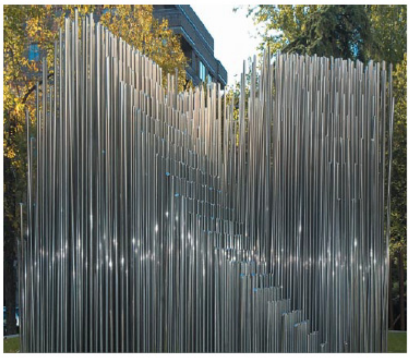
MPIP-Mainz

T.Still,W.Cheng,N.Gomopoulos
G.F

FORTH
Heraklion

G.F

Sculpture by E.Sempere (Madrid)

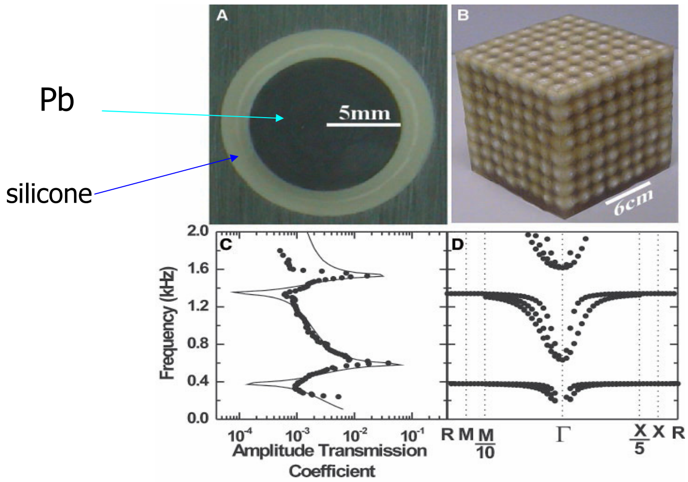


Cubic arrays of hollow stainless-steel cylinders
[diameter: 2.9 cm and lattice constant:a=10 cm]

Minimum sound transmision at f=1.67 KHz (stop band)*
(●~a)

*R.Martinez et al Nature 378,231,1995

Sonic Crystal



Spectral gab :lattice a<<λ sound wavelength (usually a/λ ~1)

silicone :soft spring , **Pb**:heavy mass

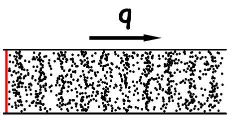
P.Sheng et al Science 2000

Strong and Deaf Periodic Structures

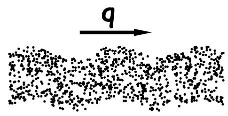
- Phononic Materials
- Experimental techniques (***ω(k)***)
- Examples of fabricated structures /phenomena
  - Colloid-based sub-μm structures (music & concert)
  - 1D Hybrid multilayer SiO2/PMMA films (unidirectional gap)
  - Biological structures (spider dragline silk)

"Material vibration"?

in bulk: *longitudinal* and *transverse* waves



longitudinal c_l



transverse c_t

structured materials: c_l , c_t & density vary in space
elastic wave equation ❿ displacement **u(r,t)**

at surfaces or in thin films: + boundary conditions

Phononic Materials

control the flow elastic energy (1993,1995)

periodic modulation (ρ, c_l,two c_t, anisotropy)

