Rainbow-trapping absorbers for transmission problems: broadband and perfect sound absorbing panels

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Metastructures for noise and vibration control
ICSV 24, 25th July 2017

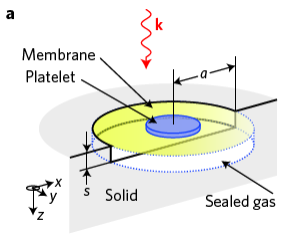


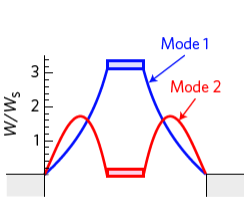




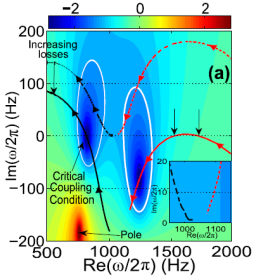
Motivation

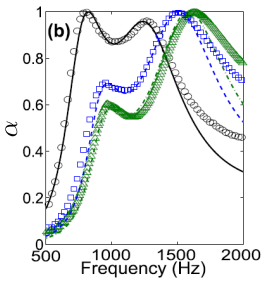
- Several solutions were proposed for perfect absorption in reflection problems



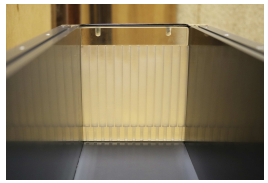


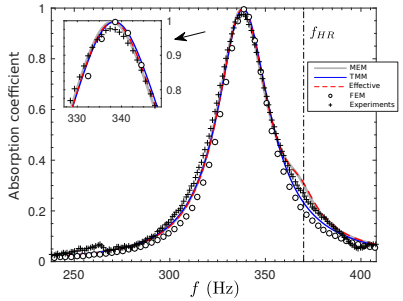
Nature Mat. 13, 813 (2014)





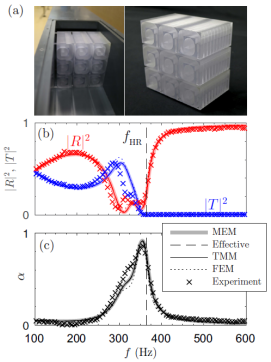
Scientific Rep. 15519 (2016)



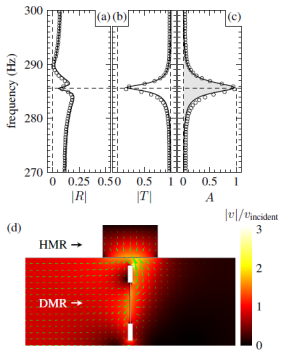


Appl. Phys. Lett., 121902 (2016)

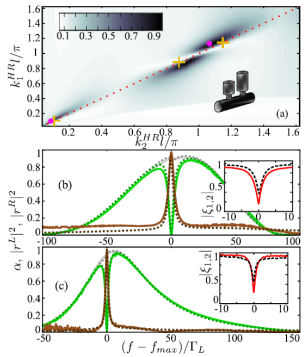
- Only a few solutions were proposed for transmition problems



Phys. Rev. B, 04205 (2017)



Appl. Phys. Lett., 104104 (2015)

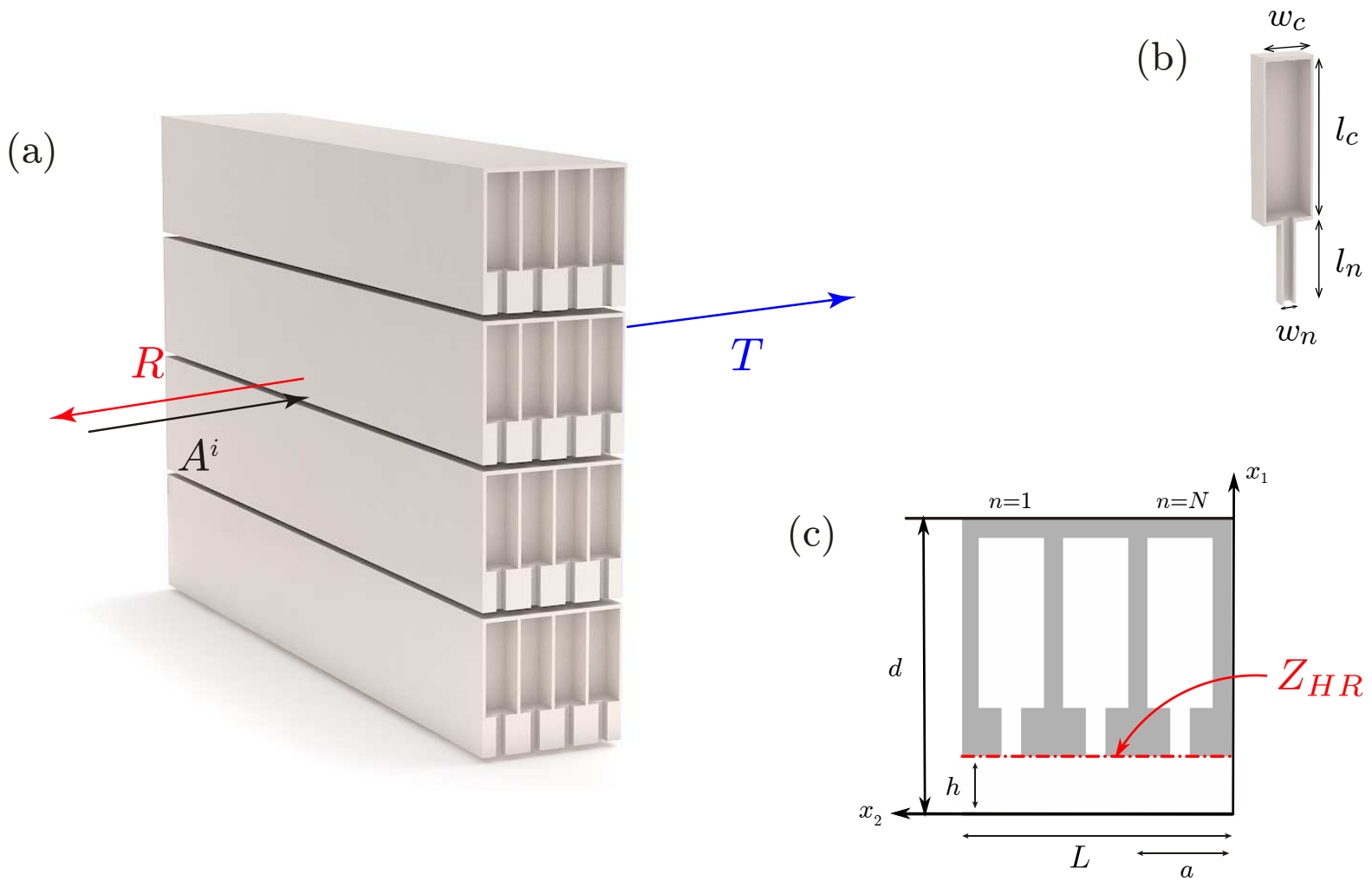


Appl. Phys. Lett., 244102 (2015)

⇒ Can we design deep-subwavelength broadband perfect absorber for ventilation configurations with slow sound or detuned resonators?

Description of the configuration

Periodic arrangement of slits loaded by Helmholtz resonators (HR)



⇒ Losses are accounted for in the slits and in the HR elements

⇒ Correction lengths in HRs and for slit radiations are accounted for

Solution of the problem

- Modal expansion method (MEM):
  Bloch waves, $k_{1q}^a = k_1^i + 2q\pi/d$ + modal expansion in the slit

$$p^a(\mathbf{x}) = \sum_{q\in\mathbb{Z}} \left[A^i e^{-\mathrm{i}k_{2q}^a(x_2-L)}\delta_q + R_q e^{\mathrm{i}k_{2q}^a(x_2-L)} \right] e^{\mathrm{i}k_{1q}^a x_1} \ ,$$

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

  $\Rightarrow$ Effective parameters can be derived

$$\rho_{eff} = \frac{\rho_s}{\phi} \quad , \quad K_{eff} = \frac{K_s}{\phi}\left[\left(1 + \frac{K_s\left(V_c K_n + V_n K_c\right)\phi_n}{K_n h\left(S_n K_c - V_c\rho_n\omega^2 I_n\right)}\right)\right]^{-1} \ ,$$

  where $\phi = h/d$ and $\phi_n = w_n^2/a^2$.

- Transfert matrix method (TMM)

