

Phononic Crystals: Towards the Full Control of Elastic Waves propagation

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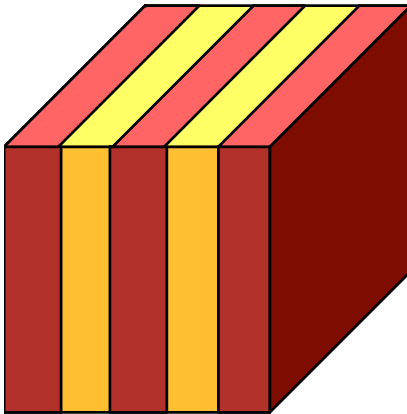
OUTLINE

- 1. Introduction**
- 2. Wave propagation through phononic crystals**
- 3. Refractive devices based on phononic crystals: lenses**
- 4. Focusing of waves by negative refraction**
- 5. Acoustic metamaterials: molding the propagation of sound**
- 6. Inverse design of phononic devices**
- 7. Conclusion**

Phononic Crystals

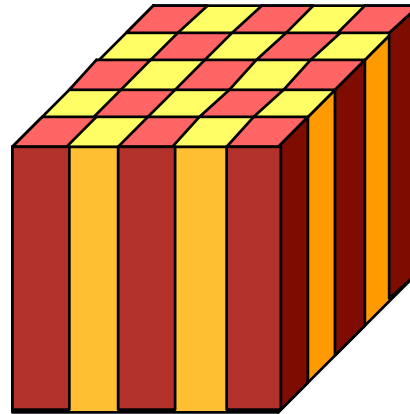
periodic elastic media

1-D



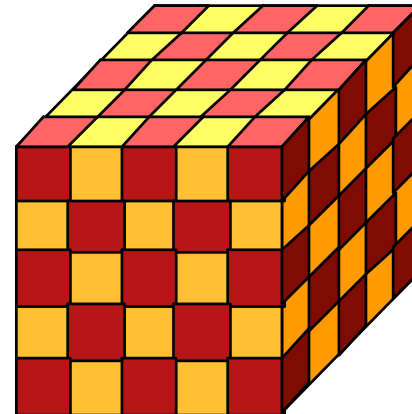
periodic in
one direction

2-D



periodic in
two directions

3-D

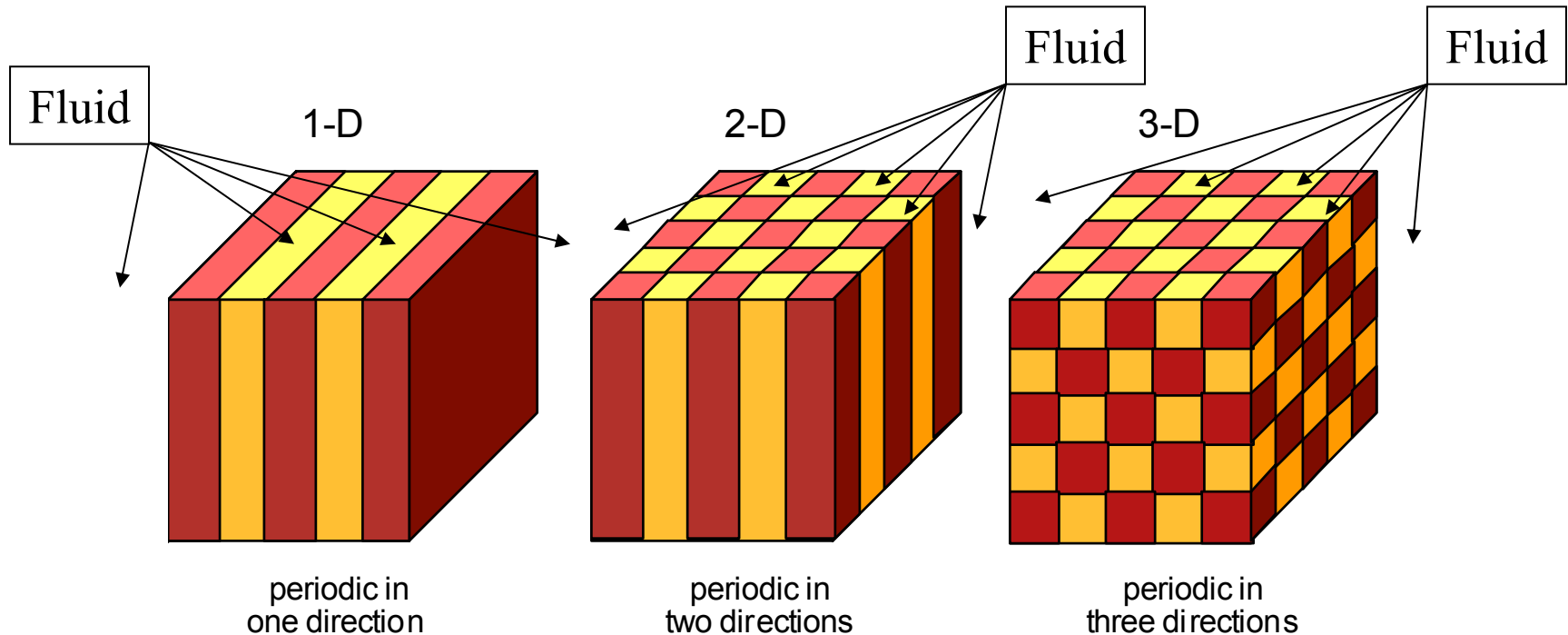


periodic in
three directions

with phononic band gaps: “**vibration insulators**”

Sonic Crystals

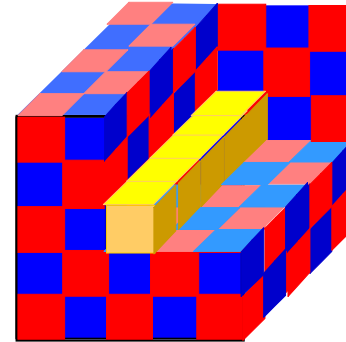
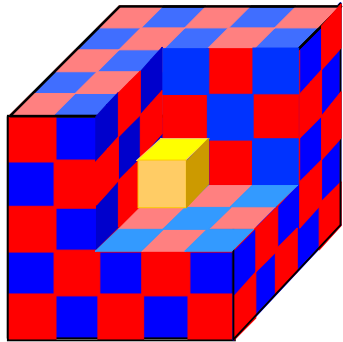
periodic media in which one material (at least!) is a fluid or gas



with sonic band gaps: “**sonic insulators**”

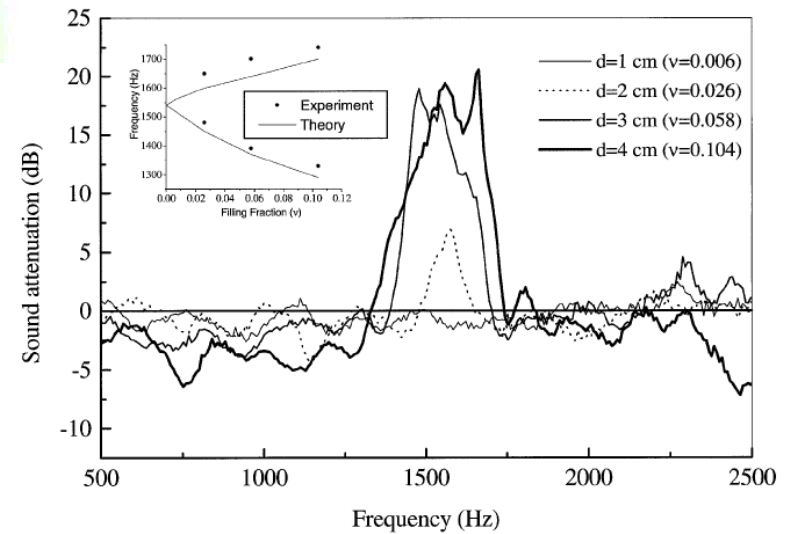
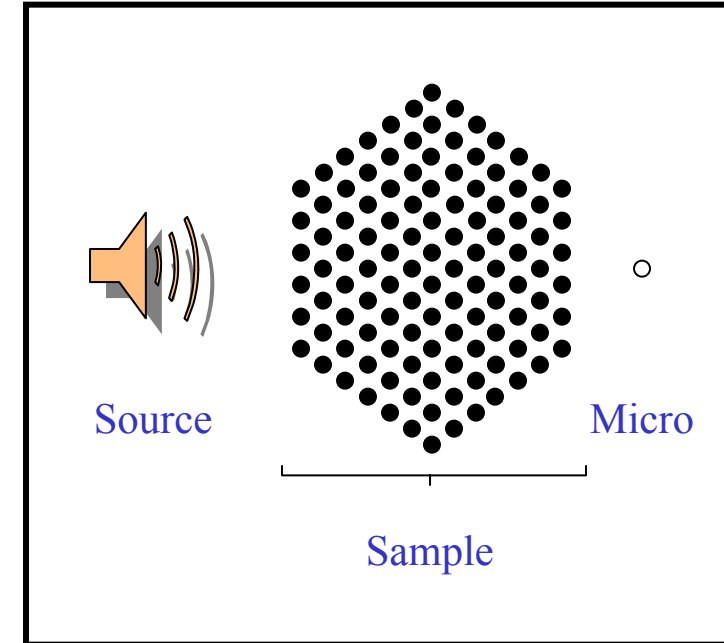
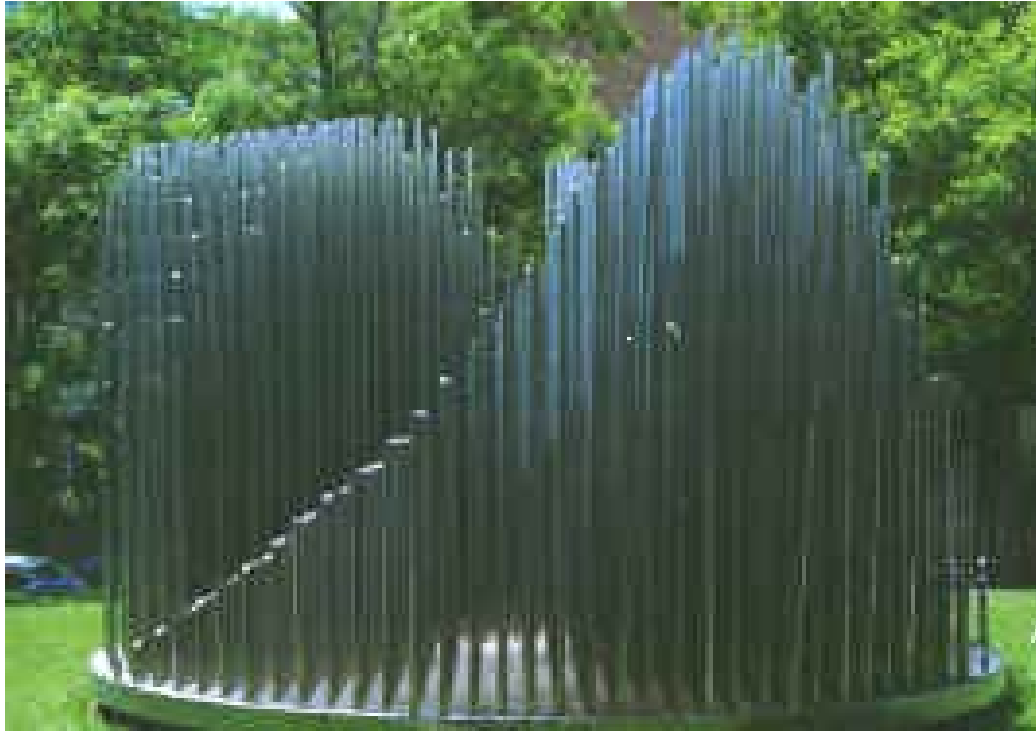
Defects in Phononic/Sonic Crystals

