Journée de lancement du GdR ARCHI-META

3D wavefront shaping with soft acoustic metalenses

Thomas Brunet
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thomas.brunet@u-bordeaux.fr

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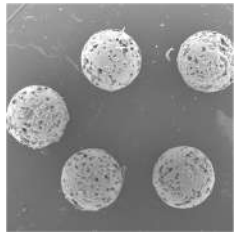
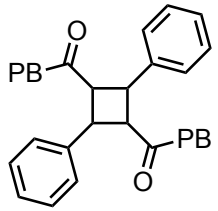
université de BORDEAUX

Outline

- Context & motivations
  - From 3D metamaterials…
  - … to 2D metasurfaces
- Soft gradient-index metasurfaces
  - Soft porous silicone rubbers
  - Wavefront shaping at ultrasonic frequencies
- Quasi-flat high-index acoustic lenses
  - A quite simple approach for…
  - … 3D underwater ultrasound focusing
- Conclusion & perspectives
  - Towards soft tuneable acoustic lenses





From 3D metamaterials…

Review Article | Published: 31 January 2019

3D metamaterials

Muamer Kadic, Graeme W. Milton, Martin van Hecke & Martin Wegener

Nature Reviews Physics **1**, 198–210 (2019) | Cite this article

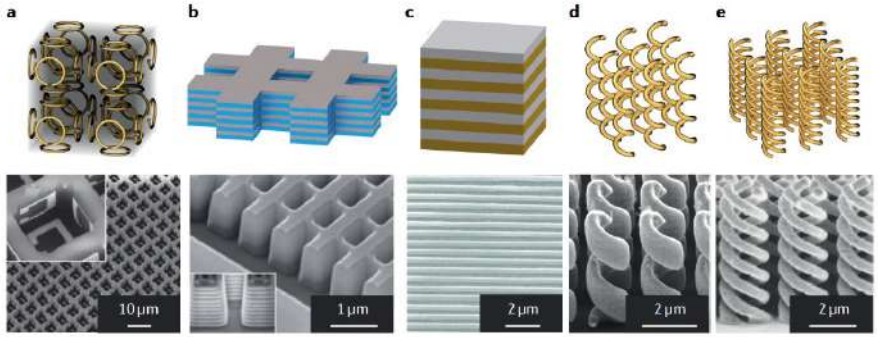


Fig. 2 | **Gallery of designed 3D optical metamaterial unit cells and corresponding experimental realizations.** **a** | An arrangement of metallic split-ring resonators leading to artificial magnetism. **b** | A fishnet arrangement for uniaxial negative refractive indices. **c** | An ABAB…AB laminate, which is a unit cell used in many metamaterials, including hyperbolic metamaterials. **d** | Helices providing chiral behaviour. **e** | Multiple intertwined helices for recovering three-fold rotational symmetry. Panel **a** is adapted with permission from REF.[192], Wiley-VCH. Panel **b** is adapted from REF.[47], Springer Nature Limited. Panel **c** is adapted from REF.[193], Springer Nature Limited. Panel **d** is adapted with permission from REF.[67], AAAS. Panel **e** is adapted with permission from REF.[70], OSA.

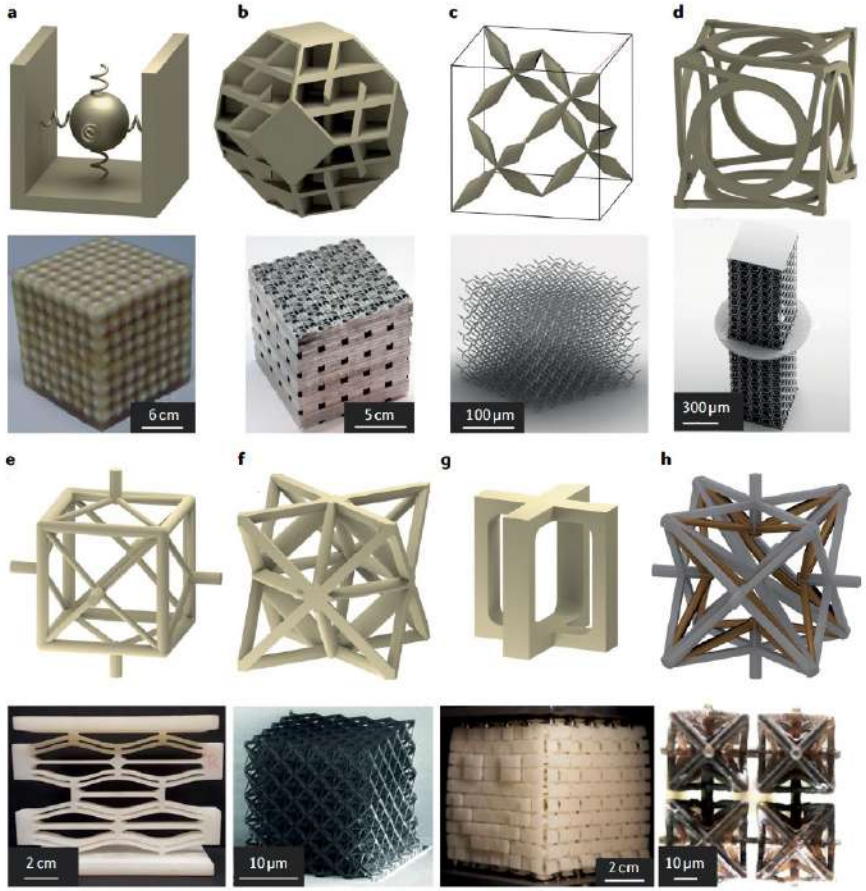


Fig. 3 | **Gallery of designed 3D acoustical and mechanical metamaterial unit cells and corresponding experimental**

From 3D metamaterials…

PERSPECTIVE | MATERIALS SCIENCE

Soft Acoustic Metamaterials

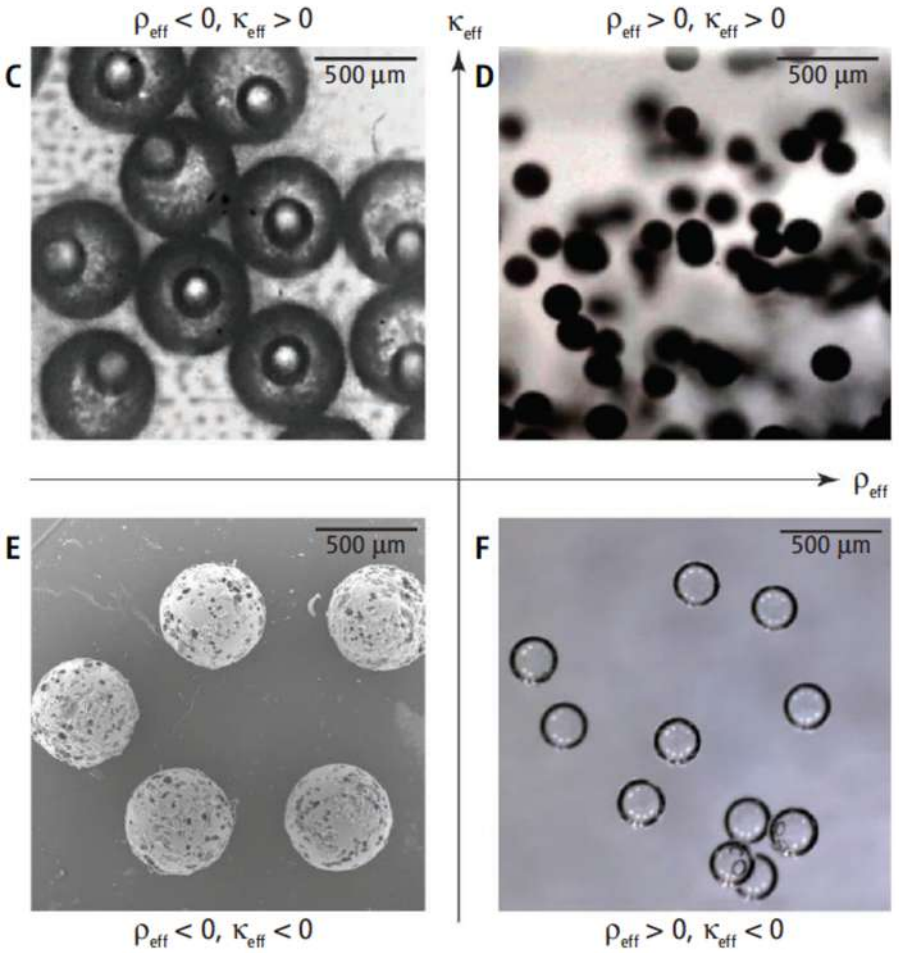
Thomas Brunet[1], Jacques Leng[2], Olivier Mondain-Monval[3]

+ See all authors and affiliations

Science 18 Oct 2013:
Vol. 342, Issue 6156, pp. 323-324
DOI: 10.1126/science.1241727

Abstract

Resonance phenomena occur with all types of vibrations or waves and may play a part in spectacular events, such as the collapse of structures—for example, the fall of the Broughton suspension bridge near Manchester in 1831 (*1*). Indeed, the oscillations of a structure submitted to harmonic excitation reaches its maximum amplitude at the resonance frequency ω_0 of the system. At low driving frequencies ($\omega < \omega_0$), its response is in phase with the forcing but becomes out of phase just beyond ($\omega_0 < \omega$). Such an out-of-phase response has been exploited with "locally resonant materials" (*2*). The proposed strategy is to embed a large enough collection of identical mechanical resonators in a passive structure to control wave propagation. These features are used to reach unusual macroscopic behaviors such as ultradamping of noise or negative refraction for imaging (*3*).



