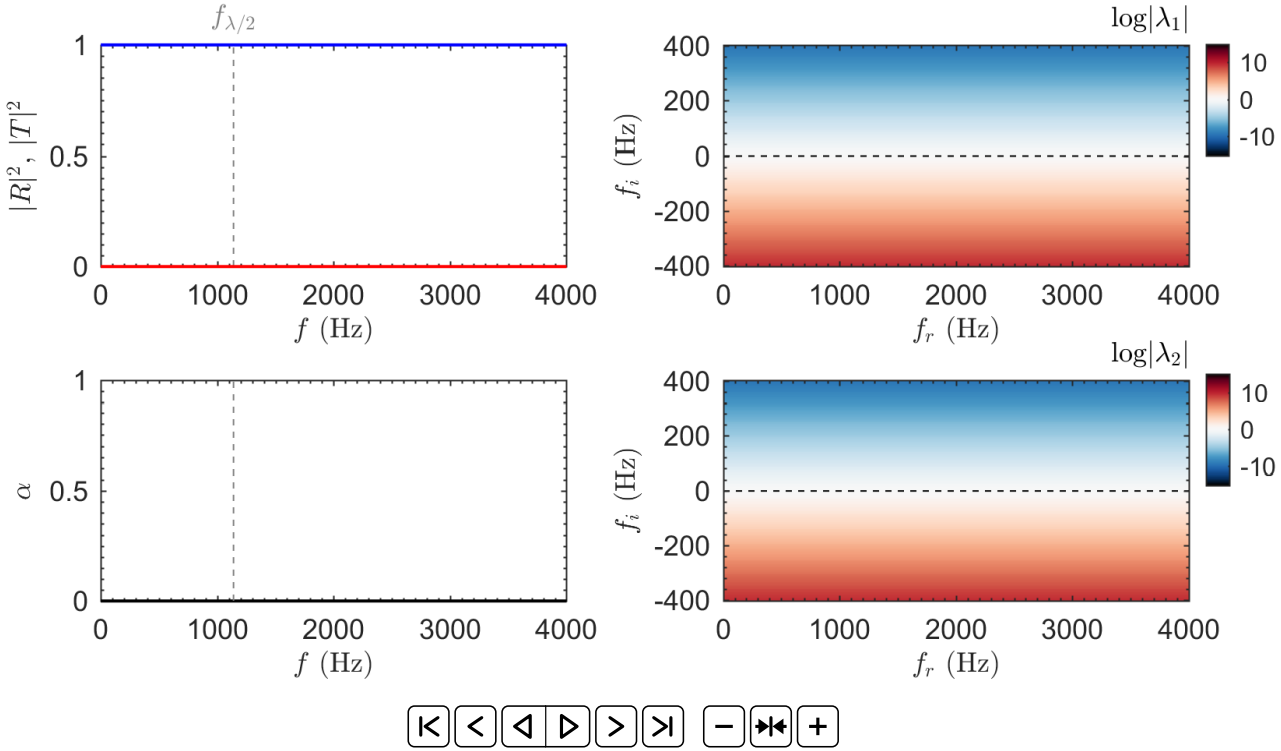
  - Eigenvectors show the asymmetry of the scattering

Symmetric and homogeneous system

Slab of absorbing material (Lossless case):

- Fabry-Pérot modes: perfect transmission / reflection
- Two eigenvalues $\lambda_1 = |R - T|$ and $\lambda_2 = |R + T|$
- The zeros of the eigenvalues are staggered in frequency





Symmetric and homogeneous system

Slab of absorbing material (Lossless case):

- Fabry-Pérot modes: perfect transmission / reflection
- Two eigenvalues $\lambda_1 = |R - T|$ and $\lambda_2 = |R + T|$
- The zeros of the eigenvalues are staggered in frequency



1 1st mode: symmetric (1000 Hz)



2 2nd mode: antisymmetric (2000 Hz)



3 3rd mode: symmetric (3000 Hz)

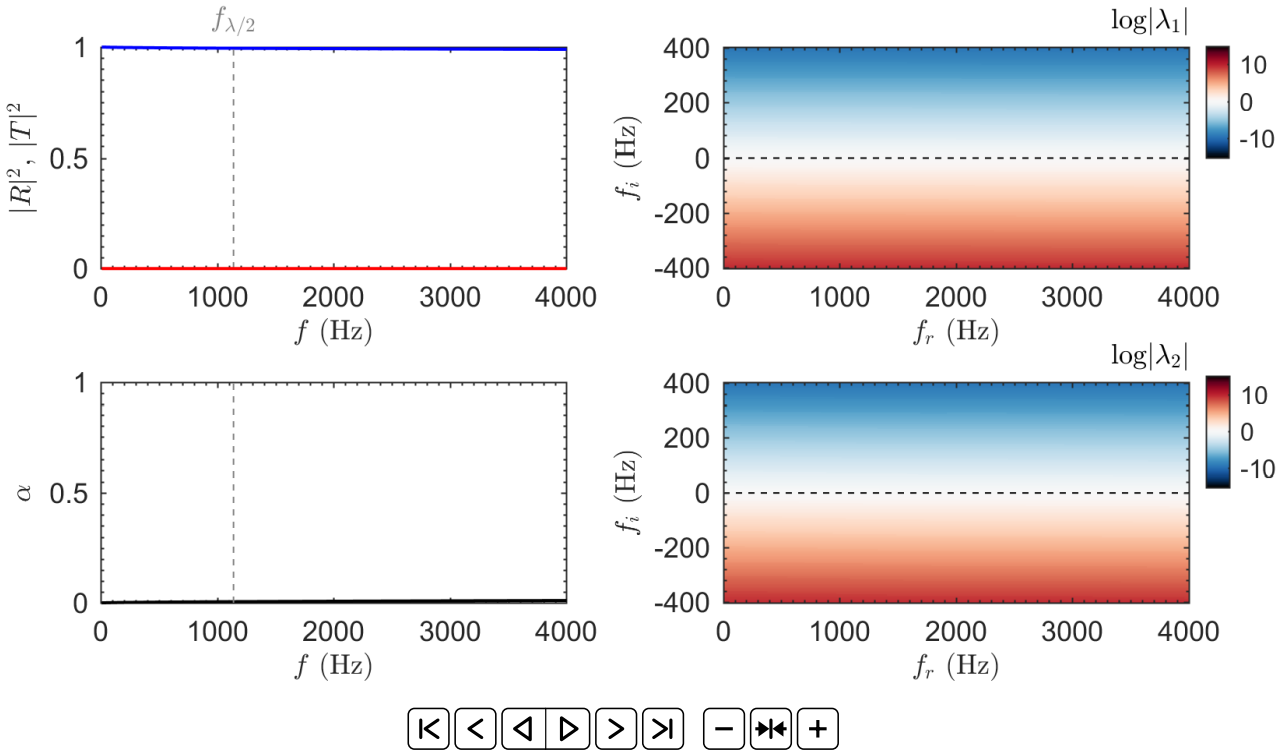


Symmetric and homogeneous system

Slab of absorbing material (Lossy case):

- Absorption at Fabry-Pérot resonances
- Zeros of $|R-T|$ and $|R+T|$ are staggered in frequency
  - $\alpha = (\alpha_{\mathrm{sym}} + \alpha_{\mathrm{asym}})/2$, so $0.5 \leq \alpha_{\max} < 1$



