Review on acoustic metamaterials

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Outline

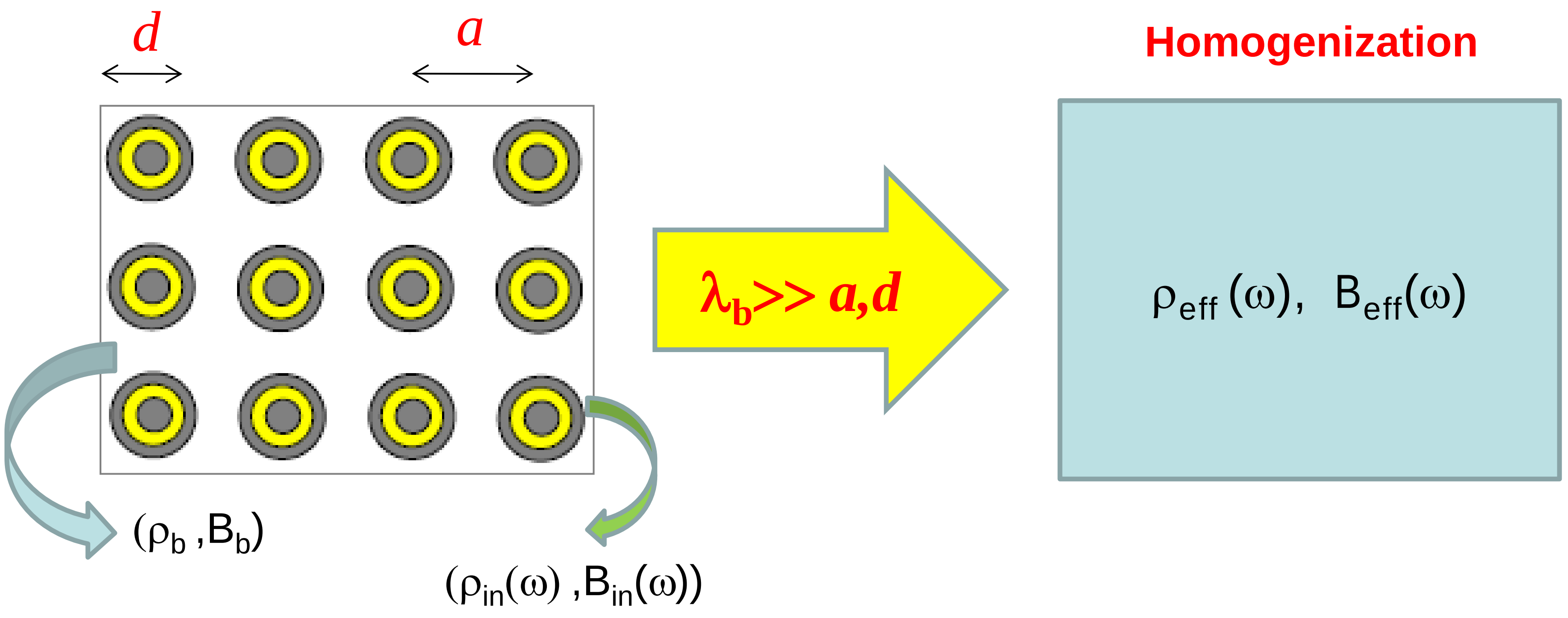
1. Introduction
2. Acoustic metamaterials with negative mass density and density-near-zero
3. Acoustic metamaterials with negative bulk modulus
4. Acoustic metamaterials with double negative parameters
5. Acoustic metamaterials with inhomogeneous and anisotropic mass density
6. Mechanical metamaterials
7. Summary

Review on Acoustic Metamaterials

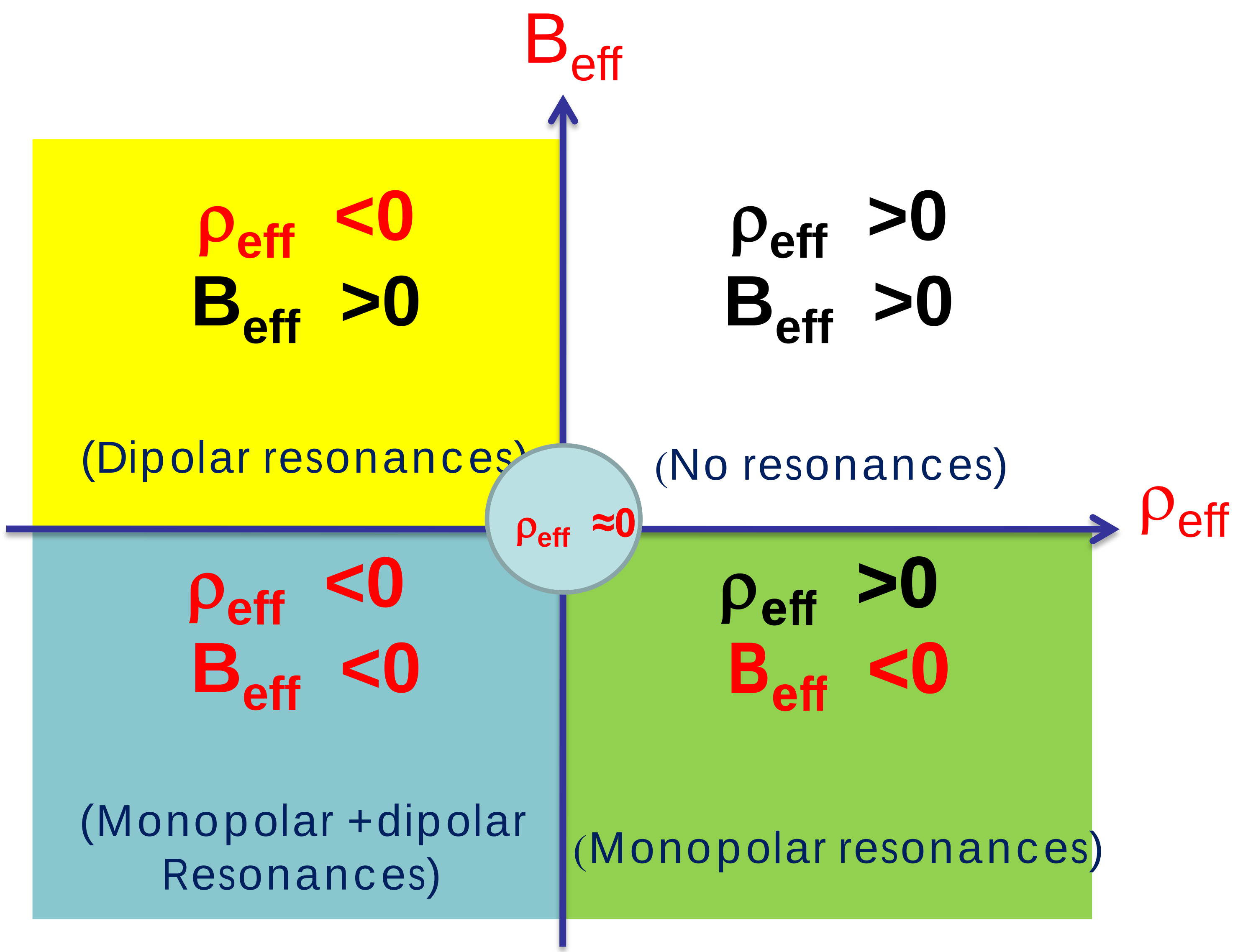
OUTLINE

Acoustic metamaterials / metafluids

Acoustic metamaterials are artificial structures made of subwavelength units such that their acoustic properties are NEW in comparison with that of the building units



Acoustic metamaterials

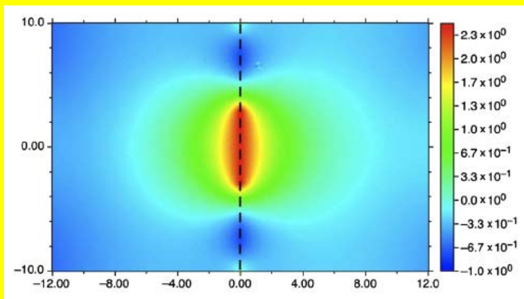


Li and Chan, PRE (2004)

Acoustic metamaterials / Metafluids

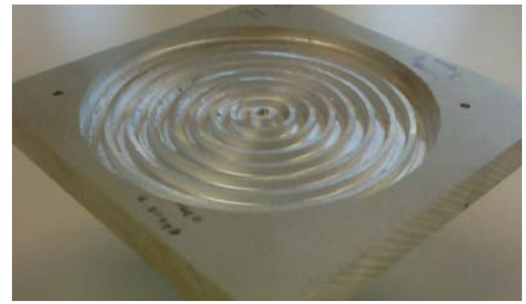
B_{eff}

ρ_{eff} <0



Z. Yang et al. PRL (2008)

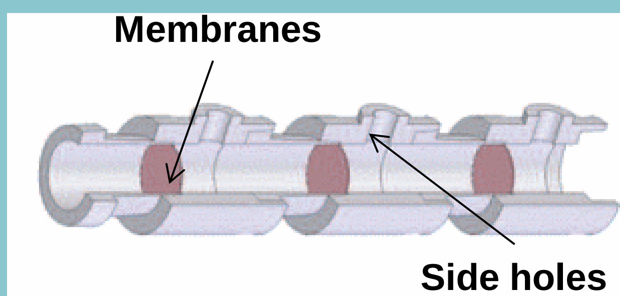
ρ_{eff} >0; B_{eff} >0



Torrent & JSD, PRL (2010)

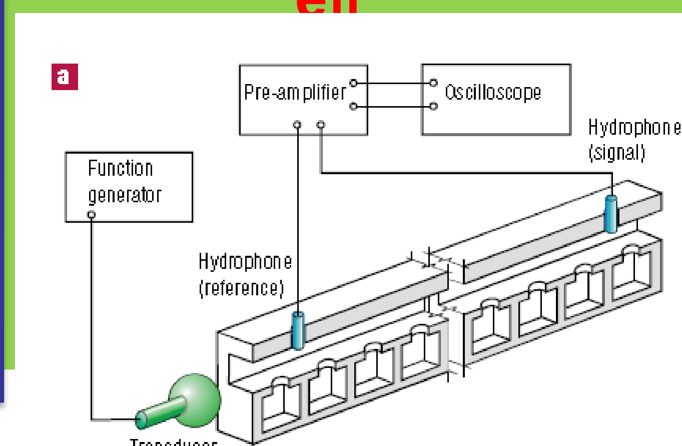
ρ_{eff}

ρ_{eff} <0 B_{eff} <0



S.H. Lee et al. PRL (2010)