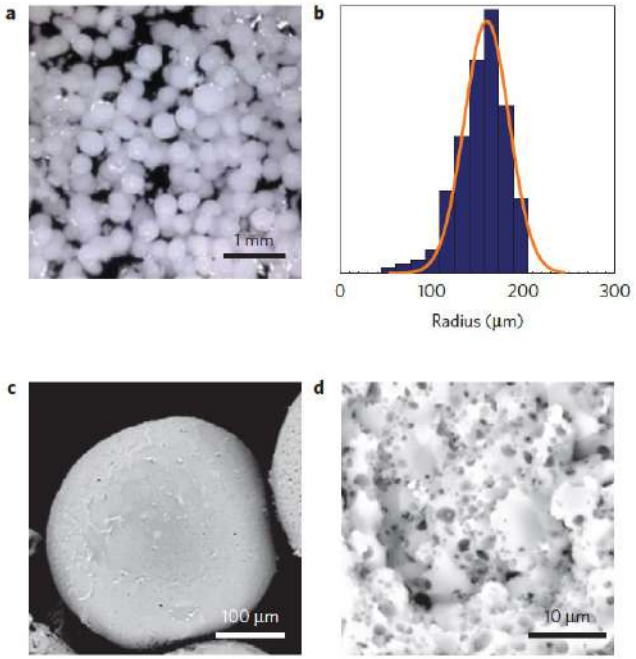
From 3D metamaterials…

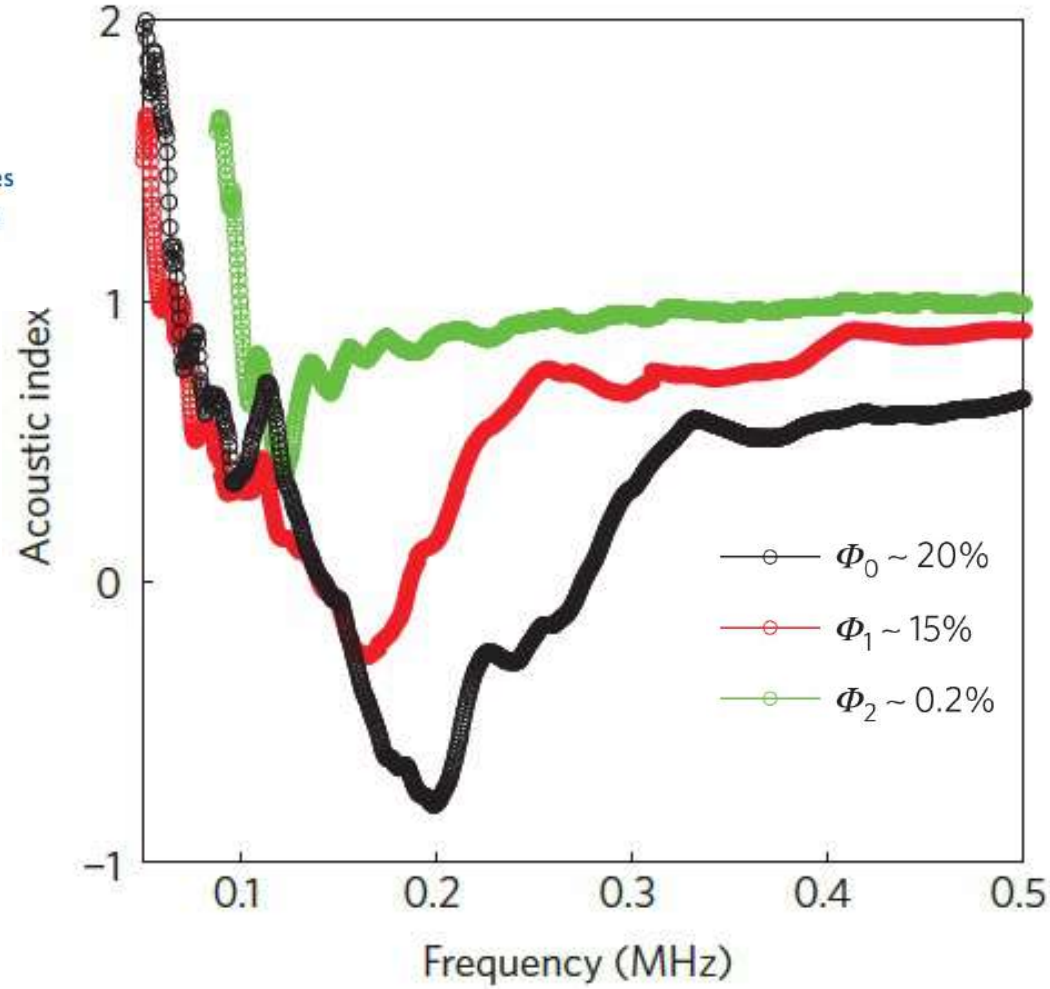
Letter | Published: 15 December 2014

Soft 3D acoustic metamaterial with negative index

Thomas Brunet, Aurore Merlin, Benoit Mascaro, Kevin Zimny, Jacques Leng, Olivier Poncelet, Christophe Aristégui & Olivier Mondain-Monval

Nature Materials **14**, 384–388(2015) | Cite this article





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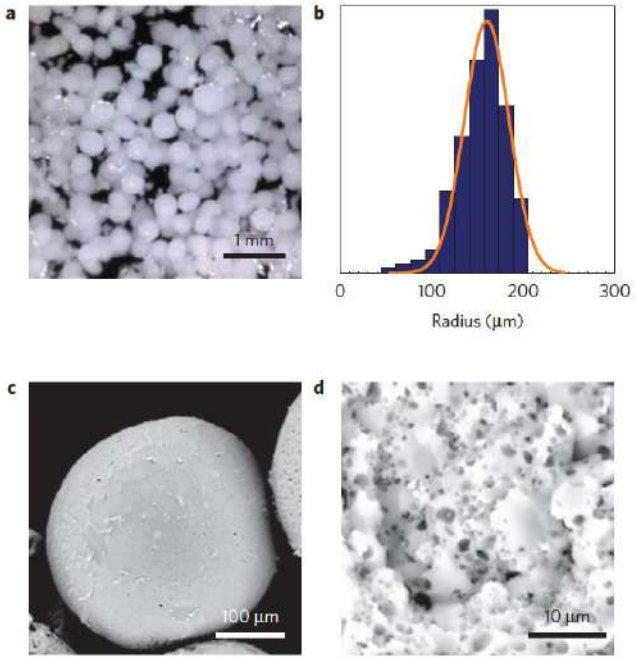
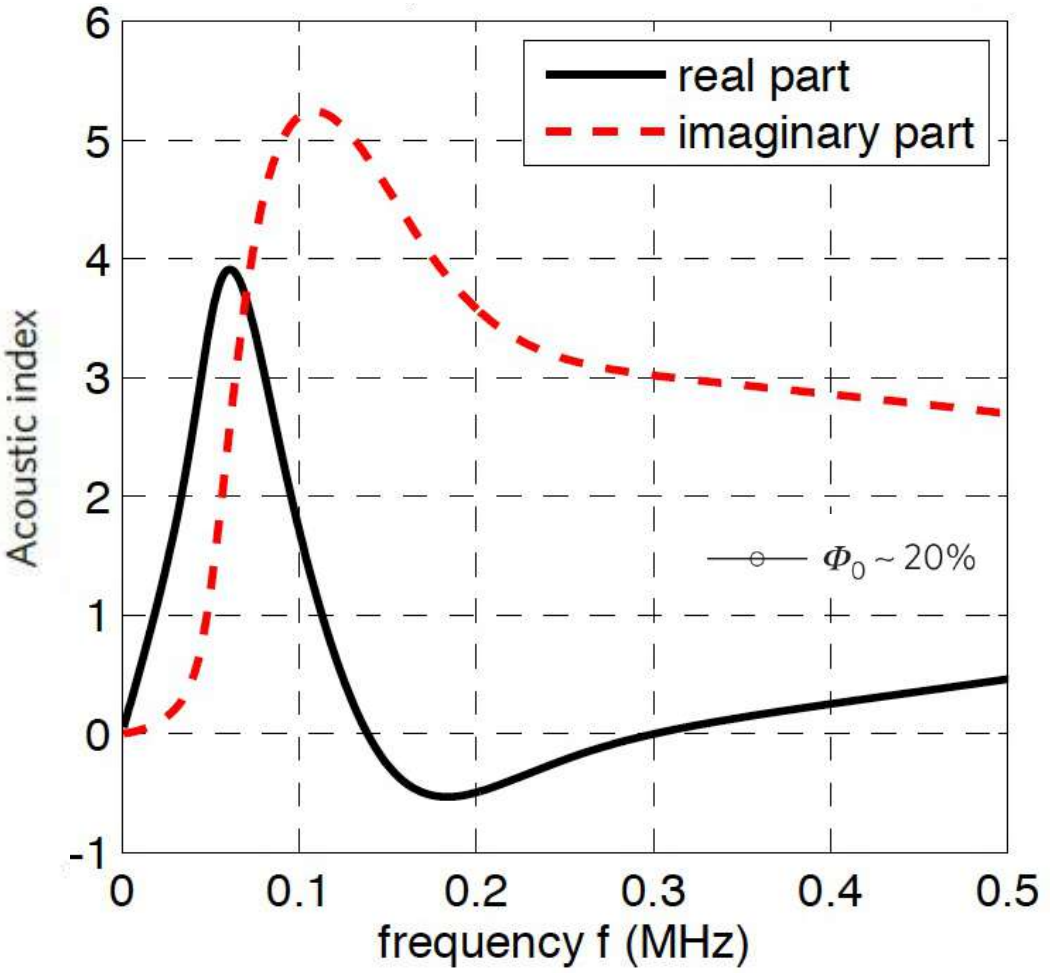