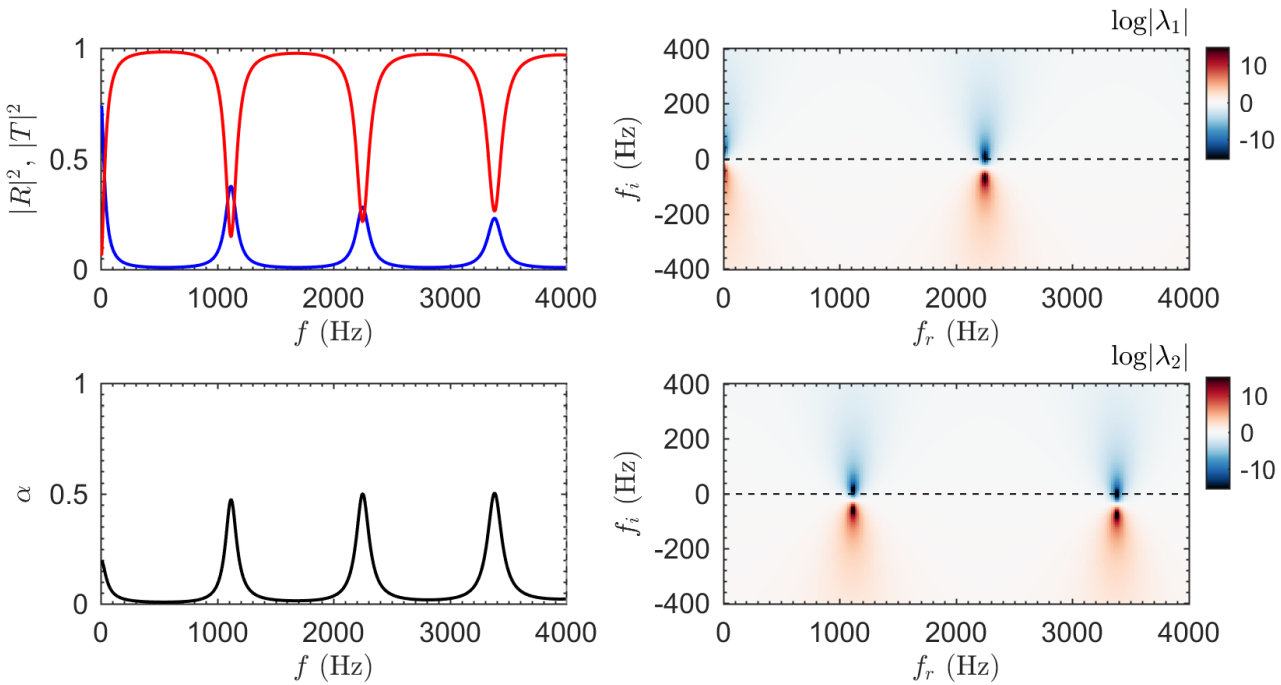


Symmetric and homogeneous system

Include and array of resonators (Lossy case):



- The resonances are accumulated due to dispersion
- We observe quasi-perfect absorption in transmission [1]
  - $\alpha = (\alpha_{\mathrm{sym}} + \alpha_{\mathrm{asym}})/2$, so $0.5 \leq \alpha_{\mathrm{max}} < 1$



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

Perfect absorption in transmission

"How to un-stagger the zero-pole structure?" ($\lambda_{1,2} = 0$)

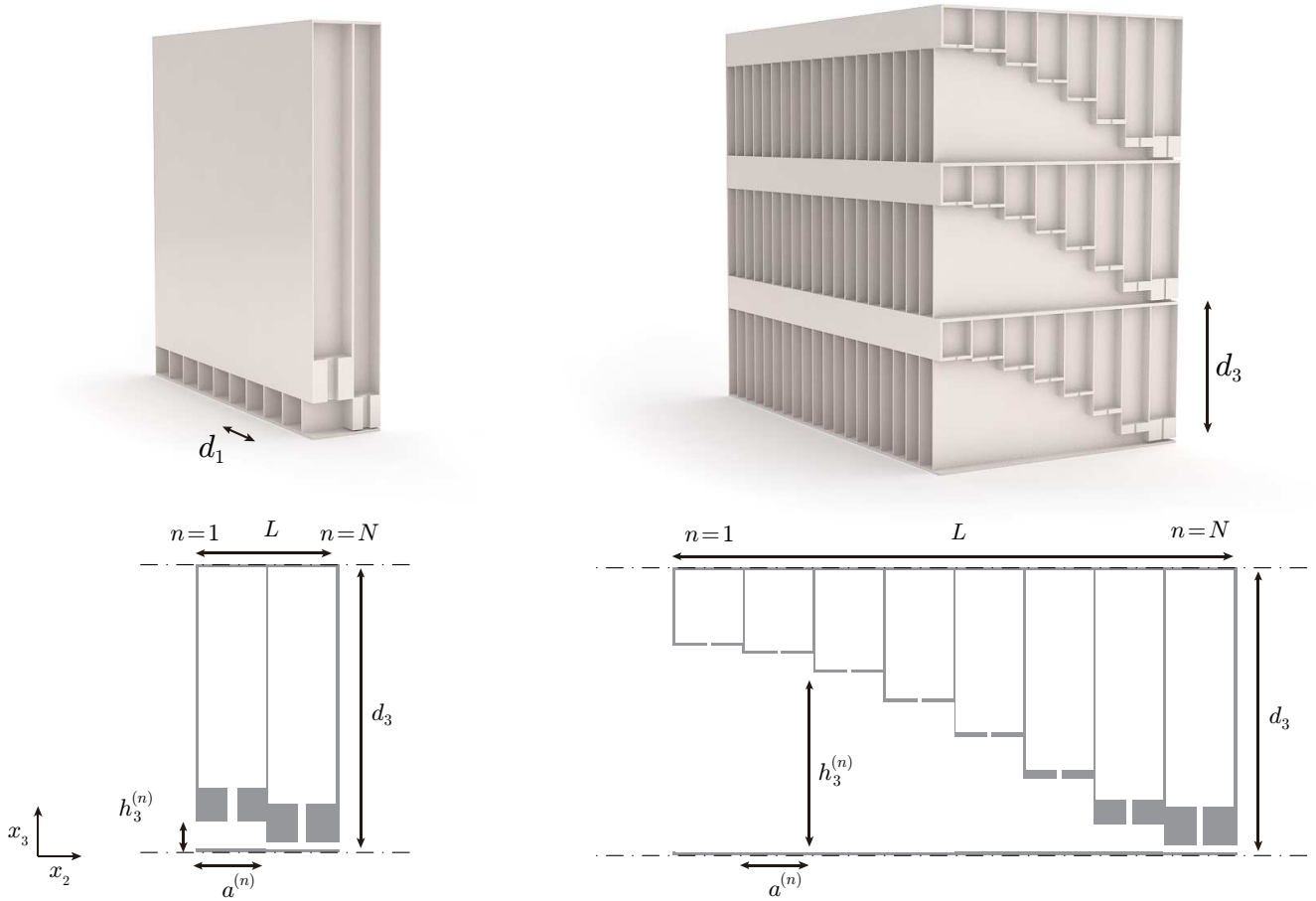
Approaches:

1. **Use strong dispersion**
   - Cavity modes can be accumulated around a flat-propagation band [1]
   - Deep subwavelength monopolar resonators (or dipolar)
   - Arrays of HRs, QWR, membranes and elastic plates, bubbles, ...
2. Combinations of **monopolar and dipolar** resonances
   - Degenerate resonators [2]
3. **Symmetry breaking** using non-identical resonators
   - Double-interacting resonators in waveguides [3]
   - Rainbow Trapping Absorbers: broadband absorption

[1] N. Jiménez, *et al*, Phys Rev B, 95 014205 (2017)
[2] M. Yang, *et al*, Appl. Phys. Lett. 107 104104 (2015)
[3] A. Merkel, *et al*, Appl. Phys. Lett. 107 244102 (2015)

Rainbow-trapping absorbers

- Subwavelength Asymmetric Panel
- Rainbow Trapping Absorber



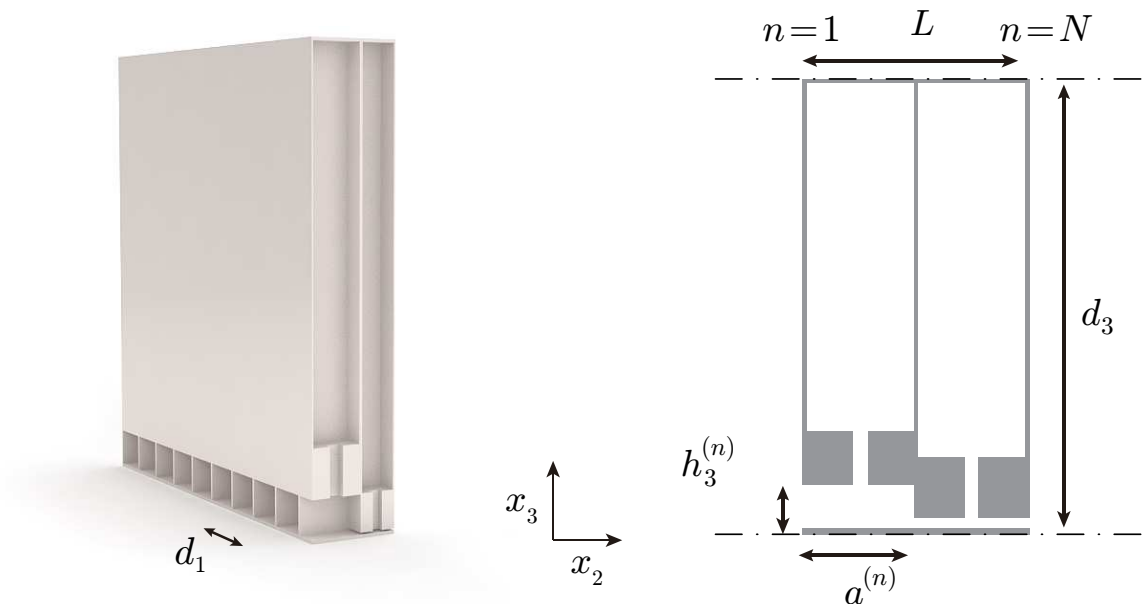
[1] Jiménez, *et. al.* Scientific Reports, 7, pp 13595, (2017)