B_{eff} <0



N. Fang et al. Nat. Mat (2006)

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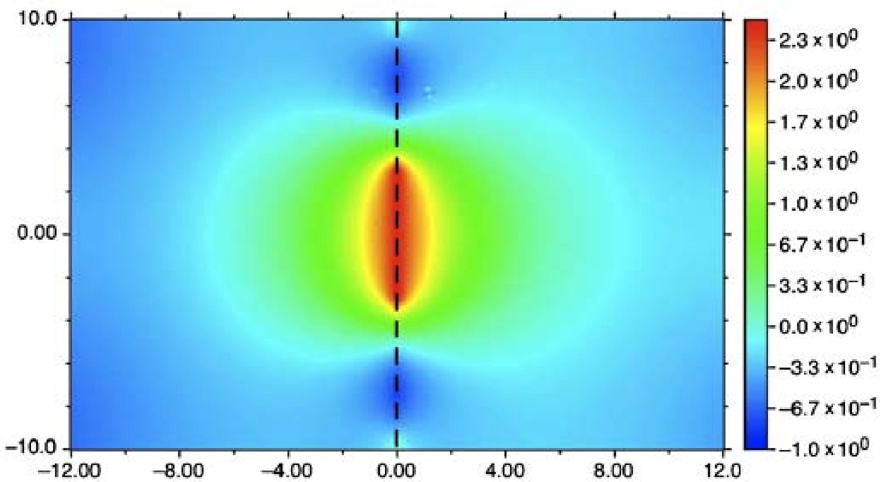
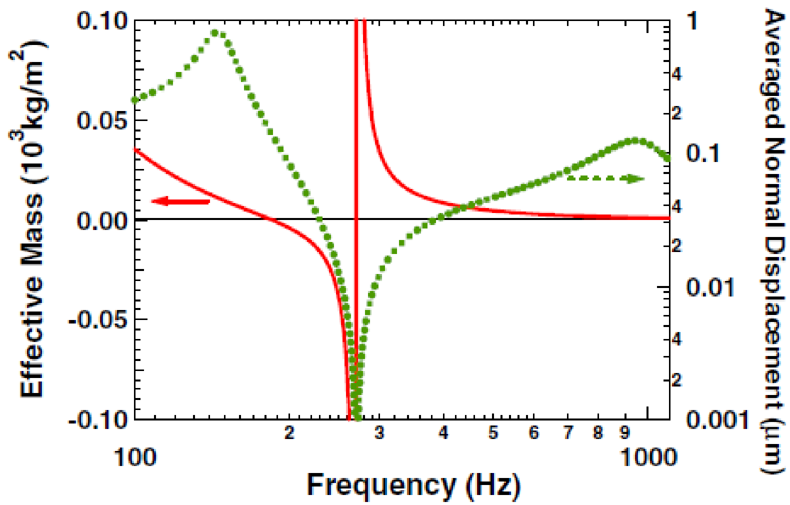
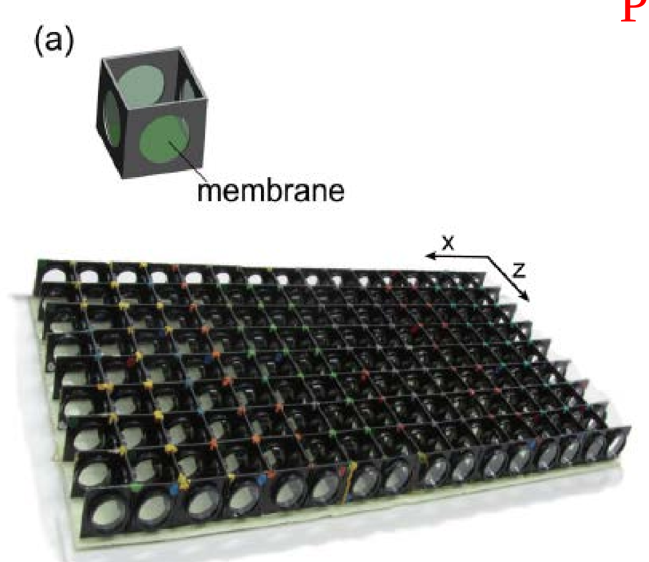
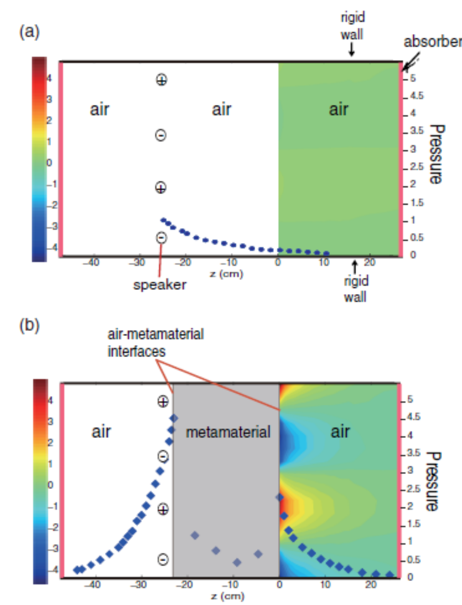
Membrane-Type Acoustic Metamaterial with ρ<0: Zhang et al., PRL (2008)





Amplification of Acoustic Evanescent Waves using Metamaterial Slabs with ρ<0: Park et al., PRL (2011)



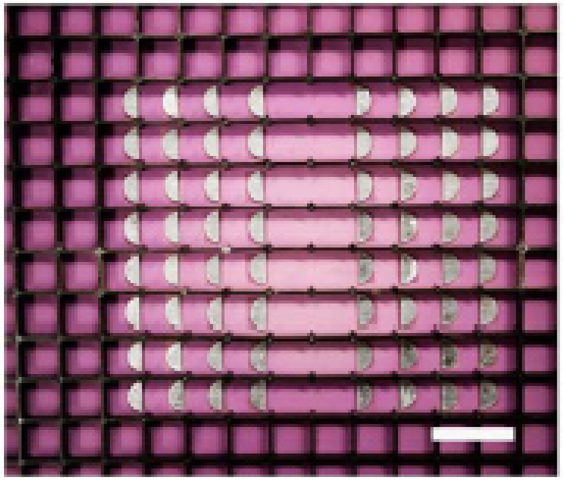


Dark acoustic metamaterials as super absorbers for low-frequency sound: Mei et al. Nat. Commun (2014)

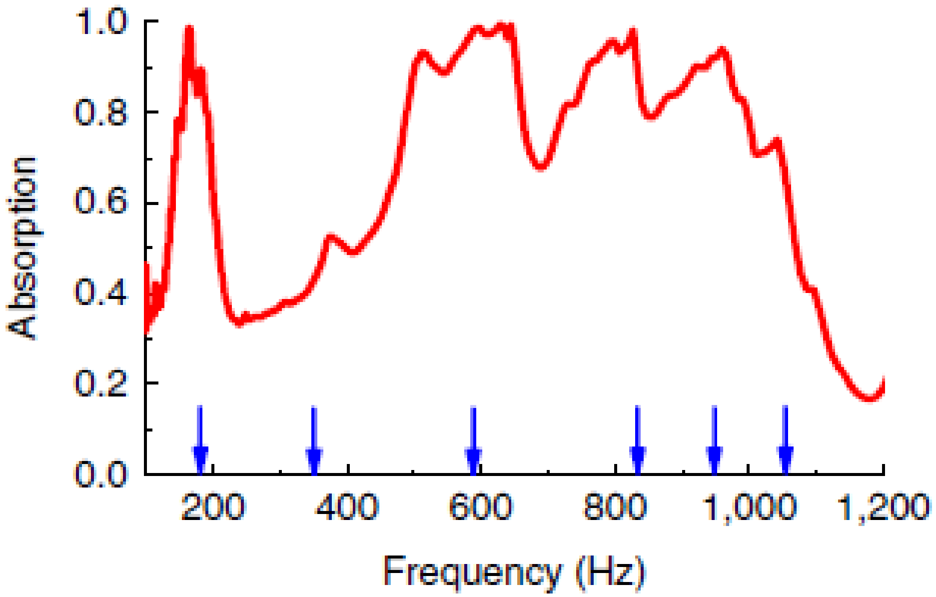
Metamaterials consisting of arrays of membranes can stop sound at the resonant frequencies of the membranes.

In order to broaden the effect Mei and coworkers have considered complex structures having hybrids resonaces:

SAMPLE



MEASURED ABSORTION COEFFICIENT



Acoustic cloaking by a near-zero-index phononic crystal: Zheng et al. APL (2013)

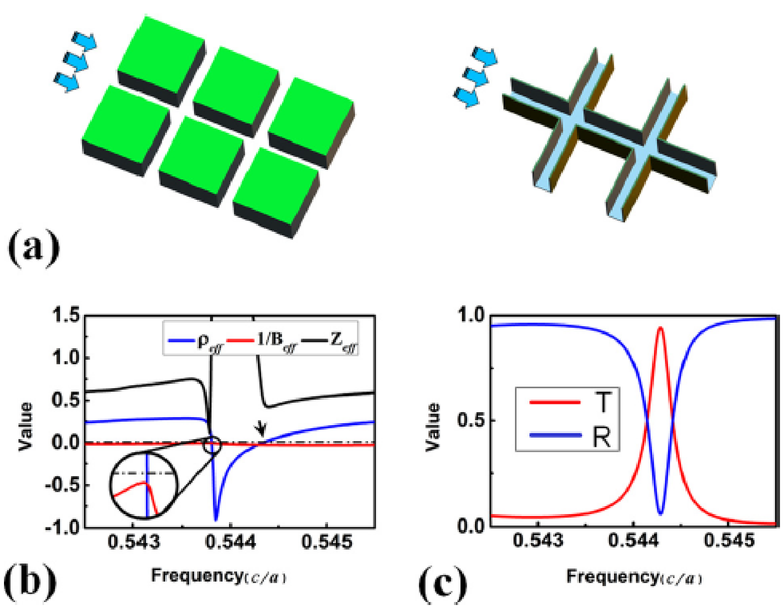
$$\rho_m < 0 \approx 0;\ B_m < 0$$

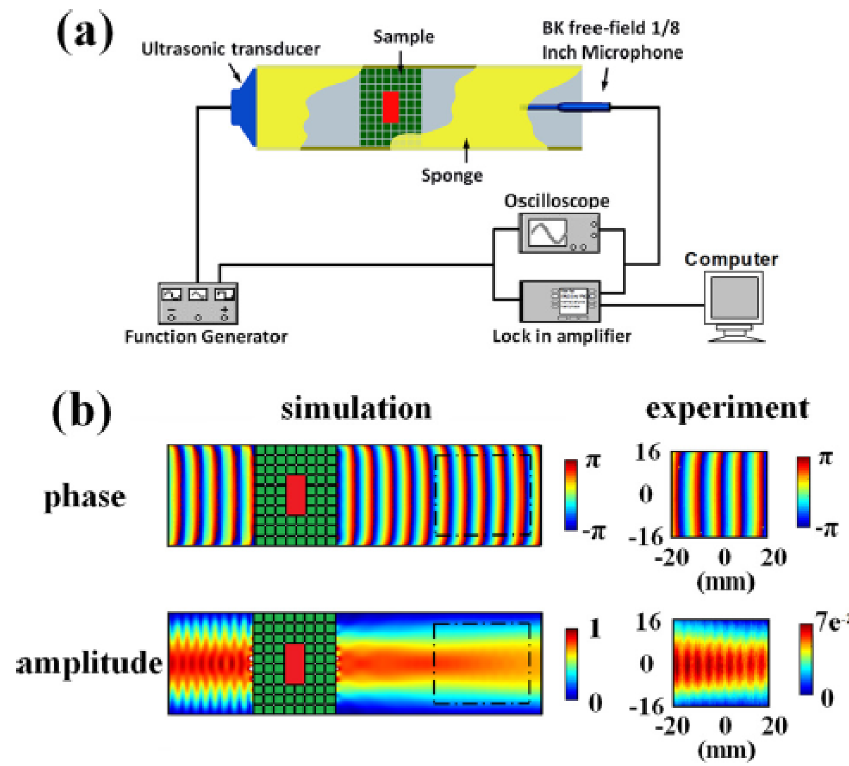
$$c_m = \sqrt{\frac{B_m}{\rho_m}} \to \infty$$

$$n_m \approx 0$$

$$e^{ik_m x} \approx 1$$

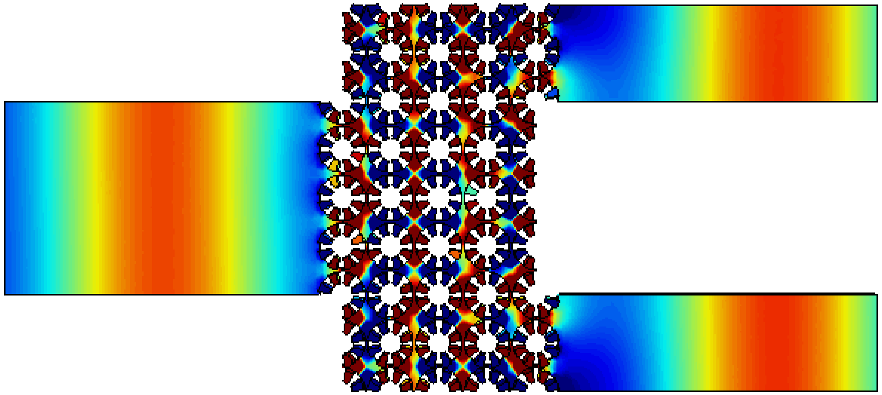
$$|Z_m|^2 = \rho_m B_m \approx \rho_b B_b = |Z_b|^2$$