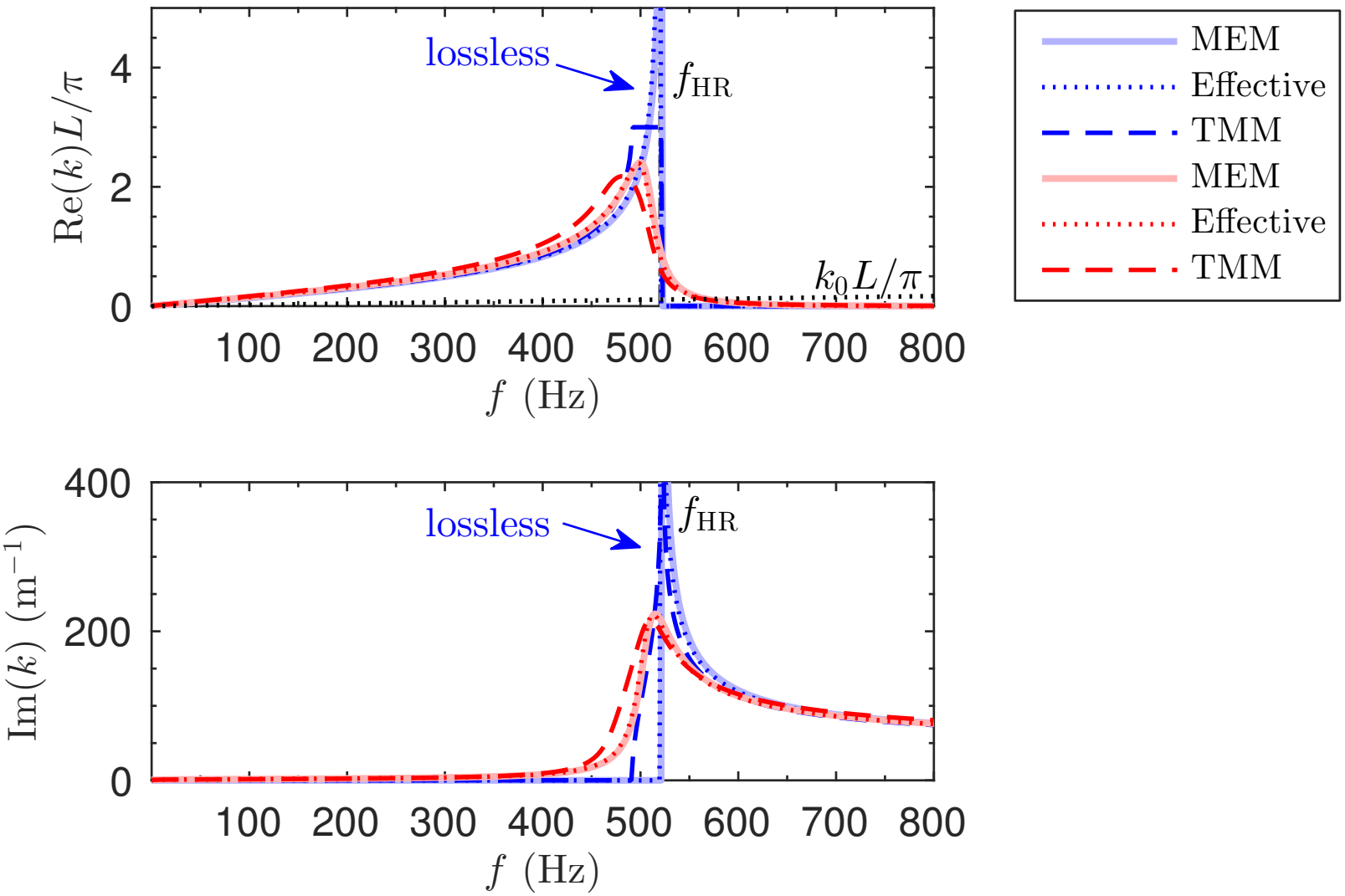
$$\mathcal{T} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} = \left(M_{HR}M_s\right)^{N-1} M_{HR}, \text{ with } M_{HR} = \begin{pmatrix} 1 & 0 \\ 1/Z_{HR} & 1 \end{pmatrix},$$

  and M_s the propagation matrix.

- Finite-Element method (Comsol ®Multiphysics)

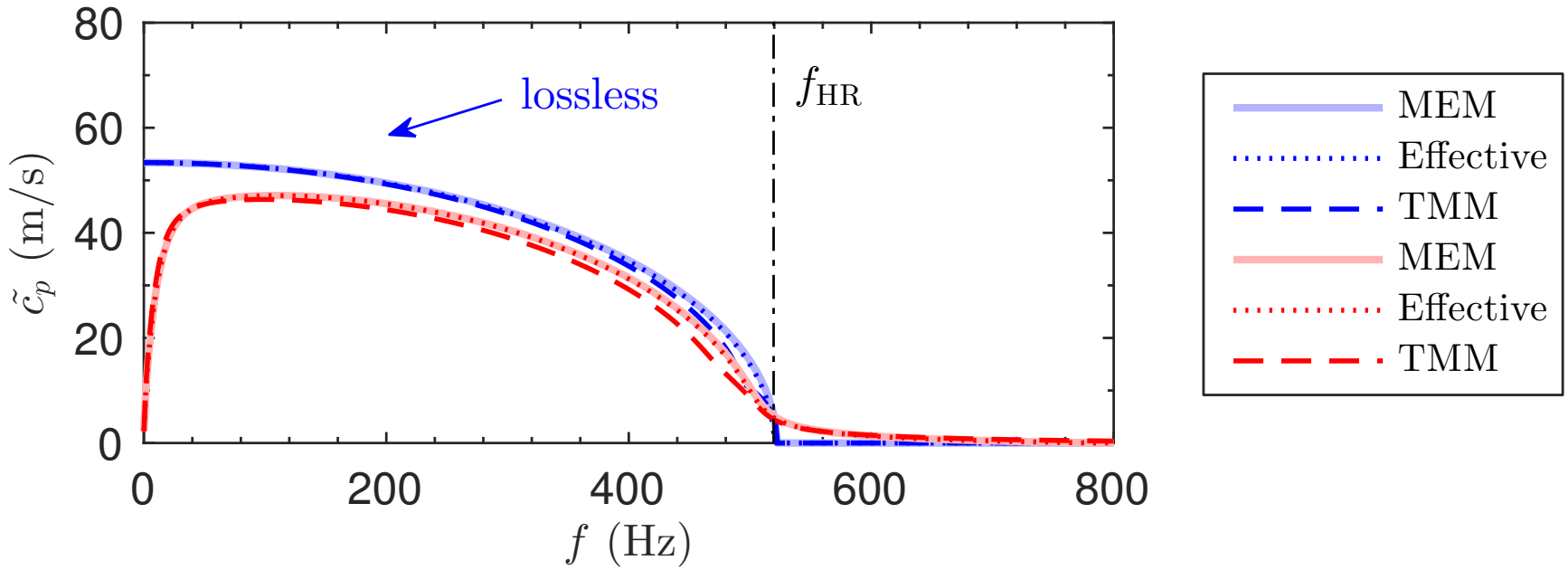
Dispersion relation in the slit

$h = 1.2$ mm, $a = 1.2$ cm, $w_n = a/6$, $w_c = a/2$, $d = 7$ cm, $l_n = d/3$, and $l_c = d - h - l_n$.



Evidence of slow sound

We look at $\mathrm{Re}\,(\tilde{c}_p) = \mathrm{Re}\,(\omega/k)$, the speed of sound travelling in the slit



Sound speed & attenuation can be tuned by $\dfrac{V_{tot}\phi^n}{hS_n}$ at low frequency

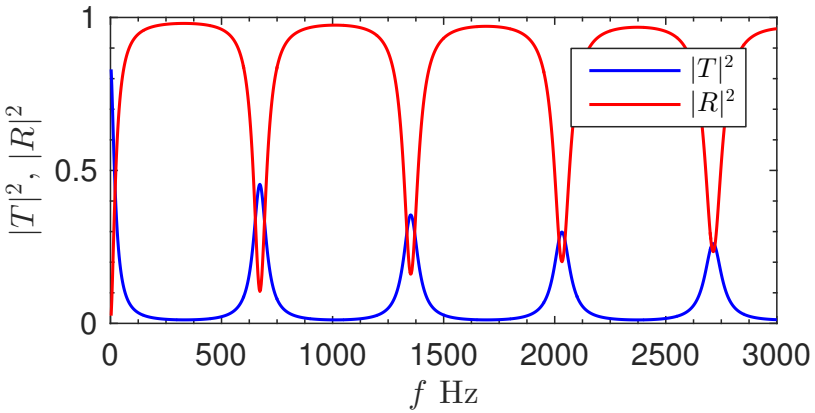
In absence of losses : $c_p = \dfrac{c^a}{\sqrt{1 + \dfrac{V_{tot}\phi^n}{hS_n}}}$.

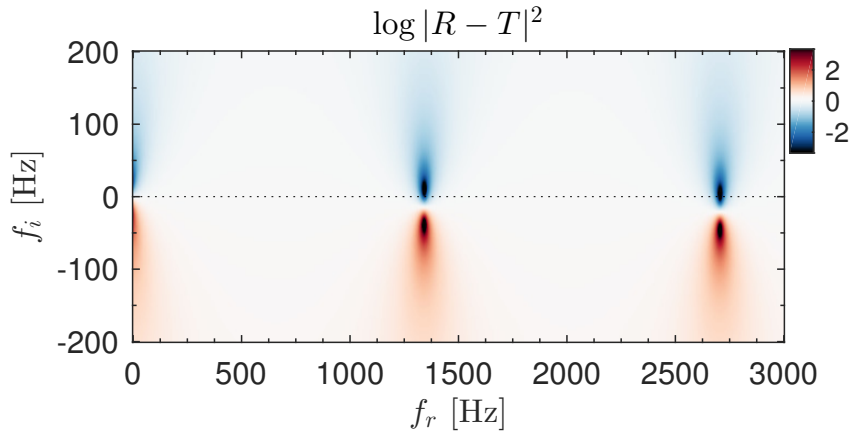
The main difficulty in ventillation problem

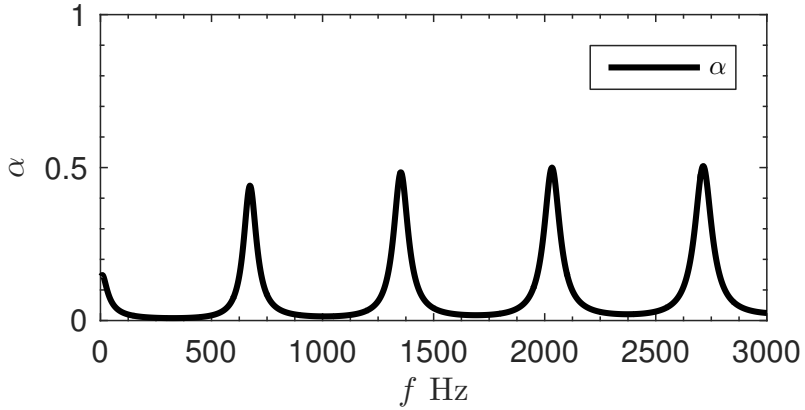
Slit: $h = 3.8$ mm, $L = 25$ cm, $d = 15$ cm

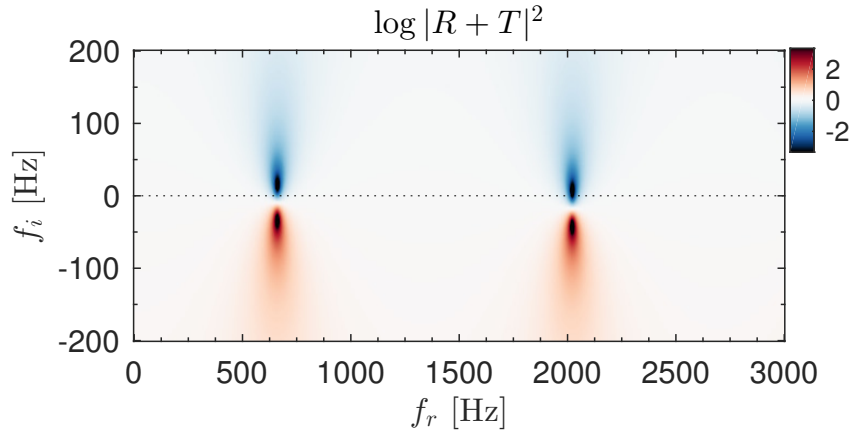
Zeros of the $|R_{sym}| = |R - T|$ and $|R_{asym}| = |R + T|$ are staggered