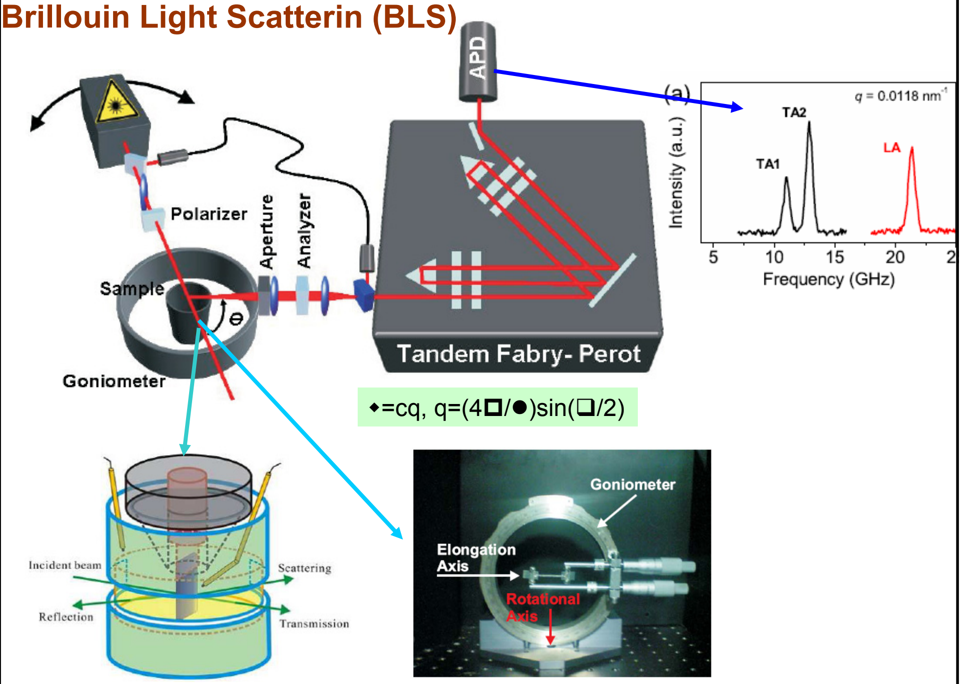
standard manufacturing: sonic,ultasonic range

Bragg gap at λ ~a commensurate lattice constant a
Strong local resonances : λ >>a (P.Sheng 2000)

Hypersonic phononics : fabrication,characterization

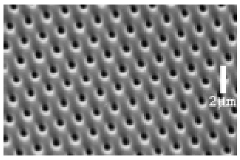
Dual gaps(PhoXonics) :
hypersonic phononics & visible wavelentgh photonics
optomechanical crystals (Nature 462,78,2009)

Brillouin Light Scatterin (BLS)

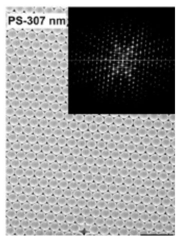


Fabricated sub-❍m structures

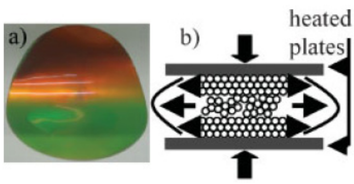
1.Polymer based Phononic Crystals
(optical lithography) PRL 94,115501(2005)



2a.Colloid- based Phononic Crystals
(vertical lifting) PRL100, 194301 (2008)

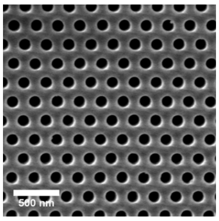


2b.Colloid- based Phononic Crystals
(melt compression,shear induced)
(Adv.Mater.20,1484(2008)

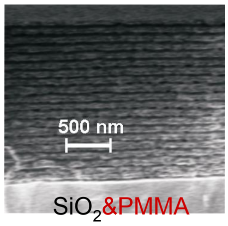


Fabricated sub-❍m structures

3.Anodic Aluminium Oxide- based Phononic Crystals
(electrochemistry) J.Chem.Phys.123,121104(2005)



4.1.D hybrid Phononic Crystals
(spincoating) Nano lett.submitted



Phononic Materials

Experimental techniques ($\omega(k)$)

- Colloid-based sub-μm structures (music & concert)

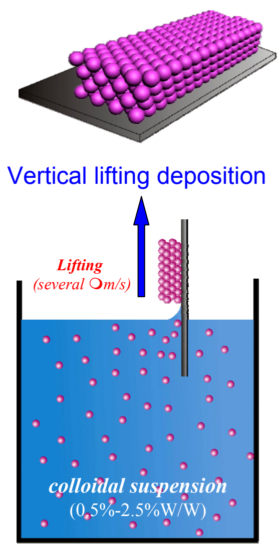
a) Particles: Local resonances (music)

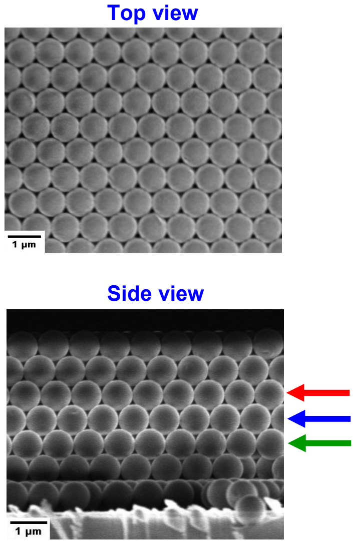
PRL(2000),J.C.P(2005),Langmuir(2005),Nano lett.(2008),JCIS(2009)