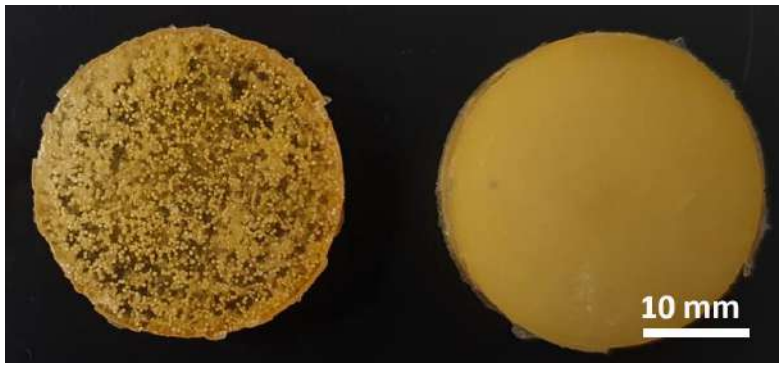
From 3D metamaterials…

RESEARCH ARTICLE | APRIL 21 2023

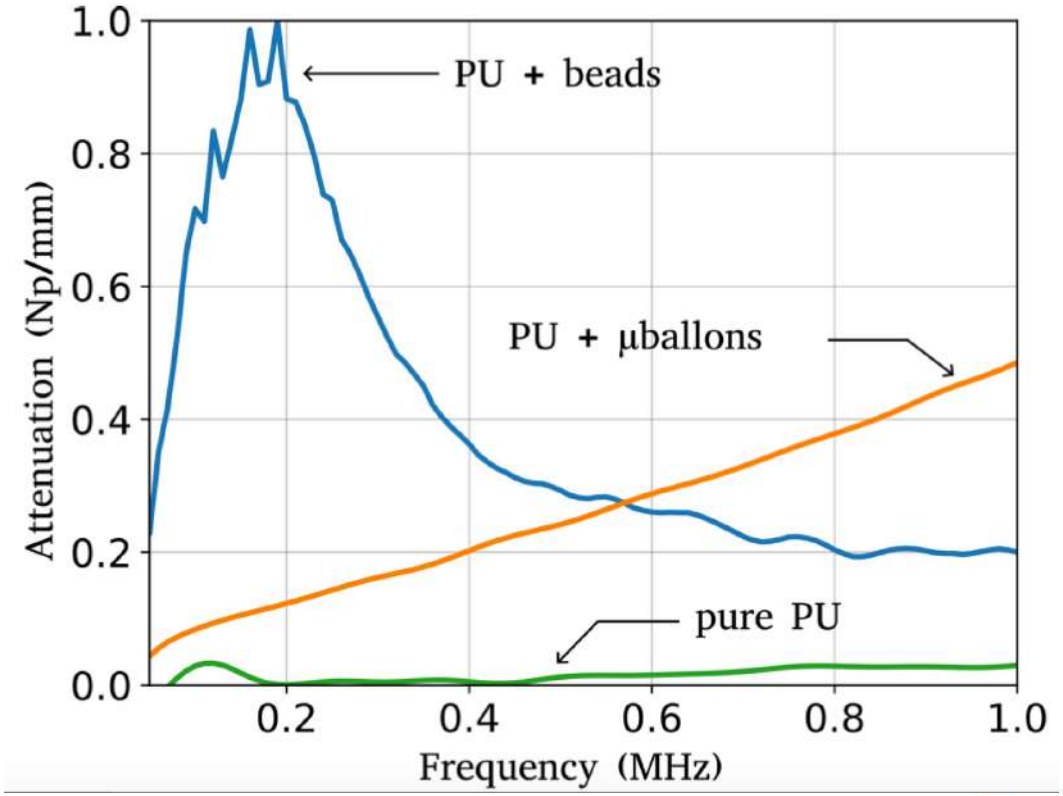
Pressure effects on the resonant attenuation of soft porous beads-based materials for underwater acoustics

Thomas Lacour ; Romain Poupart ; Olivier Mondain-Monval ; Christophe Aristégui; Olivier Poncelet; Thomas Brunet

+ Author & Article Information
J. Appl. Phys. 133, 155105 (2023)
https://doi.org/10.1063/5.0144249 **Article history**



PU + beads PU + µballons



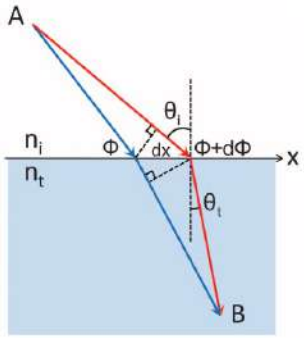
… to 2D metasurfaces

Review Article | Published: 23 January 2014

Flat optics with designer metasurfaces

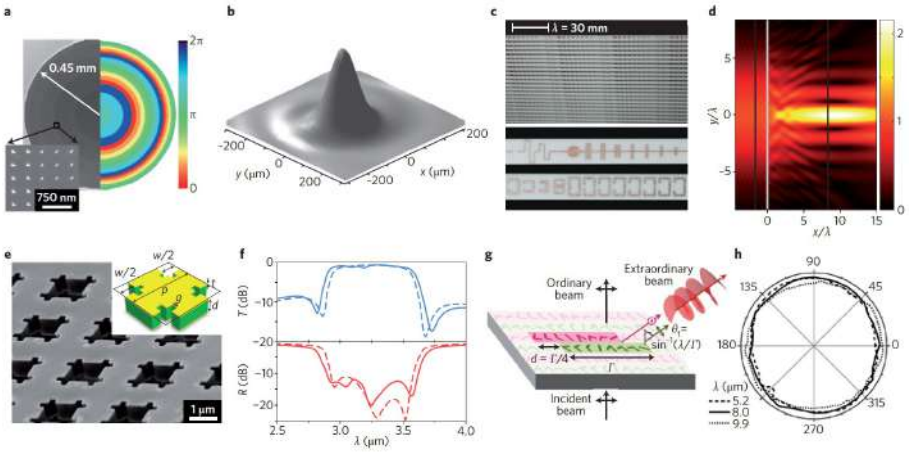
Nanfang Yu & Federico Capasso

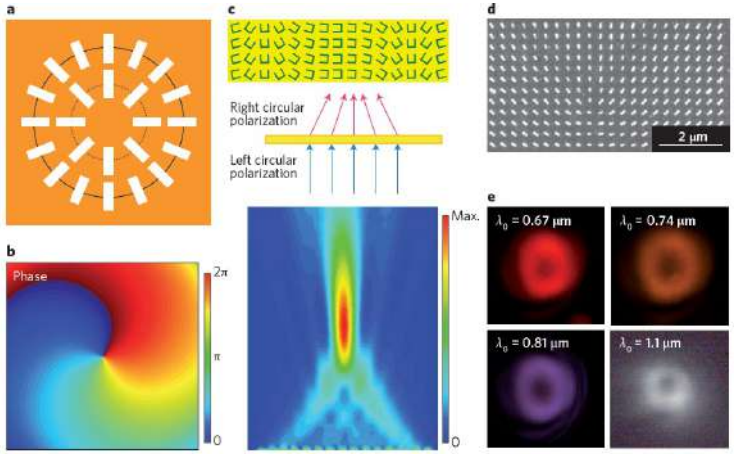
Nature Materials **13**, 139–150 (2014) | Cite this article



$$\sin(\theta_r) - \sin(\theta_i) = \frac{\lambda_o}{2\pi n_i}\frac{d\Phi}{dx}$$

$$\sin(\theta_t)n_t - \sin(\theta_i)n_i = \frac{\lambda_o}{2\pi}\frac{d\Phi}{dx}$$