$\alpha = (\alpha_{sym} + \alpha_{asym})/2$, so $\alpha_{max} \geq 0.5$: the goal is $\alpha_{max} = 1$





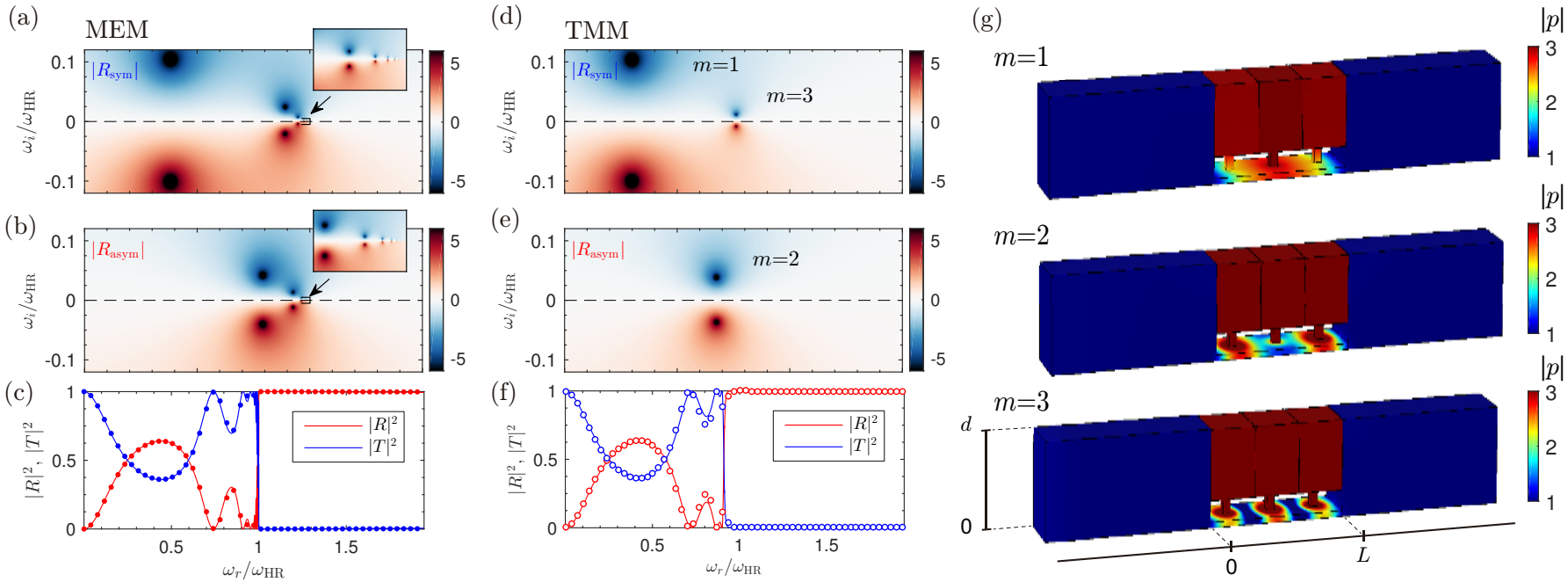




$\Rightarrow$ Use slow sound to accumulate the resonances for sound absorption

Are all the models really equivalent?

Lossless case, $N = 3$: $h = 1.2$ mm, $a = 4.95$ cm, $w_n = 7.1$ cm, $w_c = 4.9$ mm, $d = 5$ cm, $l_n = 7.3$ cm, and $l_c = 12.33$ cm.

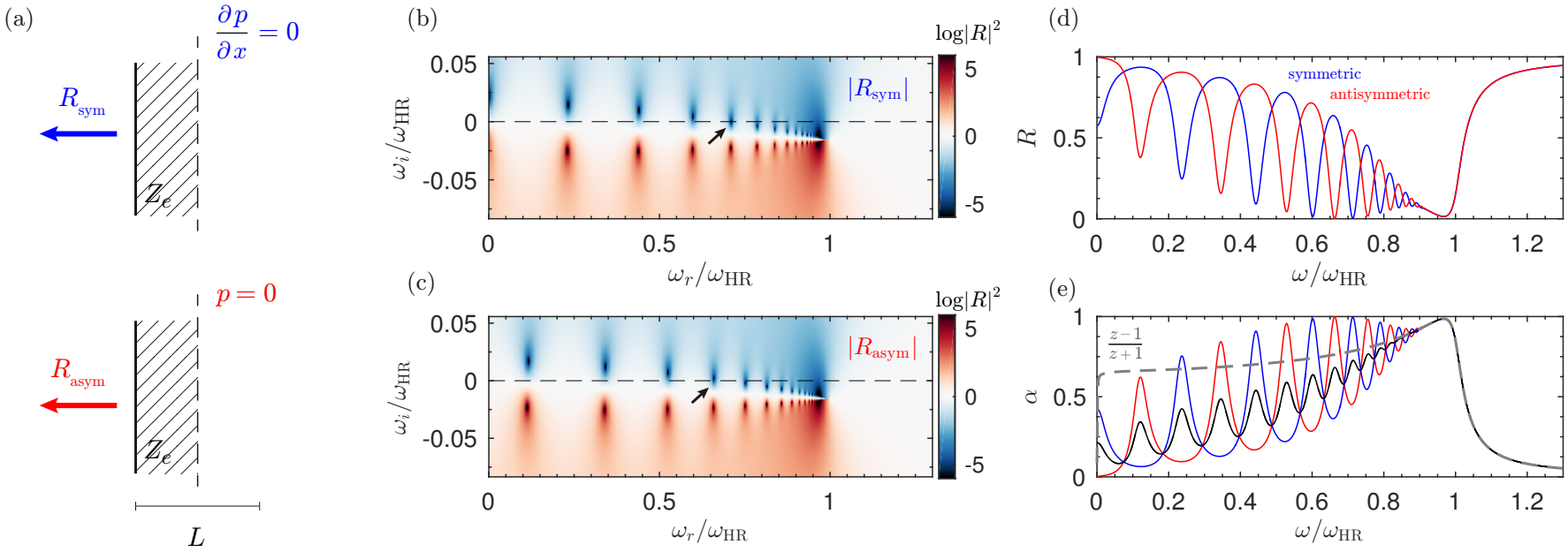


$\Rightarrow$ Models based on Z_{HR} present an infinite number of zeros which are not physical

$\Rightarrow$ Only the TMM accounts for the finite number of resonators and therefore of zeros

Evidence of the accumulation point

$N = 30$: $h = 1.2$ mm, $a = 4.95$ cm, $w_n = 7.1$ cm, $w_c = 4.9$ mm, $l_n = 7.3$ cm, and $l_c = 12.33$ cm, $d = 5$ cm, $L = 30a$.

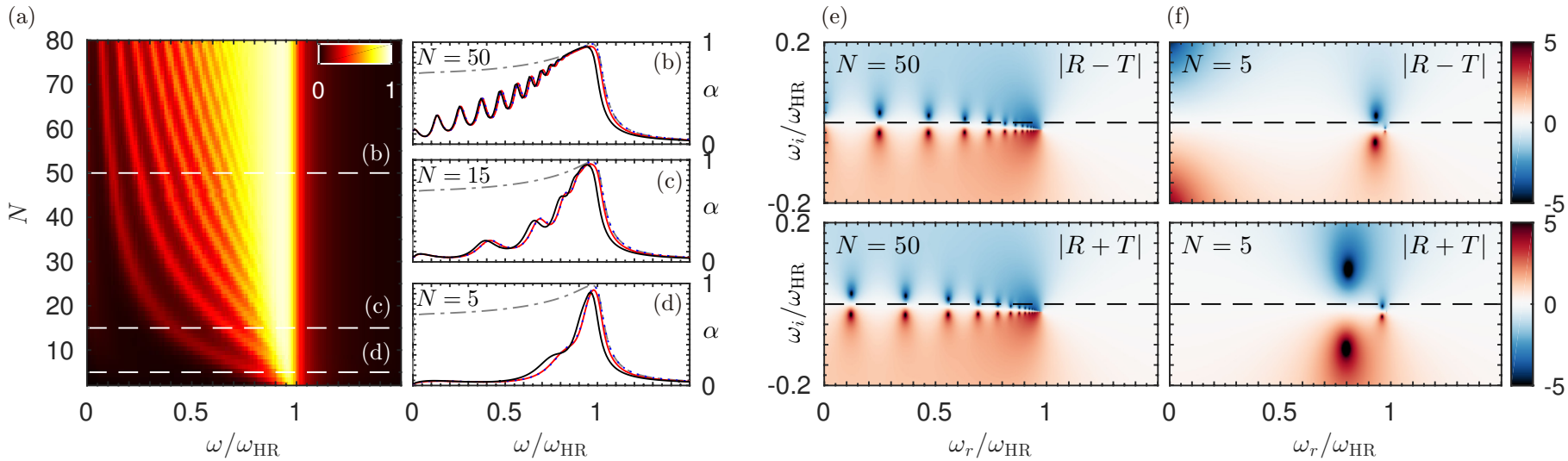


$\Rightarrow$ Accumulation point corresponds to $Z_{eff} = Z^a$, which means that perfect absorption is impossible because $\mathrm{Im}\,(Z_{eff}) \neq 0$

$\Rightarrow$ Accumulation point: $T \approx 0$ (entrance of the band gap) and $R \approx 0$ (Fabry-Perot)

Quasi-perfect absorption

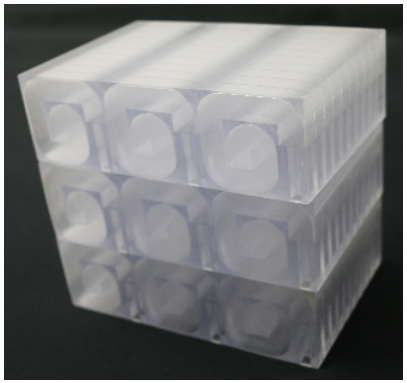
$h = 1.2$ mm, $a = 4.95$ cm, $w_n = 7.1$ cm, $w_c = 4.9$ mm, $d = 5$ cm, $l_n = 7.3$ cm, and $l_c = 12.33$ cm, $L = Na$.