1D Hybrid multilayer SiO2/PMMA films (unidirectional gap)

Biological structures (spider dragline silk)

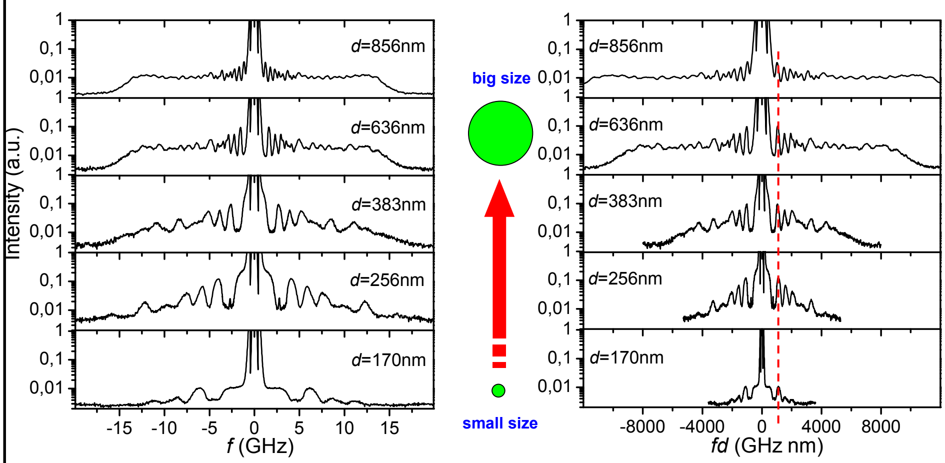
Dry colloidal crystals





J.Wang,M.Retsch U.Jonas *fcc*

BLS spectra



No **q** dependence !

Scaling f~d^{-1} !

W. Cheng et al. *J. Chem. Phys.* **123**, 121104 (2005).

Theoretical Calculations

The elastic wave equation:

$$(\lambda + 2\mu)\nabla(\nabla \cdot \mathbf{u}) - \mu\nabla \times \nabla \times \mathbf{u} + \rho\omega^2\mathbf{u} = 0$$

$\mathbf{u}$: the displacement vector, $\lambda = \rho(c_l^2 - c_t^2), \mu = \rho c_t^2$: the elastic coefficients

I. Isolated particle

Scattering cross section vs. frequency of a sound wave

Energy density distribution

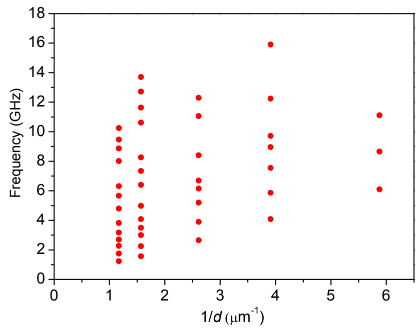
II. Periodic lattice: $\mathbf{u}(\mathbf{r},t) = \mathbf{w}(\mathbf{r}) \cdot \exp[i(\mathbf{kr} - \omega t)]$

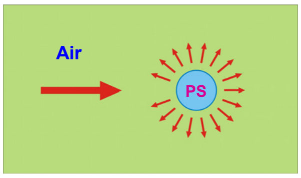
- Plane wave single scattering (G reciprocal lattice vector) $w_k = \sum_G w_G \cdot \exp(i\,\mathbf{kG})$
- Multiple phonon scattering formalism

Elastic field

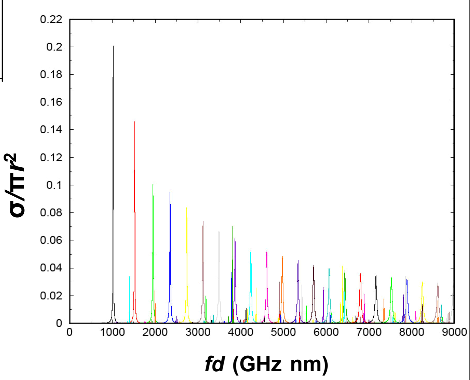
S(q,ω) (neglecting relaxation effects) **(q=k+G)**