Subwavelength asymmetric panel

Panel with $N = 2$ resonators

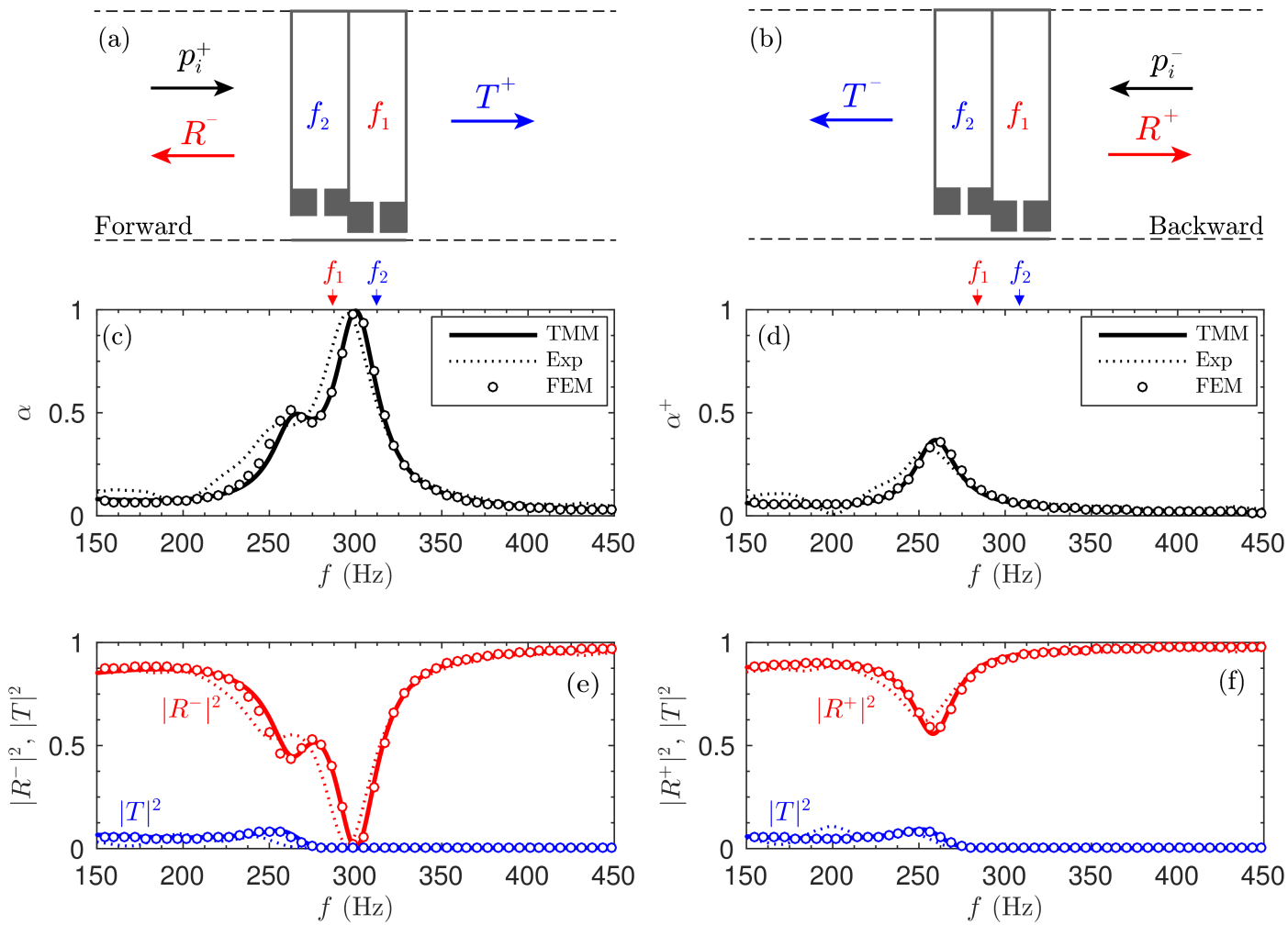
1. **Inner** resonator:
   - Lower resonance frequency
   - Induce a bandgap around its resonance frequency
   - Transmission drops drastically: it acts as a rigid wall

2. **External** resonator:
   - Slightly higher resonance frequency
   - The losses are tuned to critically couple the reflection problem



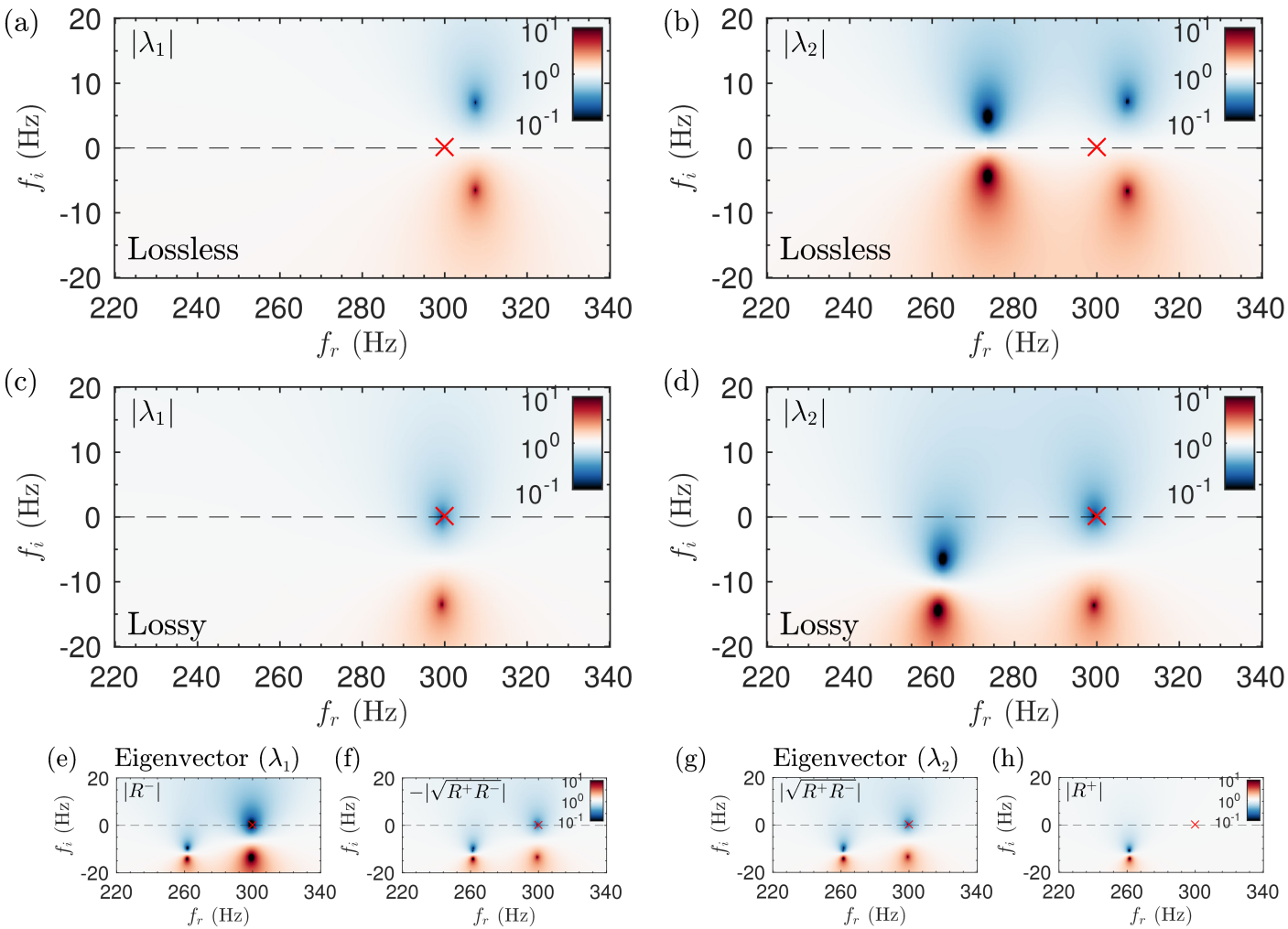
Subwavelength asymmetric absorbing panel