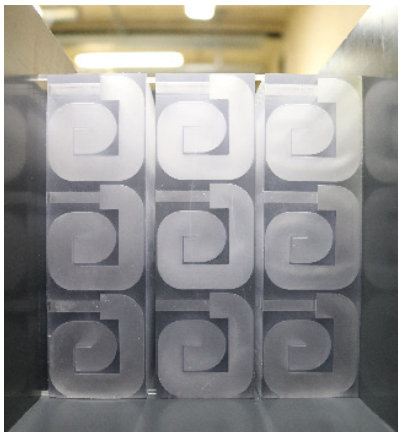


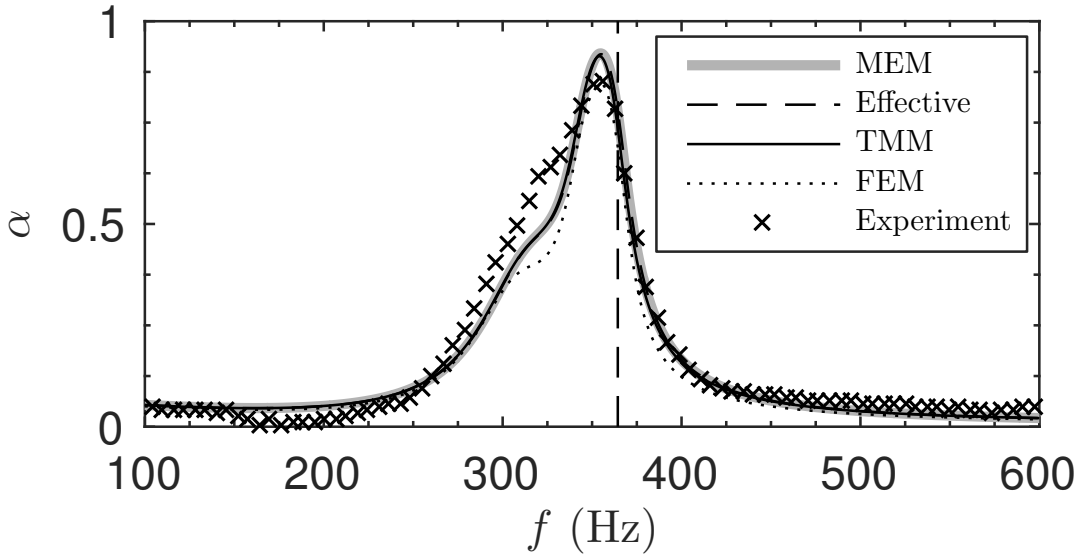
$\Rightarrow$ Quasi-perfect absorption is possible but cannot be deep sub-wavelength

Experimental validation

$N = 10$: $h = 4.4$ mm, $a = 9.8$ mm, $w_n = 5.3$ cm, $w_c = 9.3$ mm, $l_n = 2.5$ cm, and $l_c = 13.9$ cm, $d = 4.96$ cm, $L = 9.8$ cm.



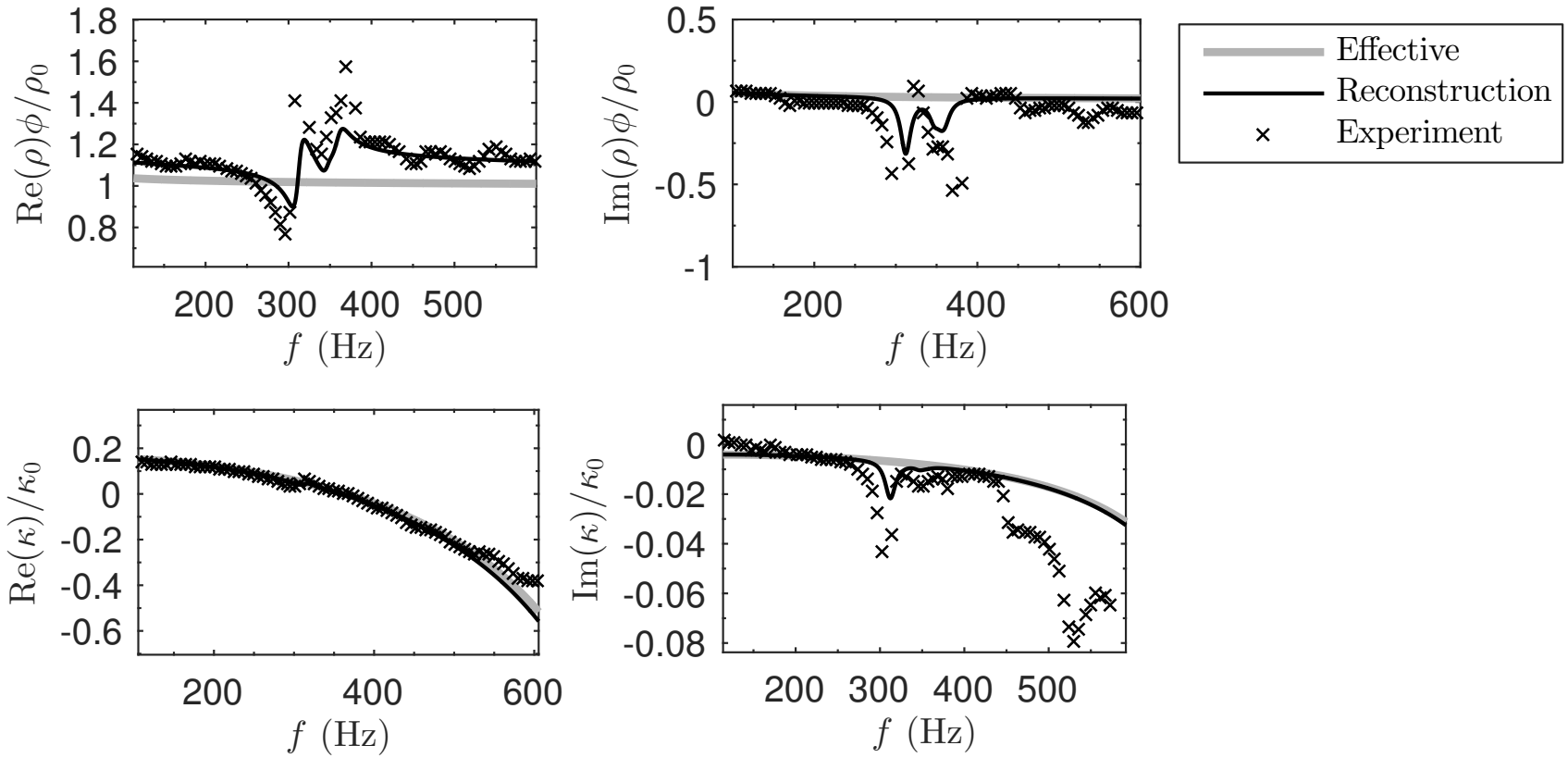




$\Rightarrow \alpha = 0.9$ for $L \approx \lambda^a/10$, with coiled HR

Effective parameters

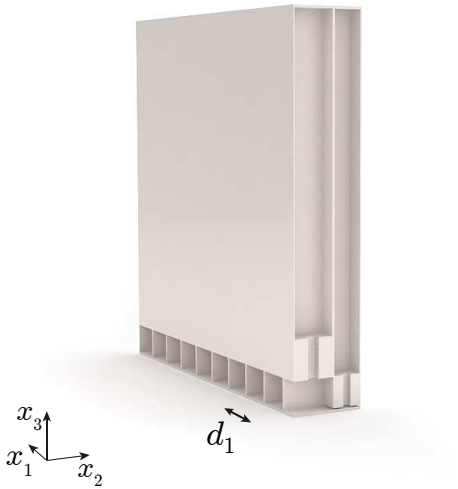
Nicolson method (IEEE Trans. Instrum. Meas., 1970) to recover ρ_{eff} and K_{eff}

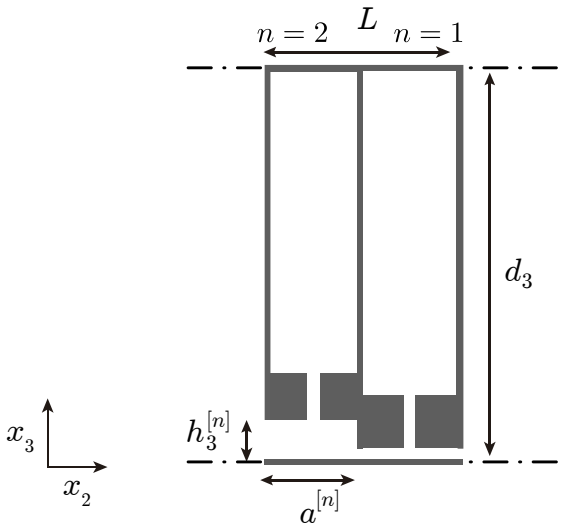


$\Rightarrow$ Low frequency slow sound is due to a lower bulk modulus

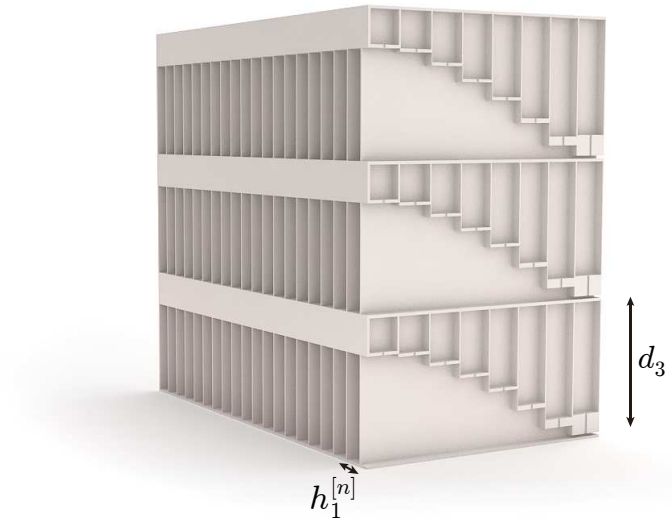
Description of the configuration

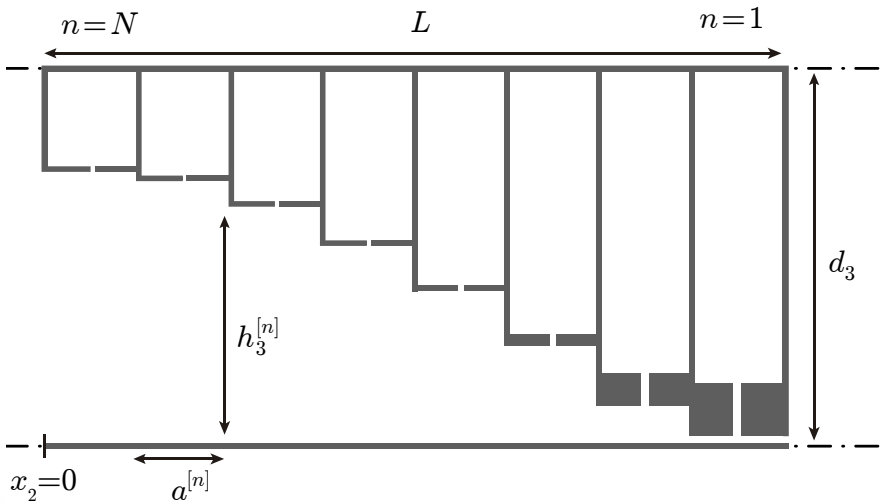
(a) Subwavelength asymetric panel (SAP)