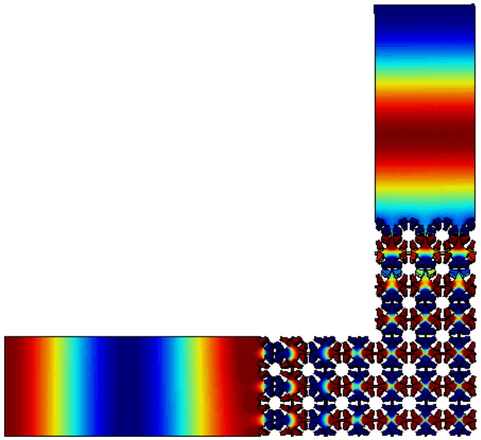


Applications of ρ≈0 metamaterials: Graciá-Salgado et al., PRB (2013)

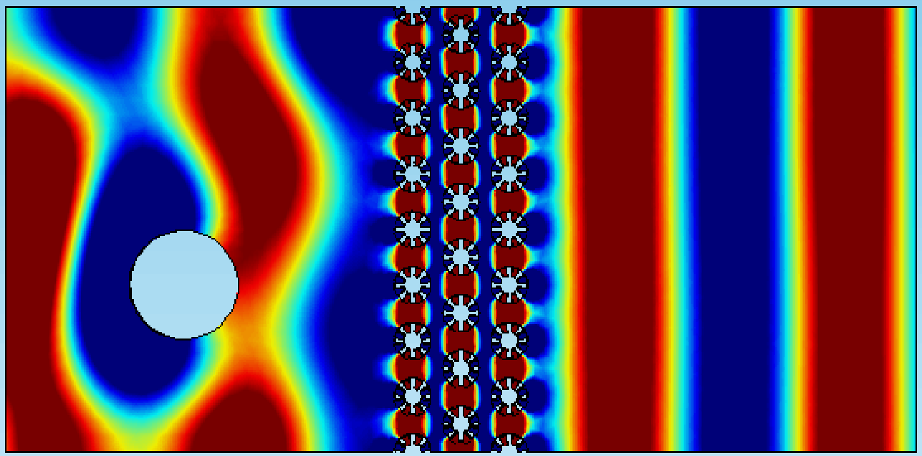
- Power splitters



- Perfect transmission through waveguides with sharp corners



Control of the radiation pattern



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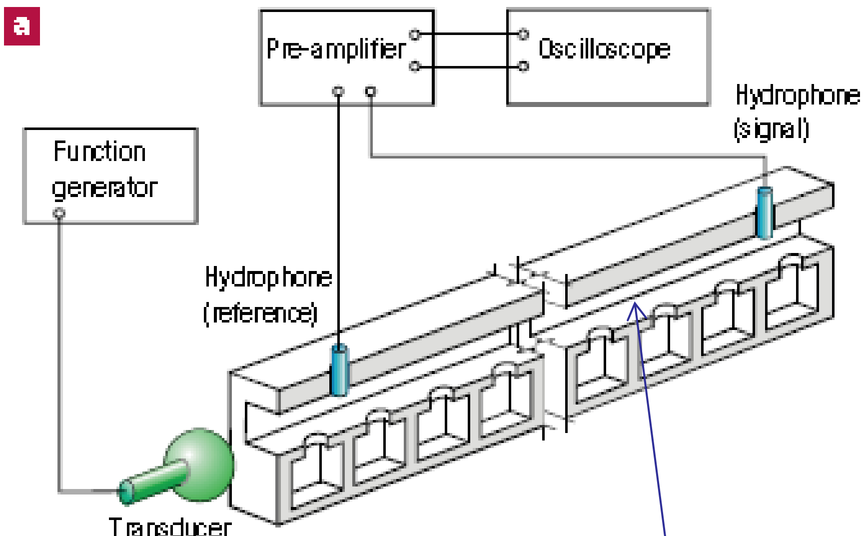
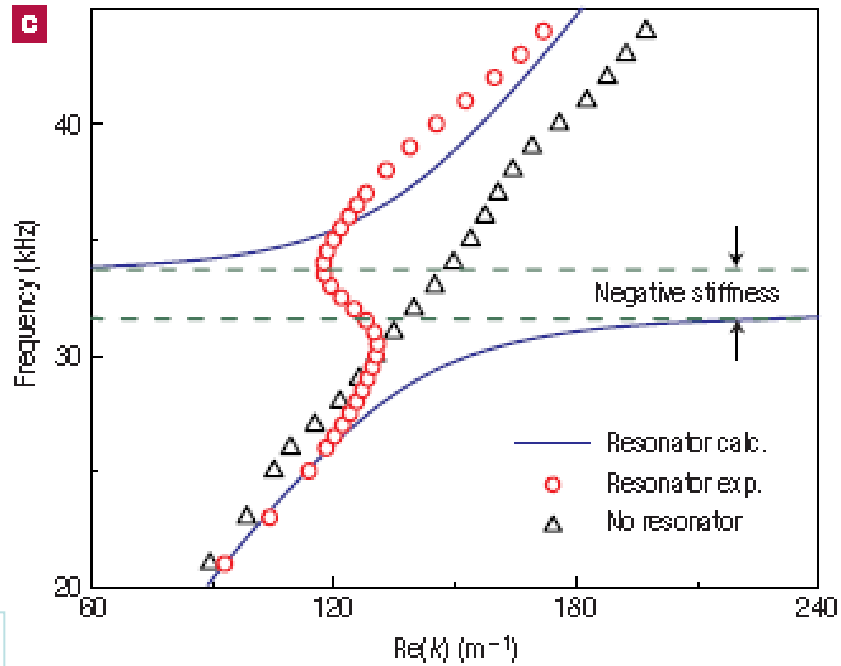
3. Acoustic Metamaterials with negative bulk modulus (1D)

N. Fang et al., *Ultrasonic metamaterials with negative bulk modulus*, Nat. Mat. 5, 452 (2006)





1D waterfilled waveguide

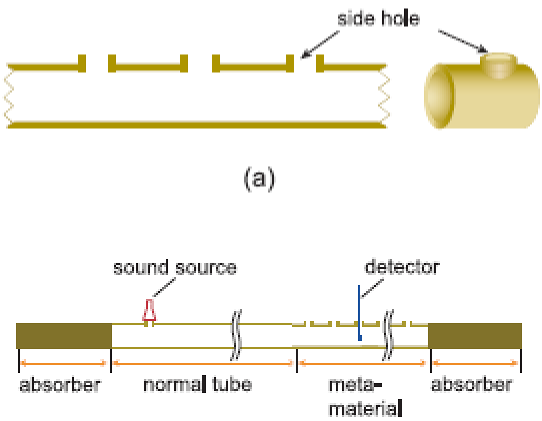
Effective modulus:

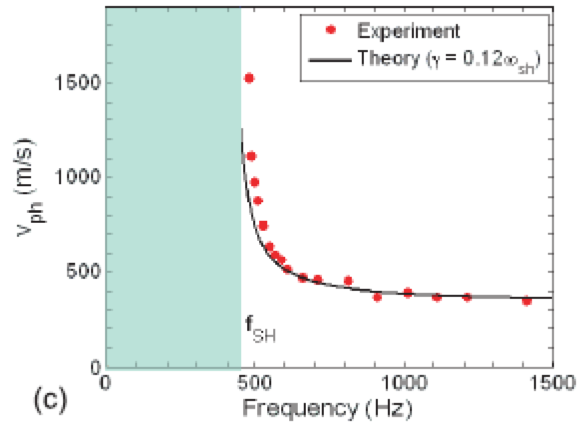
$$E_{eff}^{-1}(\omega)=E_0^{-1}\left[1-\frac{F\omega_0^2}{\omega^2-\omega_0^2+i\Gamma\omega}\right],$$ where Γ is the dissipation loss in the HR:

$\Gamma = 2\pi\times 400$Hz

Acoustic Metamaterials with negative bulk modulus (1D)

•S.H. Lee et al., *Acoustic metamaterial with negative modulus*, J. Phys.: Cond. Matt., **21**, 17504 (2009)





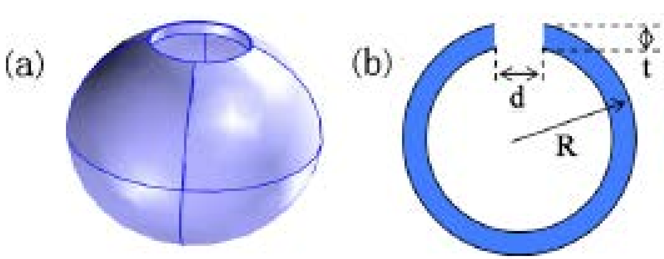
1D air waveguide

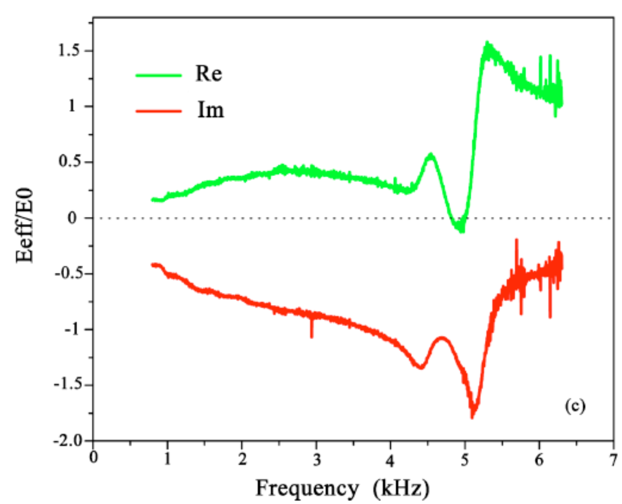
$$v_{ph} = \sqrt{\frac{B_{eff}}{\rho}} = \sqrt{\frac{B}{\rho\left(1-\omega_{sh}^2/\omega(\omega+i\gamma)\right)}}$$

where $\gamma = 2\pi\times 54\,\mathrm{Hz}$

•C. Ding et al., *Acoustic metamaterial with negative modulus*, J. Appl. Phys. **108**, 074911 (2010)