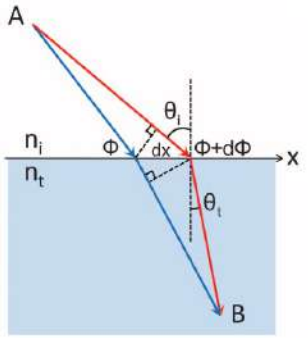
… to 2D metasurfaces

Review Article | Published: 17 October 2018

Acoustic metasurfaces

Badreddine Assouar, Bin Liang, Ying Wu, Yong Li, Jian-Chun Cheng & Yun Jing

Nature Reviews Materials **3**, 460–472 (2018) | Cite this article



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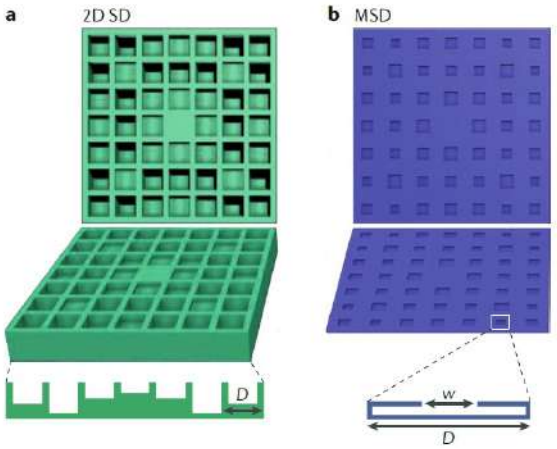
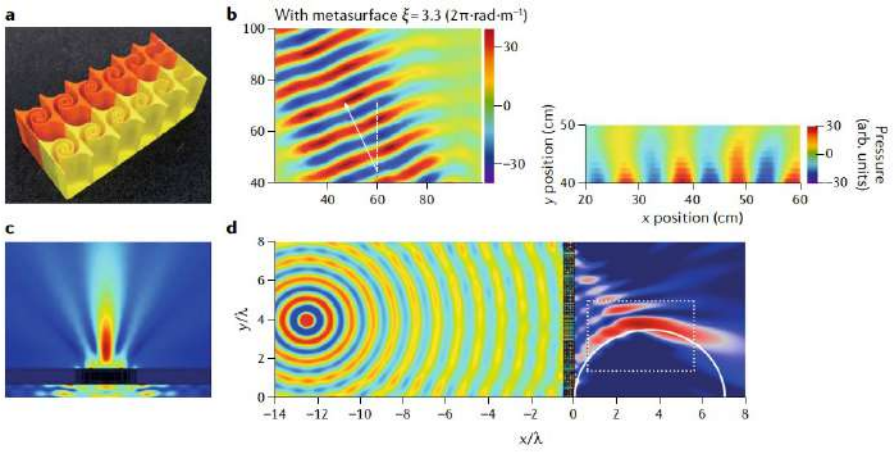
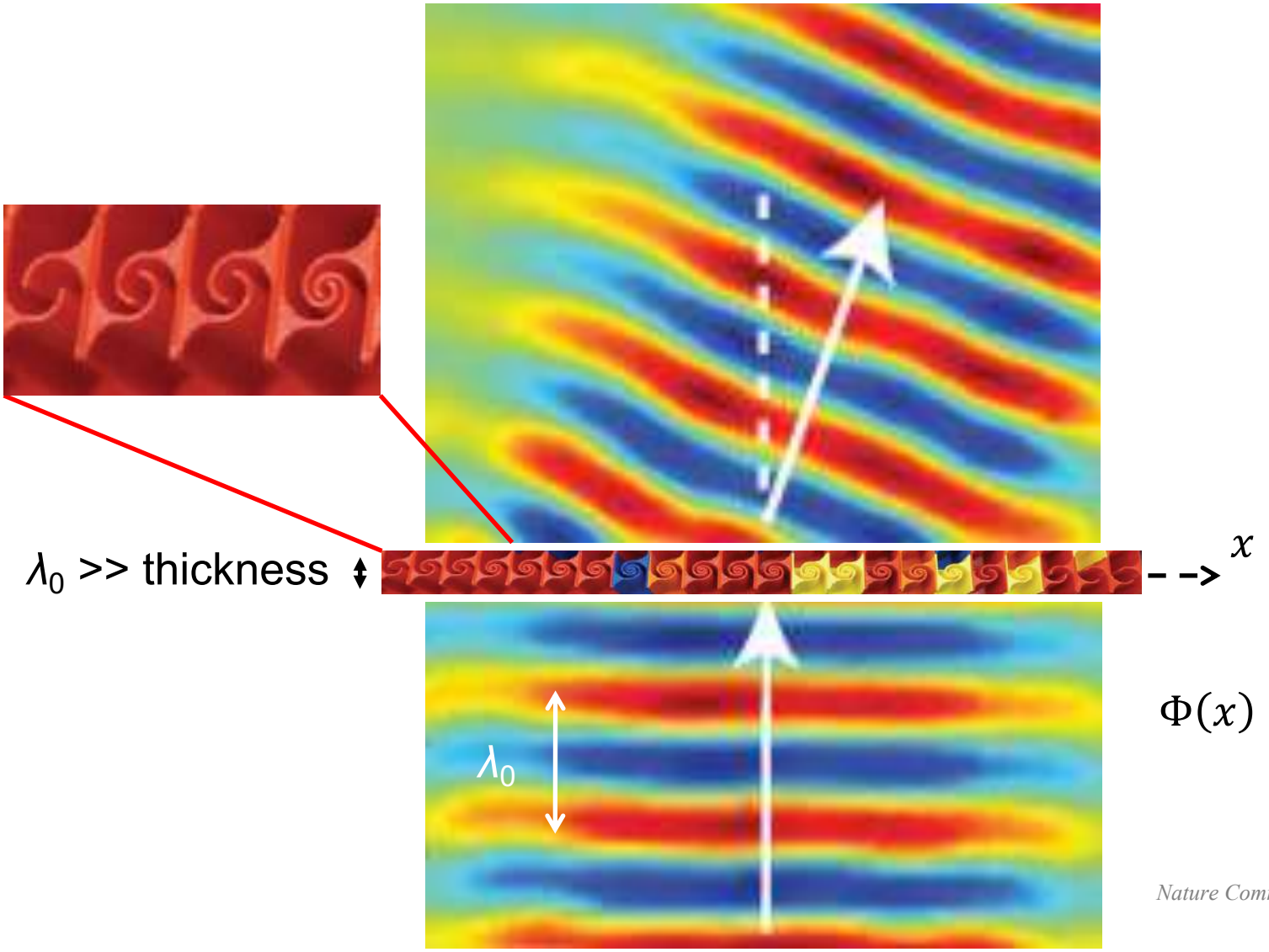




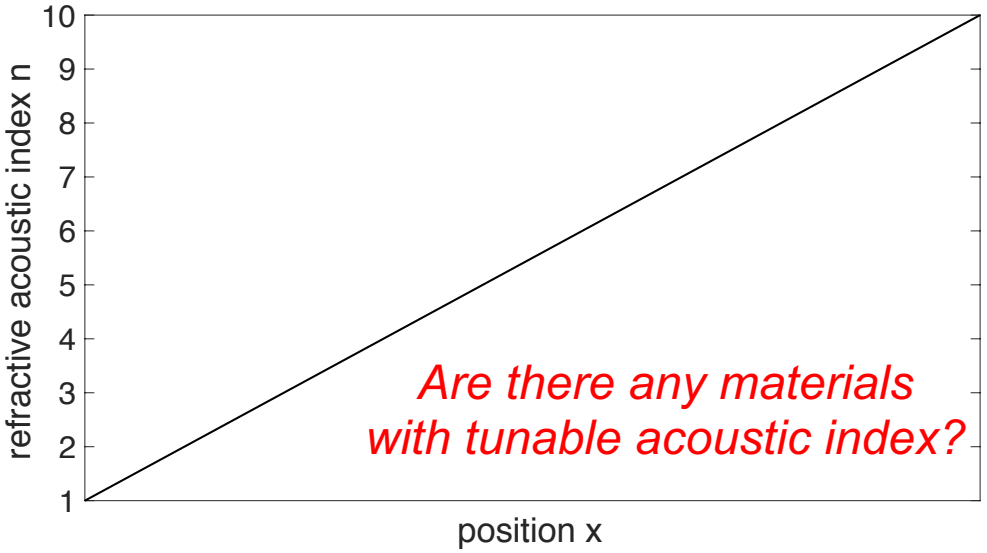
Soft gradient-index metasurfaces



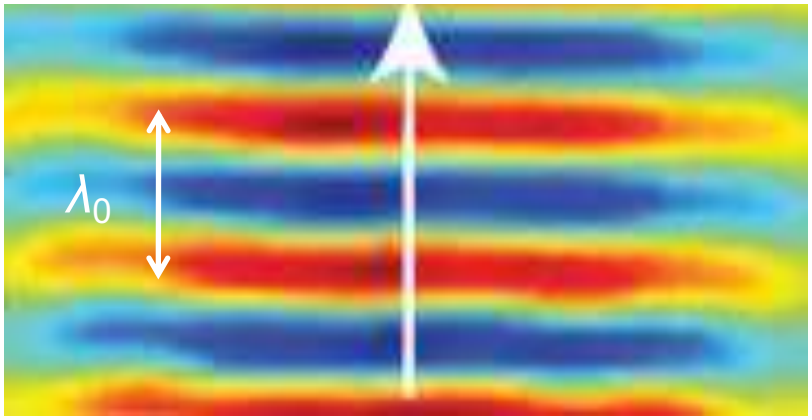
$$\Phi(x) = \frac{2\pi}{\lambda_0} n d(x)$$