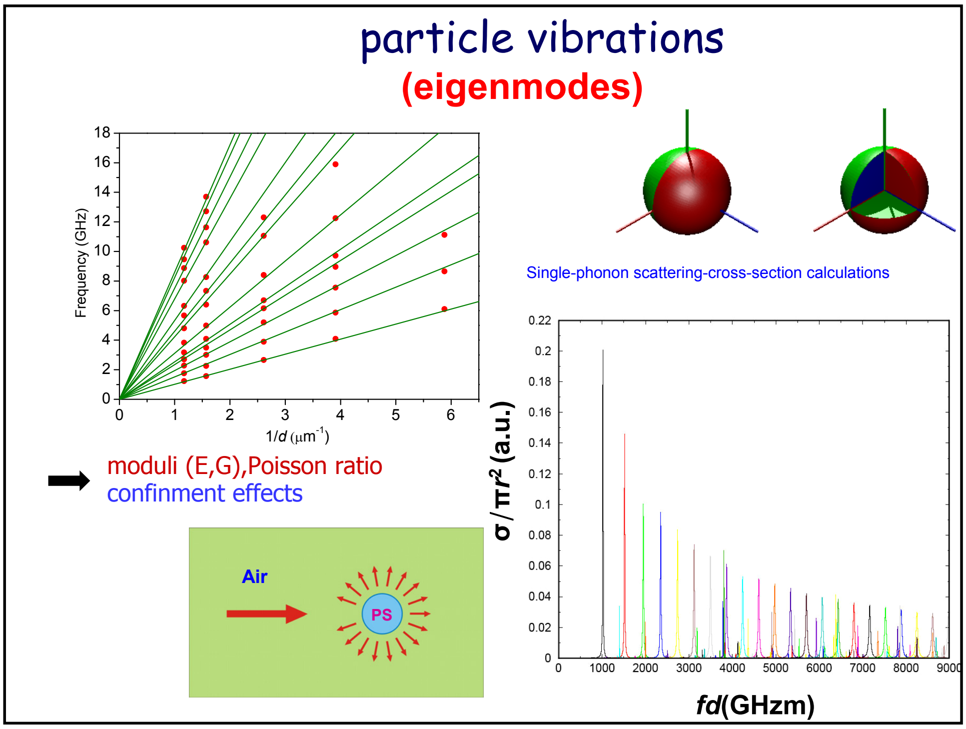
particle vibrations





Single-phonon scattering-cross-section calculations





Phononic Materials

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b) Crystal:Band gaps (particles concert)

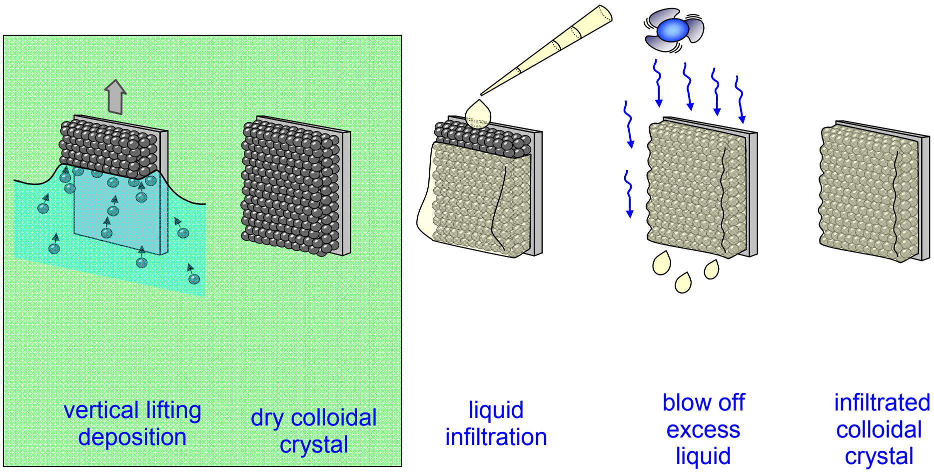
Nature Mater.(2006), PRL(2008)

1D Hybrid multilayer SiO2/PMMA films (unidirectional gap)

Biological structures (spider dragline silk)