Periodic elastic composites



can trap vibration (sound) in **cavities** and **waveguides** (“wires”)

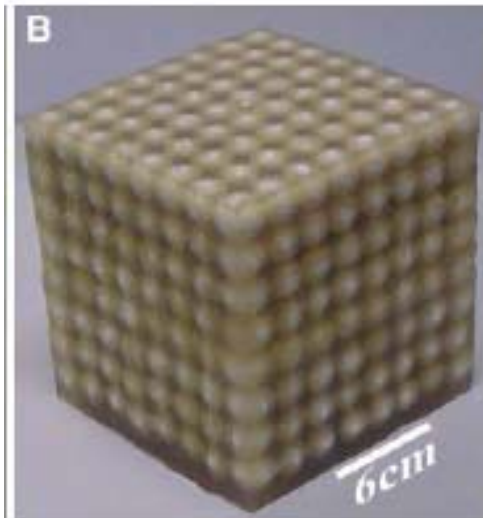
2D Phononic/Sonic Crystals



R. Martinez-Sala *et al.* Nature (1995)

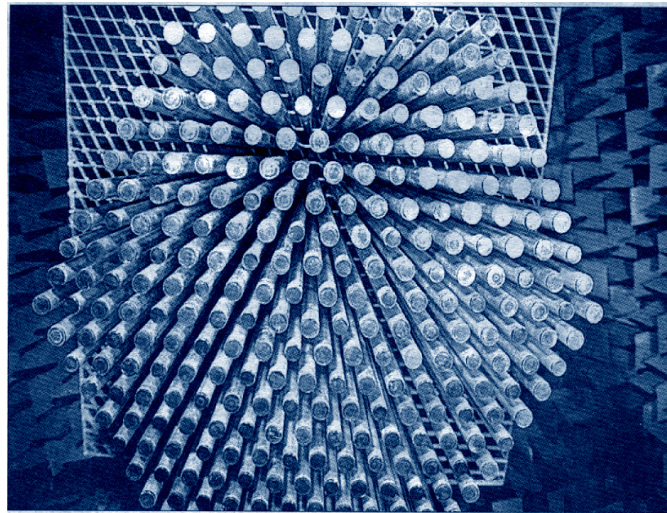
Phononic/Sonic Crystals: Practical realizations

3D



Science, **289**, 1739 (2000)

2D



PRL, **80**, 5325 (1998)

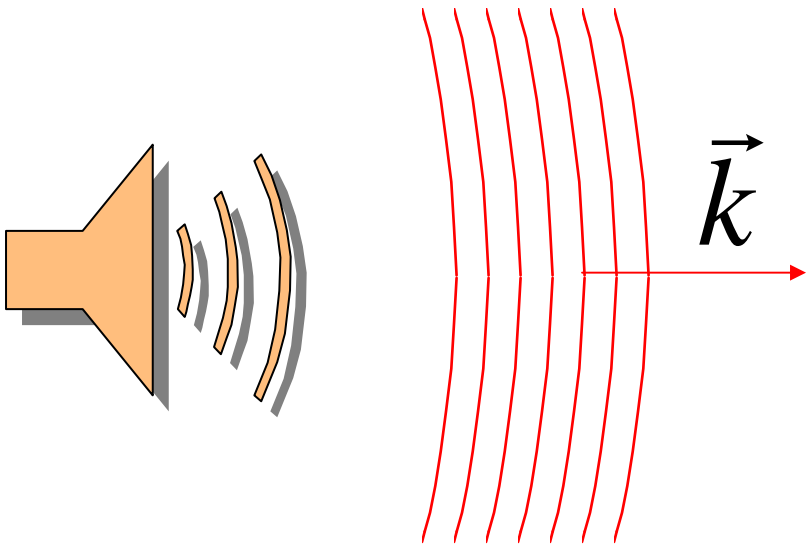
1D



PRL, **98**, 134301 (2007)

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2. **Wave propagation through phononic crystals**
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5. Acoustic metamaterials: molding the waves
6. Inverse design of phononic devices
7. Conclusion

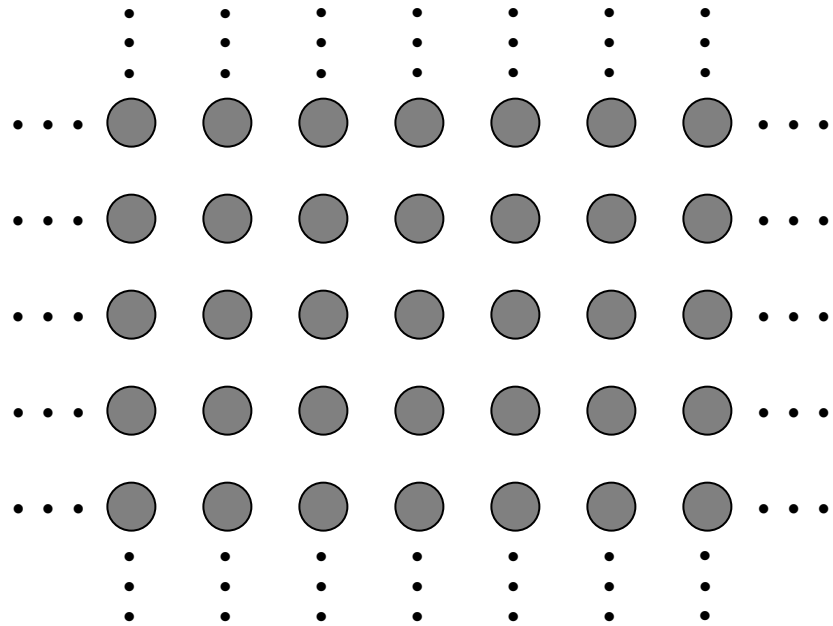
SURPRISES OF PERIODICITY



Sound waves in air

$$p(\vec{x}, t) \sim e^{i(\vec{k} \cdot \vec{x} - \omega t)}$$

$$\omega = c|\vec{k}|$$



Bloch wave

$$p(\vec{x}, t) = e^{i(\vec{k} \cdot \vec{x} - \omega t)} p_{\vec{k}}(\vec{x})$$

Plane wave

periodic “envelope”

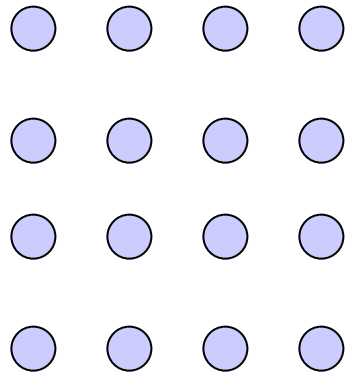
$$\omega \neq c|\vec{k}|$$



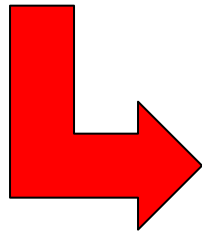
$$\omega(\vec{k})$$

SOUND PROPAGATION THROUGH PHONONIC CRYSTALS

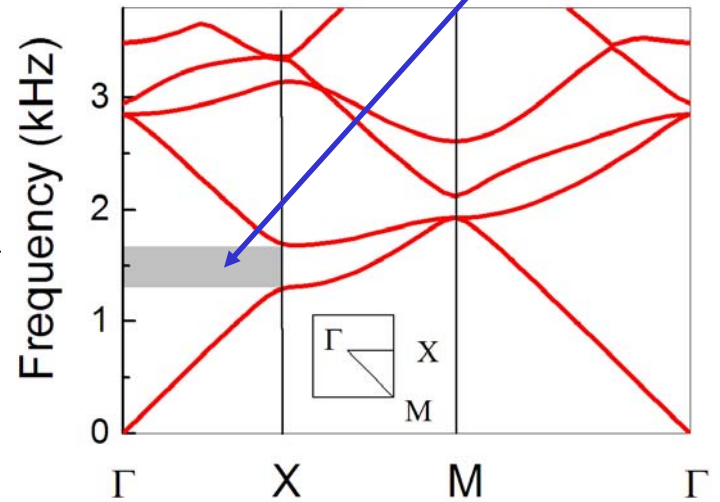
$f=0.25$



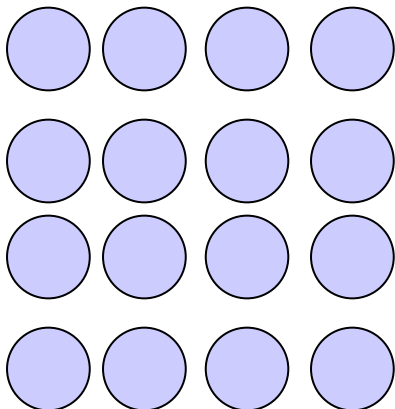
$\omega(\mathbf{k})$



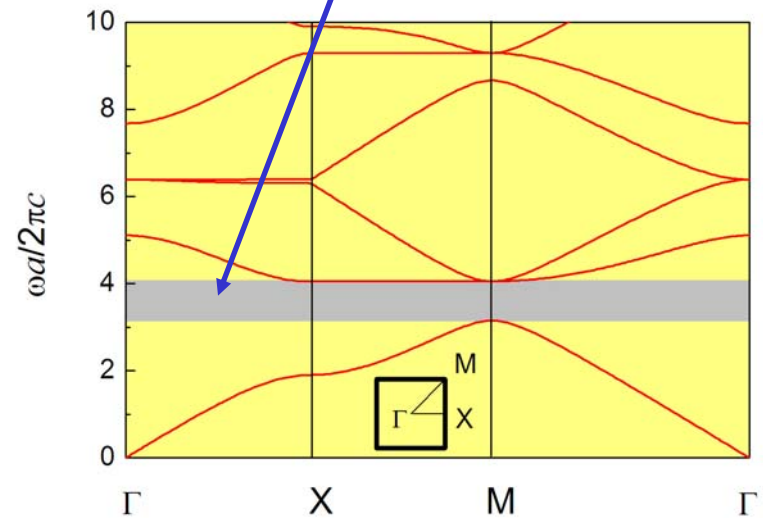
Partial bandgap (pseudogap)