Xie *et al.*
Nature Communications **5**, 5553 (2014)

Soft gradient-index metasurfaces



λ_0 >> thickness



$$\Phi(x) = \frac{2\pi}{\lambda_0} n(x) d$$

Brunet *et al.*
Nature Communications **10**, 143 (2019)

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- Context & motivations
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  - Soft porous silicone rubbers
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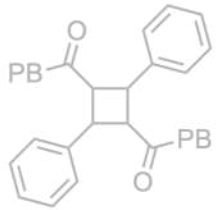
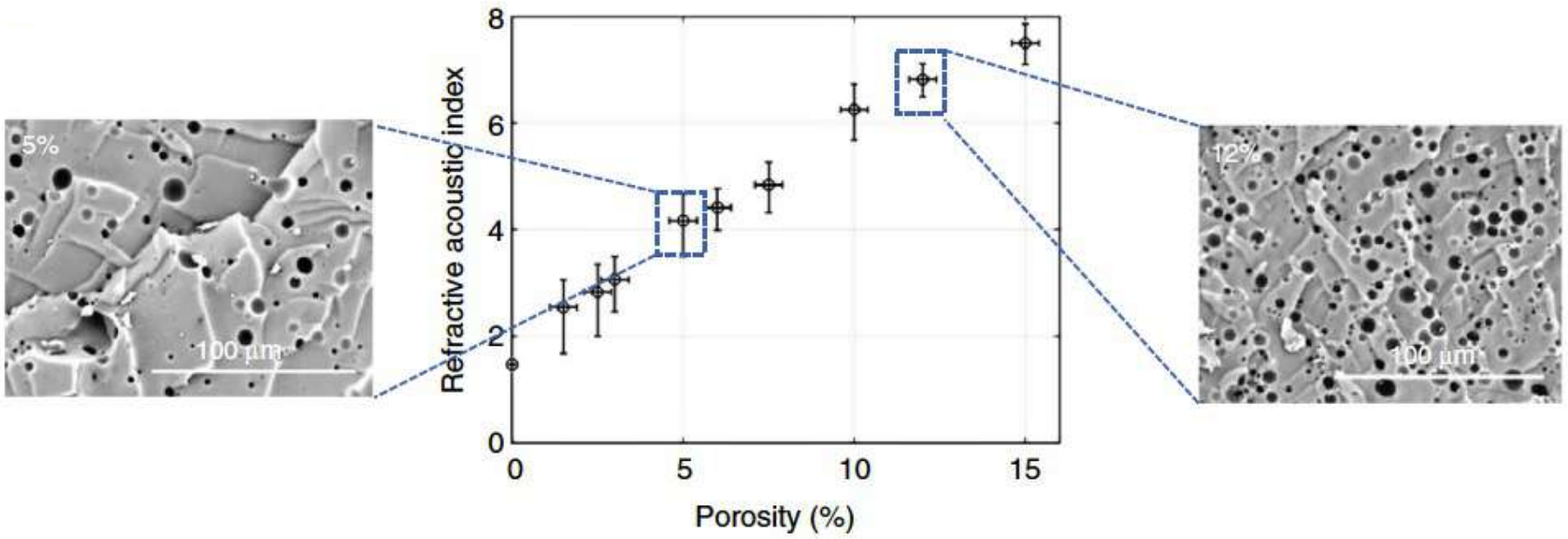


Soft porous silicone rubbers



Article | Open access | Published: 05 January 2017

Soft porous silicone rubbers with ultra-low sound speeds in acoustic metamaterials

Abdoulaye Ba, Artem Kovalenko, Christophe Aristégui, Olivier Mondain-Monval & Thomas Brunet

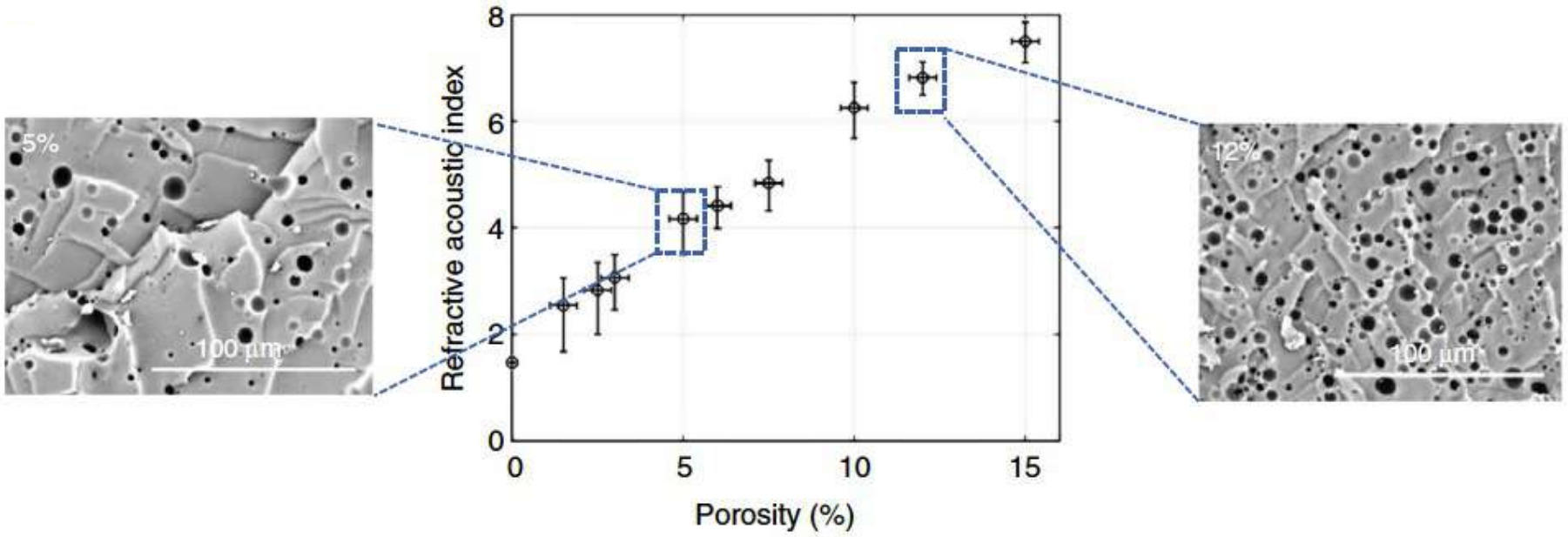
Scientific Reports **7**, Article number: 40106 (2017) | Cite this article

For soft porous silicone rubbers:

$$K_0 \approx 1\ \text{GPa} \gg G_0$$

$$\Rightarrow n \approx n_0 \sqrt{1 + \frac{3K_0}{4G_0}\phi}$$

Soft gradient-index metasurfaces

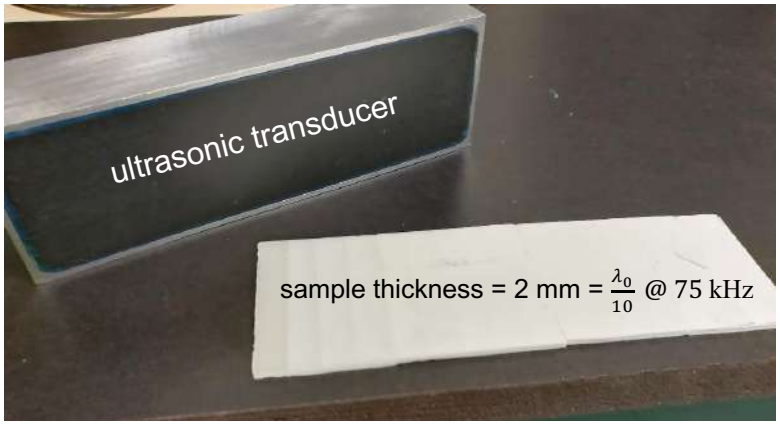


Article | Open access | Published: 11 January 2019

Flat acoustics with soft gradient-index metasurfaces

Yabin Jin, Raj Kumar, Olivier Poncelet, Olivier Mondain-Monval & Thomas Brunet

Nature Communications **10**, Article number: 143 (2019) | Cite this article



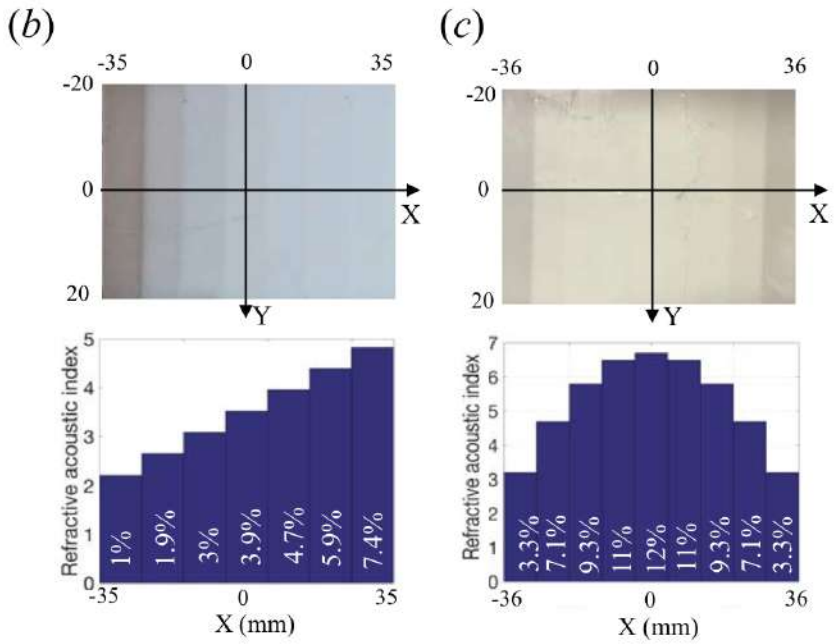
Soft gradient-index metasurfaces

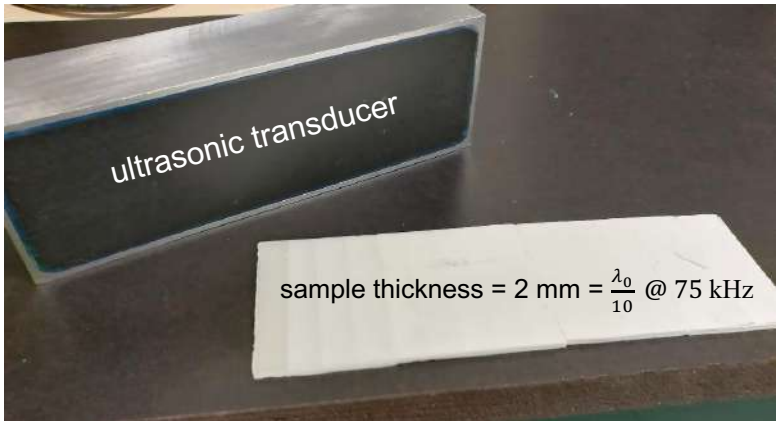
$$(b):\quad n(X)=n(X=0)+\frac{\sin(\theta)X}{d}$$

$\Rightarrow$ linear gradient of index for deflection

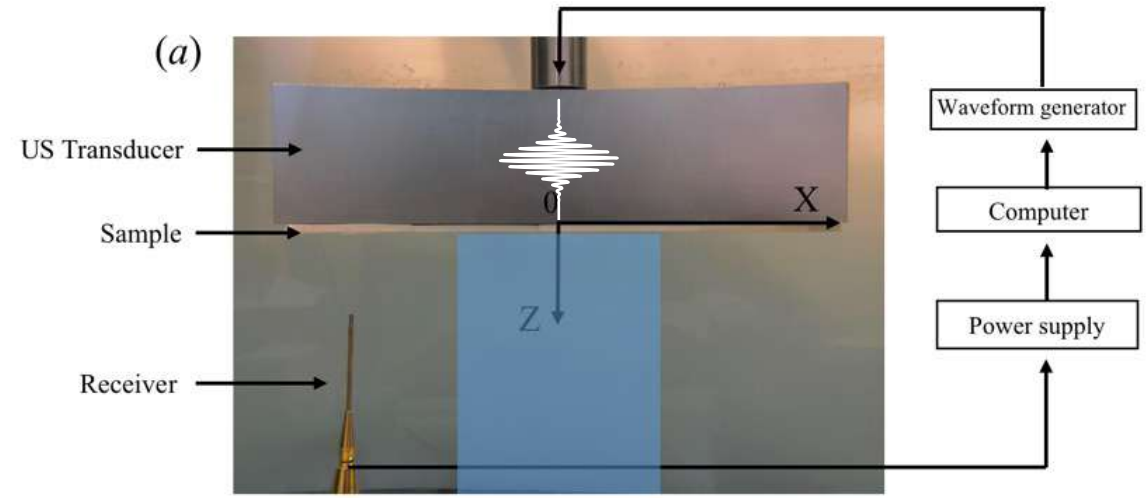
$$(c):\quad n(X)=n(X=0)-\frac{\sqrt{X^2+F^2}-F}{d}$$

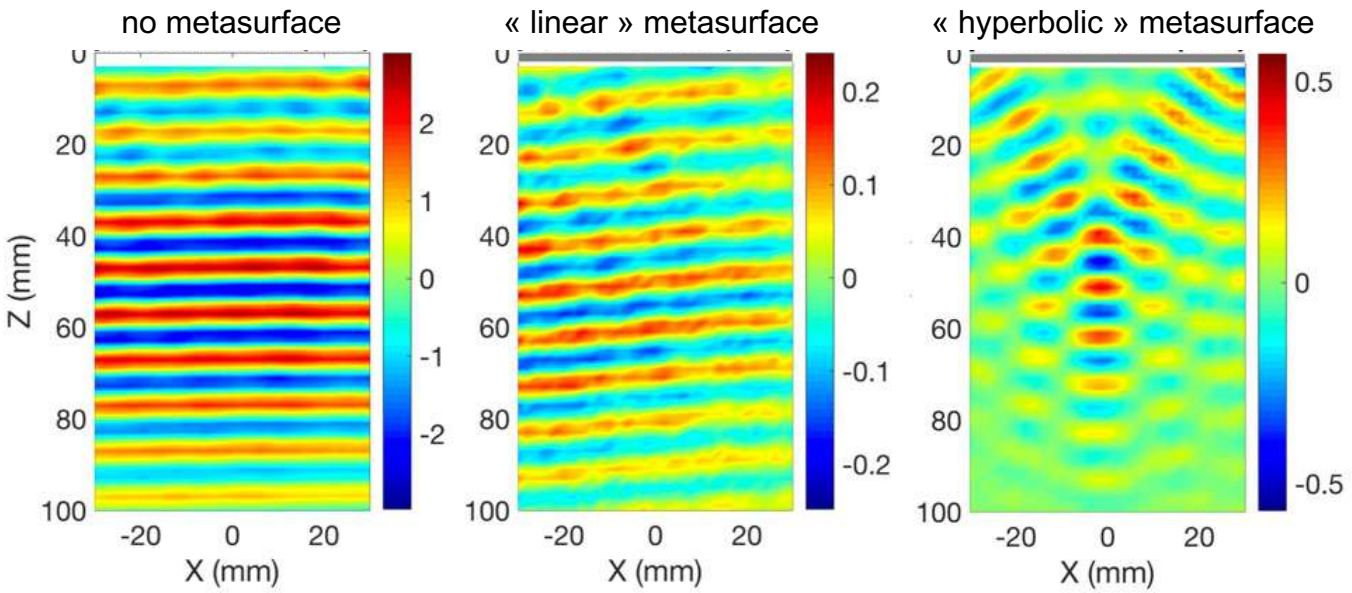
$\Rightarrow$ hyperbolic gradient of index for focusing