- Absorption becomes unidirectional
- Perfect absorption for a thickness of $L = \lambda/40$ ($L = 2.5$ cm)



Subwavelength asymmetric absorbing panel

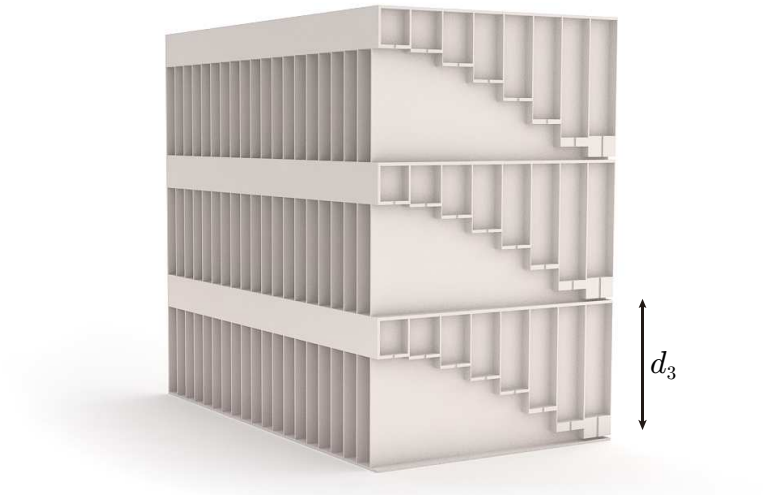
- Eigenvalues given $\lambda_{1,2} = |T \pm \sqrt{R^- R^+}|$
- Look at the complex frequency plane

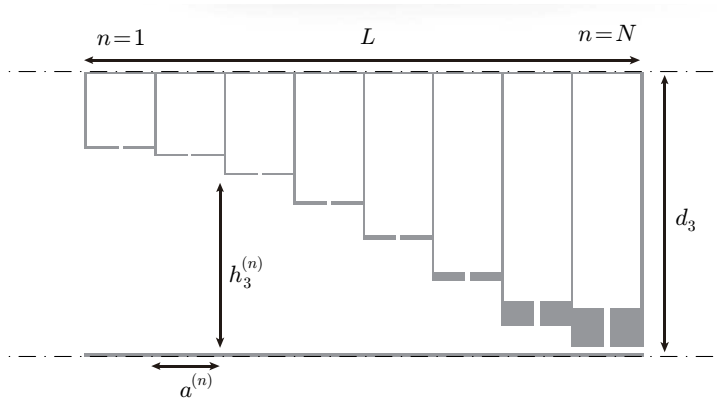


Rainbow trapping absorber

Extend this idea, but in a cascade process:

1. Resonator n:
   - Lower resonance frequency: $\omega_n < \omega_{n-1}$
   - Creates a bandgap avobe its resonance
   - Transmisión drops
2. Resonator $n-1$:
   - Sligly higher resonance frequency: $\omega_n < \omega_{n-1}$
   - Critically coupled the structure at frequency ω_{n-1}
   - It creates a new band-gap! at ω_n

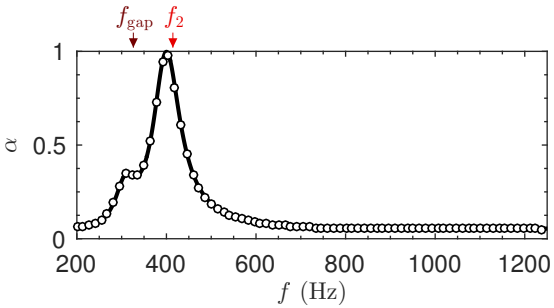


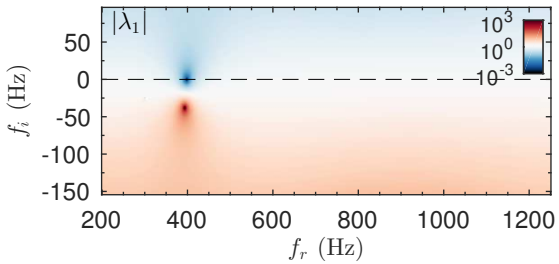


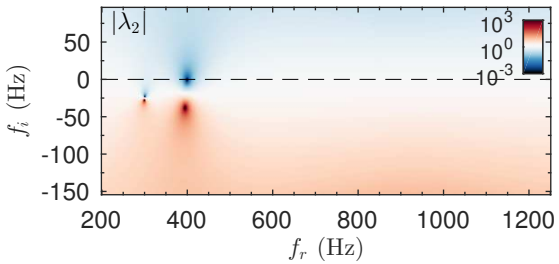
Rainbow trapping absorber

Asymmetric broadband and perfect absorption:

- Overlap of $N - 1 = 8$ peaks of perfect absorption
- Thickness of the panel $L = \lambda/12$ ($L = 10$ cm)



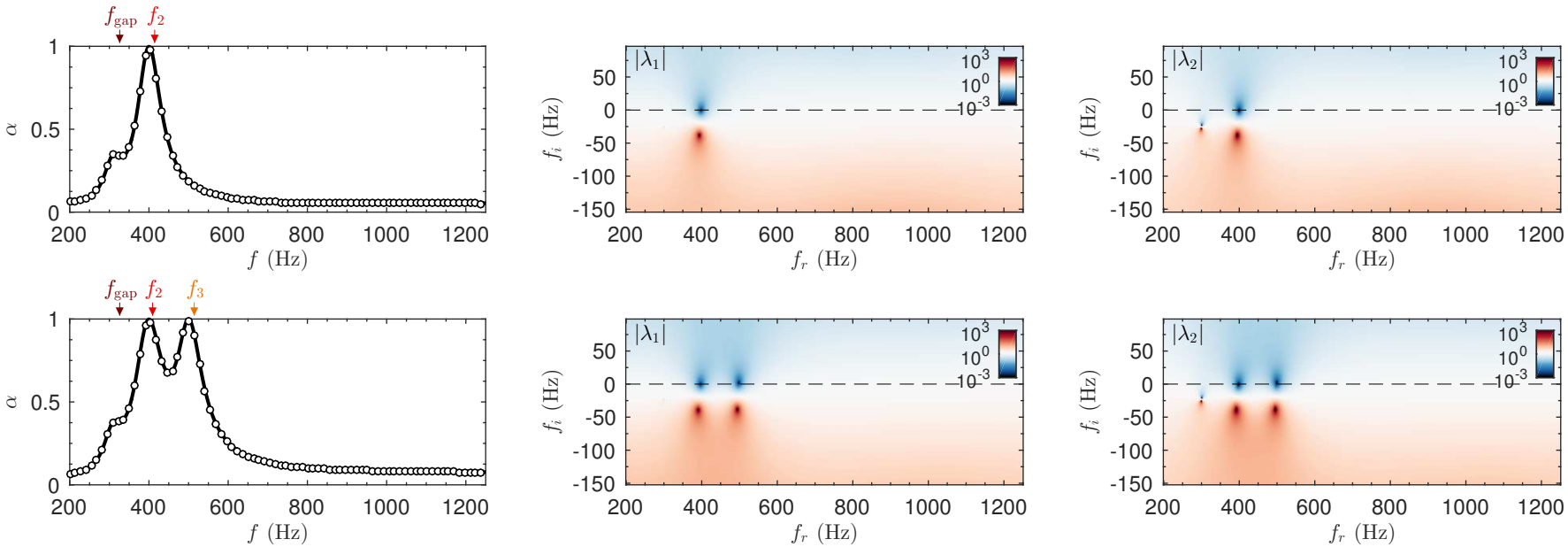




Rainbow trapping absorber

Asymmetric broadband and perfect absorption:

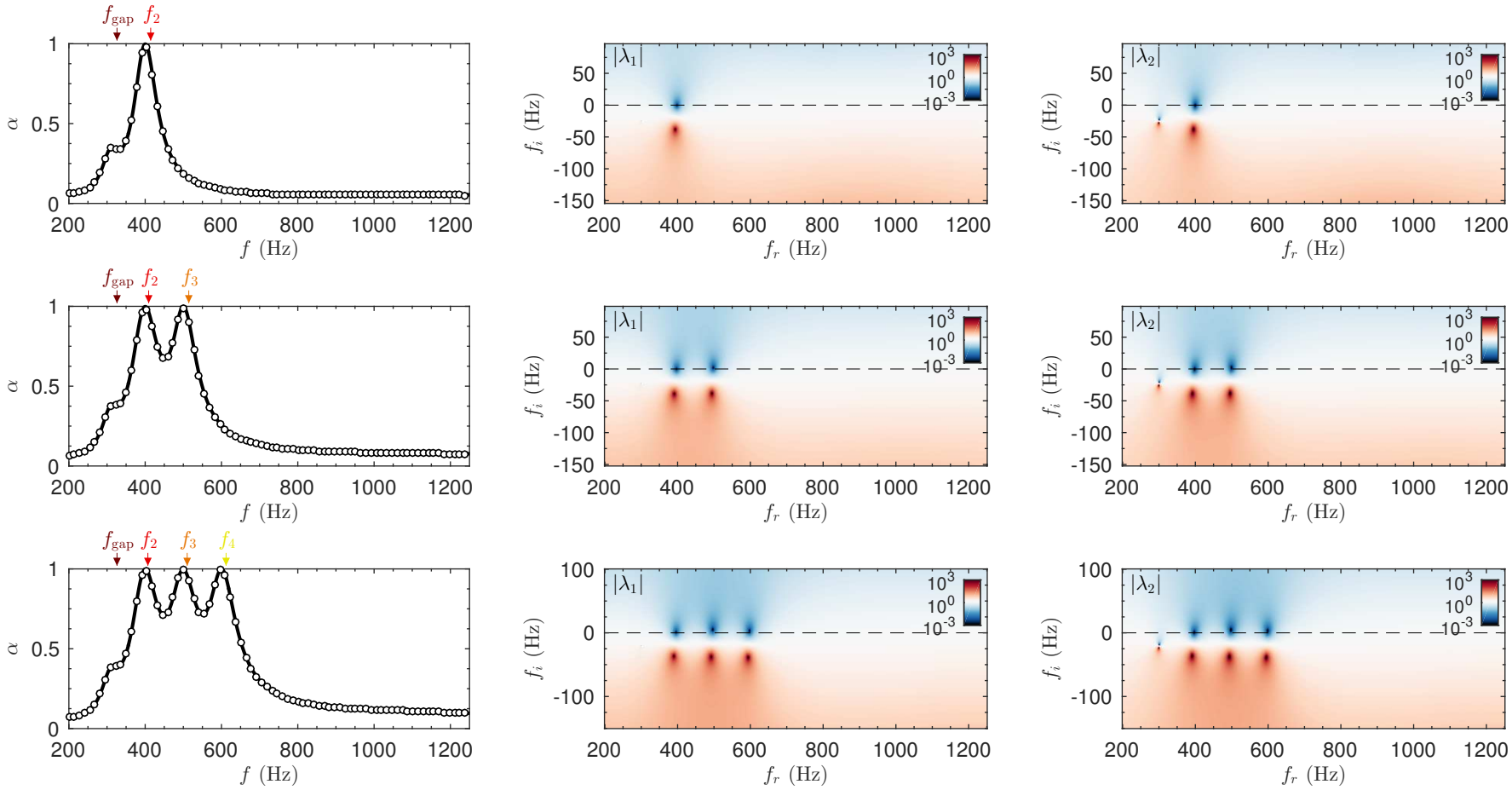
- Overlap of $N - 1 = 8$ peaks of perfect absorption
- Thickness of the panel $L = \lambda/12$ ($L = 10$ cm)



Rainbow trapping absorber

Asymmetric broadband and perfect absorption:

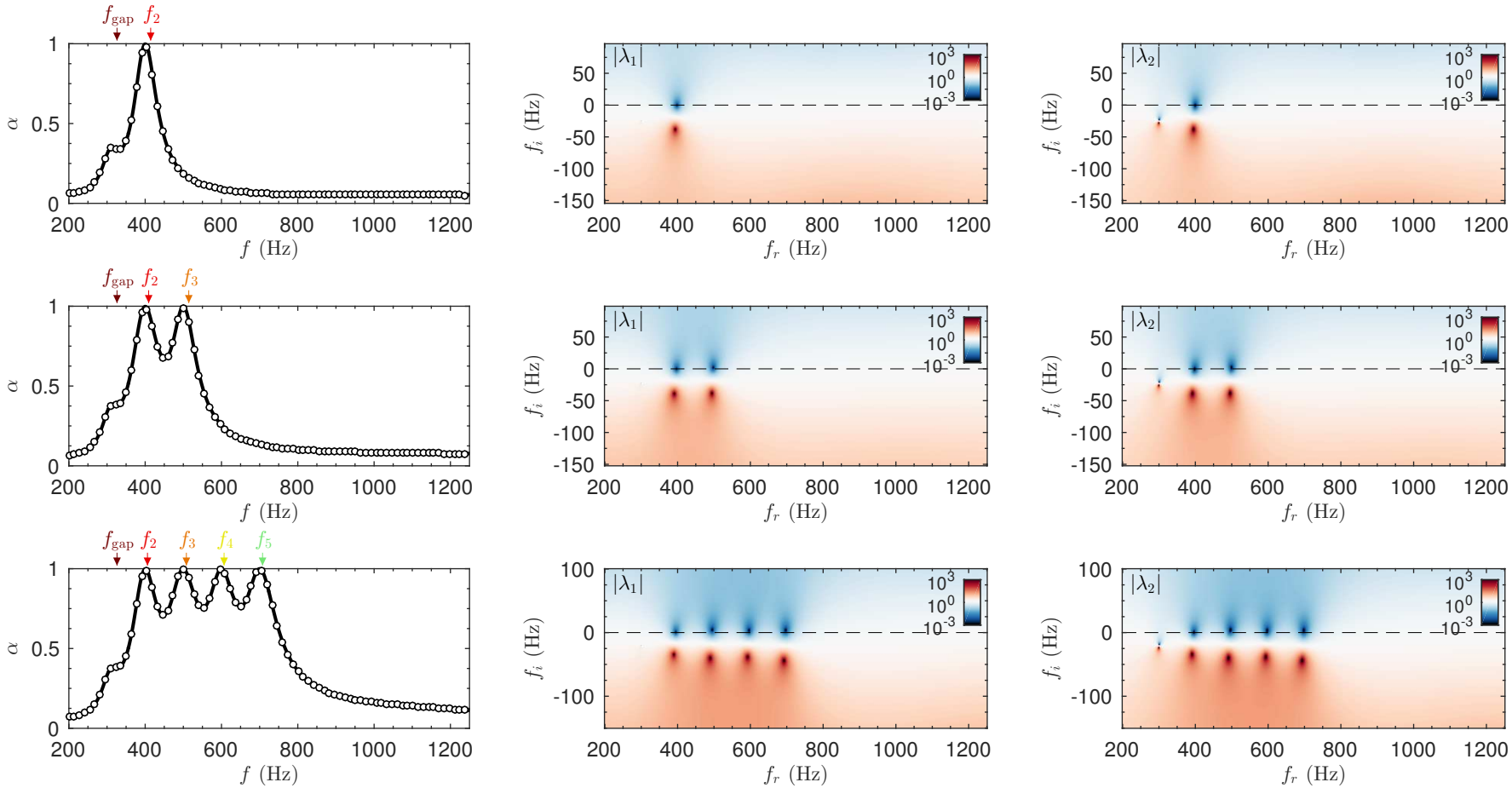
- Overlap of $N - 1 = 8$ peaks of perfect absorption
- Thickness of the panel $L = \lambda/12$ ($L = 10$ cm)



Rainbow trapping absorber

Asymmetric broadband and perfect absorption:

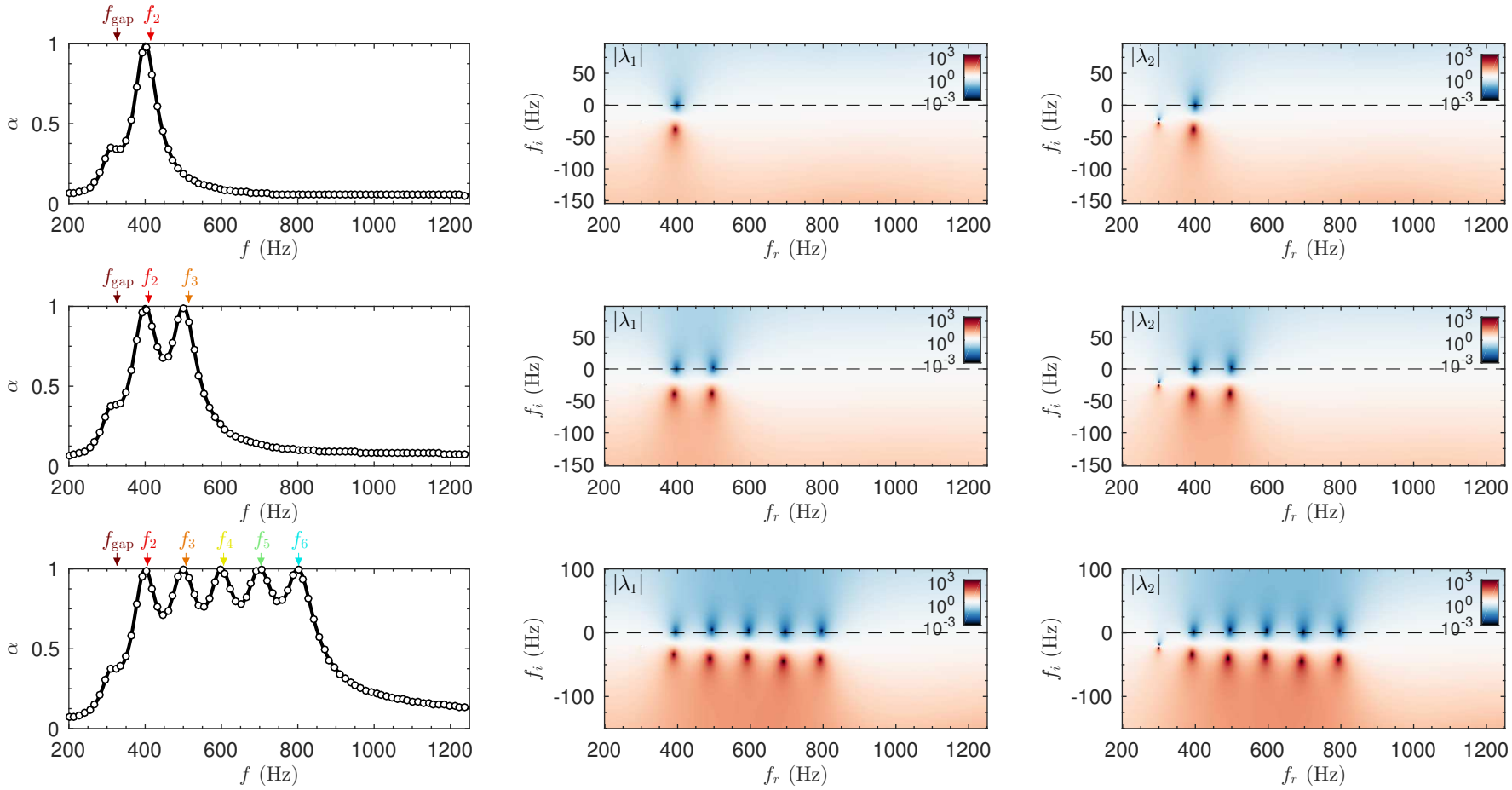
- Overlap of $N - 1 = 8$ peaks of perfect absorption
- Thickness of the panel $L = \lambda/12$ ($L = 10$ cm)



Rainbow trapping absorber

Asymmetric broadband and perfect absorption:

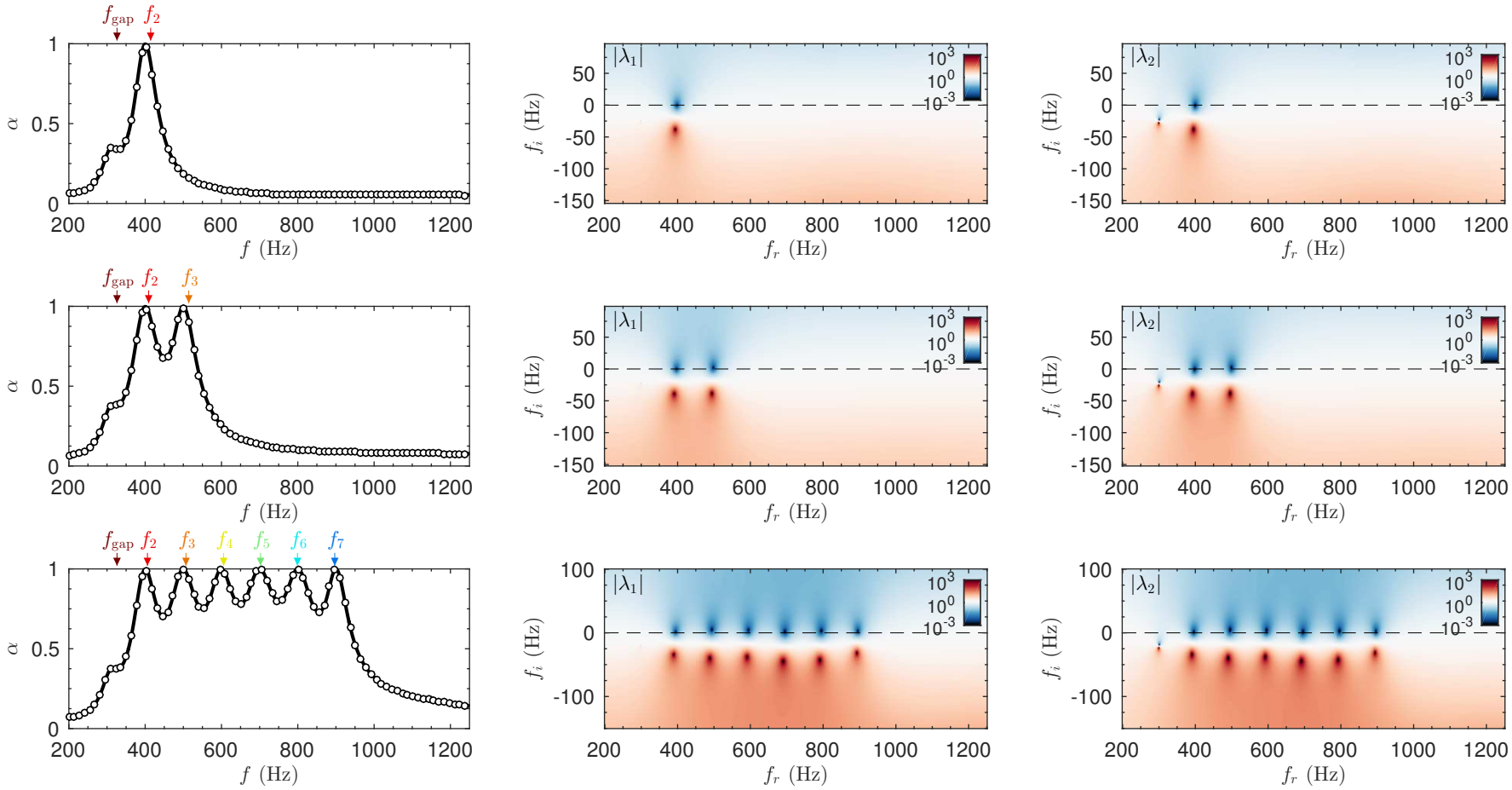
- Overlap of $N - 1 = 8$ peaks of perfect absorption
- Thickness of the panel $L = \lambda/12$ ($L = 10$ cm)



Rainbow trapping absorber

Asymmetric broadband and perfect absorption:

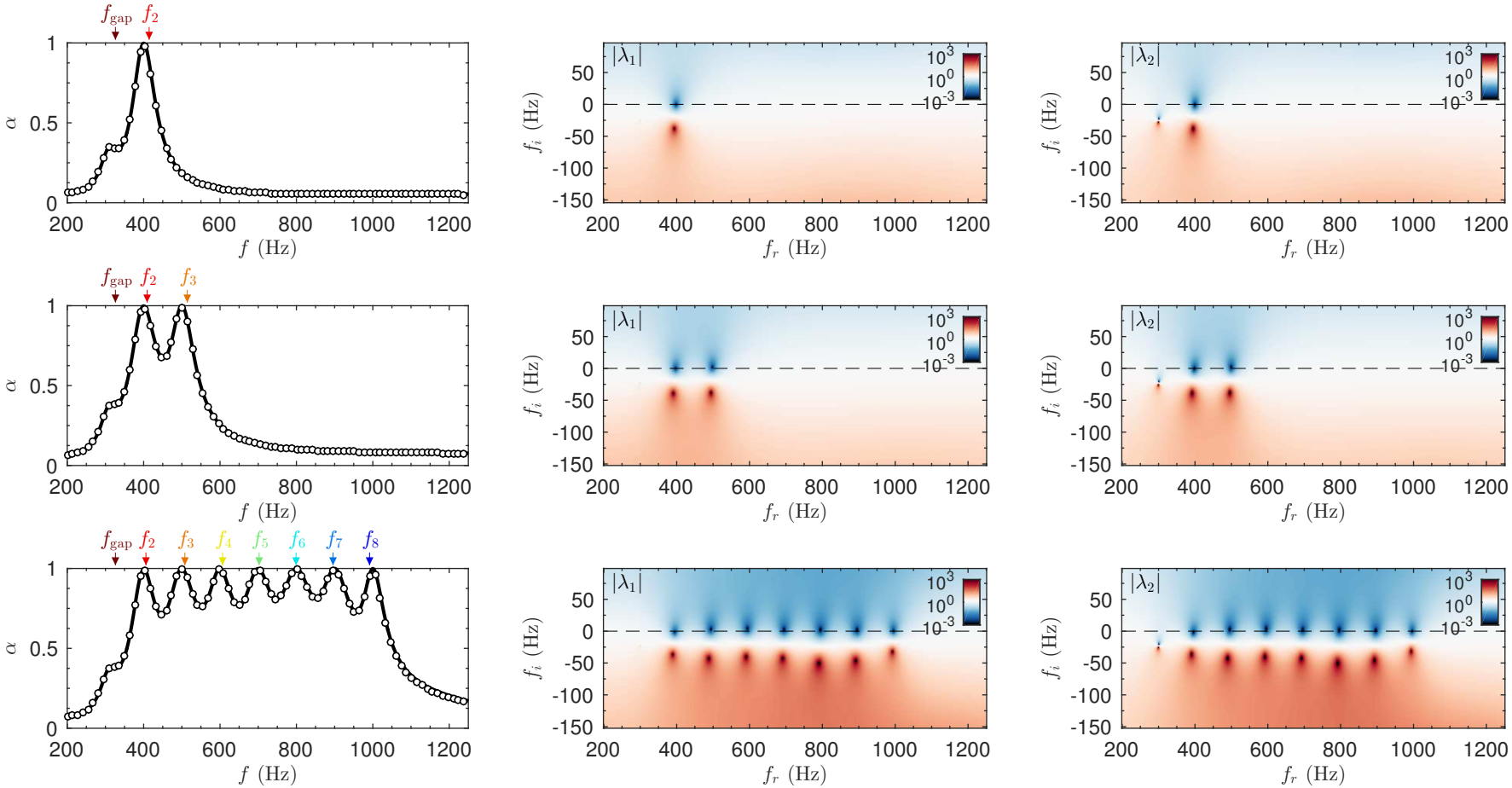
- Overlap of $N - 1 = 8$ peaks of perfect absorption
- Thickness of the panel $L = \lambda/12$ ($L = 10$ cm)



Rainbow trapping absorber

Asymmetric broadband and perfect absorption:

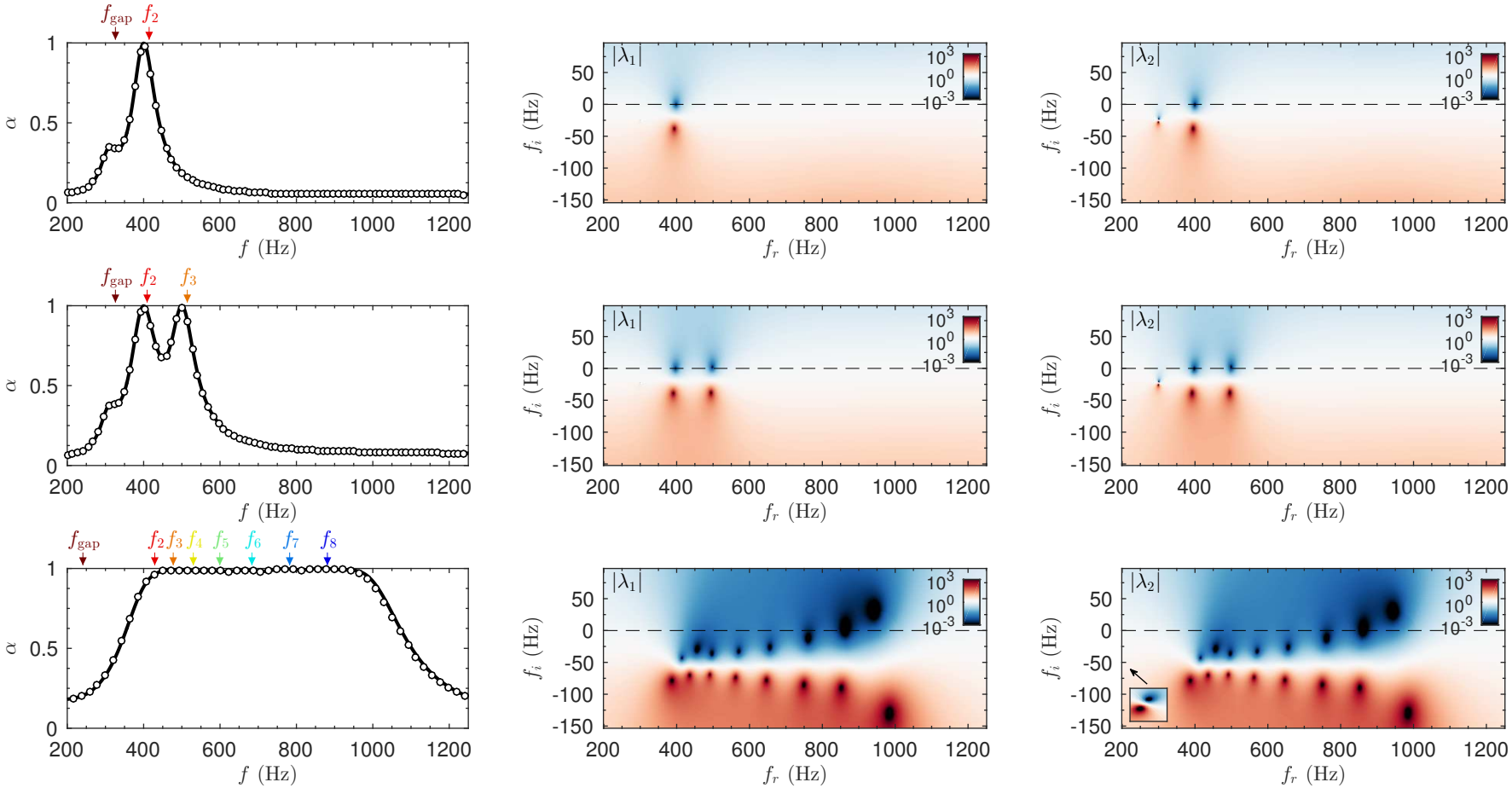
- Overlap of $N - 1 = 8$ peaks of perfect absorption
- Thickness of the panel $L = \lambda/12$ ($L = 10$ cm)



Rainbow trapping absorber

Asymmetric broadband and perfect absorption:

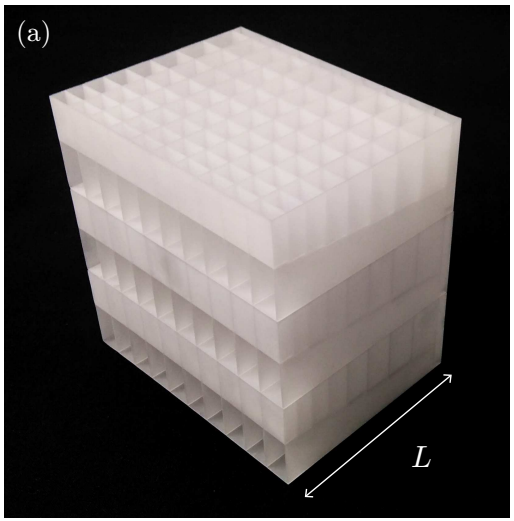
- Overlap of $N - 1 = 8$ peaks of perfect absorption
- Thickness of the panel $L = \lambda/12$ ($L = 10$ cm)