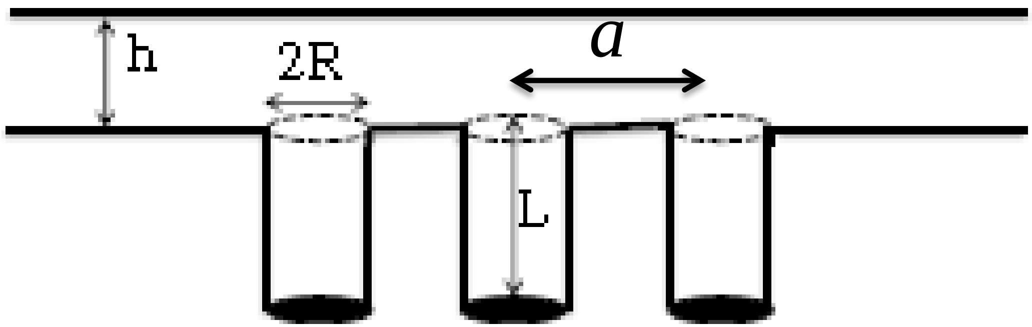
Split hollow sphere (SHS)





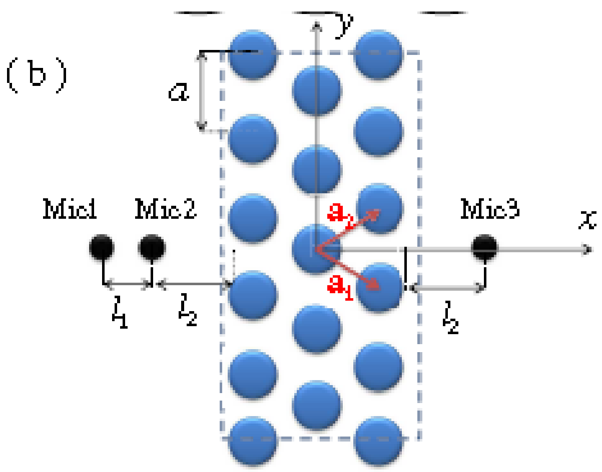
Acoustic Metamaterials with negative Bulk modulus (2D)

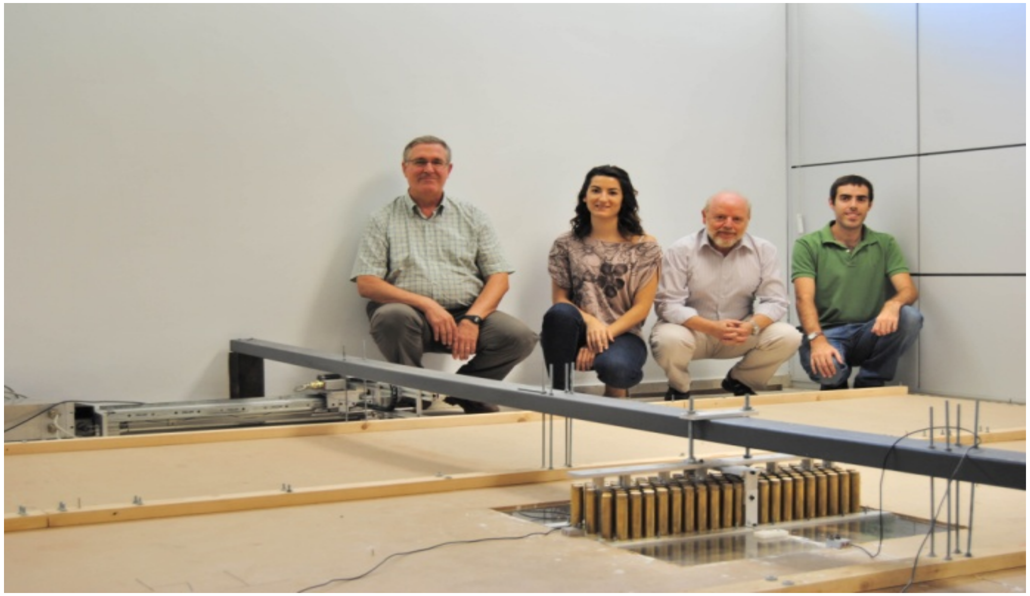
2D Waveguide (h) + cylindrical holes (R, L)



hexagonal lattice with parameter *a*

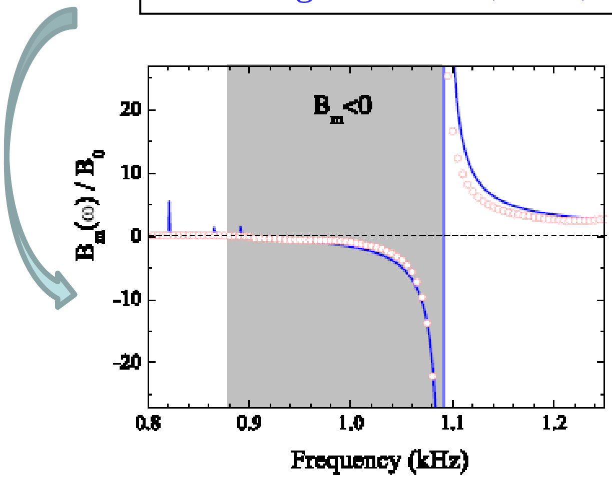
holes with R=1 *cm*, L=9 *cm*, *a*=3*cm*
2D waveguide with h= 5 *cm*





Negative bulk modulus (quasi-2D): theory *vs* experiment

Following Fokin et al., PRB, **76**, 144302 (2007)



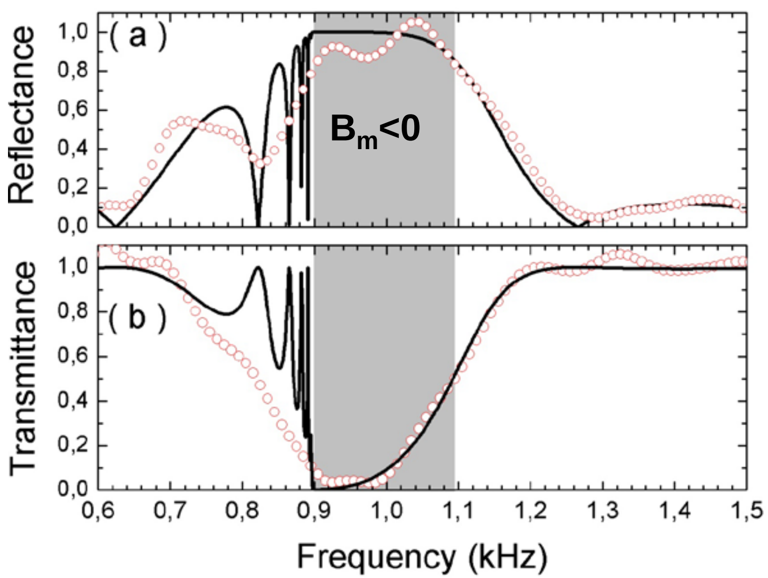
$$B_m^{-1} = B_0^{-1}\left[1 - \frac{F\omega_0^2}{\omega^2 - \omega_0^2 + i\Gamma\omega}\right]$$

$$\omega_0 < \omega < \omega_0\sqrt{1+F}$$

Parameters:

$\omega_0 = 2\pi\times 874$Hz; $\Gamma = 2\pi\times 3.4$Hz

Applications of negative Bulk modulus: Stopping sound in ducts



For a sample made of 7 layers (D=21.9 cm)

$$R = \frac{P_2 e^{-ik_0x_1} - P_1 e^{-ik_0x_2}}{P_1 e^{-ik_0x_2} - P_2 e^{-ik_0x_1}}$$

$$T = \frac{P_3}{P_2}\,\frac{e^{-ik_0x_2} - \mathrm{R}e^{ik_0x_2}}{e^{-ik_0x_3}}\,e^{-ik_0D}$$

García-Chocano et al., PRB, **85**, 184102 (2012)

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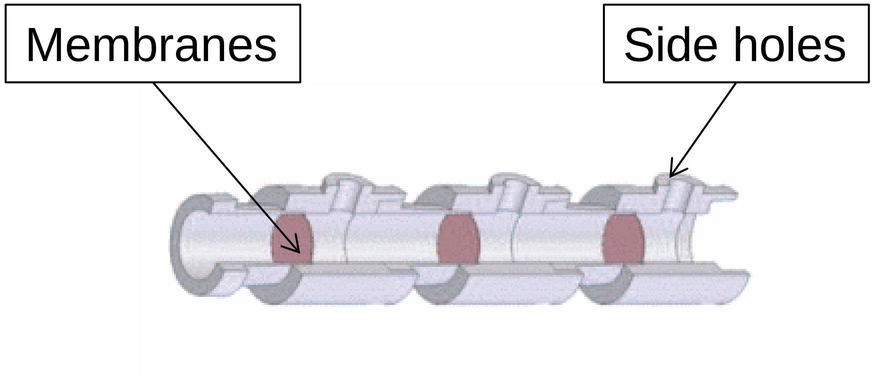
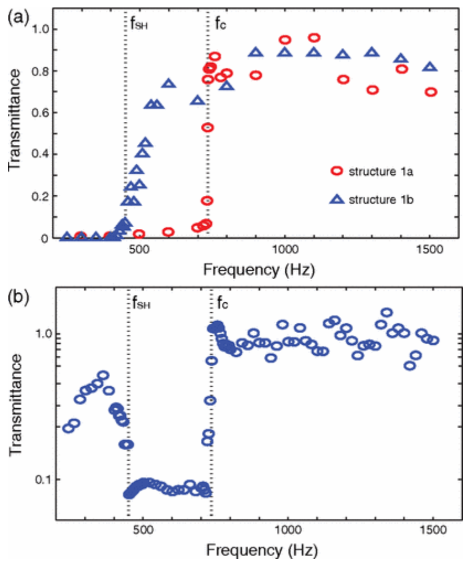
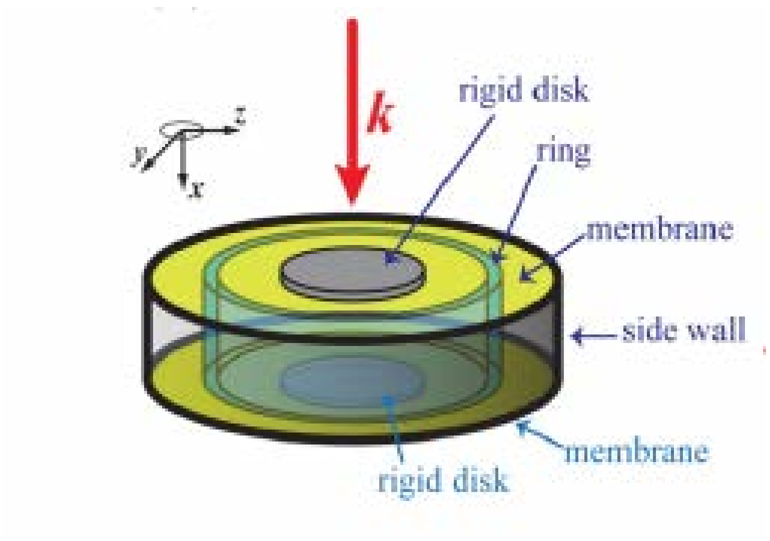
4. Acoustic MtM with double negative parameters

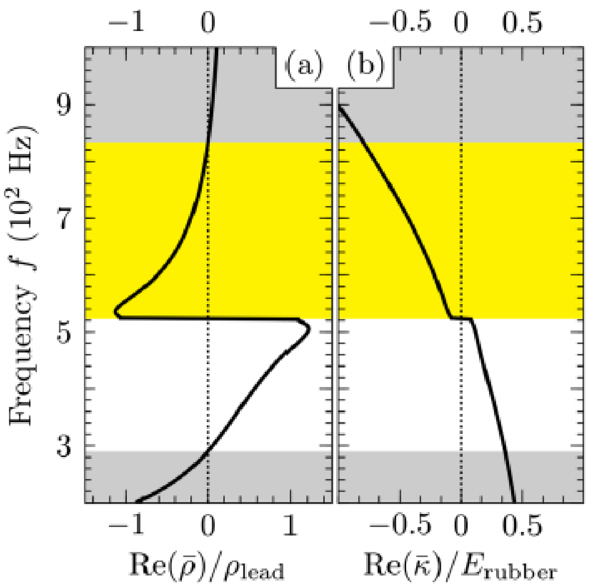
Lee et al., PRL (2010)