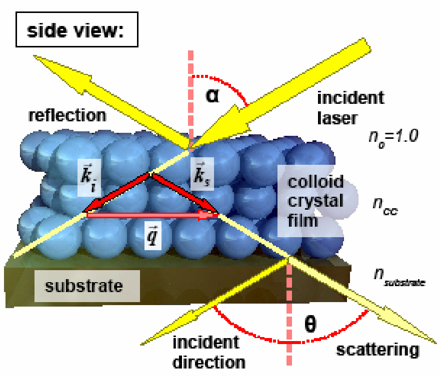
self-assembling and infiltration procedures

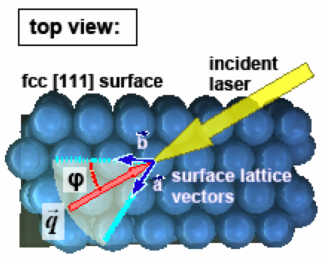
Dry opals **Wet colloidal crystals**

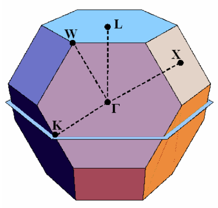


W.Cheng et.al Nature Mat.5,830,2006

Scattering Geometry

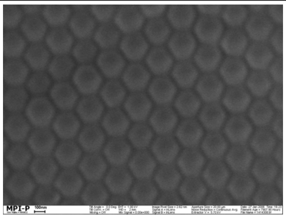




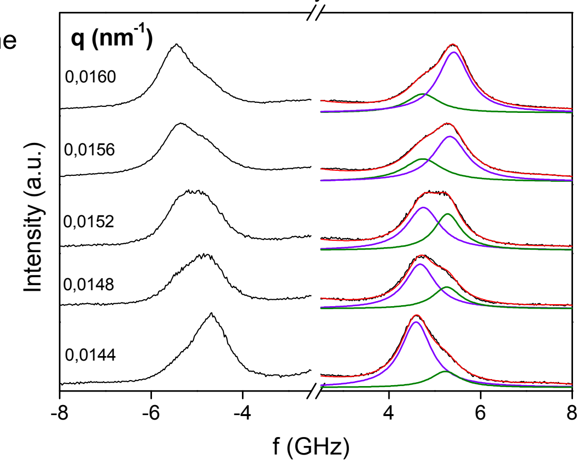


$$q=(4\pi/\lambda)\sin\alpha$$

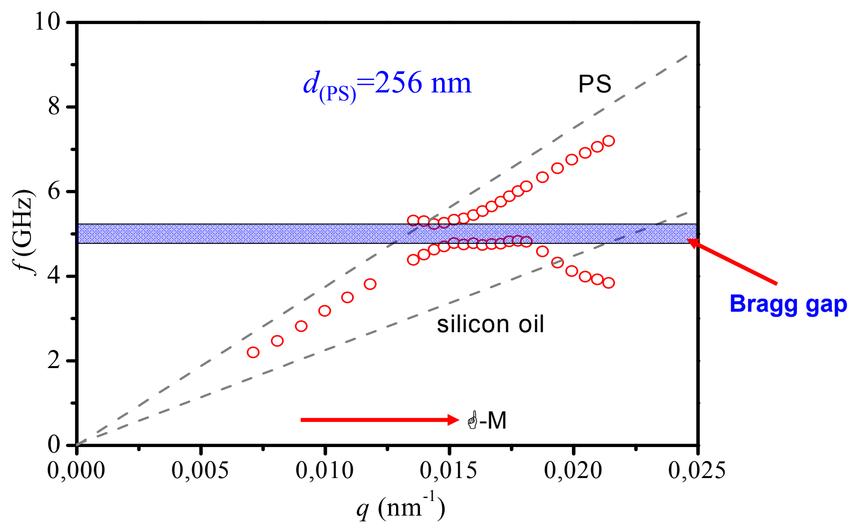
2.Wet Opals
(in silicon oil)



q in (111) plane



Dispersion (ω(q)) relation



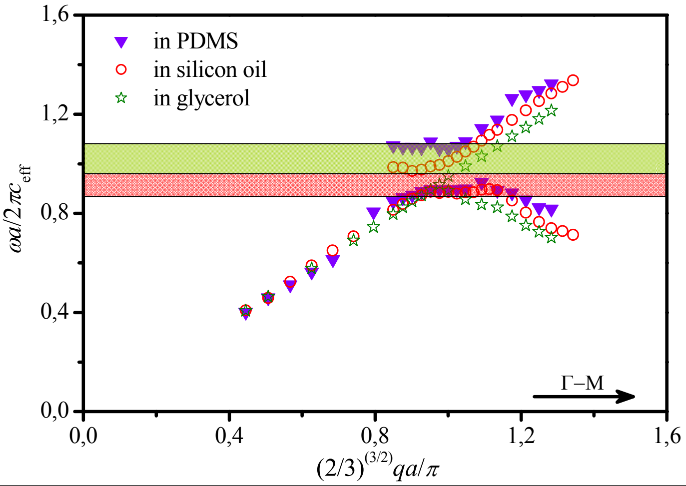
W. Cheng et al. *Nature Mater.* **5**, 830 (2006).