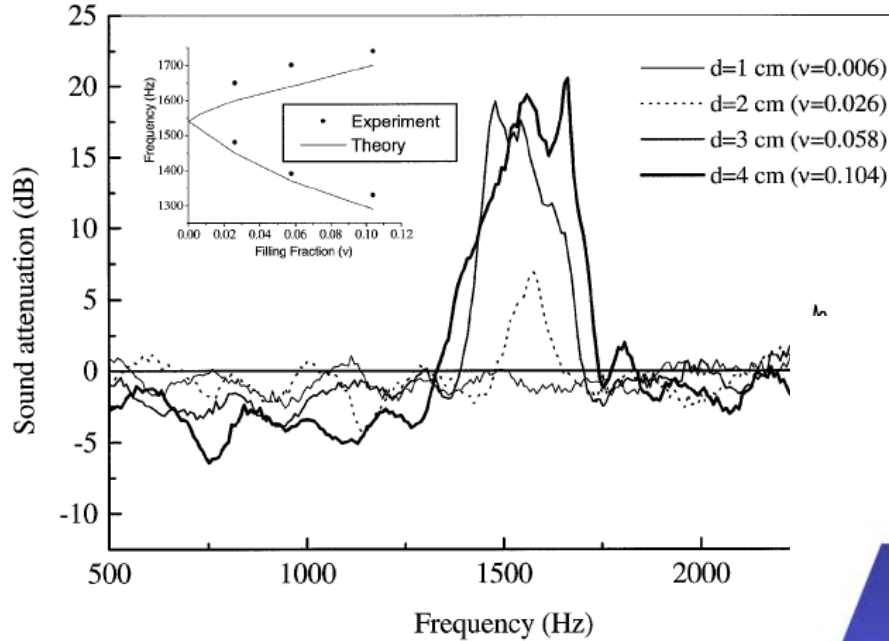
$f=0.4$



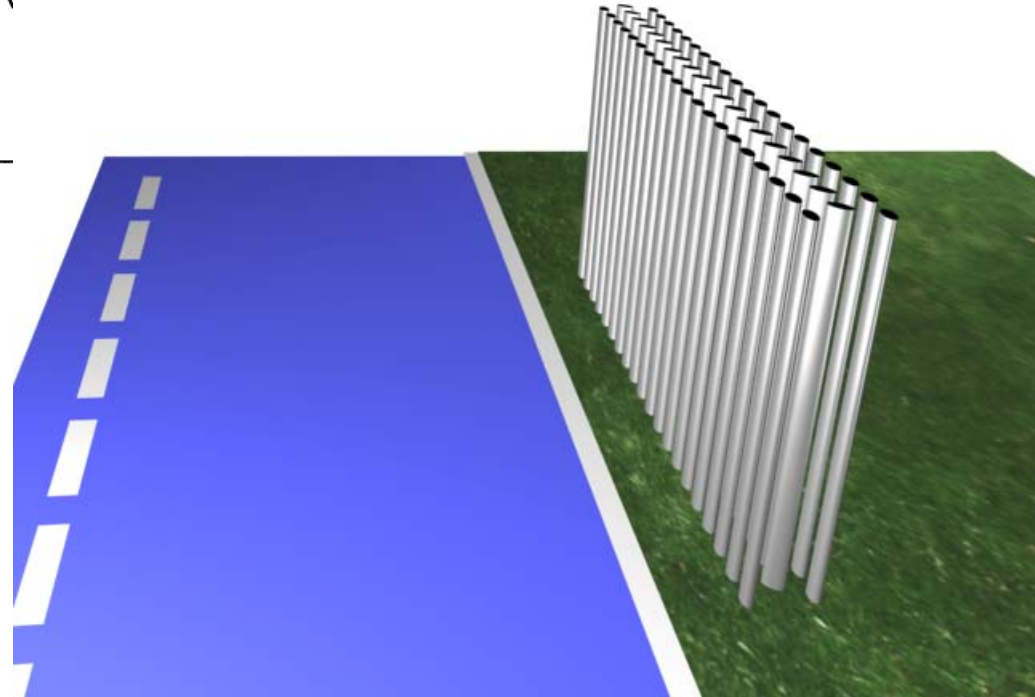
Complete bandgap



Sound attenuation by phononic crystals



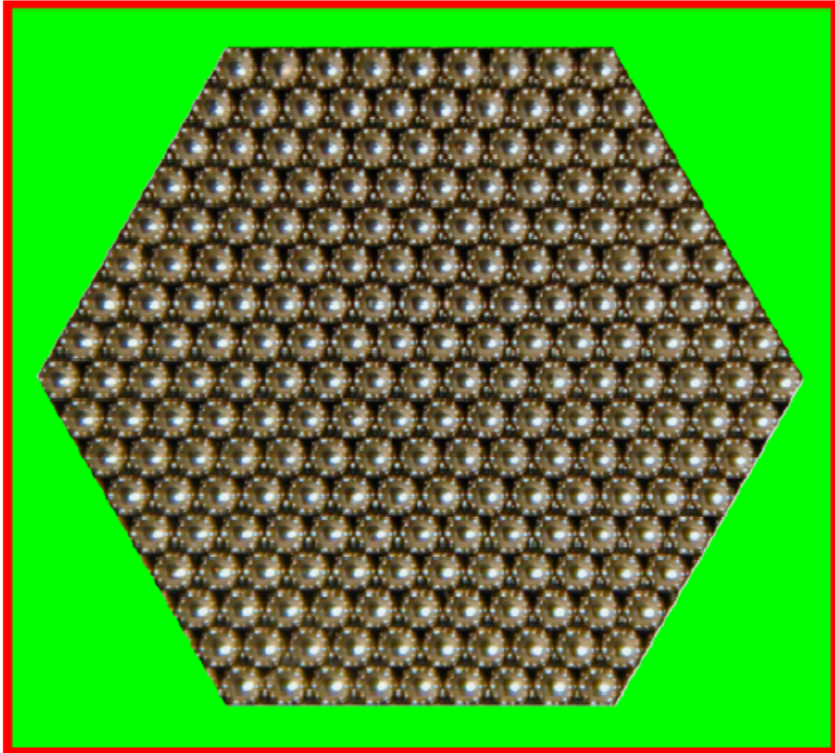
Noise barriers based on phononic crystals



PRL, 80, 5325 (1998)

Only 3 rows are enough to efficiently reduce the traffic noise !!

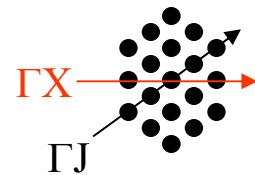
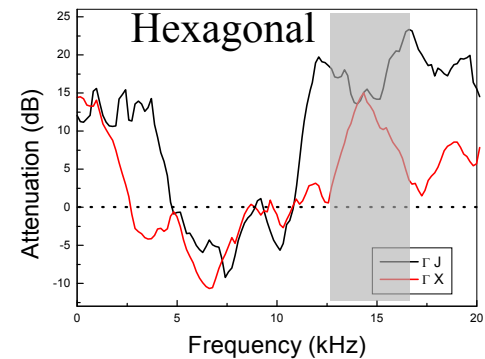
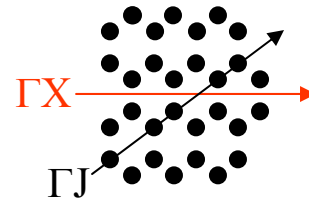
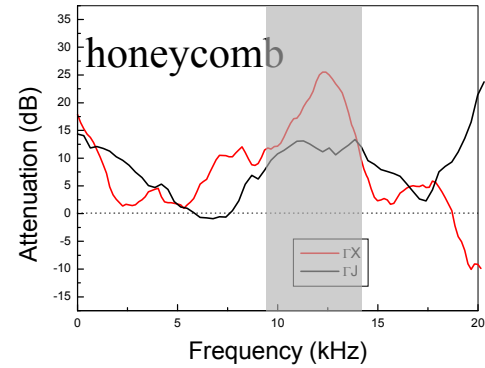
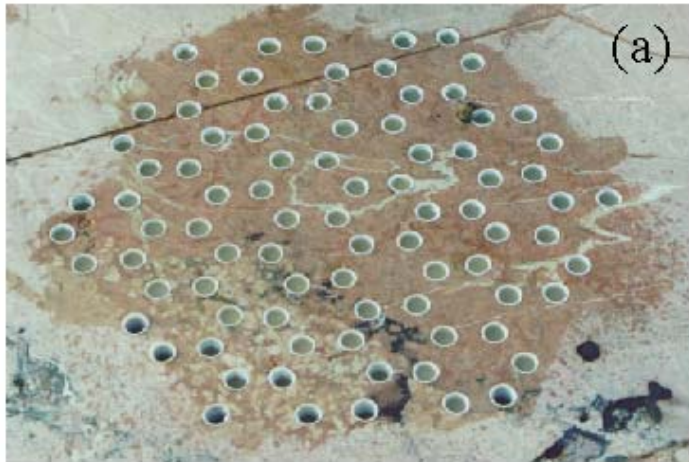
PHONONIC CRYSTALS : PERIODIC COMPOSITES with SONIC/ELASTIC BANDGAPS



Possible applications

- filters
- vibration/sound insulation
- waveguides for vibrations/sound

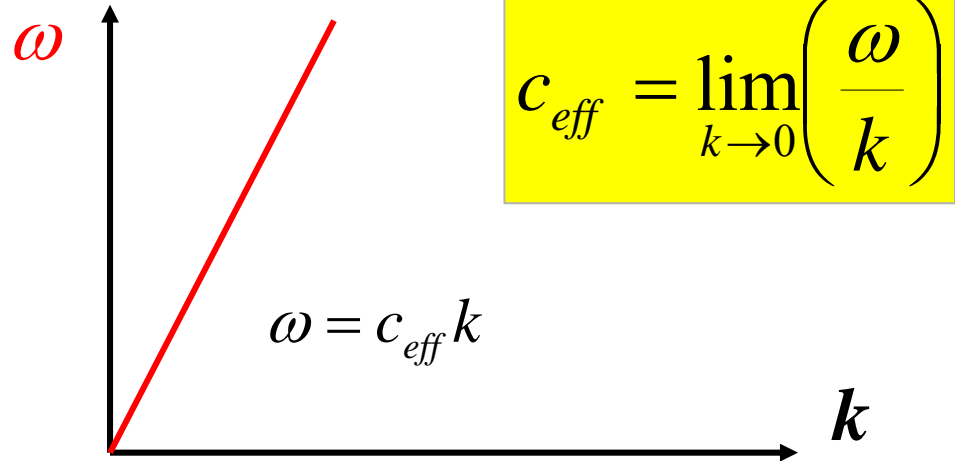
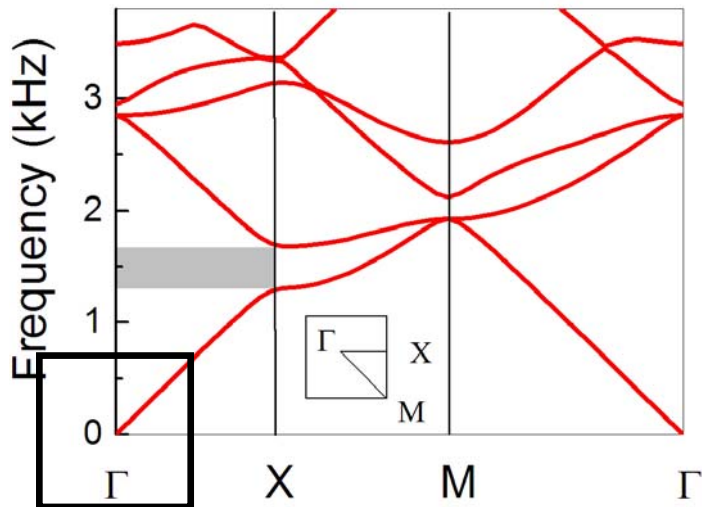
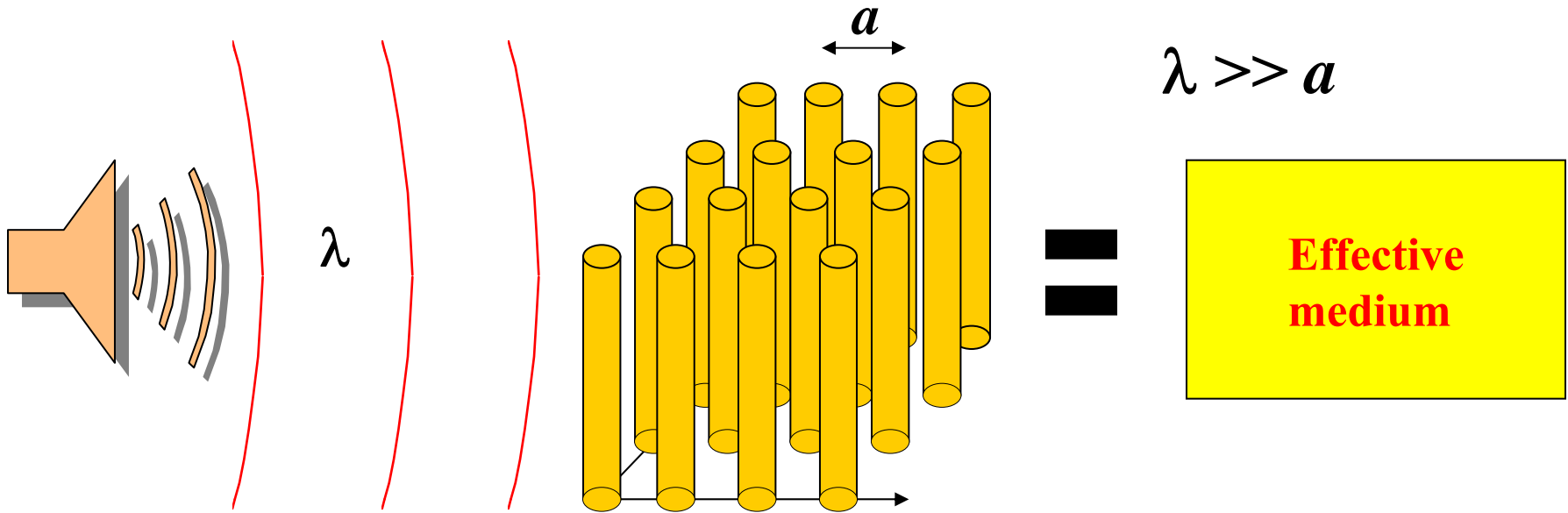
Attenuation of surface elastic waves (earthquakes) by phononic crystals