Coupled Membranes with double negative parameters: Yang et al., PRL (2013)



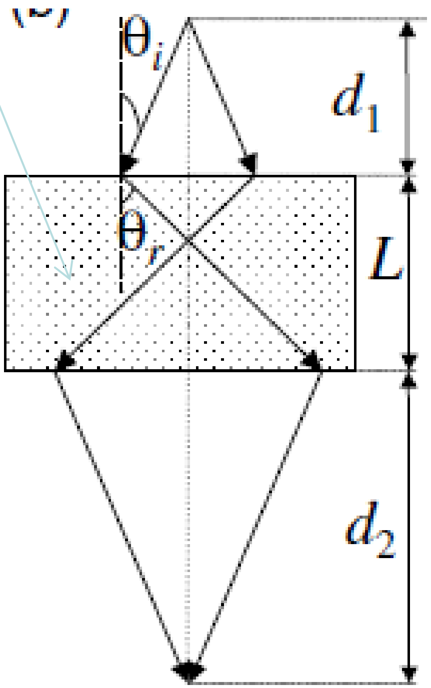


4. Acoustic MtM with double negative parameters

Acoustic waves propagate with the wave vector reversed to the energy flow, and the refractive index n becomes negative, given by:

$$n = -\sqrt{\rho / B}$$

Double negative metamaterial



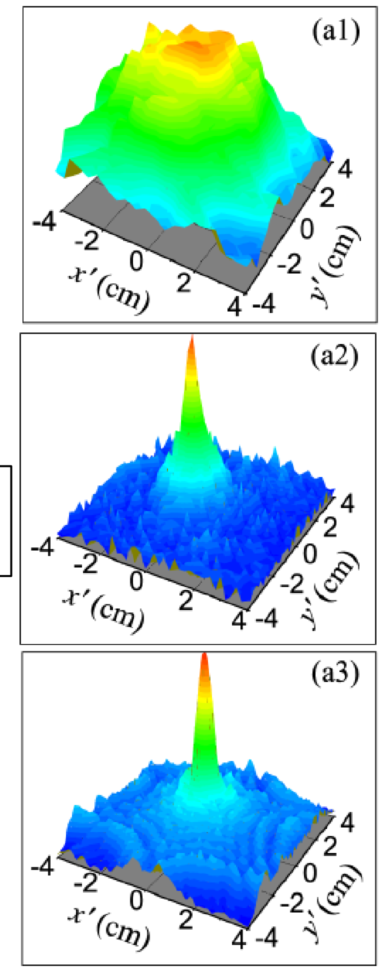
Yang et al., PRL (2004)

a diverging ultrasonic beam becomes a narrow focal spot.

Without the Xtal

With the Xtal
With n<0

Theory



Review on Acoustic Metamaterials

OUTLINE

5. Acoustic MtM with inhomogeneous and anisotropic mass density

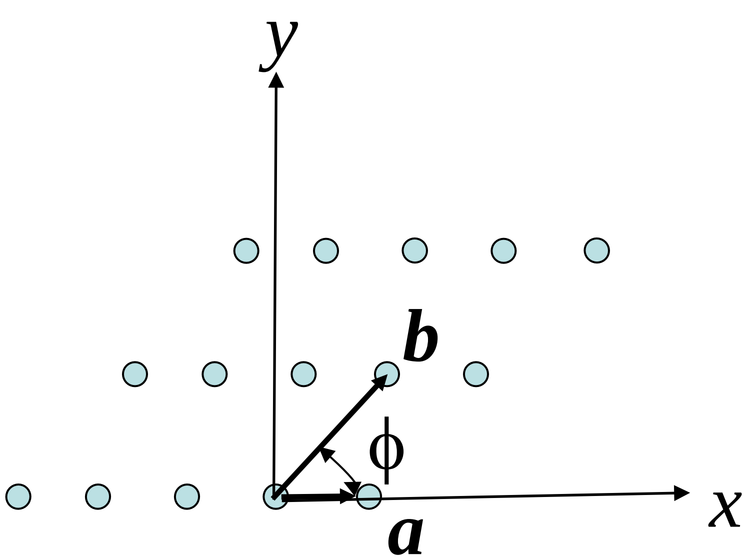
Isotropic:

$$\boxed{c^2 = B / \rho}$$

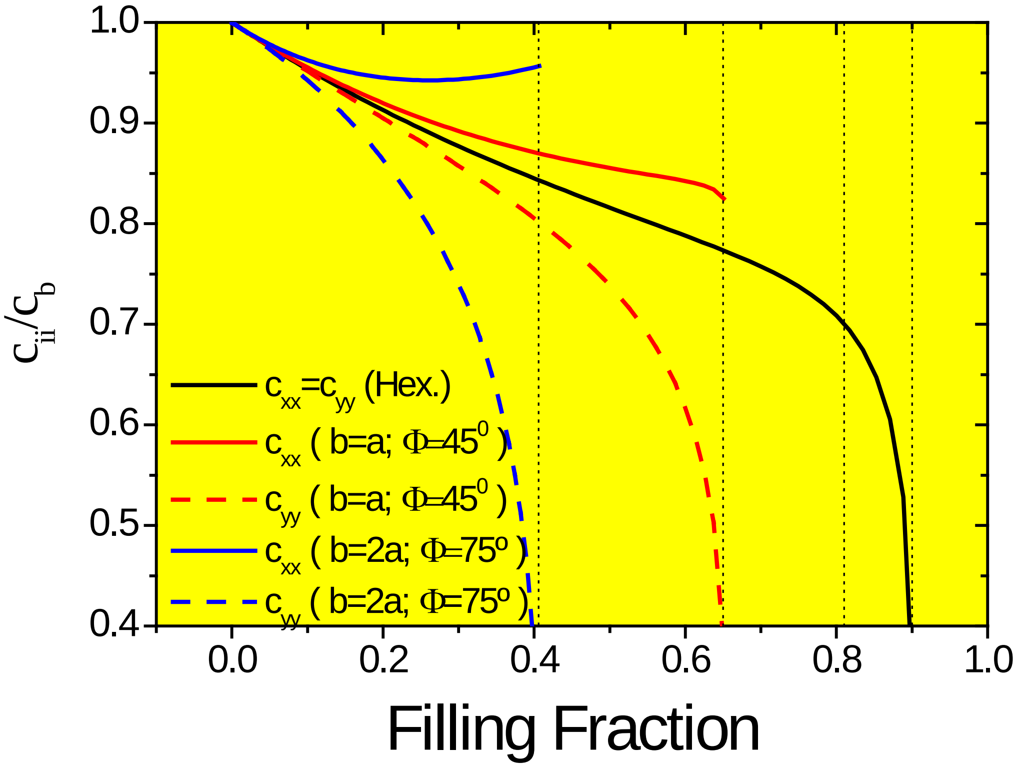
Anisotropic:

$$\boxed{c_{ij}^2 = B\rho_{ij}^{-1}}$$

Non-isotropic lattices:

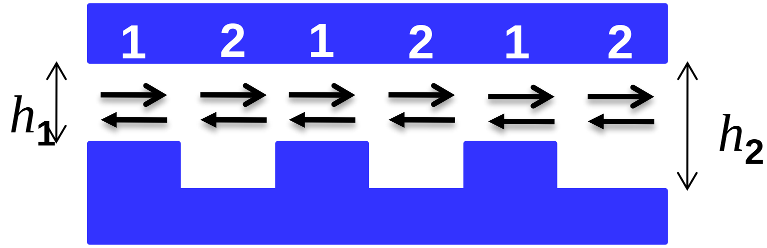


Components of the tensor of the effective speed of sound (Rigid cylinders)

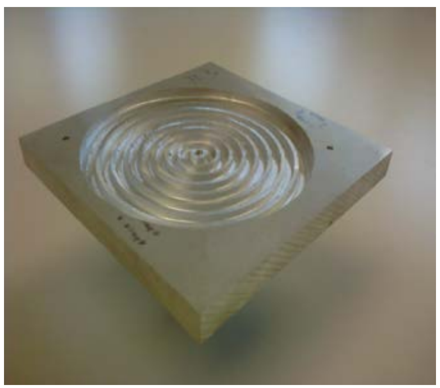


MtM with (cylindrical) anysotropic mass density $\rho(r, \theta)>0$

Bradley, JASA (1994)



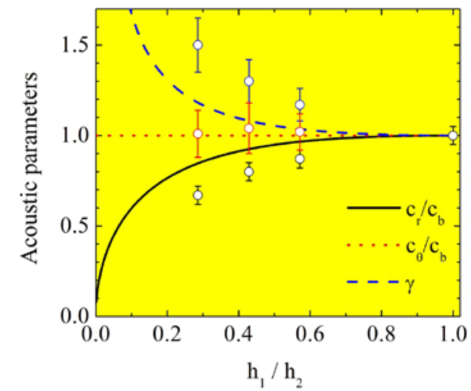
$$\frac{\rho_1}{\rho_2} = \frac{h_2}{h_1}$$



Phys. Rev. Lett., **105,** 174301 (2010)

$$c_r = c_b \frac{2}{\sqrt{\left(1+\frac{h_2}{h_1}\right)\left(1+\frac{h_1}{h_2}\right)}} \le c_b$$

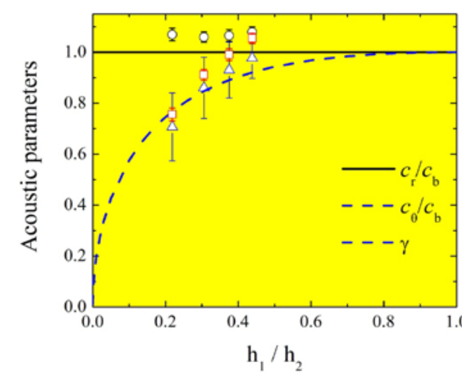
$$c_\theta = c_b$$



Appl. Phys. Lett., **98**, 244102 (2011)

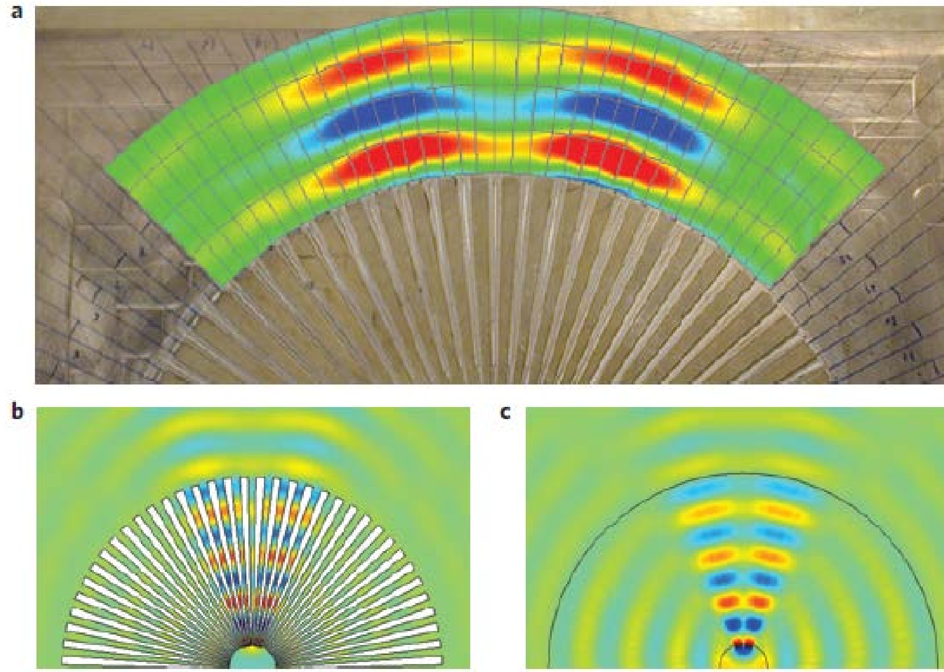
$$c_r = c_b$$

$$c_\theta = c_b \frac{2}{\sqrt{\left(1+\frac{h_1}{h_2}\right)\left(1+\frac{h_2}{h_1}\right)}} \le c_b$$