(b) Rainbow-trapping absorber (RTA)





$\Rightarrow$ Losses are accounted for in the duct and HR elements

$\Rightarrow$ Correction lengths are accounted for in the HR and duct elements

Solution of the problem

- Modal expansion based on effective impedance as well as effective parameter description cannot be used, but it shows that in each duct element slow waves propagates

$$\rho_{eff} = \frac{\rho_d}{\phi} \quad , \quad K_{eff} = \frac{K_d}{\phi}\left[\left(1 + \frac{K_d\phi\left(V_c K_n + V_n K_c\right)\phi_n}{K_n h\left(S_n K_c - V_c \rho_n \omega^2 l_n\right)}\right)\right]^{-1} \quad ,$$

  where $\phi = h_3 h_1 / d_3 d_1$ and $\phi_n = w_n^2 / a^2$.

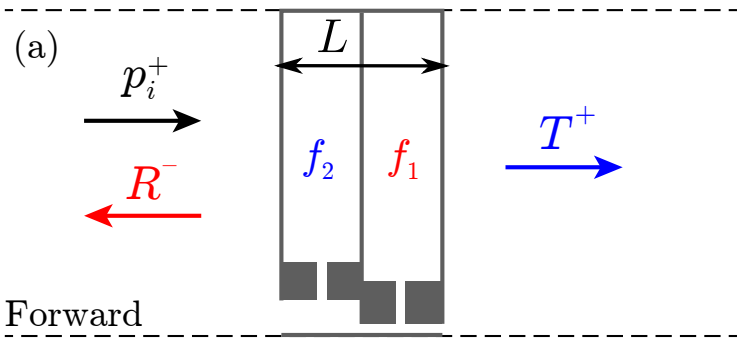
- Transfert Matrix Method (TMM) is prefered, because it accounts for the finite number of resonators

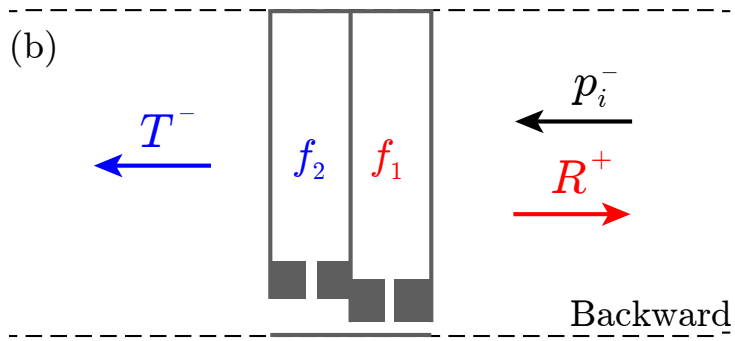
$$\mathcal{T} = M^{[1]}_{\Delta l_{\text{duct}}} \prod_{n=1}^{N} M^{[n]}_{\mathbf{s}} M^{[n]}_{\text{HR}} M^{[n]}_{\mathbf{s}} M^{[n+1]}_{\Delta l_{\text{duct}}}, \text{ with } M^{[n]}_{HR} = \begin{pmatrix} 1 & 0 \\ 1/Z^{[n]}_{HR} & 1 \end{pmatrix},$$

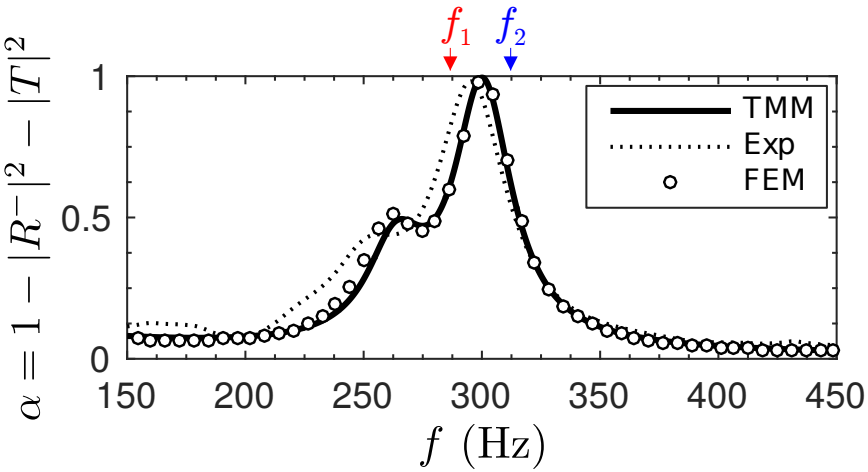
  $M_s^{[n]}$ the propagation matrix, and $M^{[n]}_{\Delta l_{\text{duct}}}$ accounts for the radiation correction of the n-th waveguide segment.

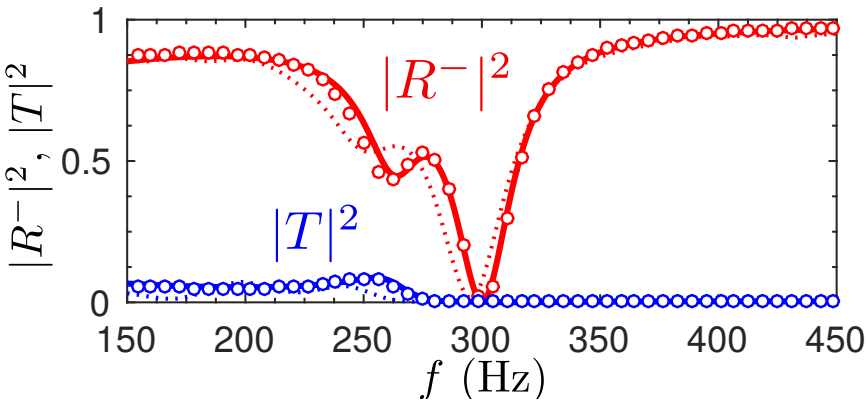
- Finite-Element method (Comsol ®Multiphysics)

Design of the Sub-wavelength Asymetric Panel







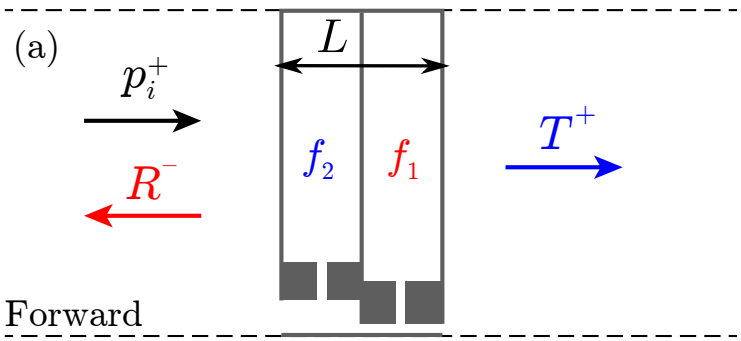


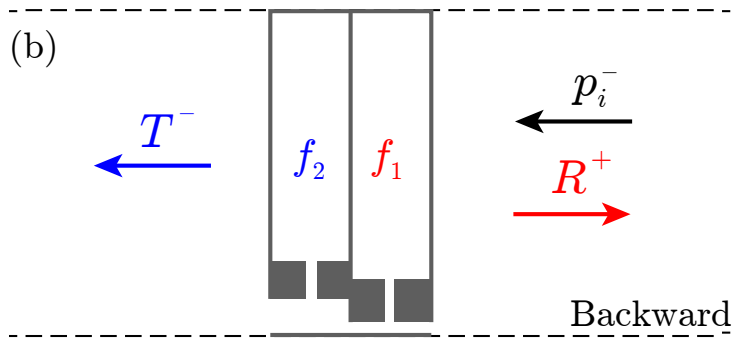
$f_1 < f_2$

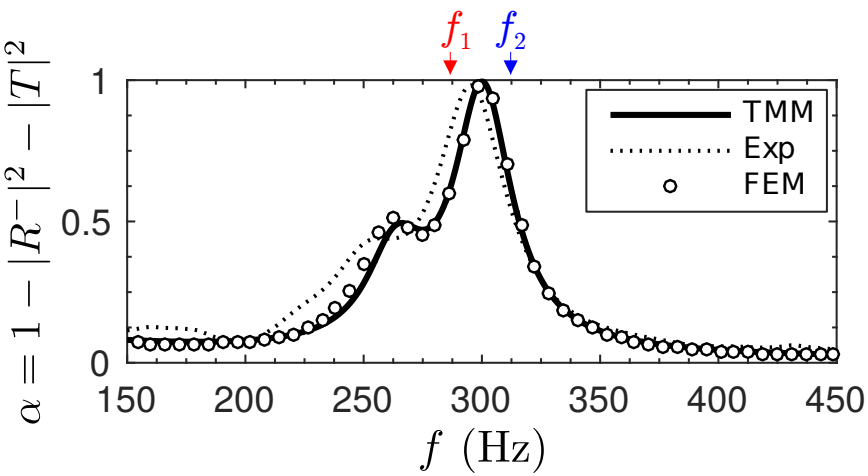
- when 1 resonate, a bandgap is open
- 2 is tuned to critically couple the system
- the duct section is also modified

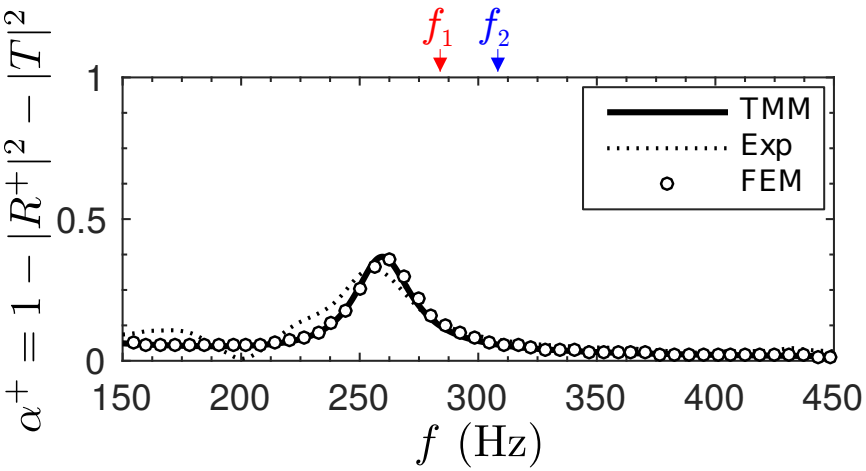
Perfect absorption is achieved for $L = 2.64$ cm, i.e., $\lambda_a \approx 40L$.

