Imperial College London

Horizon 2020 Programme

19 July 2020

Elastic Metasurfaces

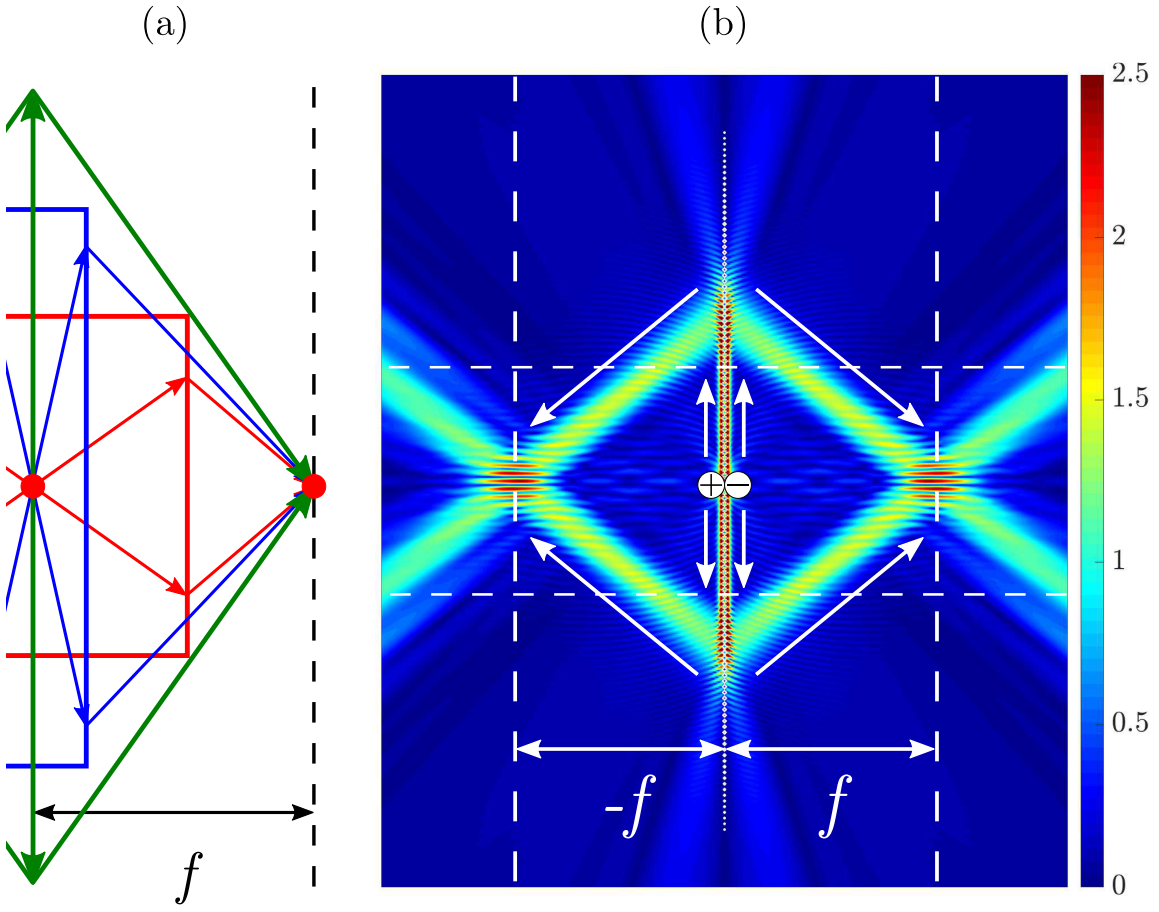
R. V. Craster Imperial College London and Director of Imperial-CNRS IRL Abraham de Moivre

Motivation

- Control over surface Rayleigh waves - direction on a surface.
- Mode conversion into P and/or S body waves (selecting them and the angles).
- Rainbow trapping and energy harvesting.
- Applications in NDE/ Ultrasonics, Ground vibration, Seismic protection.
- Challenge to control low frequency/ long waves with sub-wavelength devices. Broadband?
- Metamaterials use resonators to achieve wave control - well understood in the bulk for simpler systems, but here for elasticity and also surfaces.

Challenges: Make a Veselago-Pendry flat lens on a line?