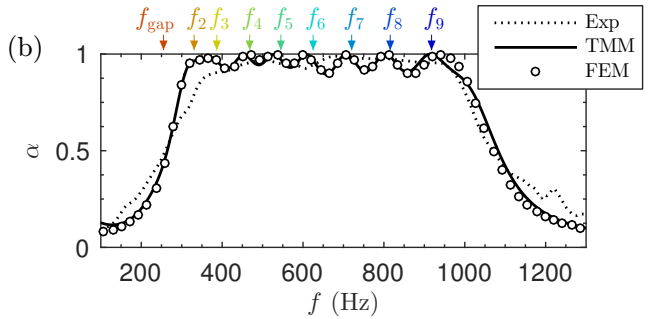


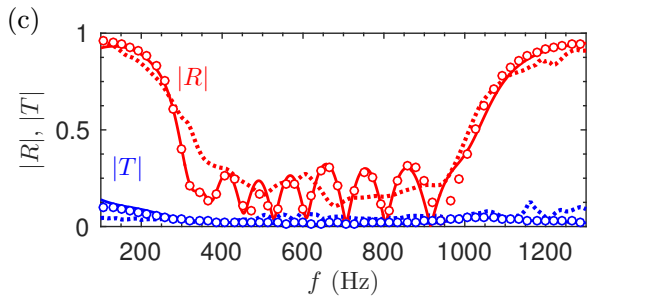
Experimental verification

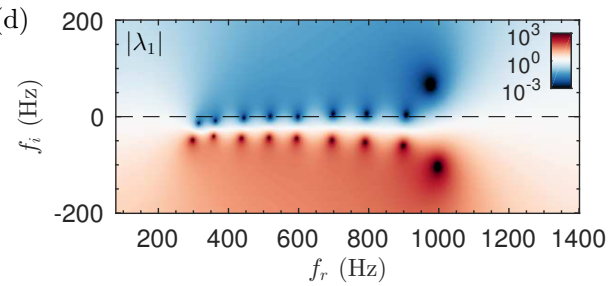
Asymmetric broadband and perfect absorption:

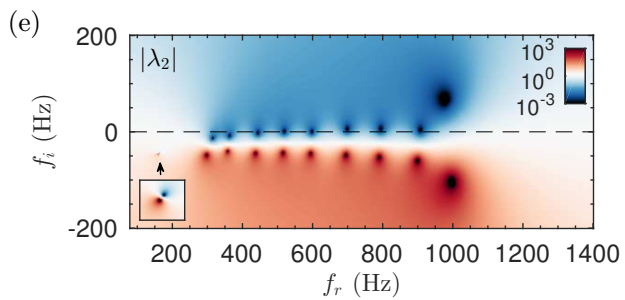
- Overlap of $N - 1 = 8$ peaks of perfect absorption
- Thickness of the panel $L = \lambda/12$ ($L = 10$ cm)
- Experimental limitation: 3D printing device step 0.1 mm





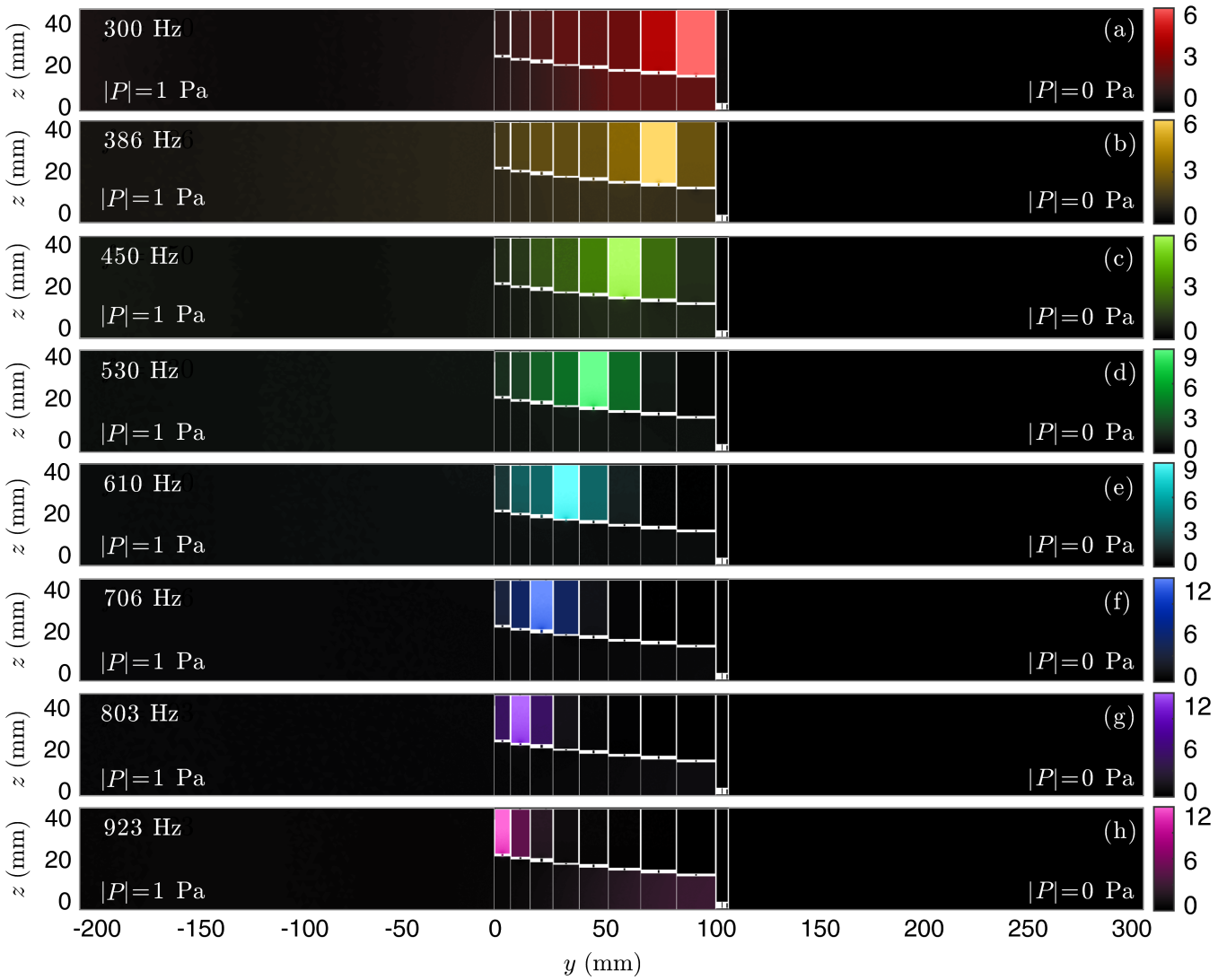






Rainbow trapping effect

Energy density for each resonance is localized in a position:



Conclusions

1. **Subwavelength Perfect Absorbers**
   - Reflection problems: Ultra-thin panel ▶ $L = \lambda/86$
   - Transmission problems: Subwavelength asymmetric panel ▶ $L = \lambda/40$
   - Broadband problem in transmission: Rainbow trapping absorber ▶ $L = \lambda/12$

Conclusions

1. **Subwavelength Perfect Absorbers**
   - Reflection problems: Ultra-thin panel ▶ $L = \lambda/86$
   - Transmission problems: Subwavelength asymmetric panel ▶ $L = \lambda/40$
   - Broadband problem in transmission: Rainbow trapping absorber ▶ $L = \lambda/12$

2. **Metamaterials**: based on Helmholtz resonators
   - Versatile: broad range of problems
   - HR: age, harsh environments
   - Open and void materials: lightweight, transparent to light, air flows
   - High degree of freedom: multifunctional optimization, structural, aesthetics
   - Manufacture: complex 3D structures ...

Project funded by the Metaudible ANR project ANR-13-BS09-0003

Thanks for your attention!

Find extended details in

Noé Jiménez[1,*], V Romero-García[1], V Pagneux[1], JP Groby[1], *Sci. Rep.* 7(1) 5389 (2017)

[1] Laboratoire d'Acoustique de la Université du Maine, UMR CNRS-6613 (France)

[*] *Now at*: Instituto de Instrumentación para Imagen Molecular (i3M), CSIC - UPV (Spain)