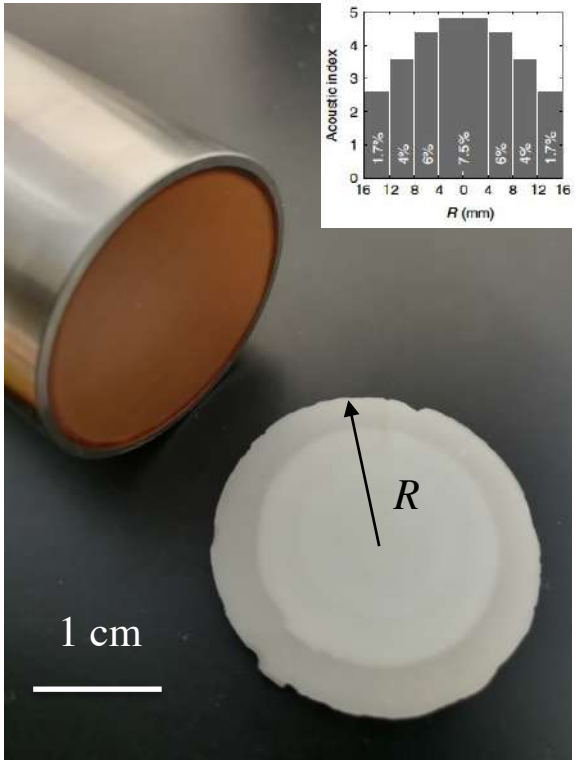


2D wavefront shaping at ultrasonic frequencies

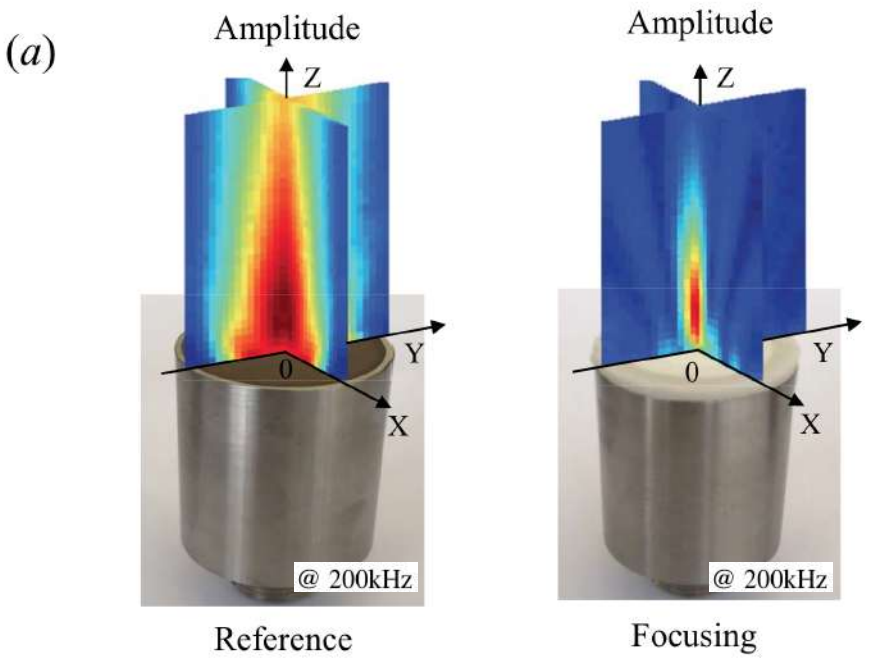


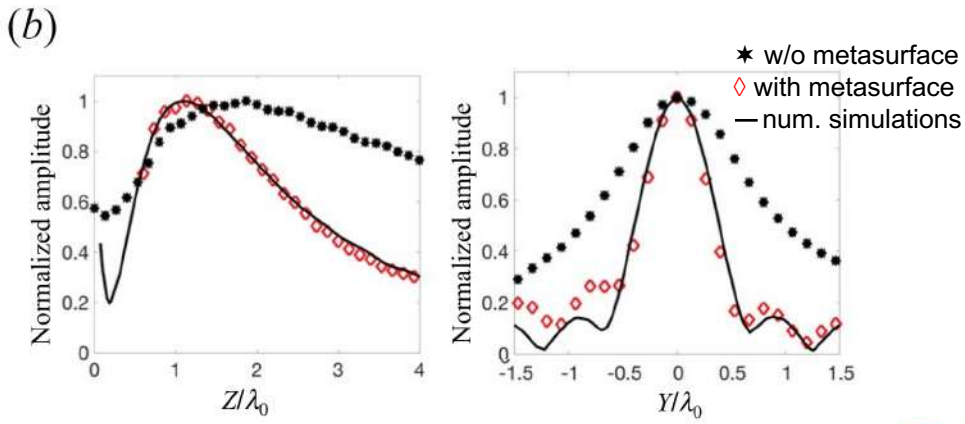


3D wavefront focusing at ultrasonic frequencies

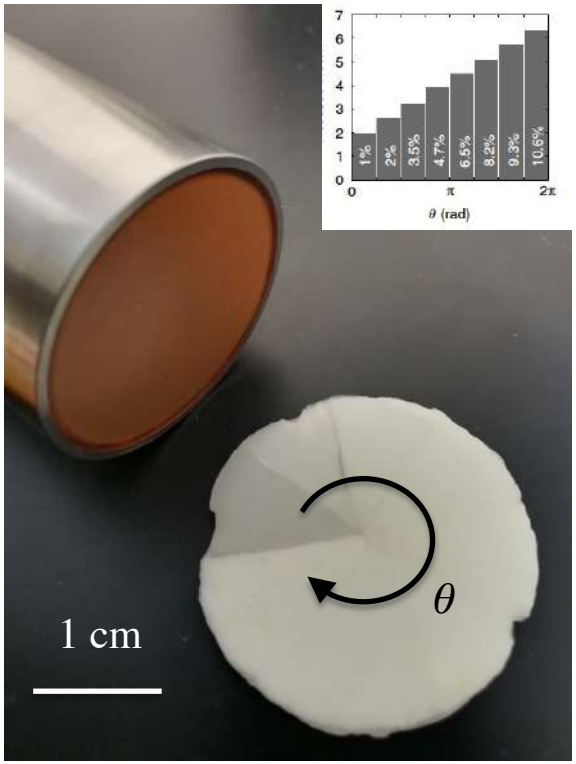


Radially graded flat lens

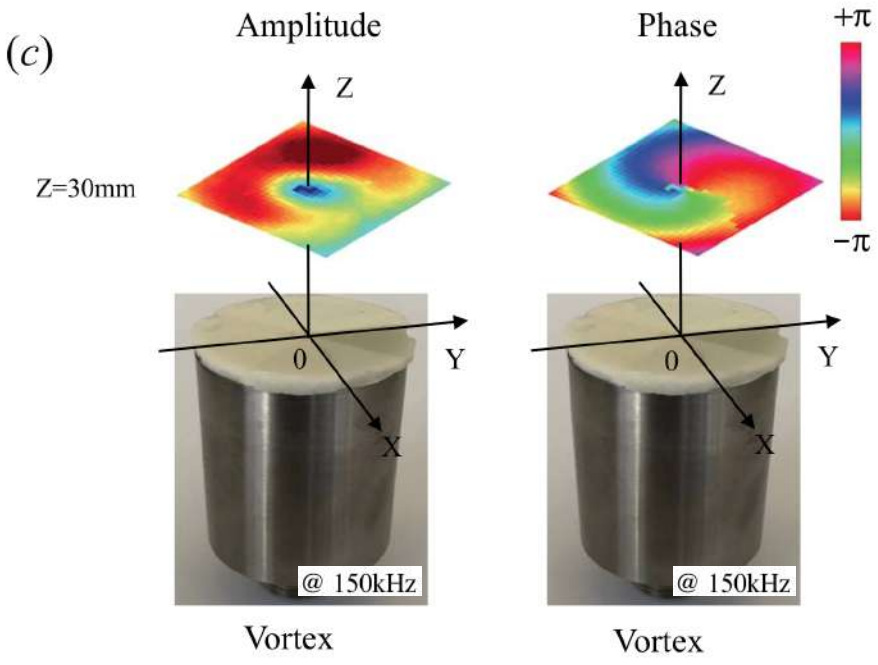


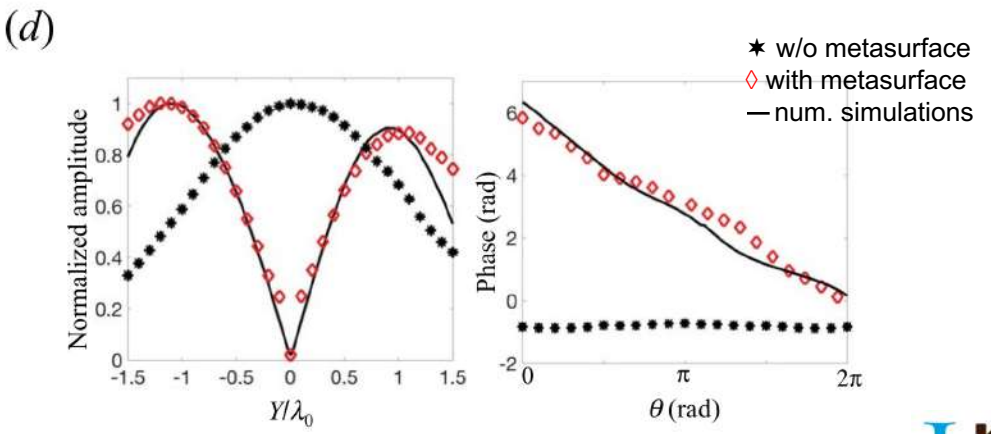


3D wavefront twisting at ultrasonic frequencies



Azimuthally graded flat lens





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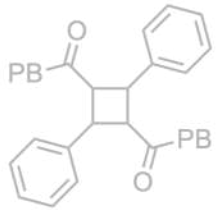
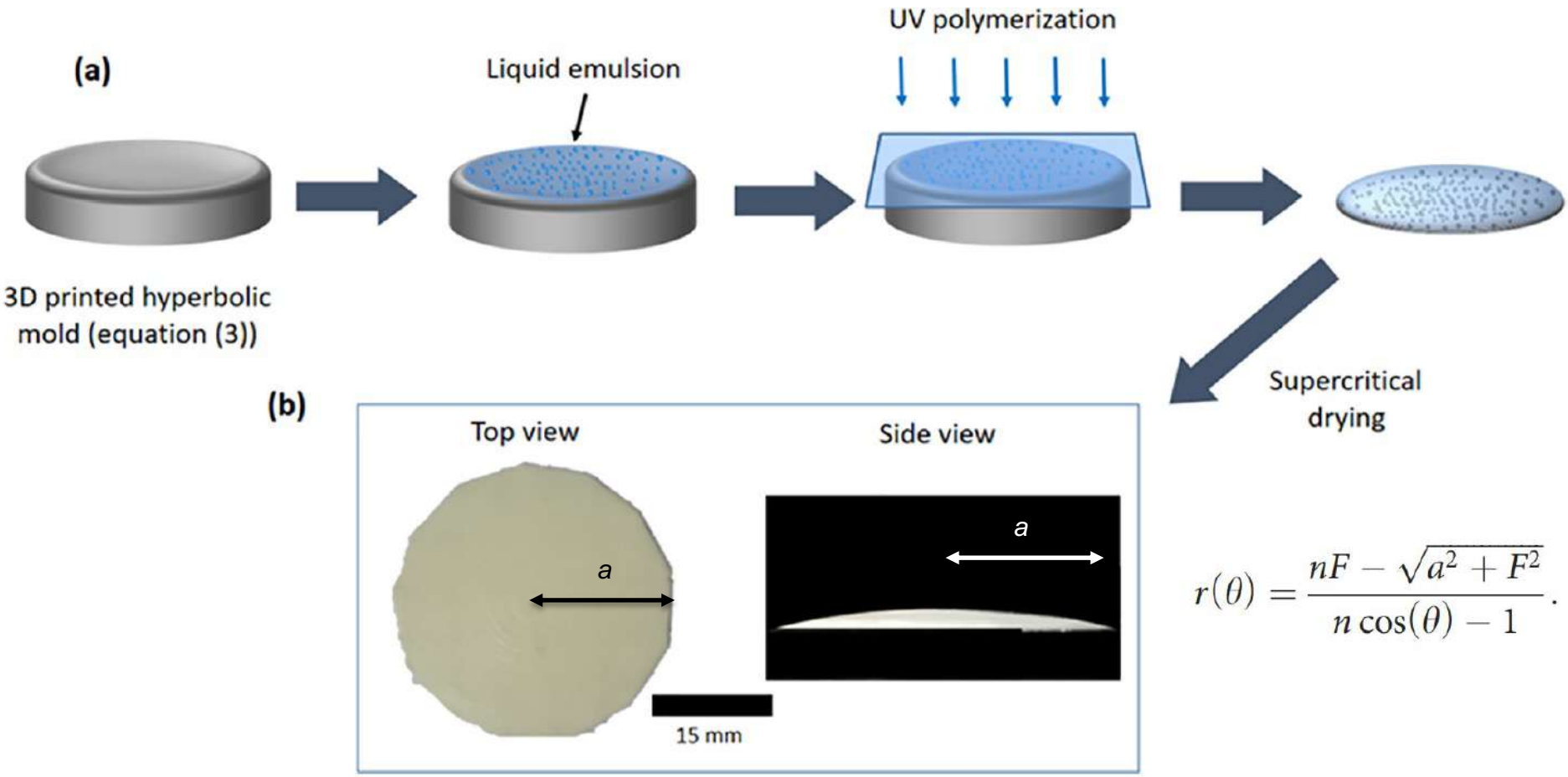


Quasi-flat high-index acoustic lenses



$$r(\theta) = \frac{nF - \sqrt{a^2 + F^2}}{n\cos(\theta) - 1}.$$

Quasi-flat high-index acoustic lenses

Applied Physics Letters ARTICLE scitation.org/journal/apl

Quasi-flat high-index acoustic lens for 3D underwater ultrasound focusing

Cite as: Appl. Phys. Lett. **120**, 221701 (2022); doi: 10.1063/5.0088503
Submitted: 17 February 2022 · Accepted: 12 May 2022
Published Online: 31 May 2022