PRB, **59**, 12169 (1999)

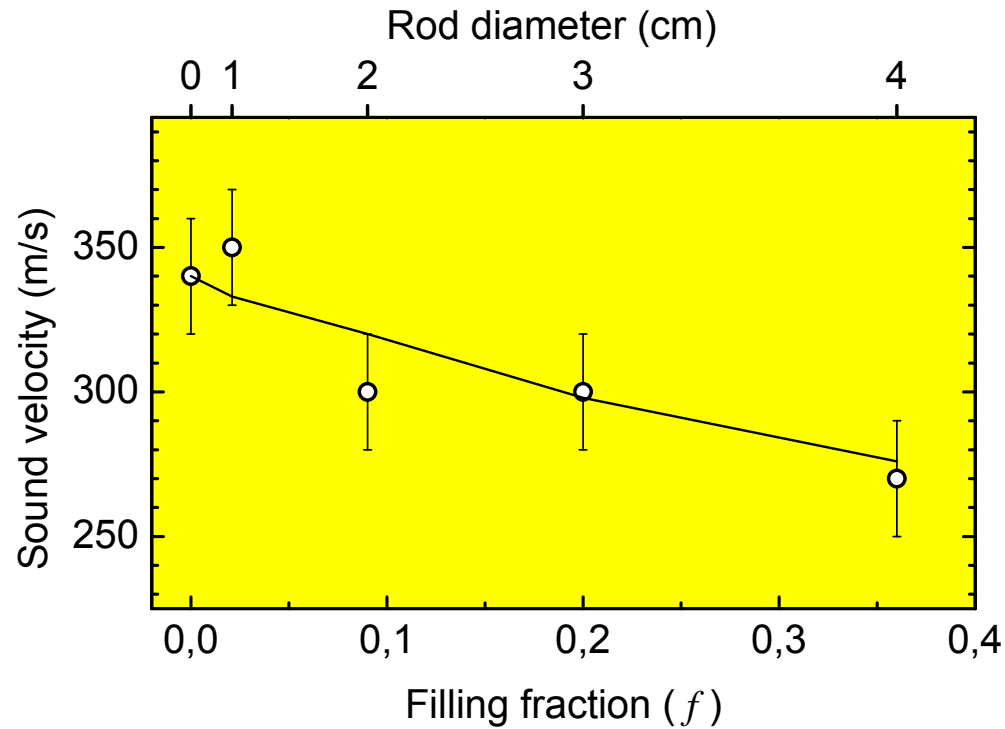
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HOMOGENIZATION = LIMIT $\omega \rightarrow 0$



Sound propagation trough lattices of solid cylinders in air

Hexagonal lattice ($a=6.35$)



$$c_{\text{eff}} = c_{\text{air}}/n \approx c_{\text{air}}/\sqrt{1+f}$$

PRL, 88, 023902 (2003)

Refractive devices based on PHONONIC CRYSTALS: lenses

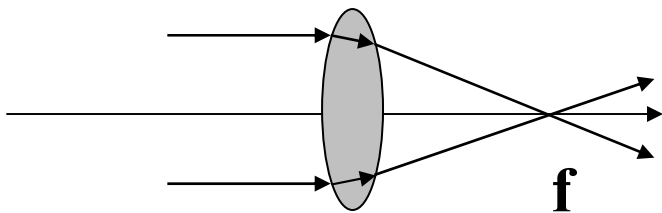
Why optical lenses are possible?

- a) Light velocity is lower in solids than in air:

$$c_{\text{solid}} < c_{\text{air}} \quad (n_{\text{solid}} > n_{\text{air}})$$

- b) Dielectric materials exist that are transparent to light :

$$n_{\text{solid}} \approx n_{\text{air}}$$



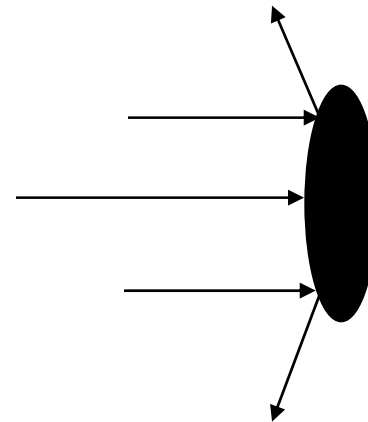
Why sonic lenses did not exist?

- a) Sound velocity is larger in solids than in air:

$$v_{\text{solid}} < v_{\text{air}} \quad (\approx 340 \text{ m/sec})$$

- b) Solids materials are not transparent to sound:

$$Z_{\text{solid}} \gg Z_{\text{air}}$$

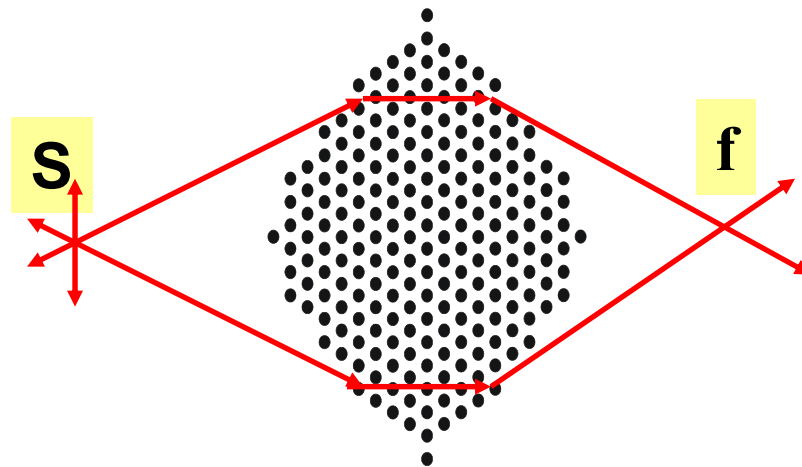


PHONONIC CRYSTALS make sonic lenses possible

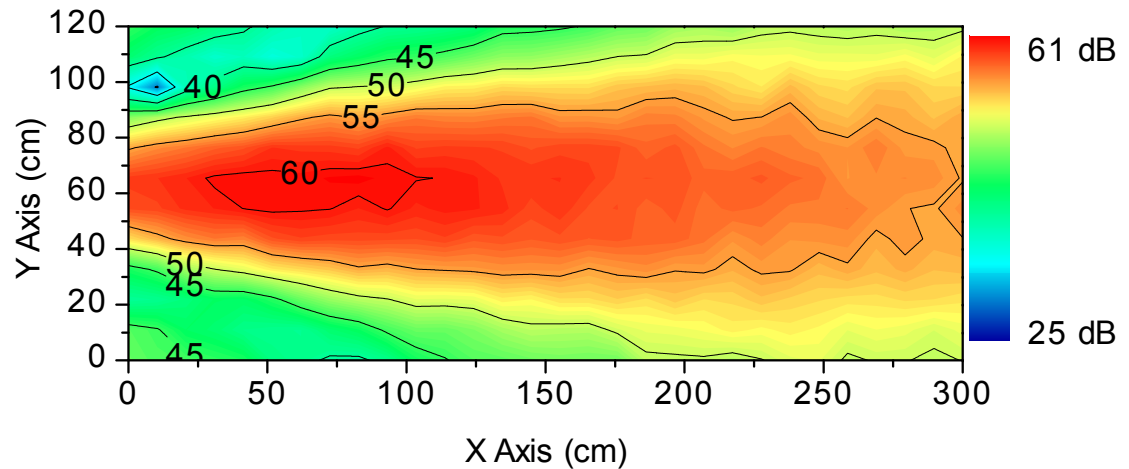
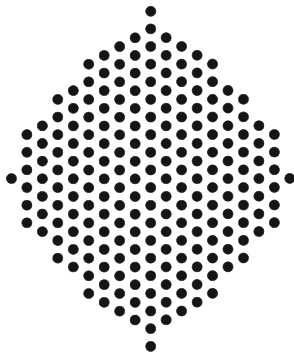
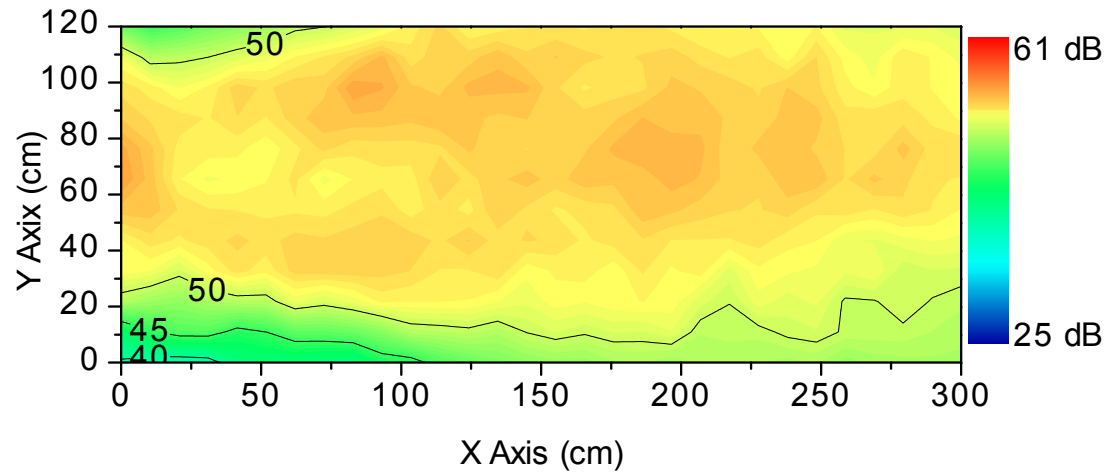
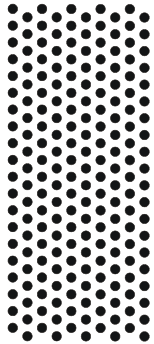
Why?

a) Sound propagation inside the PC is lower than in air: $v_{SC} < v_{air}$

b) They are almost transparent to sound (low reflectance at the air/PC interface): $Z_{SC} \approx Z_{air}$