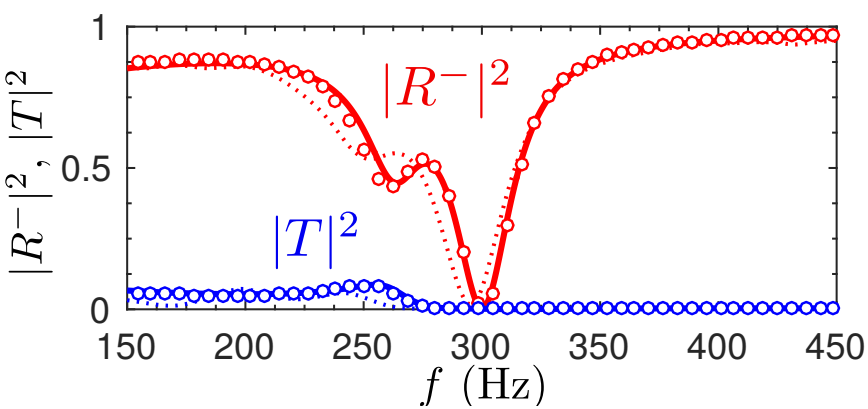
Design of the Sub-wavelength Asymetric Panel

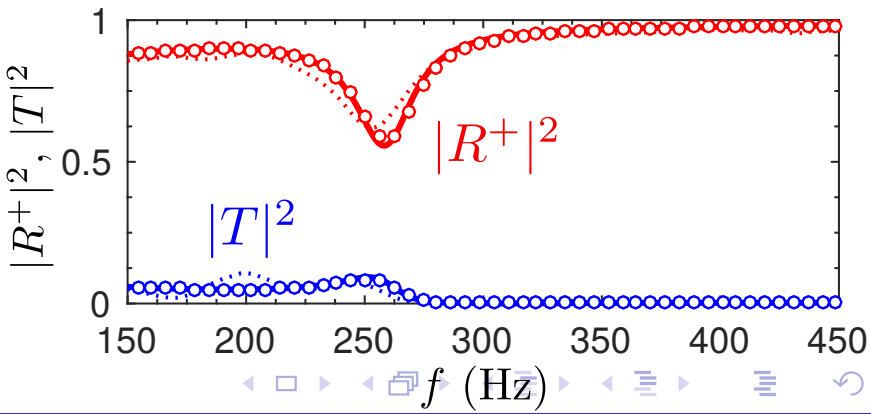




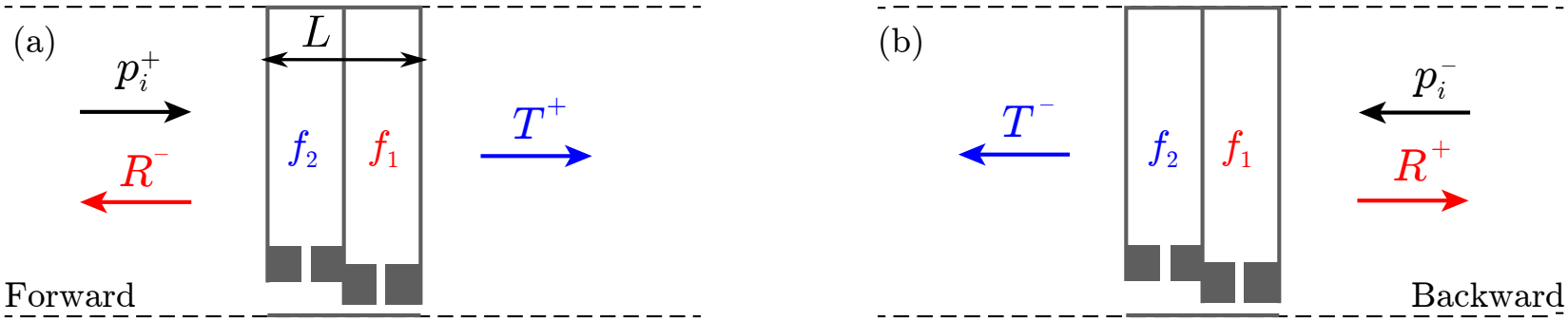








Analysis of the SAP



The system is analyzed through the scarreting matrix $\mathcal{S}$.
The system is reciprocal ($T^+ = T^- = T$) but antisymetric:

$$\mathcal{S} = \begin{pmatrix} T & R^- \\ R^+ & T \end{pmatrix}.$$

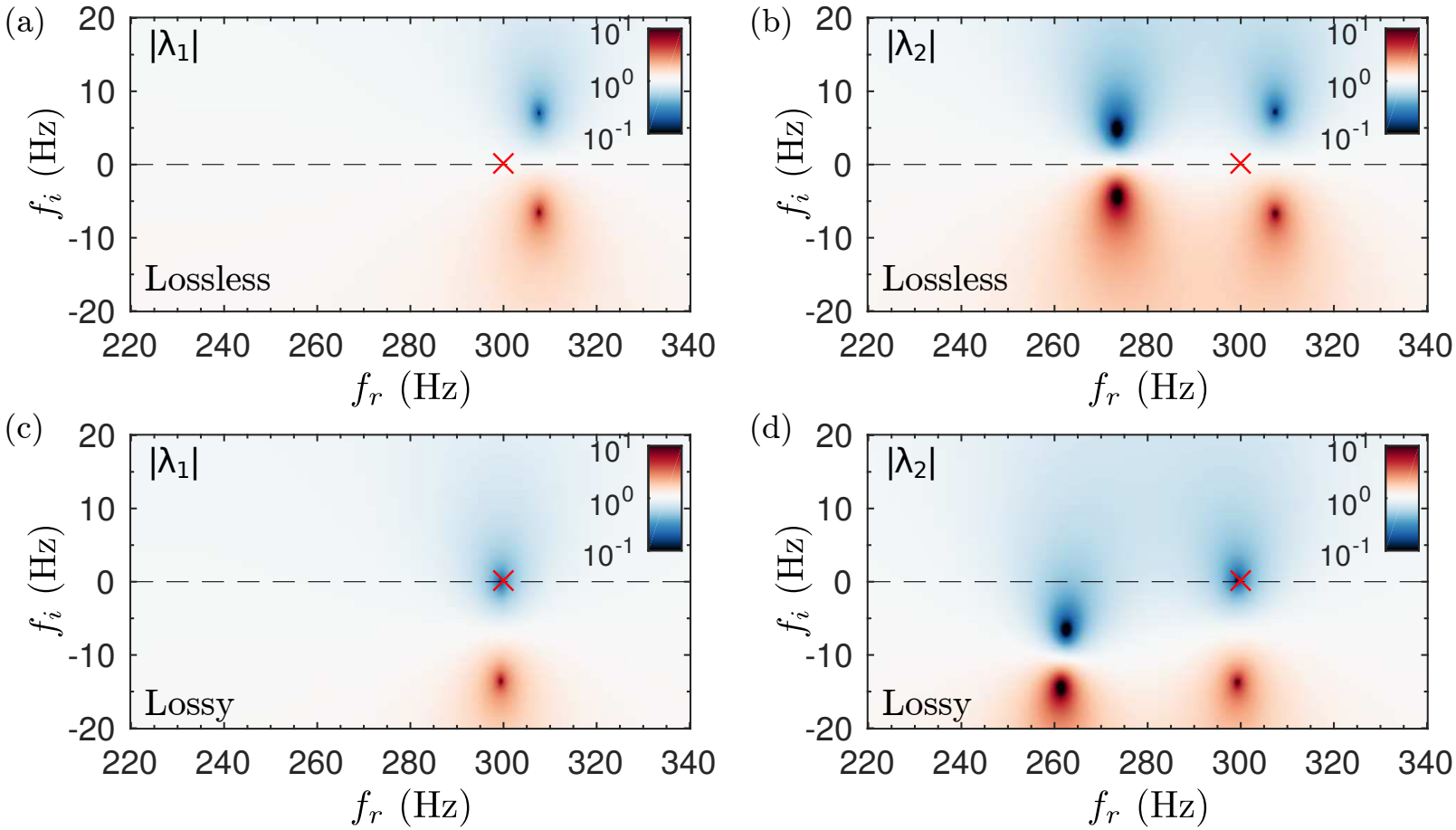
The scattering matrix possesses two eigenvalues