elastic contrast :

$\Delta Z=(\rho_p c_p/\rho_f c_f)-1$

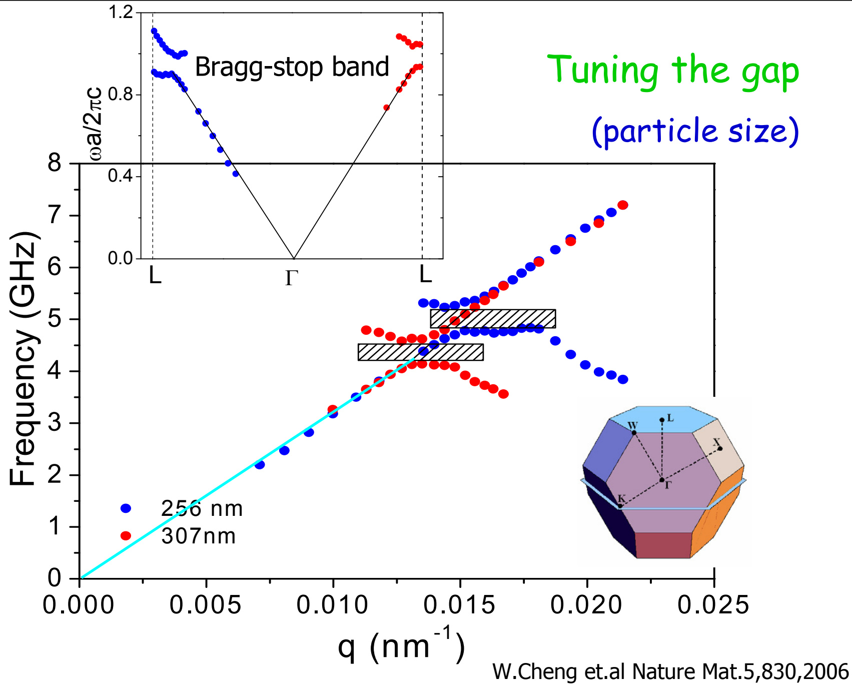
Glycerol : $\Delta Z\sim 0$
Silicon oil: $\Delta Z\sim 0.7$
PDMS : $\Delta Z\sim 1.2$

Tuning the gap (different fluids)



Tuning the gap

(particle size)



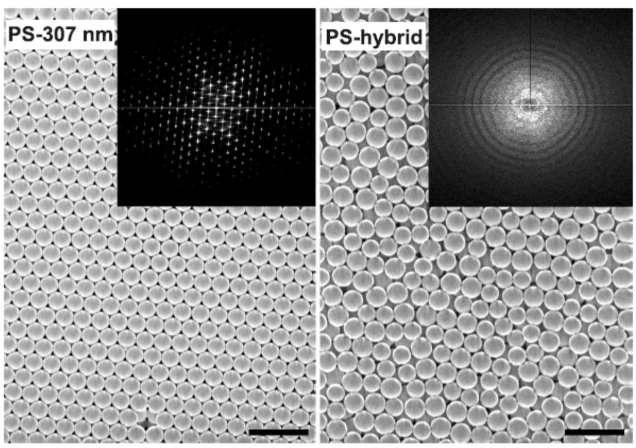
W.Cheng et.al Nature Mat.5,830,2006
Views&News p.773