Acoustic magnifying hyperlens based on anisotropic metamaterials:

Li et al., Nat. Mater. (2009)

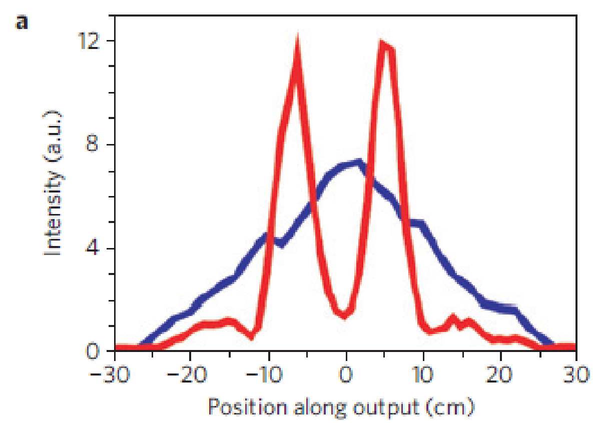


$$\frac{1}{\rho_r} = \frac{f}{\rho_1} + \frac{1-f}{\rho_2}$$

$$\rho_\theta = f\rho_1 + (1-f)\rho_2$$

$$\frac{1}{B} = \frac{f}{B_1} + \frac{1-f}{B_2}$$

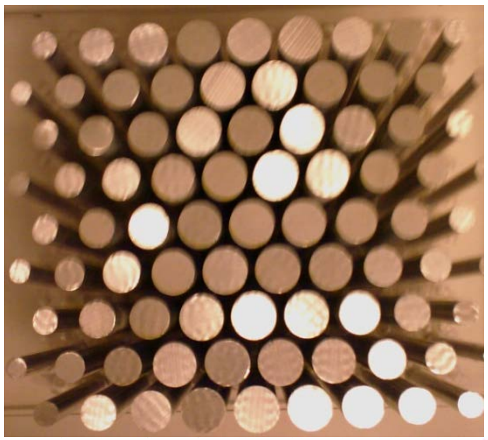
Hyperlens imaging at 6.6 kHz.

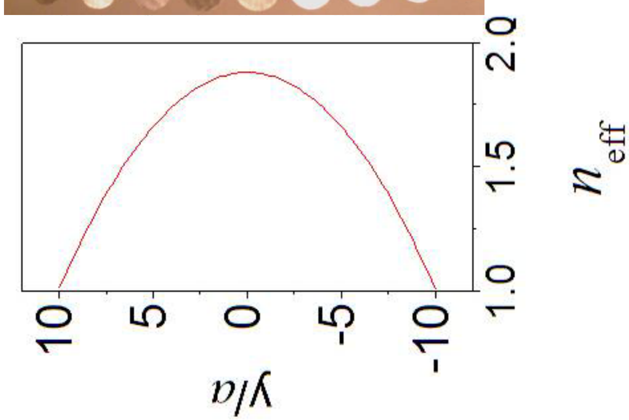


Gradient Index (GRIN) acoustic lenses for airborne sound in 2D

Hexagonal array of Al cylinders in air (a = 2cm)

SOUND AMPLIFICATION (3.5 kHz-4.5 kHz)

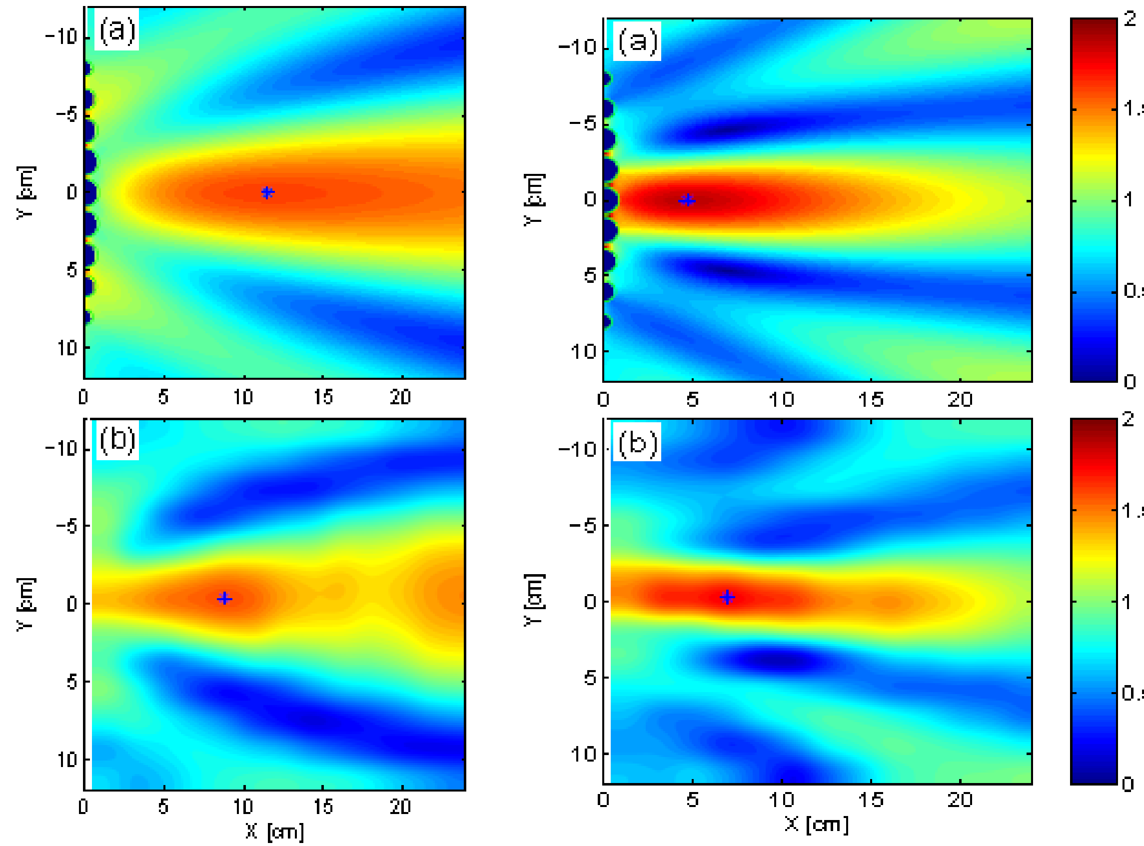




$$n(y) = n_0 \, \mathrm{sech}(\alpha y)$$

Theor

Ex

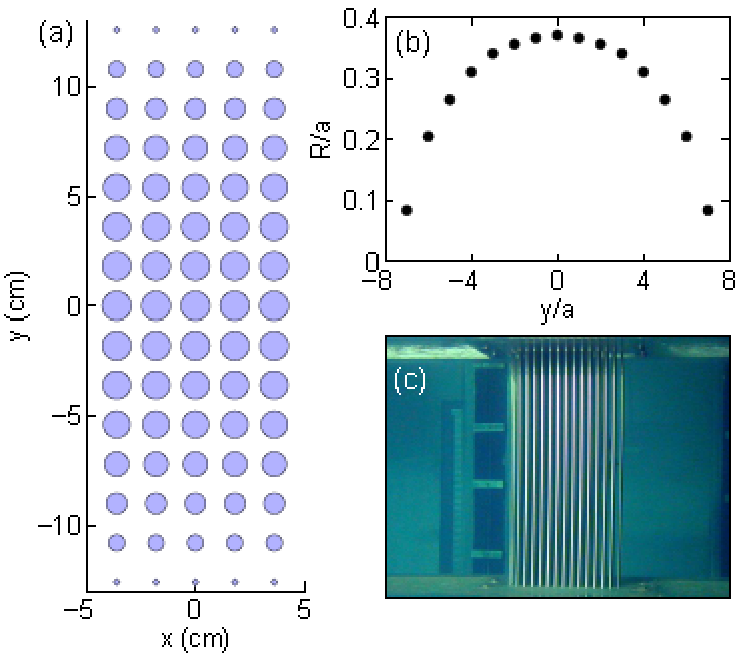


Focusing at 3.5 kHz **Focusing at 4.5 kHz**

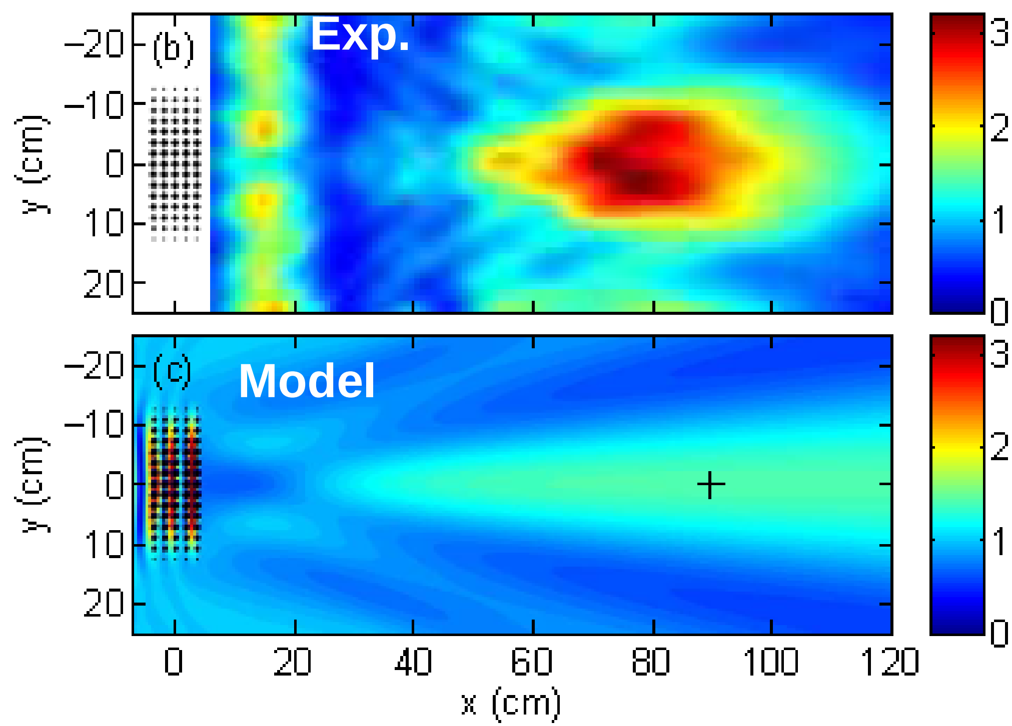
Climente et al., APL (2010)