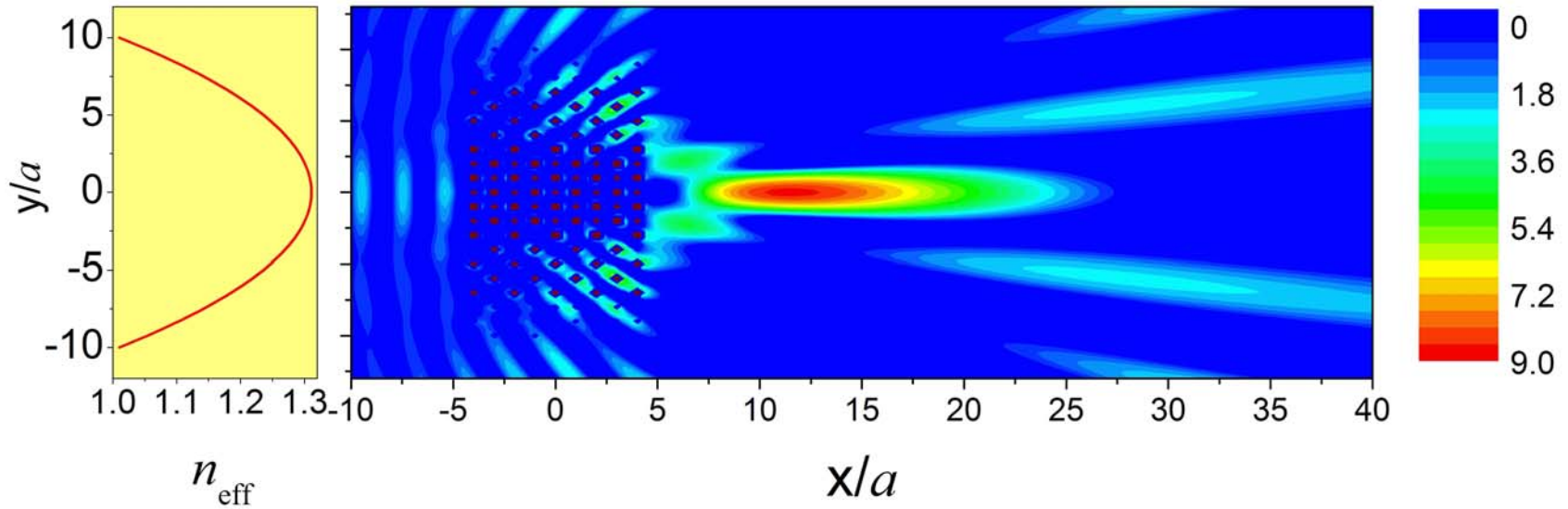


Acoustic lenses in the audible based on PHONONIC CRYSTALS



Phononic crystals made of mixing two different elastic materials in air

Refractive device proposed: **A gradient index sonic lens**

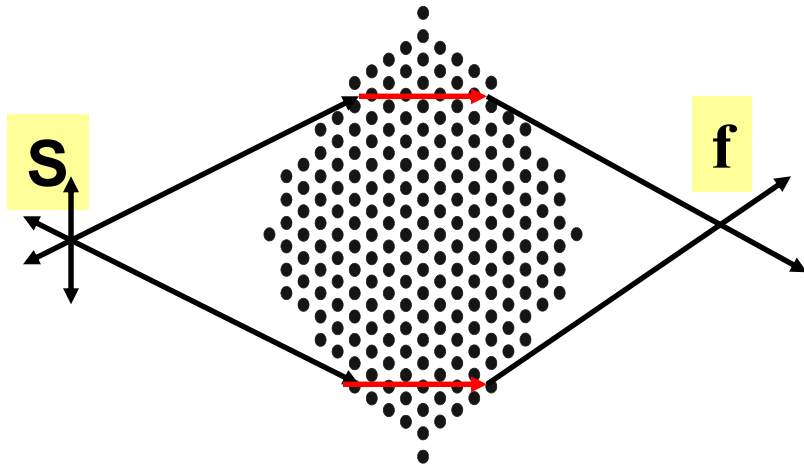


New J. Phys. **9**, 323 (2007)

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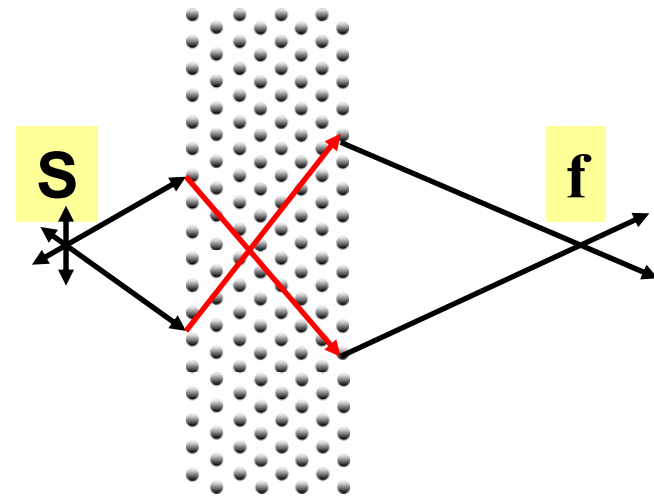
PHONONIC CRYSTALS also present “negative refraction”

Positive refraction



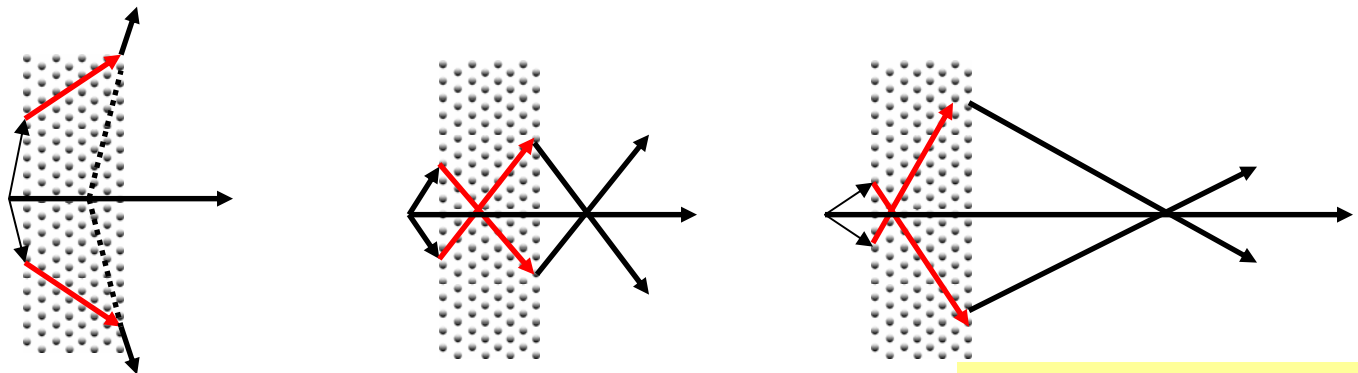
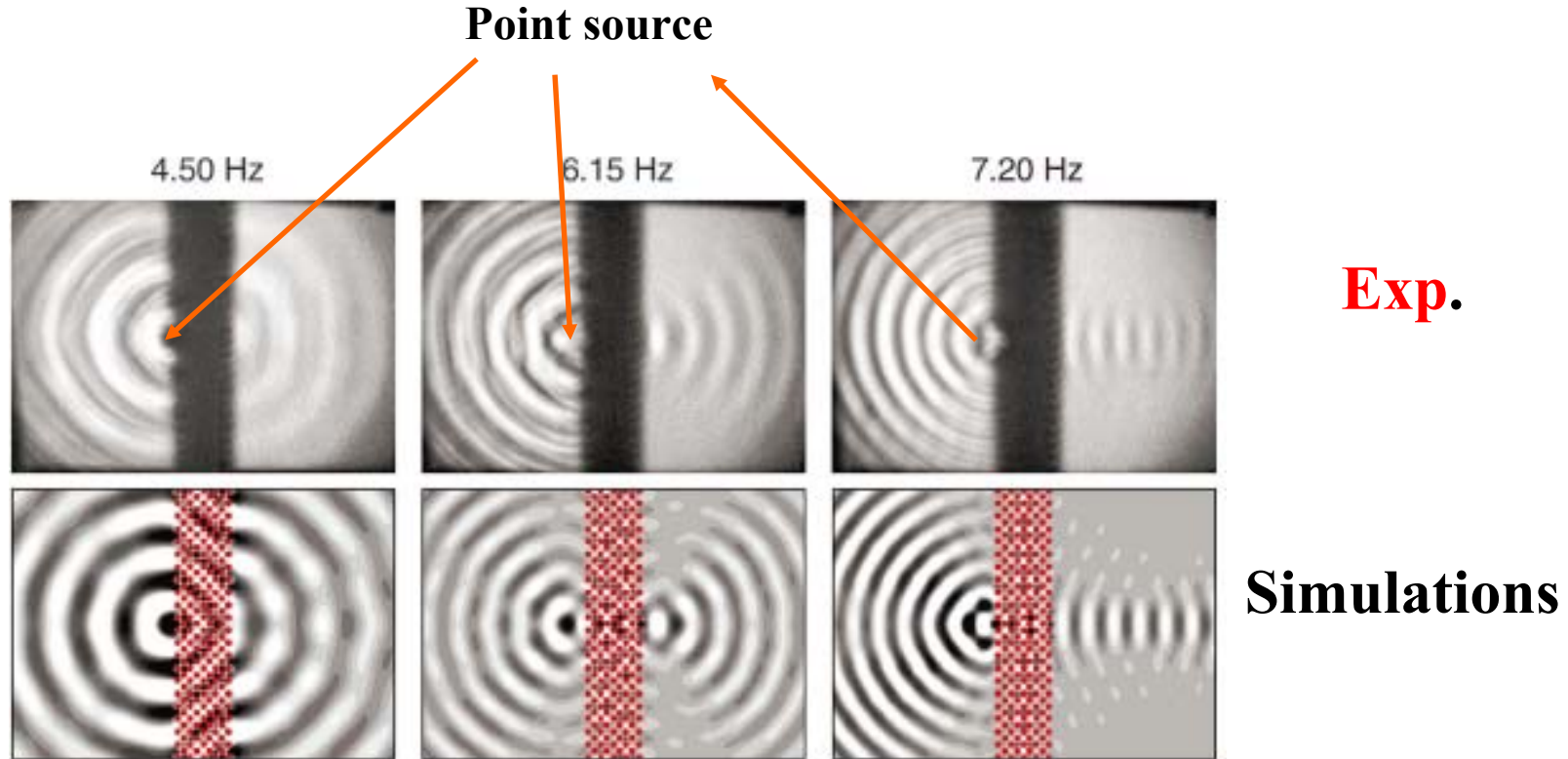
$$\lambda \gg a$$

Negative refraction

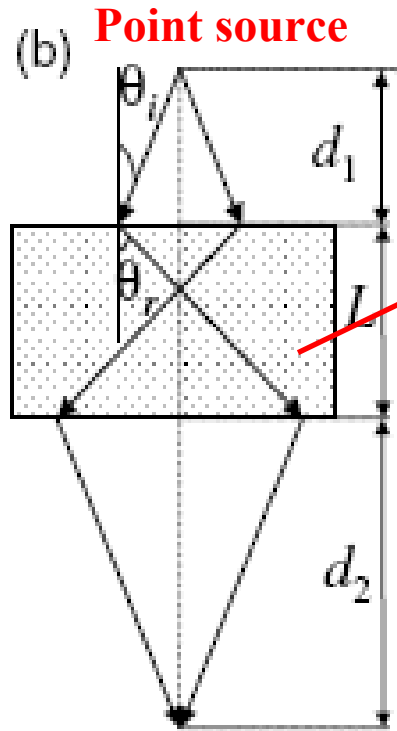


$$\lambda \approx a$$

Imaging and focusing of water waves by negative refraction

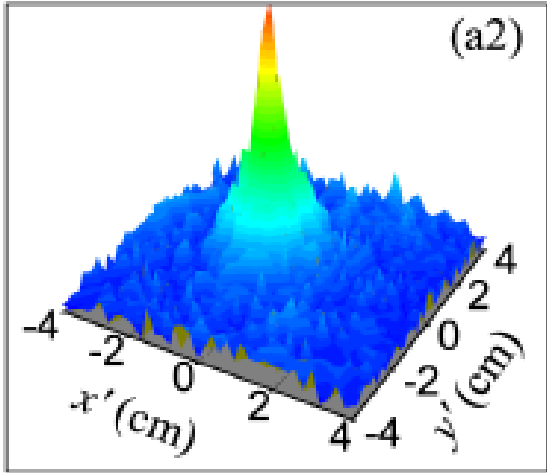


Sound focusing by 3D phononic crystal



0.8 mm diameter WC beads in water
fcc (111)

**Negative refraction
and focusing by a
3D phononic crystal
demonstrated!**



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Photonic/Sonic crystals

Acoustic metamaterials

$$\lambda \approx a$$

$$\lambda \gg a$$

band structure description

Effective medium description

Negative refraction and other band structure effects

Positive acoustic parameters

Negative acoustic parameters

Positive refraction, acoustic-like behavior with unusual parameters by using solid structures...