current situation

structure signature → Bragg-gap

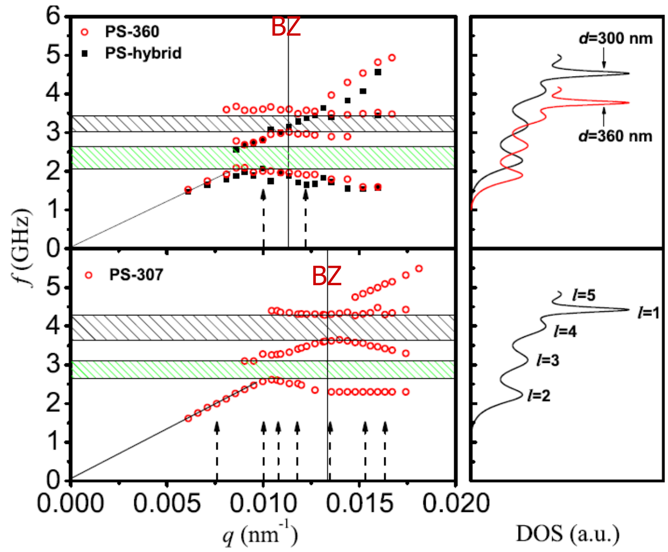
particle properties → multipole resonances

→ hybridization- gap



SEM images of a colloidal crystal (PS-307nm) and a hybrid(PS-307nm/360nm
(FT-images over an area of 4μm x 4μm)

Phononic band diagrams of soft opals



T.Still et al. PRL 100,194301,2008

So far ,

2D and 3D systems and longitudinal polarization

1D periodic structures are model systems:

- separate treatment of the longitudinal and transverse polarizations
- prove the robustness of ♦(q) to disorder, structural imperfections

- deal with the vector nature of the elastic wave propagation
- corroborate the theoretical predictions with experiment (impedance, moduli ,Poisson ratio, mass density)

- Create a facile platform for 1D-phononics

Phononic Materials

Experimental techniques ($\omega(k)$)

Sub-μm structures:**Colloid**-based

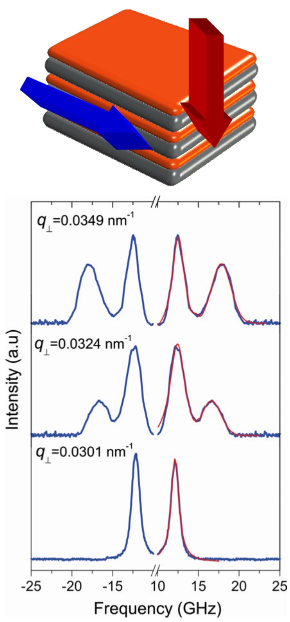
a) Particles:Local resonances (music)

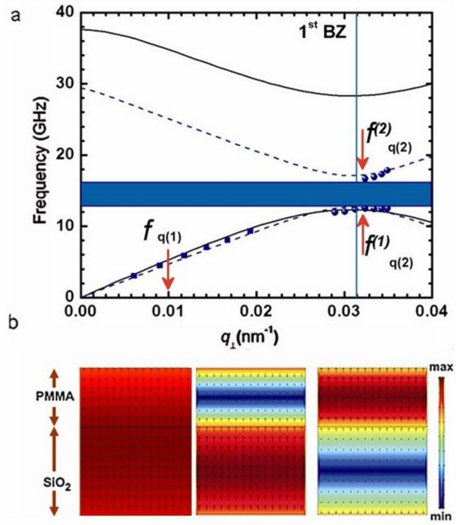
b) Crystal:Band gaps (particles concert)

1D Hybrid multilayer SiO2/PMMA films

Biological structures (spider dragline silk)

1D Hybrid multilayer SiO2/PMMA films





N.Gomopoulos et. al Nano lett.

Phononic Materials

Experimental techniques ($\omega(k)$)

Sub-μm structures: **Colloid**-based

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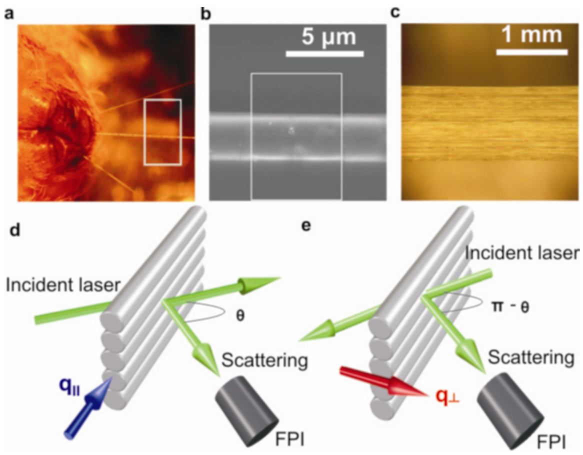
1D Hybrid multilayer SiO2/PMMA films