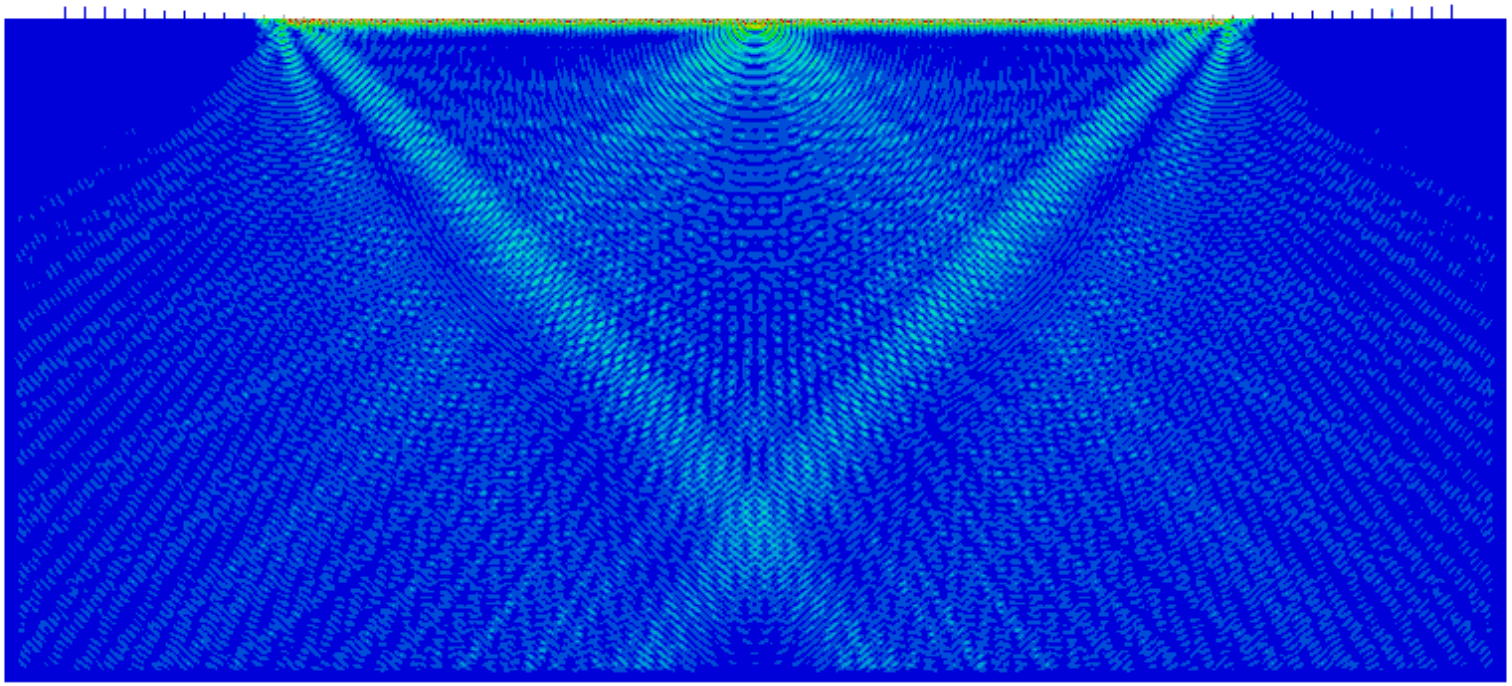
Using structure in line arrays to make waves go where **we** want.



G.J. Chaplain, R. V. Craster, *Phys. Rev. B (Rapids)*, 2019

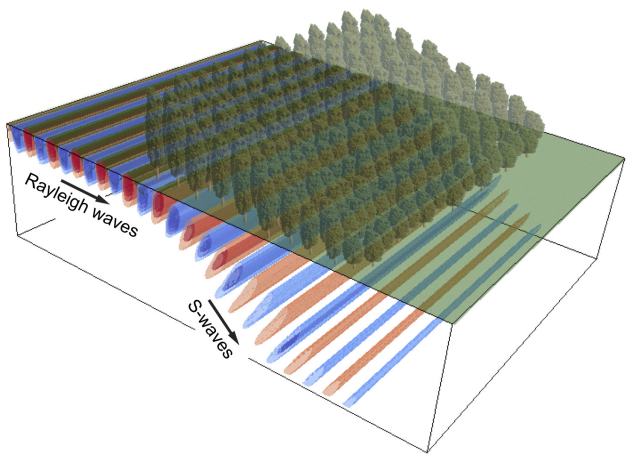
Elastic surface

These ideas are applicable in water waves, underwater acoustics, elasticity and are quite general.