Negative group velocity, negative refraction, subwavelength imaging...

Bragg scattering

Homogenization

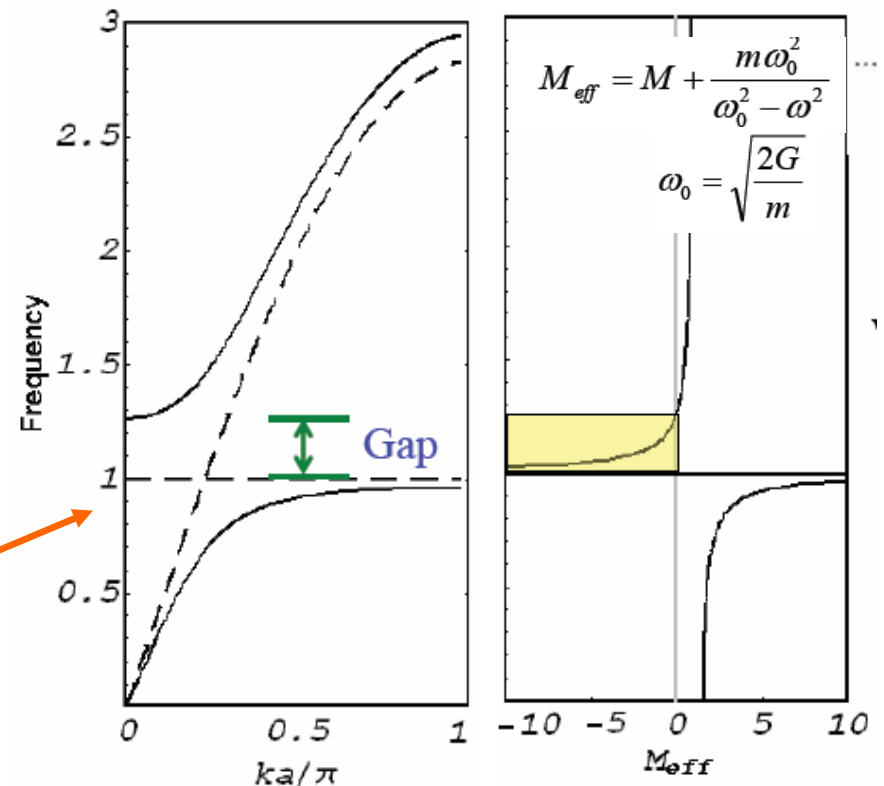
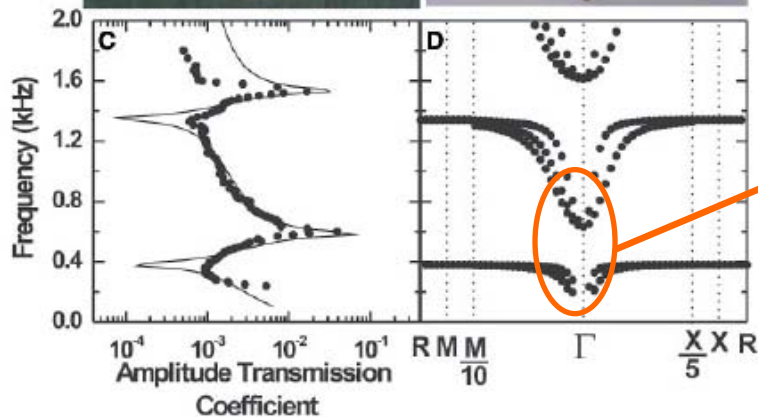
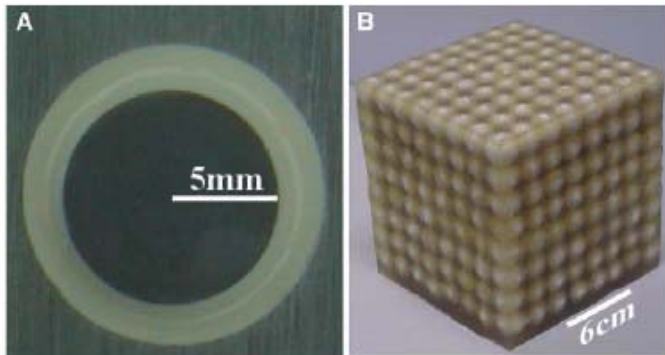
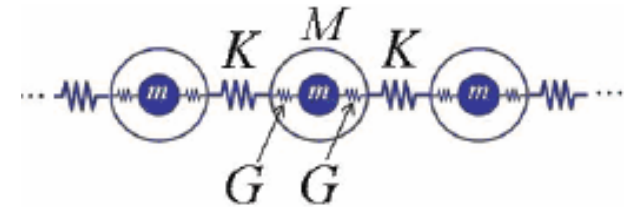
Resonances of building blocks

Acoustical metamaterials

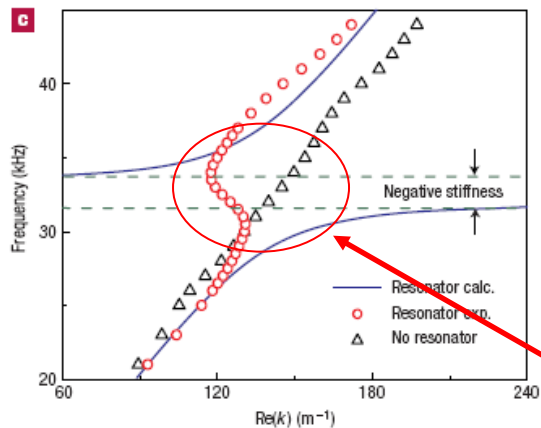
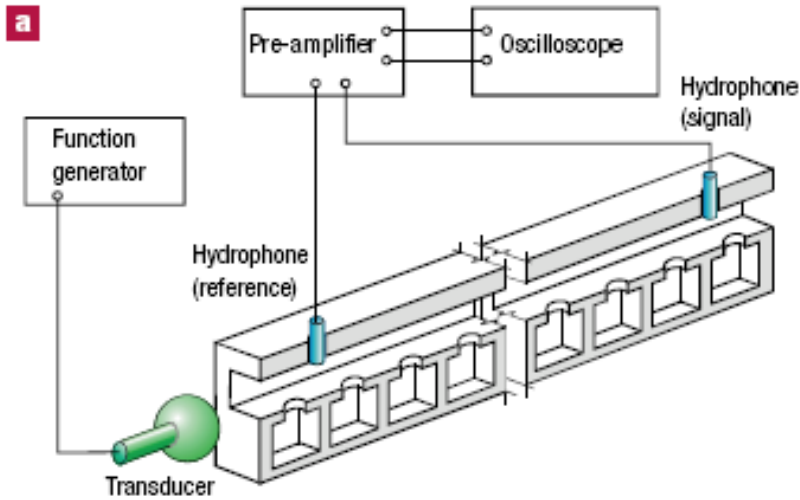
- Wave transport is controlled by only two parameters: ρ , K
- Resonances can make one or both negative
- If only one is negative \rightarrow forbidden propagation
- If both are negative \rightarrow propagation is allowed with negative group velocity, negative refractive index

Negative mass materials (attenuation of low frequency sound!)

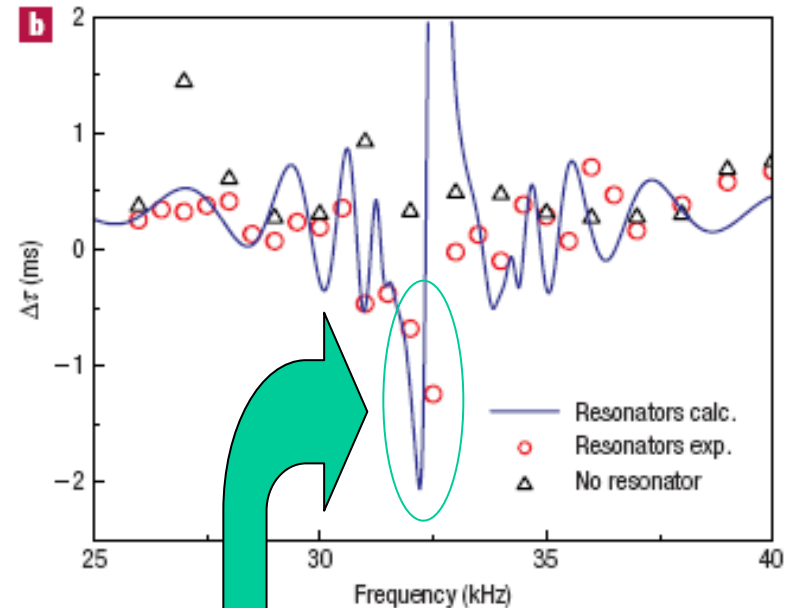
Metal spheres coated with Silicon rubber embedded in a epoxy matrix



Negative effective modulus obtained by (monopolar) resonances in 1D array of subwavelength Helmholtz resonators in water



Group transit delay time



Negative group delay

•Group velocity antiparallel to phase velocity

Negative K and Negative ρ

Bubble-contained water spheres

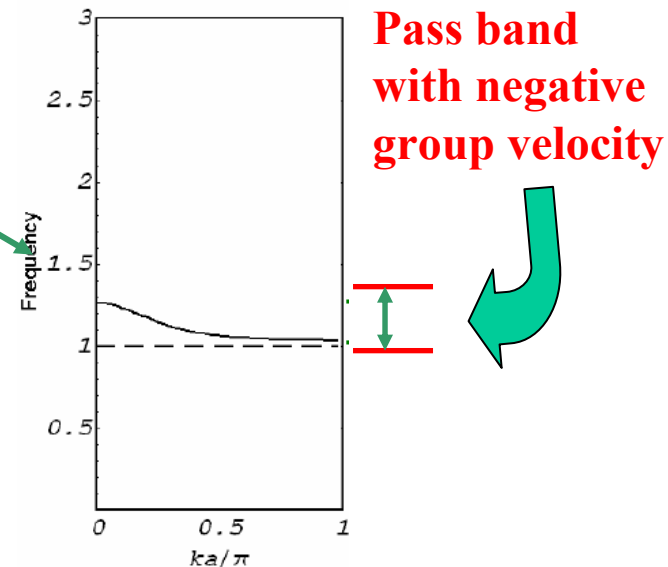
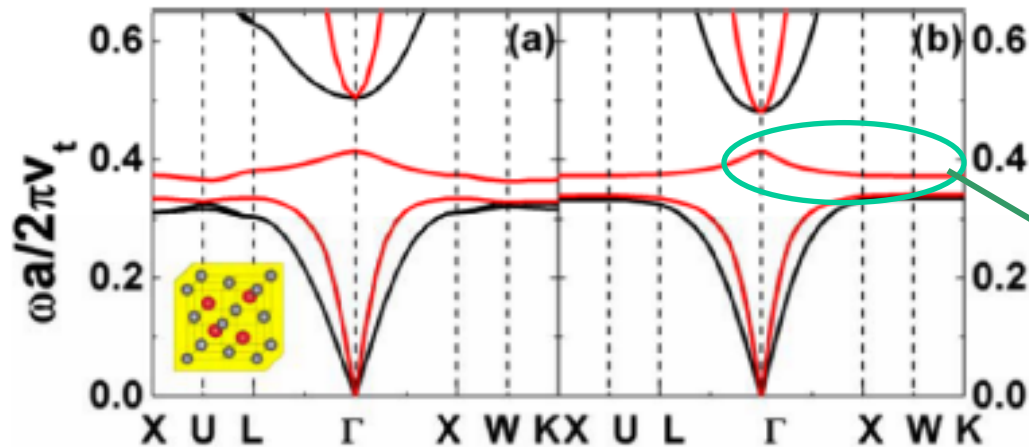
+