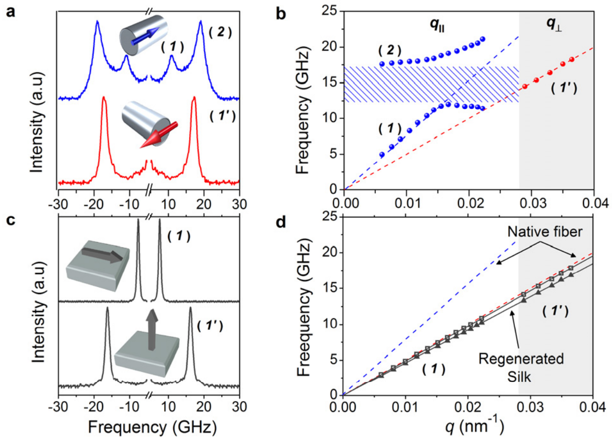
Biological structures (spider dragline silk)

spider dragline silk



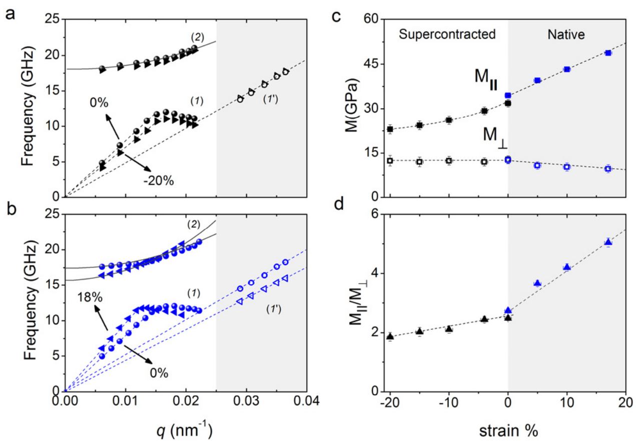
a. View of the spider spinnerets under the microscope.
b. Major ampullate fiber is probed along two symmetry directions

spider dragline silk



- Erase the stop band in regenerated amorphous and semicrystalline silk
- Mechanical anisotropy.
- A unidirectional phononic gap.

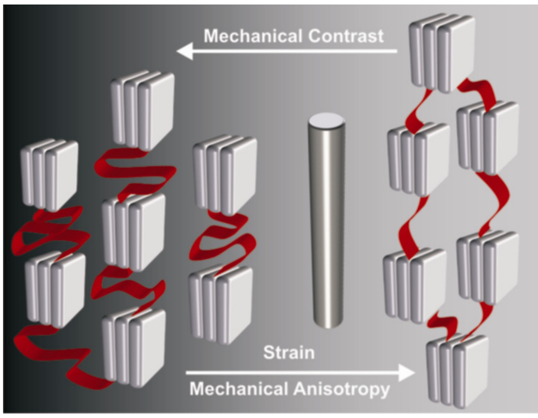
spider dragline silk



The effect of strain on the : dispersion diagram and mechanical anisotropy .

N.Gomopoulos et al Nature Materials ?

spider dragline silk



Scheme of the structure of dragline spider silk

N.Gomopoulos et al Nature Materials ?

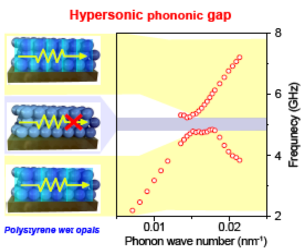
Summary

- Wave Propagation in Microstructured Materials

(Tailor the band structure :unexplored fundamental research)

→ Particle vibration modes (flat $\omega \sim q^0$)
→ Acoustic phonons ($\omega \sim q$) (average medium

Hypersonic Band Gaps (Bragg, hybridization) in fabricated structures



Band gap in natural structures origin?

Geometrical/Morhological characteristics
Micro-nanomechanical properties

Acknowledgments

M.Retsch,U.Jonas, M. D'Acunzi,D. Vollmer (MPIP)
(colloidal systems)

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R.Sainidou(Lille)
(theory)

H.Koh,E.L.Thomas (MIT)
1D Hybrid structures

P.Papadopoulos,F.Kremer (Leipzig)
Spider dragline silk

DFG for funding

Thank you very much!!!

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