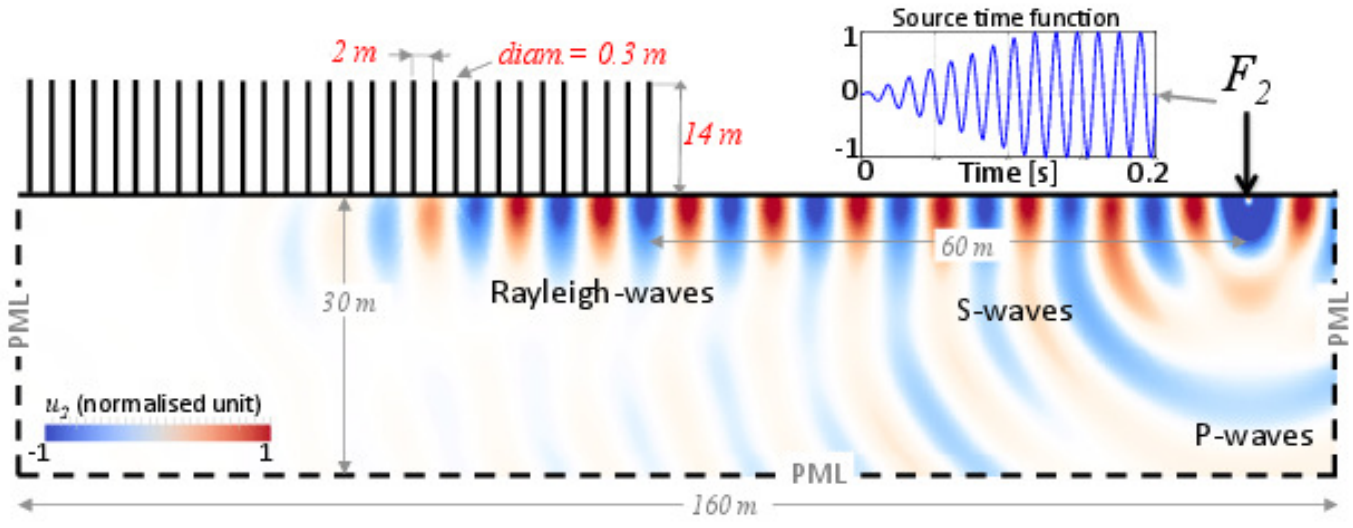


Seismic metameterials - Metaforet

A forest metamaterial !? See the recent experiments of Roux and collaborators https://metaforet.osug.fr
A paradigm for interacting buildings and their effect on seismic waves and vice-versa.