Gold spheres coated with rubber

(in a epoxy matrix)

Monopolar resonances

Dipolar resonances



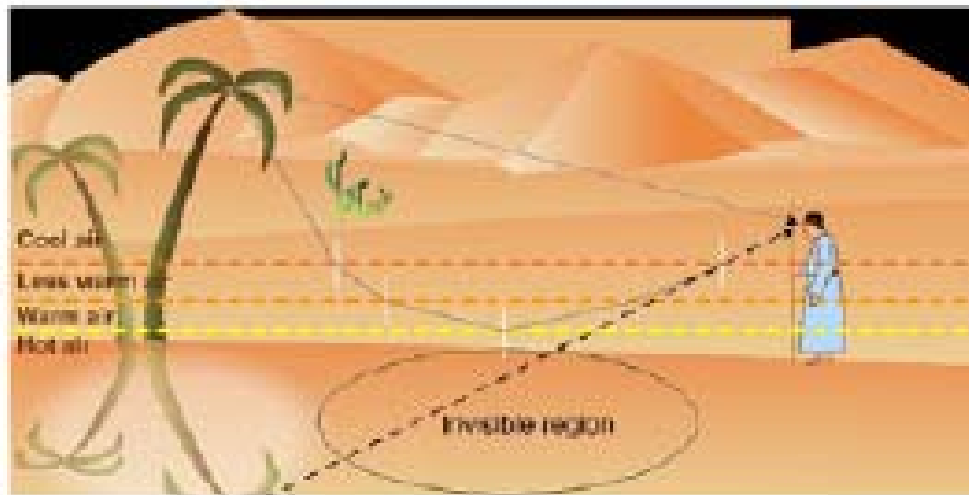
PRL 99, 093904 (2007)

Wave manipulation using acoustic metamaterials

Guide the sound as desired

Acoustic cloaking:

- Inspired in the similar phenomenon already demonstrated for EM waves
- Principle like mirage

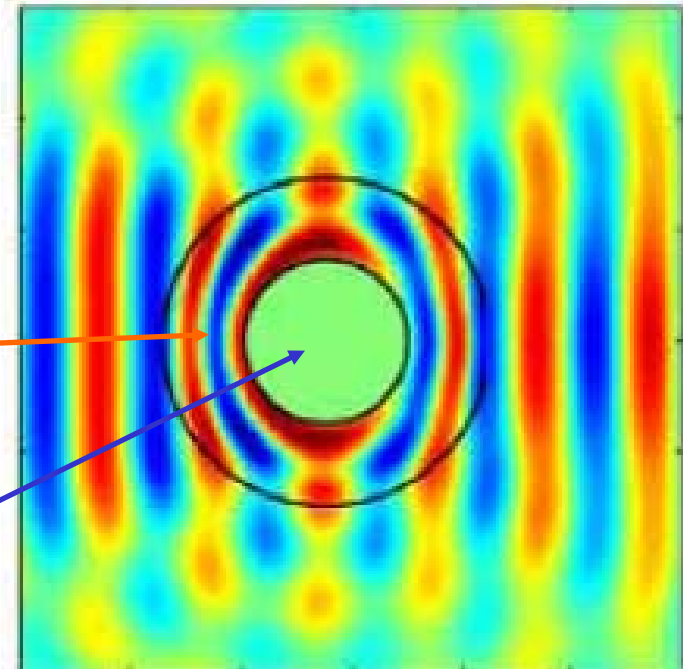


Wave manipulation using acoustic metamaterials

2D Acoustic cloaking

Acoustic metamaterial:

$$\begin{aligned}\frac{\rho_r}{\rho_0} &= \frac{r}{r - r_1}, \\ \frac{\rho_\theta}{\rho_0} &= \frac{r - r_1}{r}, \\ \frac{\lambda_c}{\lambda_0} &= \left(\frac{r_2}{r_2 - r_1} \right)^2 \frac{r}{r - r_1},\end{aligned}$$

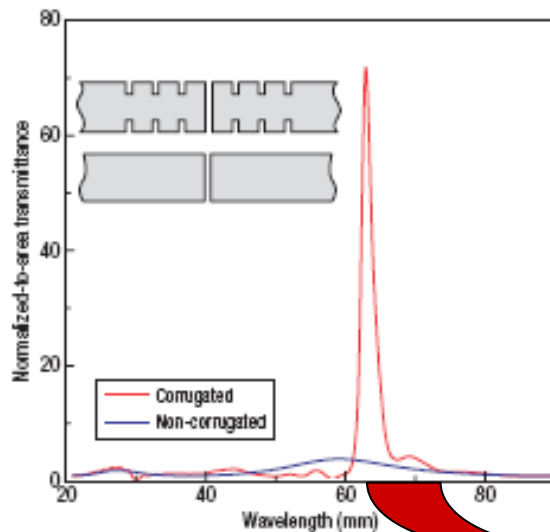
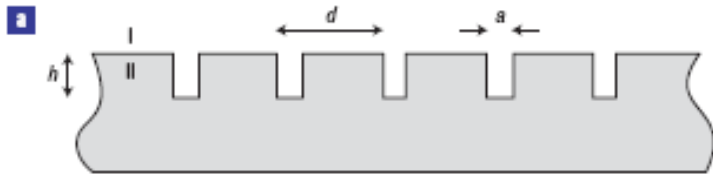


This region is invisible to sound!

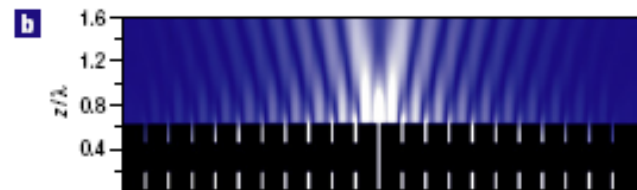
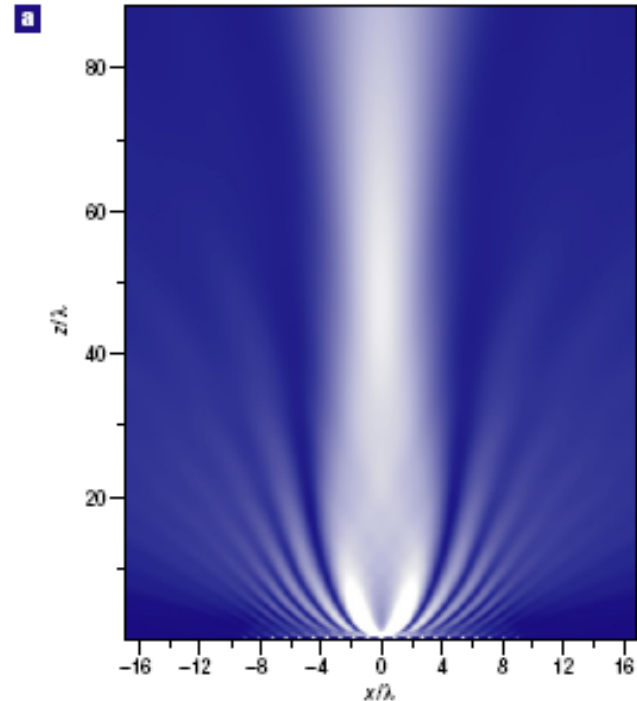
New J. Phys. **9**, 45 (2007)

Collimation of sound assisted by ASW

Surface acoustic waves are possible in corrugated surfaces:



$$\lambda > 10a$$



↑↑↑↑↑↑↑↑↑↑
Incident acoustic plane wave

Nat. Photonics (2007)

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PHONONIC CRYSTALS show astonishing properties that can be use to construct a new generation of devices to control propagation of mechanical waves

But....

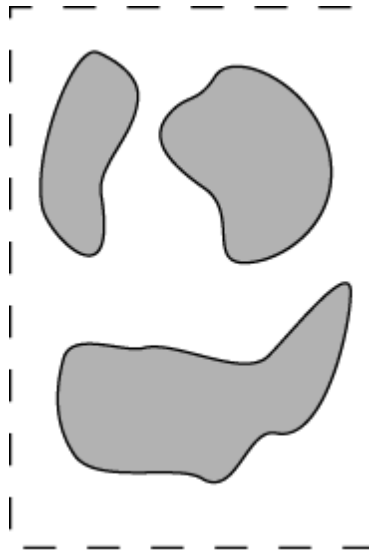
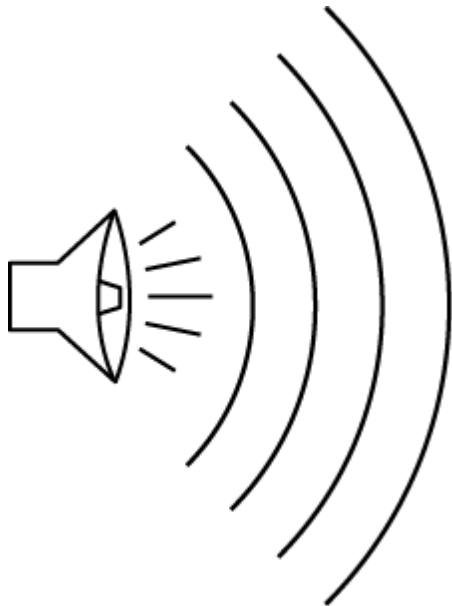
Optimization algorithms (Inverse design) can be used to create new functionalities by using the Phononic Crystals as starting structures

Inverse design of phononic devices

Wave source
(s)

Material dist.
(m)

Performance
 $d=[G(m)]_s$



Scattering Acoustical Elements (SAE)

$$G(m) = E_1(m_1, m_2, m_3) + E_2(m_1, m_2, m_3) + E_3(m_1, m_2, m_3)$$

Controlling the multiple scattering of waves!