Olivier Lombard,[1,a)] Raj Kumar,[2] Olivier Mondain-Monval,[2,b)] Thomas Brunet,[1,b)] and Olivier Poncelet[1]

AFFILIATIONS

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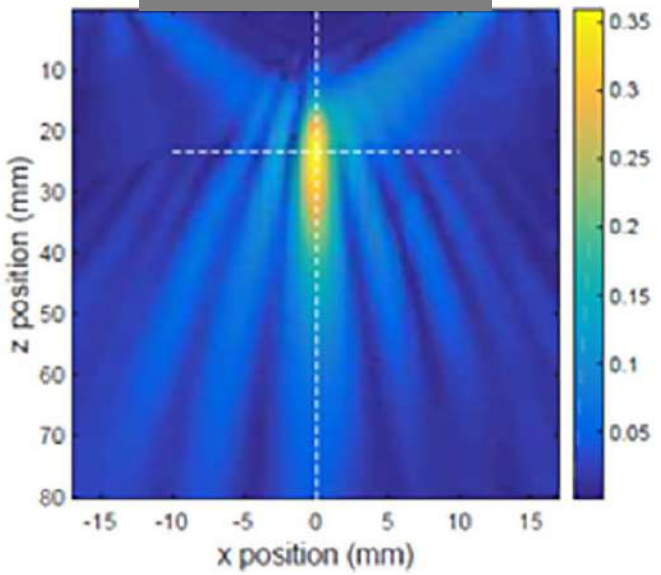
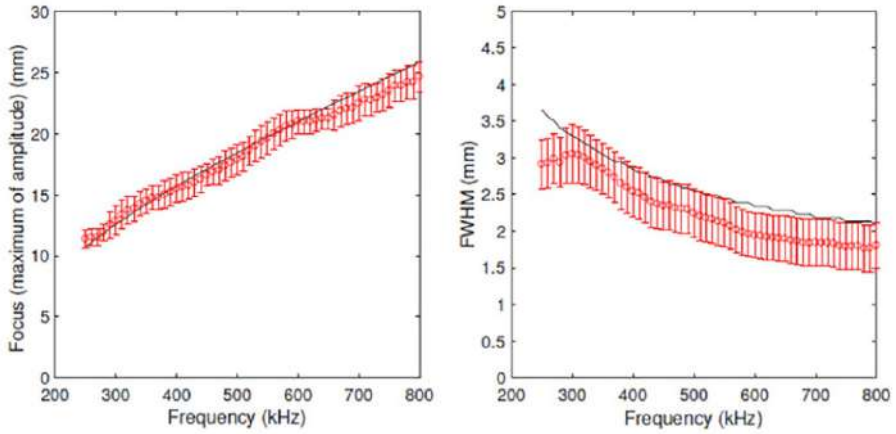
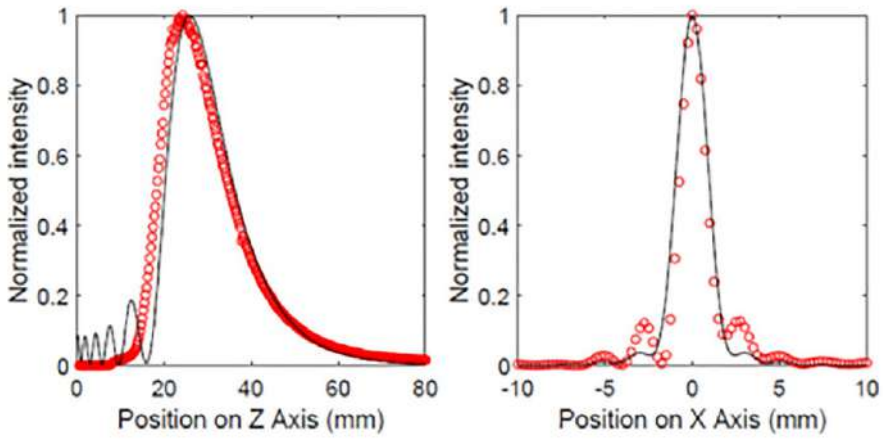
[2]University Bordeaux, CNRS, UMR 5031 CRPP, F-33600 Pessac, France

Note: This paper is part of the APL Special Collection on Acoustic and Elastic Metamaterials and Metasurfaces.
[a)]Present address: University Avignon, UMR 1114 EMMAH, Avignon, France.
[b)]Authors to whom correspondence should be addressed: olivier.mondain@icrpp.cnrs.fr and thomas.brunet@u-bordeaux.fr

US transducer with the lens







Acknowledgements

I2M BORDEAUX INSTITUT DE MÉCANIQUE ET D'INGÉNIERIE


O. Poncelet


Y. Jin


O. Lombard

CRPP Centre de Recherche Paul Pascal

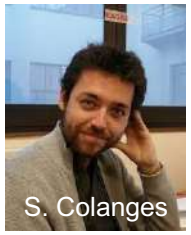
cnrs université BORDEAUX


O. Mondain-M.


A. Kovalenko


R. Kumar

LCPO Laboratoire de Chimie des Polymères Organiques


S. Colanges


A. Lamouroux


H. Cramail


E. Grau


T. Vidil