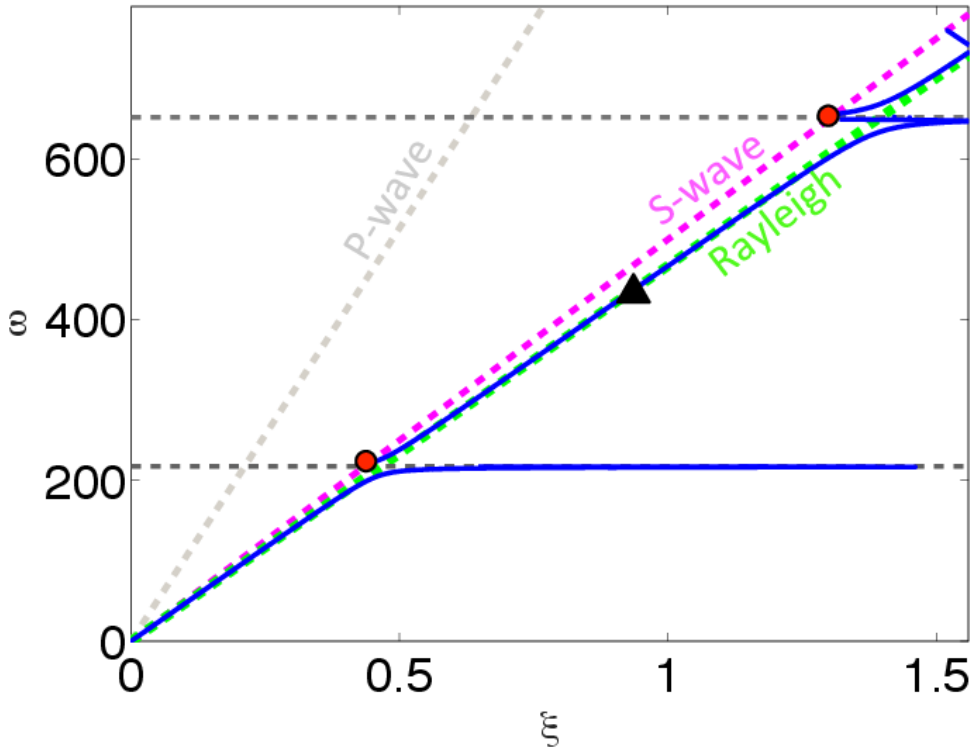
Surface sub-wavelength resonators



This can be solved exactly for an infinite array using Fourier transforms and the Bloch problem gives the dispersion curves.

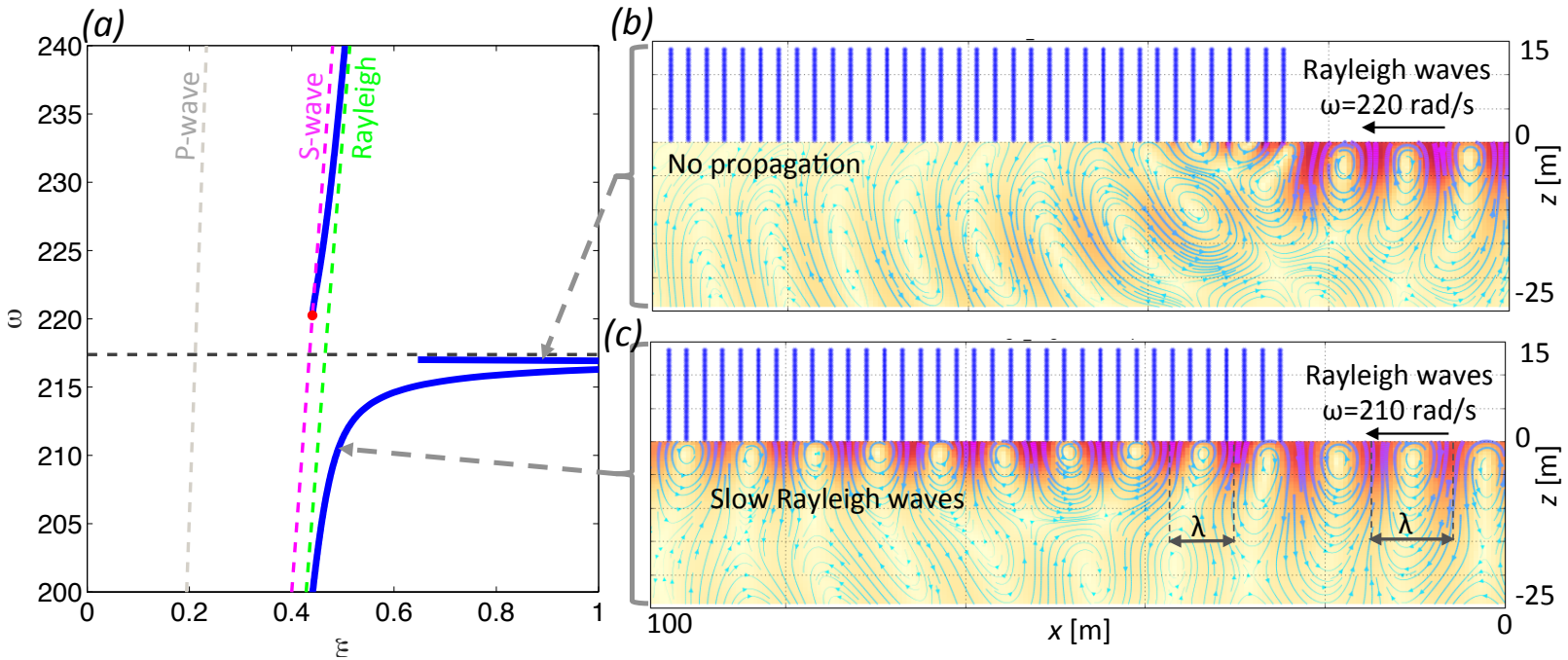
[D. J. Colquitt, A. Colombi, R. V. Craster, P. Roux, and S. R. L. Guenneau *J. Mech. Phys. Solids* 99, 379-393, 2017]