The inverse problem is solved through optimization

Inverse Design-Tool

Direct Solver – Multiple Scattering Theory

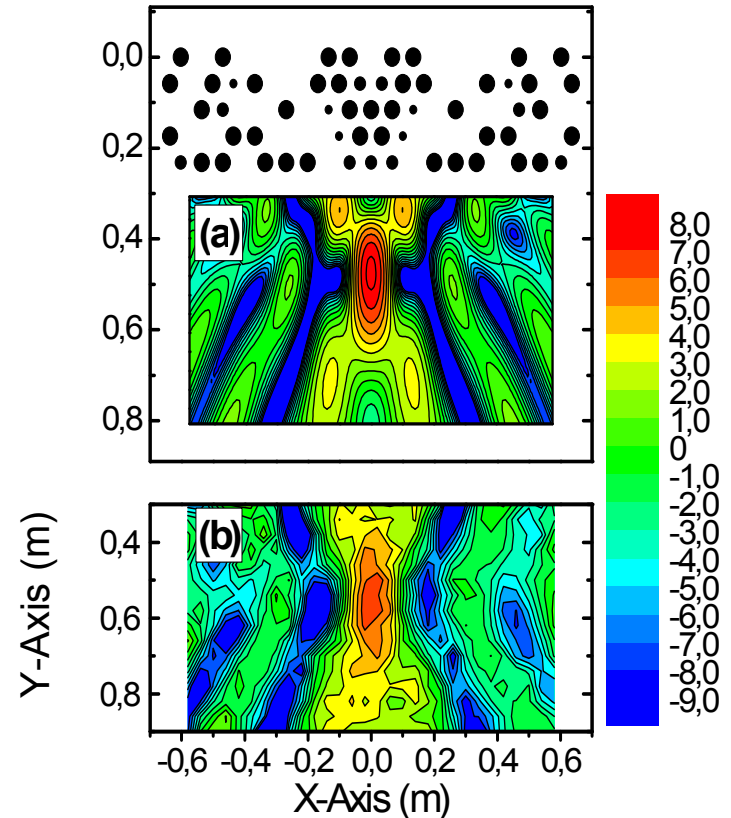
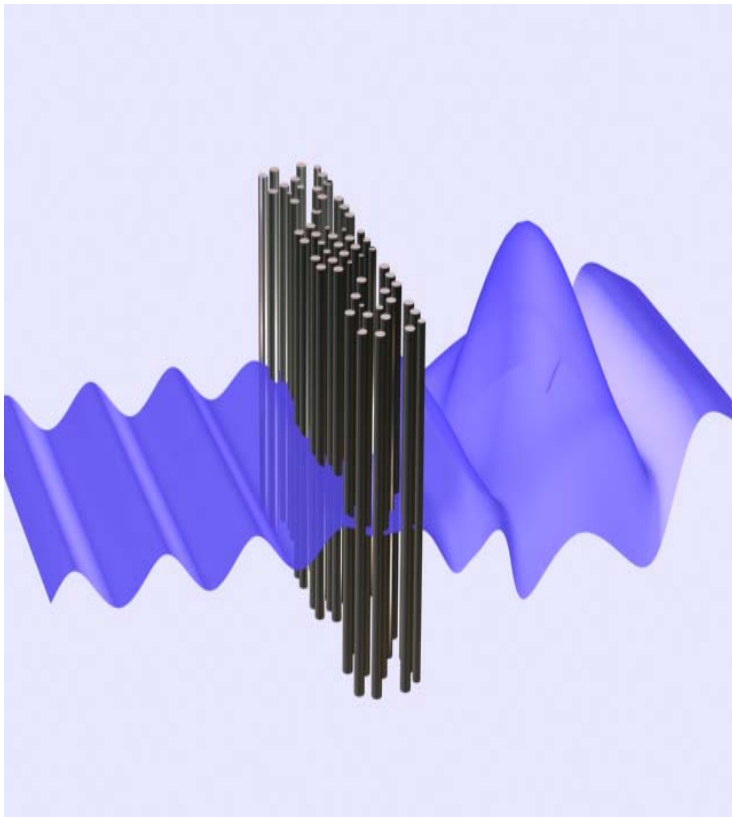
- Semi analytical
- Fast

Optimization Method – Genetic Algorithm

- Great history
- Easy implementation

Inverse design of flat acoustic lens

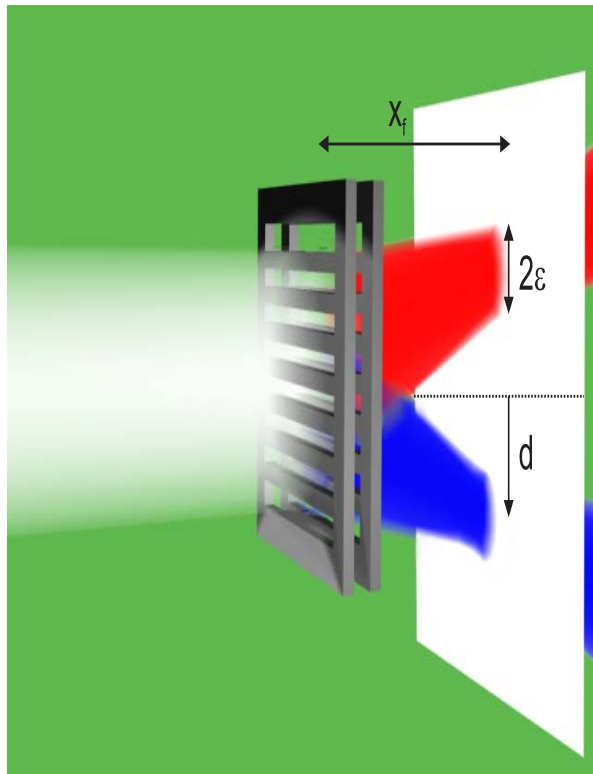
Functionality: sound focusing at selected wavelengths



APL, 86, 054102 (2005)

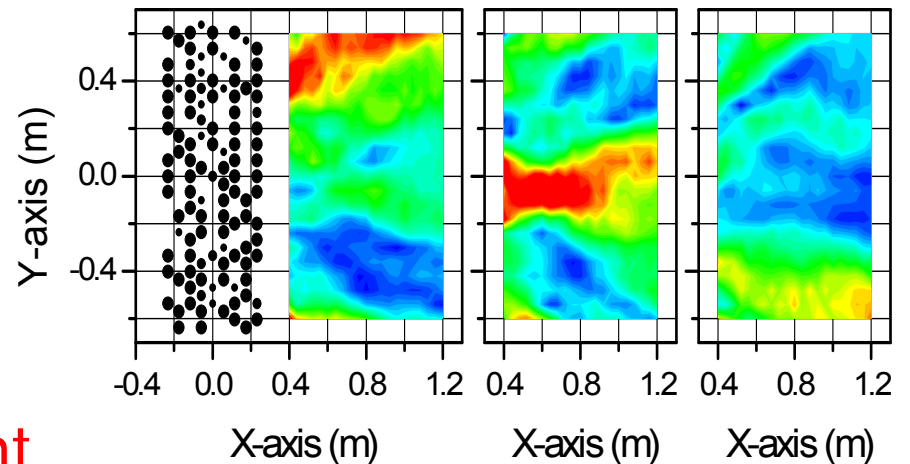
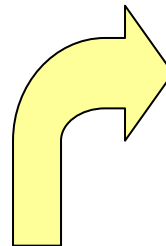
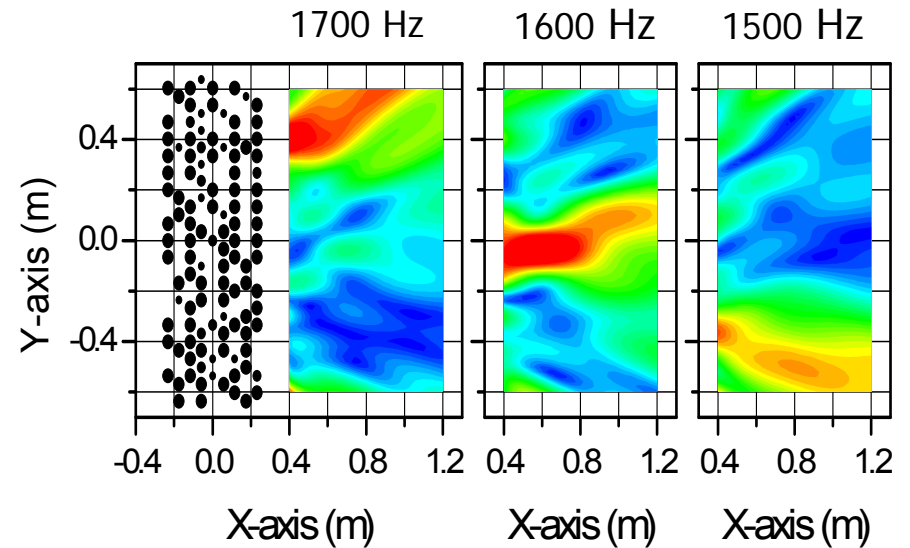
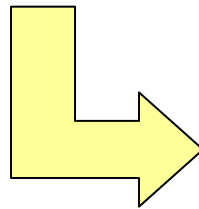
Inverse design of a sonic demultiplexor

Functionality: spatial separation of several wavelengths



APL, **88**, 163506 (2006)

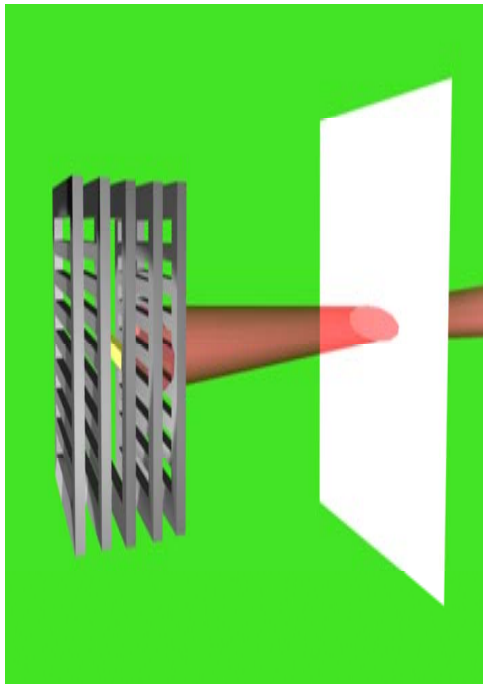
Prediction



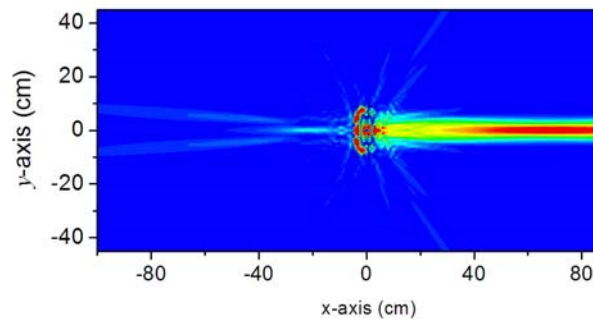
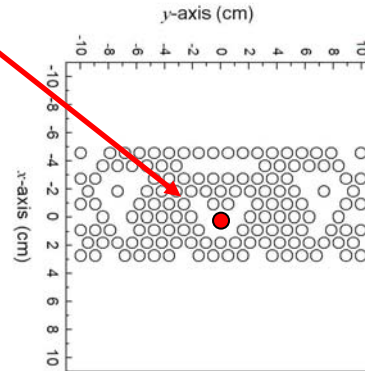
Experiment

Inverse design of highly directional sound sources

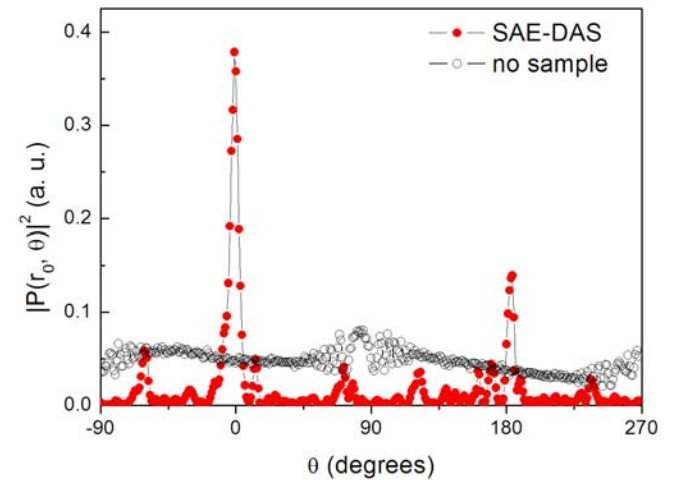
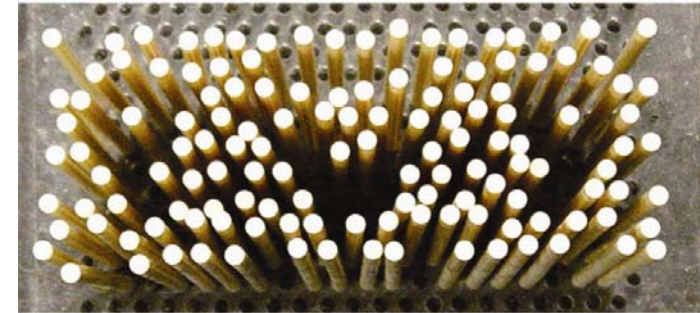
Onmidirectional point source



Theoretical prediction



Practical realization



APL, 90, 224107 (2007).

PHONONIC CRYSTALS is going to be a hot topic in the next few years

Many device applications are expected from PHONONIC CRYSTALS in acoustics, elasticity and.....optics

Thanks for your attention!