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

whose associated eigenvectors are

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

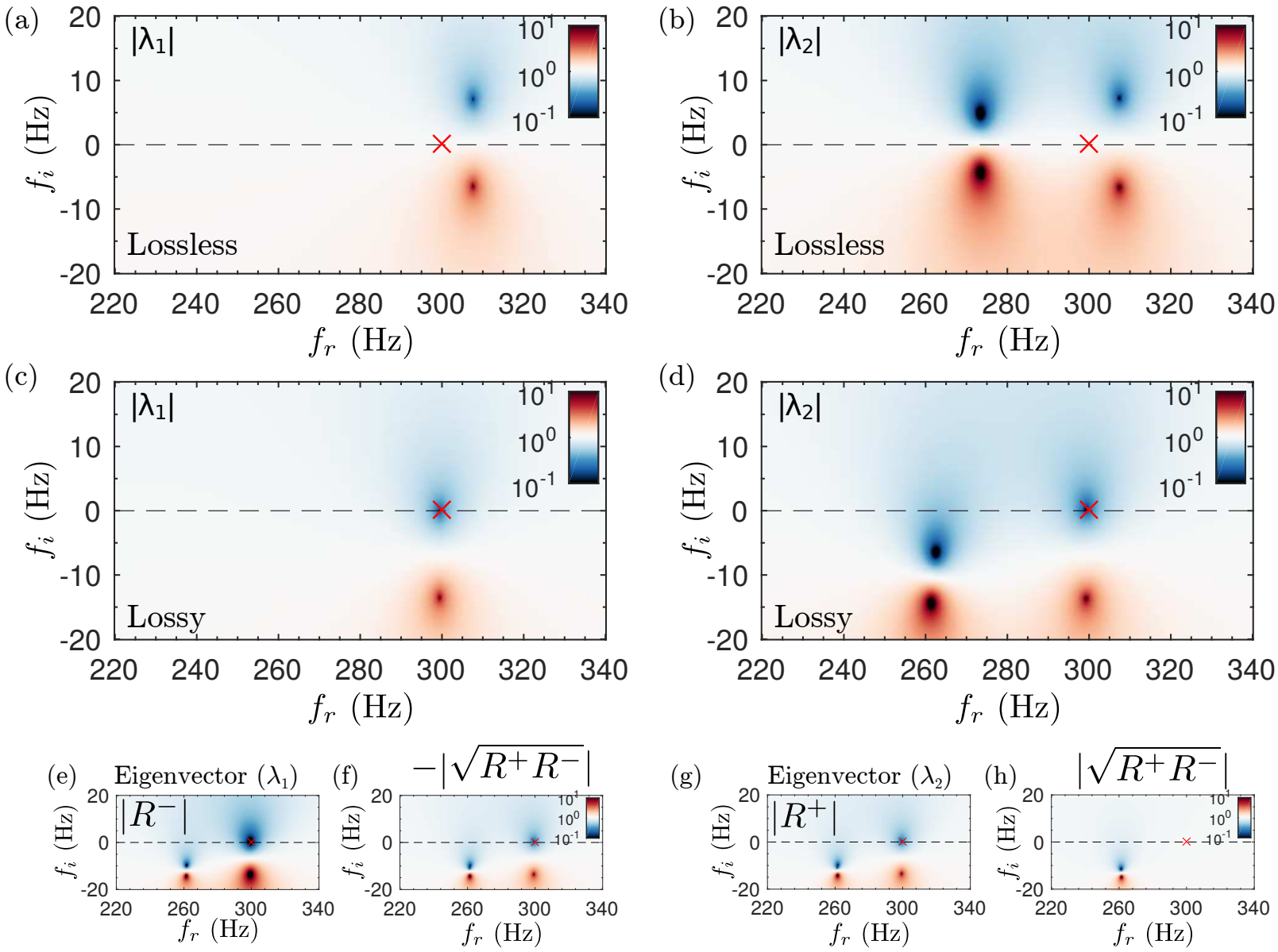
Analysis of the eigenvalues and eigenvectors



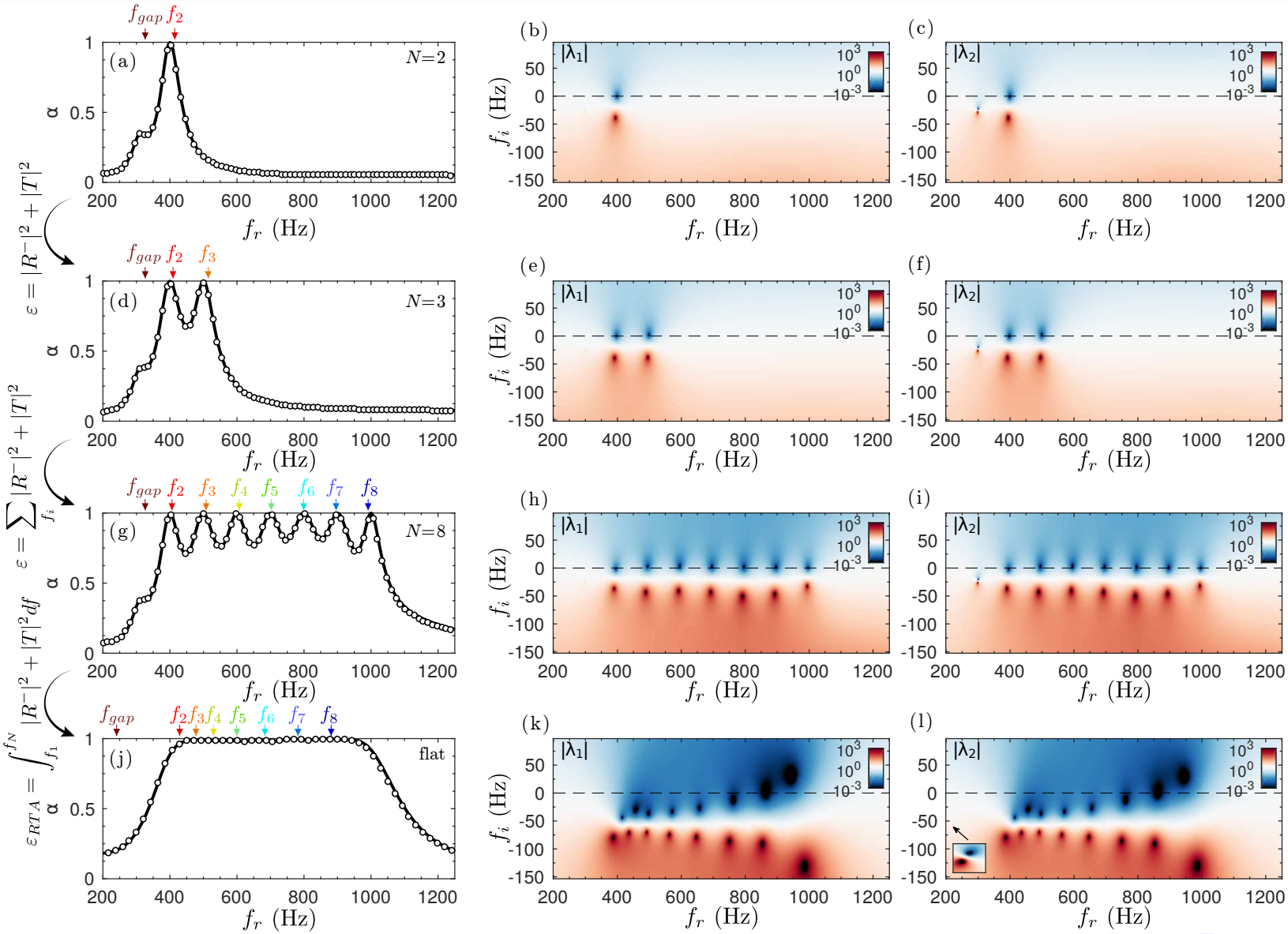
At $f \approx 300$ Hz both $\lambda_1 = \lambda_2 = 0$, i.e., perfect absorption

$\Rightarrow$ Which side the perfect absorption is produced?

Analysis of the eigenvalues and eigenvectors

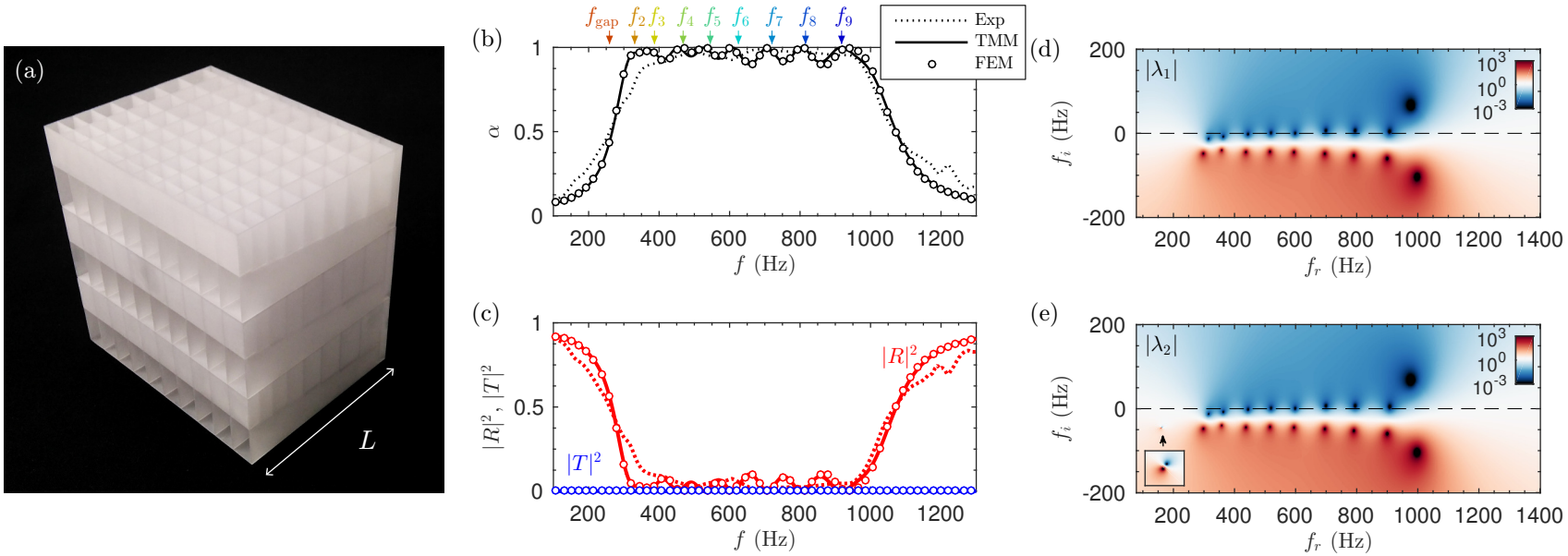


How to design a broadband perfect absorbers in ventilation problem?