GRIN acoustic lenses for underwater operation

GRIN lens made of metal cylinders embedded in water



$(P/P_0)^2$



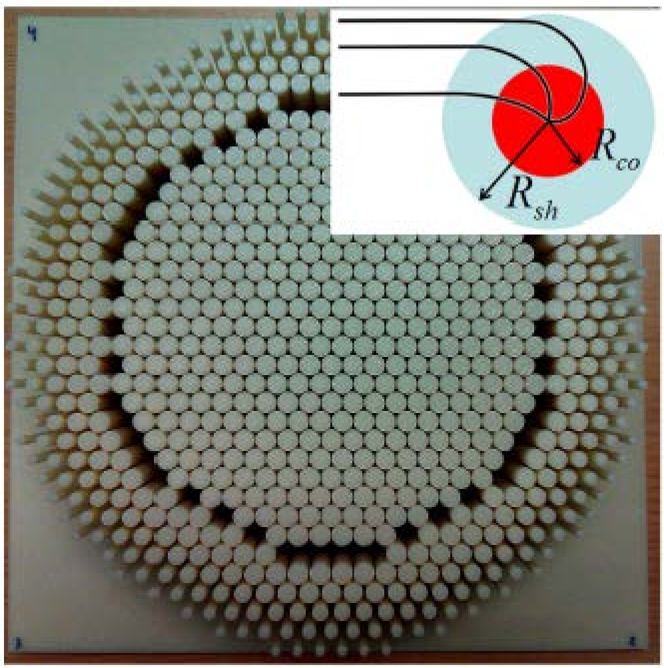
T. Martin et al., APL (2010)

Focusing at 20 kHz (**$\lambda \approx 4a$**)

Broadband Omnidirectional absorber: Acoustic black hole

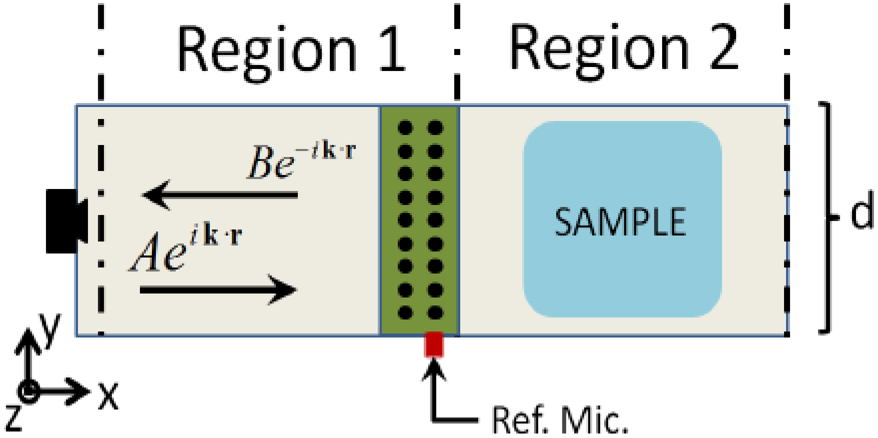
Omnidirectional acoustic absorber (disipative core + GRIN shell)

$$n(r) = \begin{cases} n_b & R_s < r \\ \frac{R_s}{r} n_b & R_c < r < R_s, \\ n_c + i\gamma & r < R_c \end{cases}$$

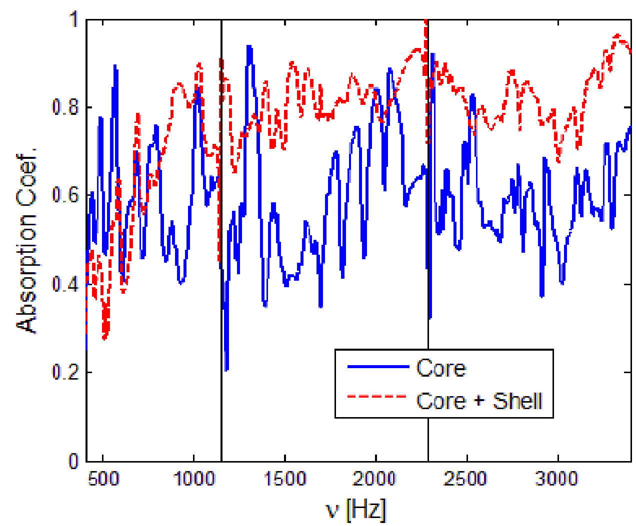


Climente et al. APL **100**, 144103 (2012)

Experimental setup



Absorption

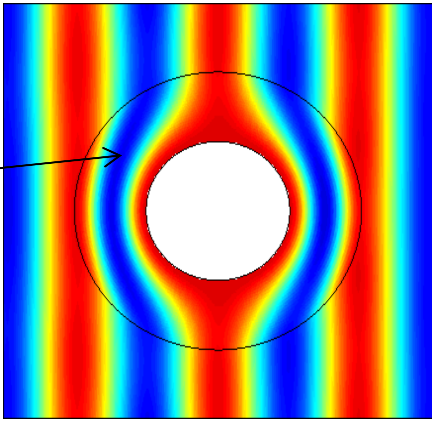


Cloaks based on transformation methods

$$\rho_r(r) = \frac{r}{r-R_1}\rho_b$$

$$\rho_\vartheta(r) = \frac{r-R_2}{r}\rho_b$$

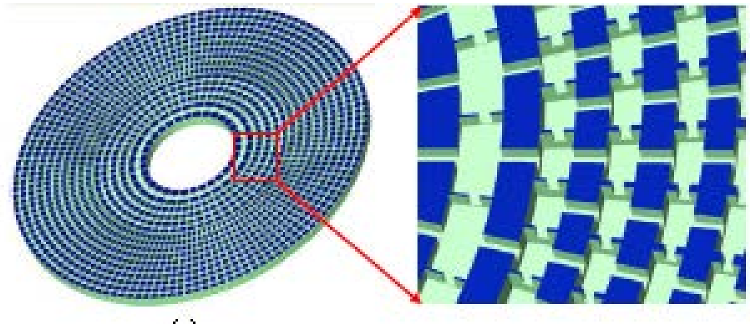
$$B(r) = \left(\frac{R_2-R_1}{R_2}\right)^2 \frac{r}{r-R_1} B_b$$

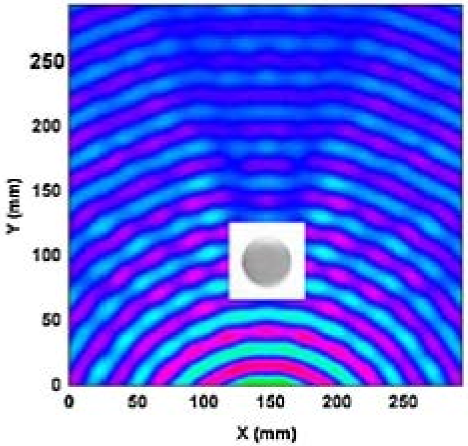


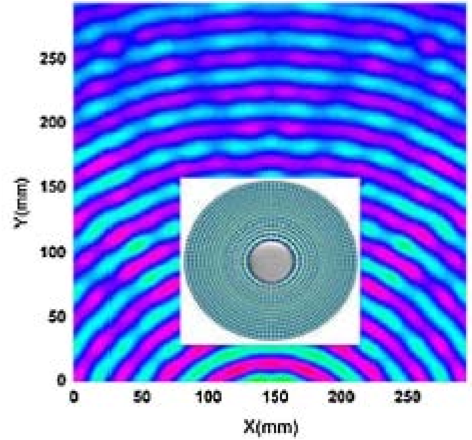
For airborne sound:

Cummer & Schurig, NJP **9**, 45 (2007) **2D**
H. Chen and C.T. Chan, APL (2007) **3D**
S.A. Cummer et al, PRL (2008) **3D**

2D cloaks for underwater operation [Zhang, Xia & Fang, PRL (2011)]





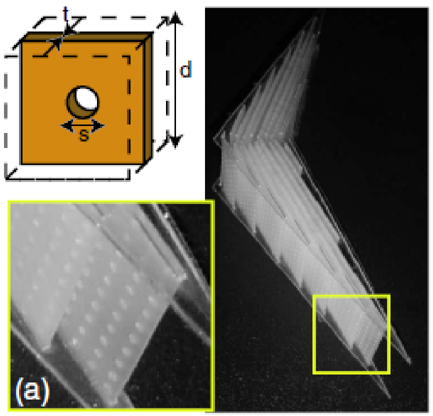


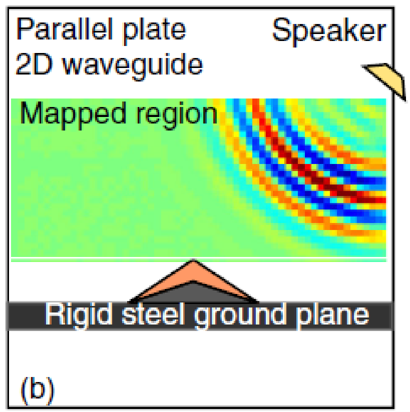
Ground cloaks based on anisotropic MtM

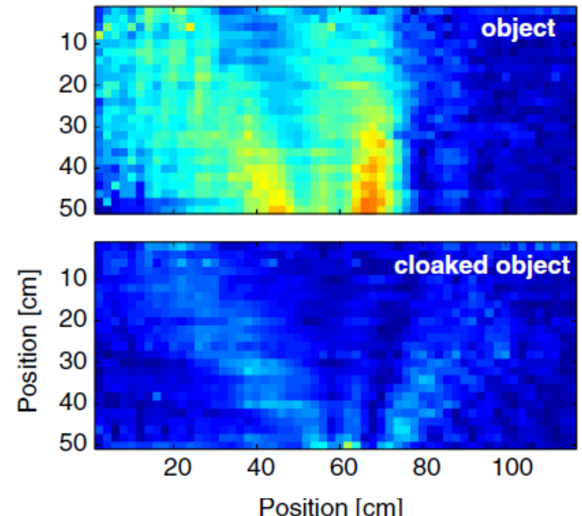
2D ground cloak: Popa, Zigoneanu & Cummer, PRL, **106**, 253901 (2011)

D=1.6mm; d=5mm; t=1mm

D/d=0.32; t/d=0.25; t/λ=0.01 (3kHz)

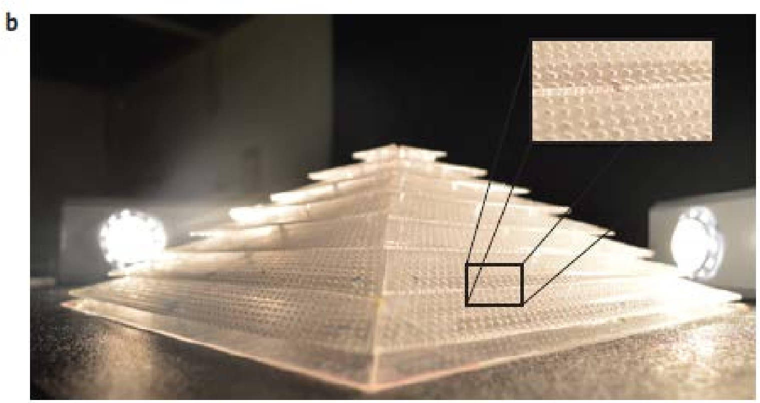


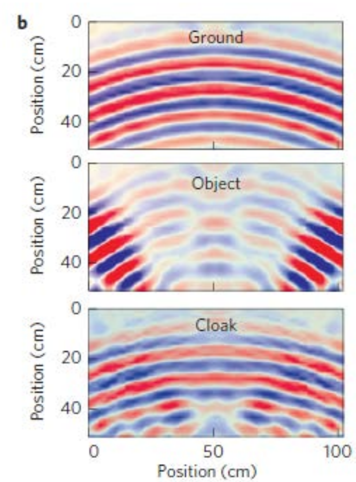




3D ground cloak: Zigoneanu. Popa & Cummer, Nat. mat., 3901 (2014)