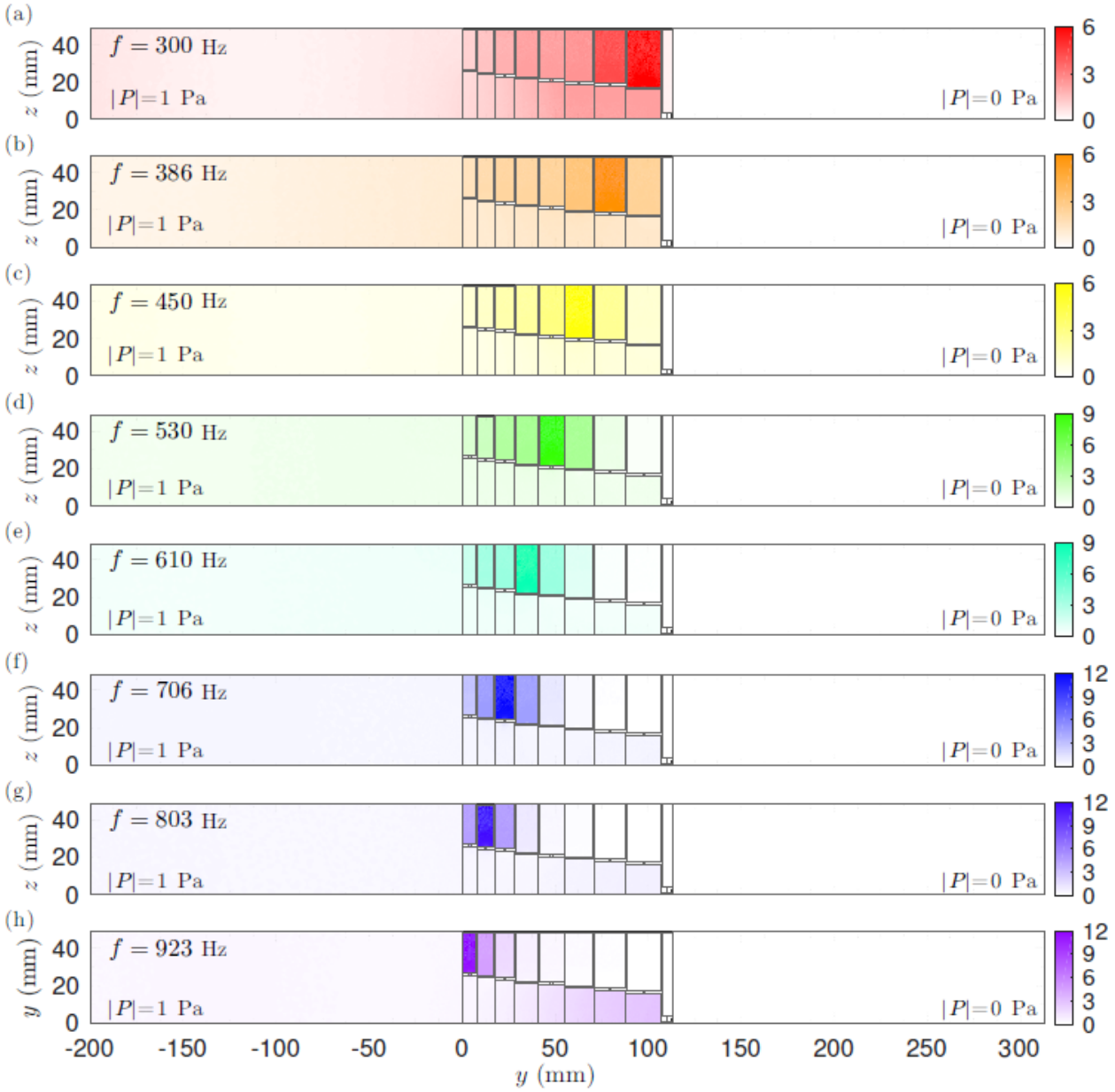
Experimental validation of the RTA

Due to precision of the available 3D printing system (the minimum step was 0.1 mm), the RTA presented previously cannot be easily manufactured.



Perfect absorption is achieved over $[300\ \text{Hz}, 1000\ \text{Hz}]$ for $L = 11.3\ \text{cm}$, i.e., $\lambda_a > 10L$.

Evidence of the Rainbow Trapping Absorber



Conclusion and perspectives

- For identical resonators
  - impossible to reach perfect absorption
  - only quasi-perfect absorption is possible for $\lambda^a \approx 10L$
  - effective parameters have to be manipulated with care

  $\Rightarrow$ Jimenez *et al.*, Phys. Rev. B, 95:014205, 2017
- Sub-wavelength Asymetric Panel which perfectly absorbed at ≈ 300 Hz for $\lambda_a \approx 40L$
  - perfect absorption is achieved when $\lambda_1 = \lambda_2 = 0$
  - incidence side for perfect absorption is determined by looking at $\vec{v}_1$ and $\vec{v}_2$
- Rainbow-trapping absorber which perfectly absorbed over $[300\ \text{Hz}, 1000\ \text{Hz}]$ for $\lambda_a > 10L$
  - the design procedure of the SAP is repeated in cascade
  - the flat absorption is not only due to critical coupling of the resonators, i.e., large influence of duct section change and cavity mode

$\Rightarrow$ Problem of causality which limits the broadband and low frequency efficiency of absorbers as pointed out in *Optimal sound-absorbing structures*, Materials Horizon, 2017.

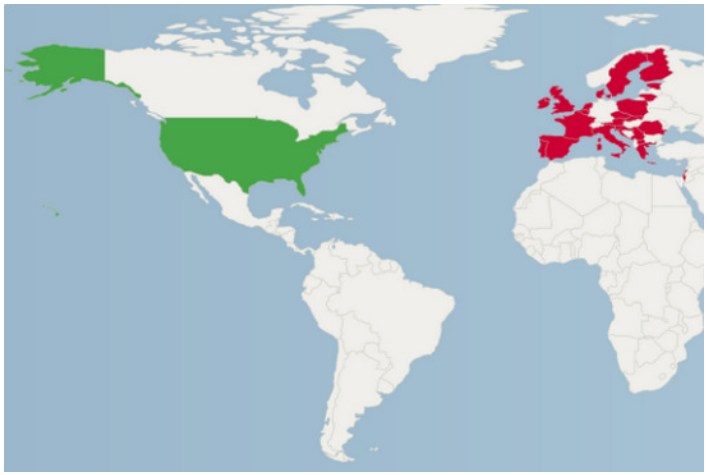
DENORMS Action (CA 15125)

DENORMS (Designs for Noise Reducing Materials and Structures) aims at **designing multifunctional, light and compact noise reducing treatments**, which will be used in **realistic environments**.

DENORMS **brings together** skills and knowledge of the complementary communities of scientists working on **acoustic metamaterials, sonic crystals and conventional acoustic materials** across Europe and overseas.

⇒ 3 interacting Working Groups (WG)

- WG1. Modelling of sound interaction with noise reducing materials and structures
- WG2. Experimental techniques
- WG3. Industrial applications



DENORMS currently gathers Laboratories and Industrial partners from 27 Participating countries and 1 (4) International Parner Country.

⇒ DENORMS Activities for 2017-2018

- Workshop *Brainstorming*, Novi-Sad, 14-15th Sept 2017.
- Training School *Experiments on porous materials and acoustic metamaterials*, Le Mans, 4th-6th Dec. 2017
- Workshop *Experimental techniques in porous materials and acoustic metamaterials*, Leuven, 7th-9th Feb 2018

Further information on
https://denorms.eu/
Contact denorms@univ-lemans.fr

cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

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Symposium on the Acoustics of Poro-Elastic Materials
December 6-7-8, 2017
Le Mans (France)

Welcome to SAPEM 2017

University of Le Mans and the Laboratory of Acoustics are happy to welcome you for the fifth edition of the Symposium on the Acoustics of Poro-Elastic Materials to be held on the 6th, 7th and 8th of December 2017.

The symposium aims:

- presenting the most up-to-date researches in modelling, characterisation
- promoting industrial applications of porous materials,
- bringing together researchers and engineers working in adjacent disciplines concerned with porous media,
- discussing future challenges for this area of research.

During this edition, a special focus will be put on metamaterials involving porous media and viscothermal dissipation and on the interaction of porous materials with flow.

Program

The non-parallel sessions of this fifth edition will include:

- Physical models for porous materials
- Experimental methods for porous materials
- Numerical models for porous materials
- Industrial applications
- Metamaterials with porous materials
- Interaction of Porous materials and flows

Special attention will be paid to reserving time for discussion.
A fruitful poster session will be organised alongside with exhibition by our industrial partners.

International Scientific Committee

Keith Attenborough (The Open-University London, UK)
Yves Aurégan (LAUM - CNRS, France)
Susan Boij (KTH, Sweden)
Stuart Bolton (Purdue University, USA)
Laurent De Ryck (LMS Siemens, Belgium)
Elke Deckers (KU Leuven Belgium)
Ludovic Desvard (Dyson, UK)
Arnaud Duval (Treves, France)
Peter Göransson (KTH, Sweden)
Kirill Horoshenkov (The University of Sheffield, UK)
Anton Krynkin (The University of Sheffield, UK)
Emmanuel Perrey-Debain (UTC, France)
Vicente Romero-Garcia (LAUM - CNRS, France)

Organising Committee

Olivier Dazel, Jean-Philippe Groby, Aroune Duclos, Valérie Hermann (LAUM - CNRS)
Jean-Christophe Le Roux (CTTM)
François-Xavier Bécot, Luc Jaouen (Matelys - Research Lab)
Claude Boutin (ENTPE - CNRS)

Abstract submission

There is no requirement to submit a full paper, but presenters should submit an abstract of up to 1,500 words (about two pages), including details of their results and references. The Conference Committee reserves the right to decline submissions that are not in line with the objectives of the Symposium.

Presentations will be collected and compiled in a digital form. Selected papers will be recommended for publication in a special section of a peer-review journal.

Registration

The full registration fee is € 460, € 410 for EAA members and € 310 for students. It covers attendance, instructional materials, proceedings, coffee breaks, lunches and social events. There will be a € 60 discount off the full registration fee for registration made prior to October 20th 2017.
Registration must be carried out following the link available on the Conference website :

http://sapem2017.matelys.com

Important dates

Deadline for abstract submissions: Sep. 8th 2017
Deadline for early bird registrations: Oct. 20th 2017
Deadline for registrations: Nov. 17th 2017

Contacts

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Thank you for your attention



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