D=1.7mm; d=5mm; t=1.6mm





$D/d_x=0.34$;
$t/d_x=0.32$;
$t/\lambda=0.01$ (3kHz)

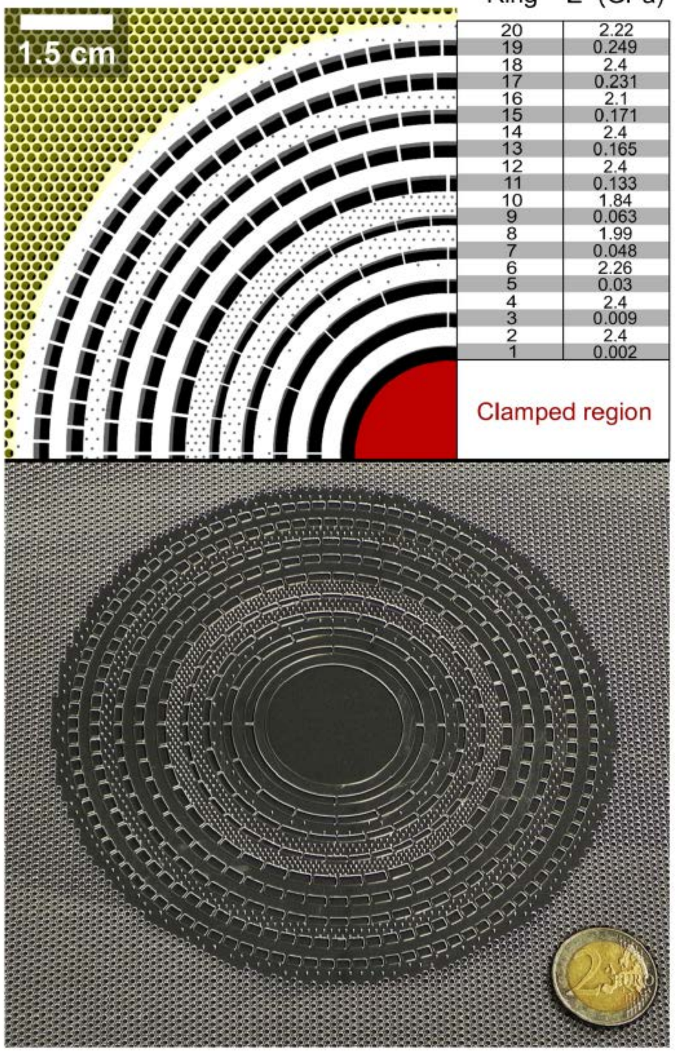
Review on Acoustic Metamaterials

OUTLINE

1. Introduction
2. Acoustic metamaterials with negative mass density and density near zero
3. Acoustic metamaterials with negative bulk modulus
4. Acoustic metamaterials with double negative parameters
5. Acoustic metamaterials with inhomogeneous and anisotropic mass density
6. Mechanical metamaterials
7. Summary

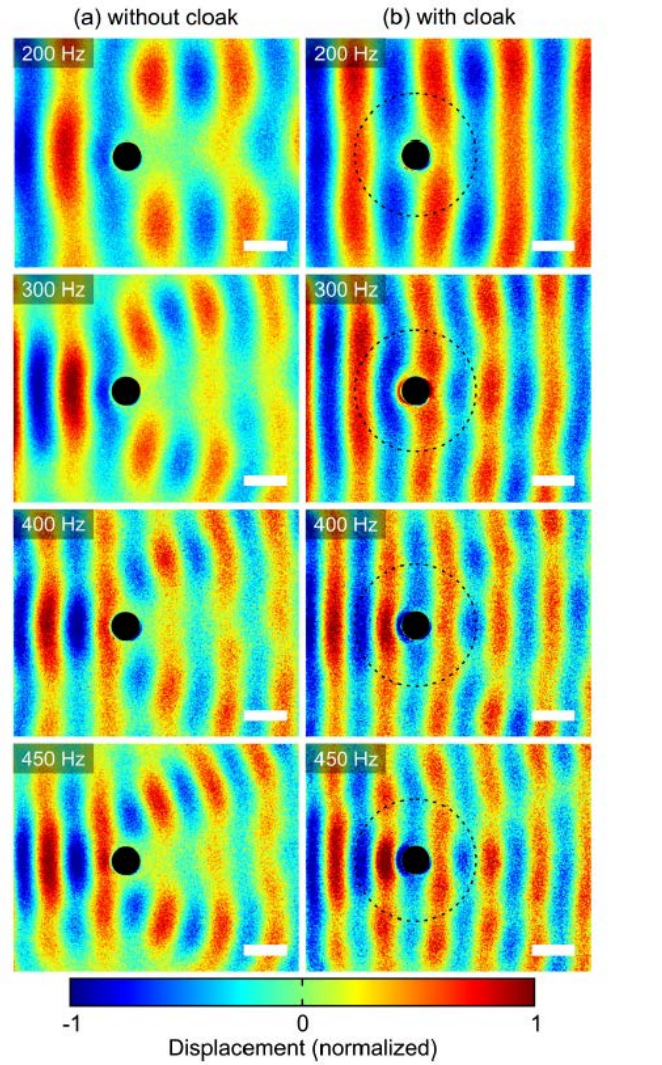
7. Mechanical Metamaterials

- Controlling flexural waves: Elastic cloaking in thin plates



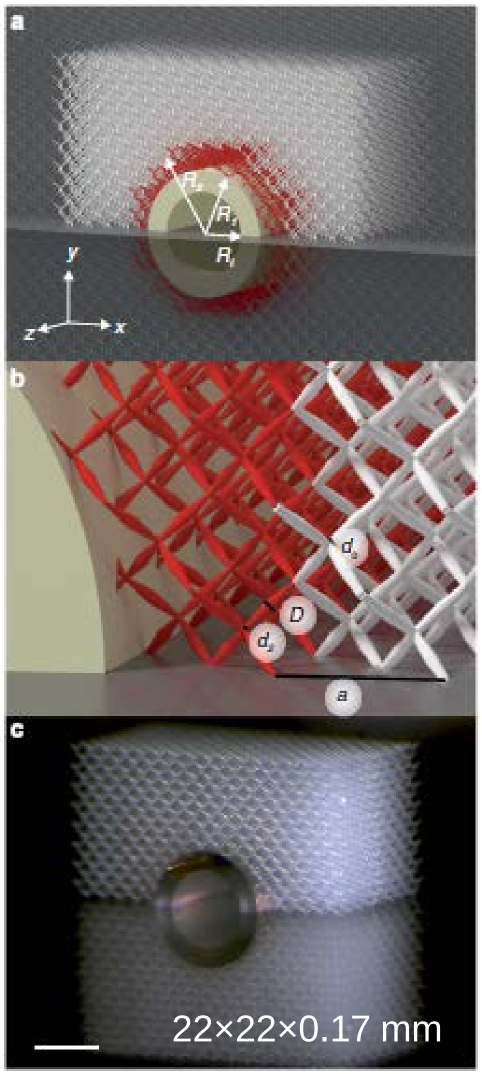
Ring	E´ (GPa)
20	2.22
19	0.249
18	2.4
17	0.231
16	2.1
15	0.171
14	2.4
13	0.165
12	2.4
11	0.133
10	1.84
9	0.063
8	1.99
7	0.048
6	2.26
5	0.03
4	2.4
3	0.009
2	2.4
1	0.002

Normal displacement
$W(x, y; t)$

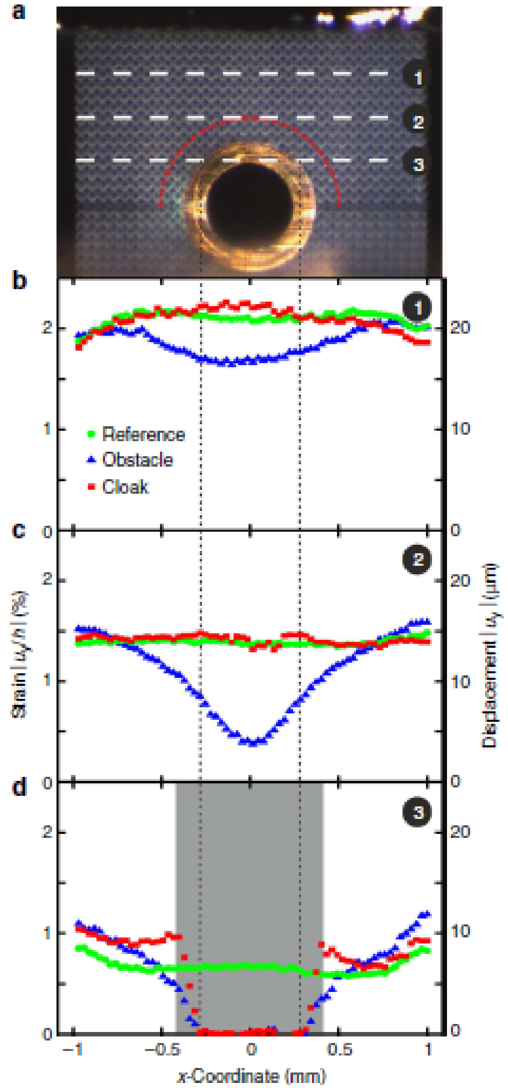


Stenger et al., PRL**108**, 014301 (2012).

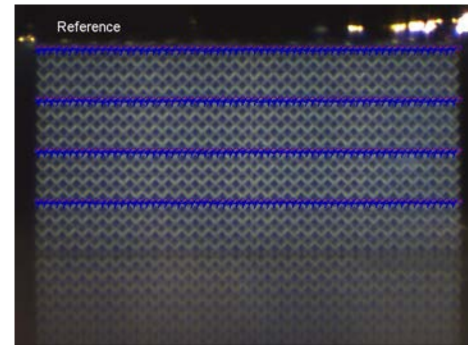
An elasto-mechanical “unfeelability” cloak:
Bückman et al, Nat. Comunn (2014)



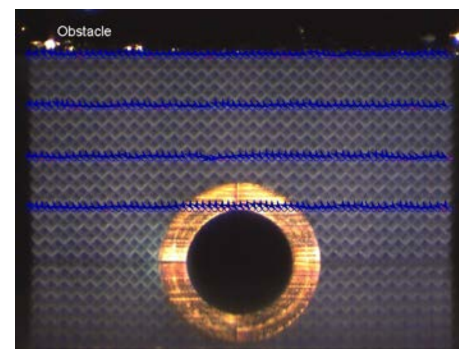
Elasto-mechanical measurements



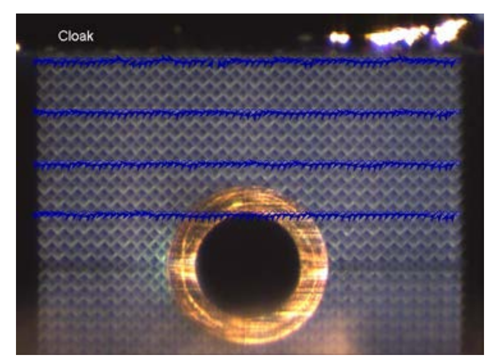
Reference



Obstacle



Cloak



4. Summary

- ✓ A review has been presented on Acoustic Metamaterials
- ✓ These artificial structures have properties that are unusual in natural material
- ✓ Their extraordinary properties can be employed to develop amazing acoustic devices: Acoustic cloaks, acoustic hyperlenses, Gradient index lenses, acoustic black holes, negative refraction, etc.
- ✓ Mechanical metamaterials are the next problem to tackle. They are very promising to get new devices in the elasticity domain.

Thanks for your attention!