Dispersion curves

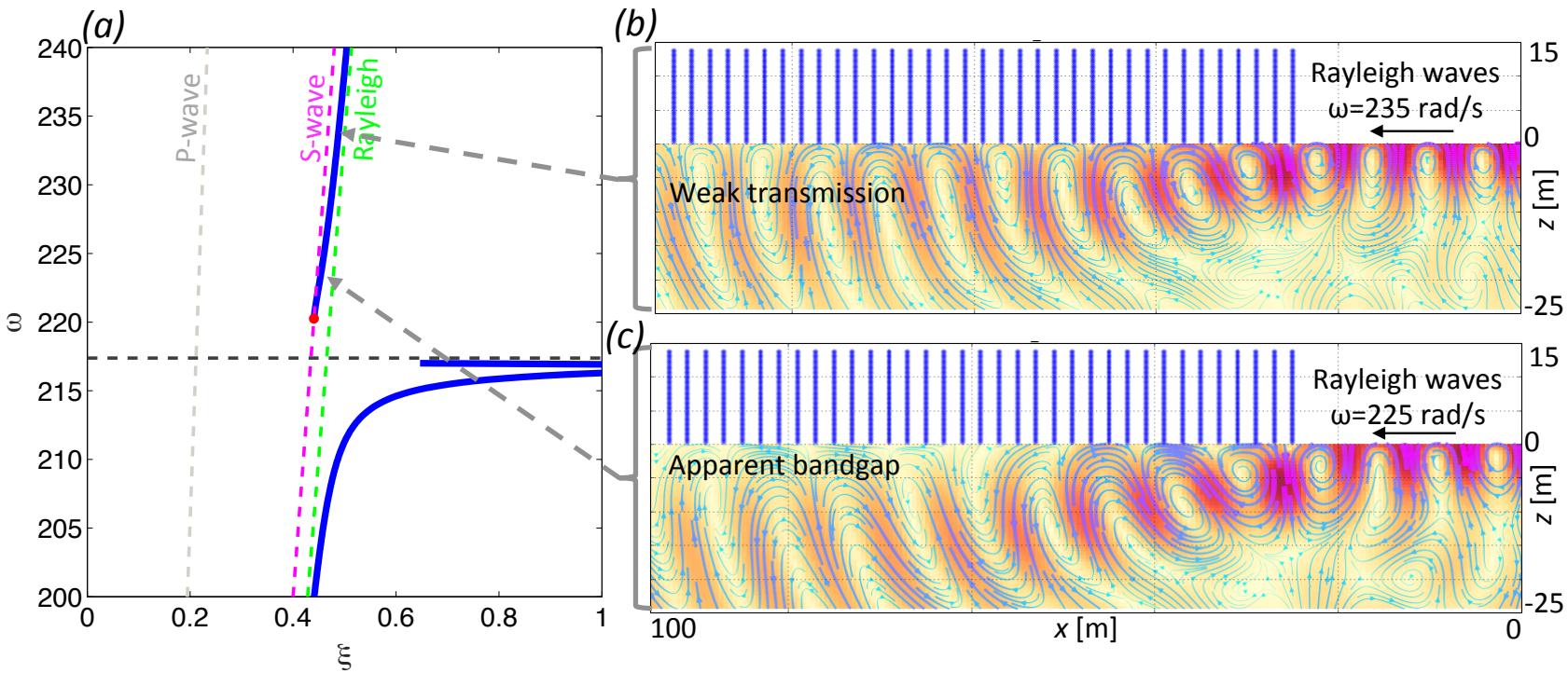


The dispersion curves for an infinite periodic array found using Bloch theory. Note the very narrow stop-band, the slow waves and hybridisation of Rayleigh wave.

Below the stop-band

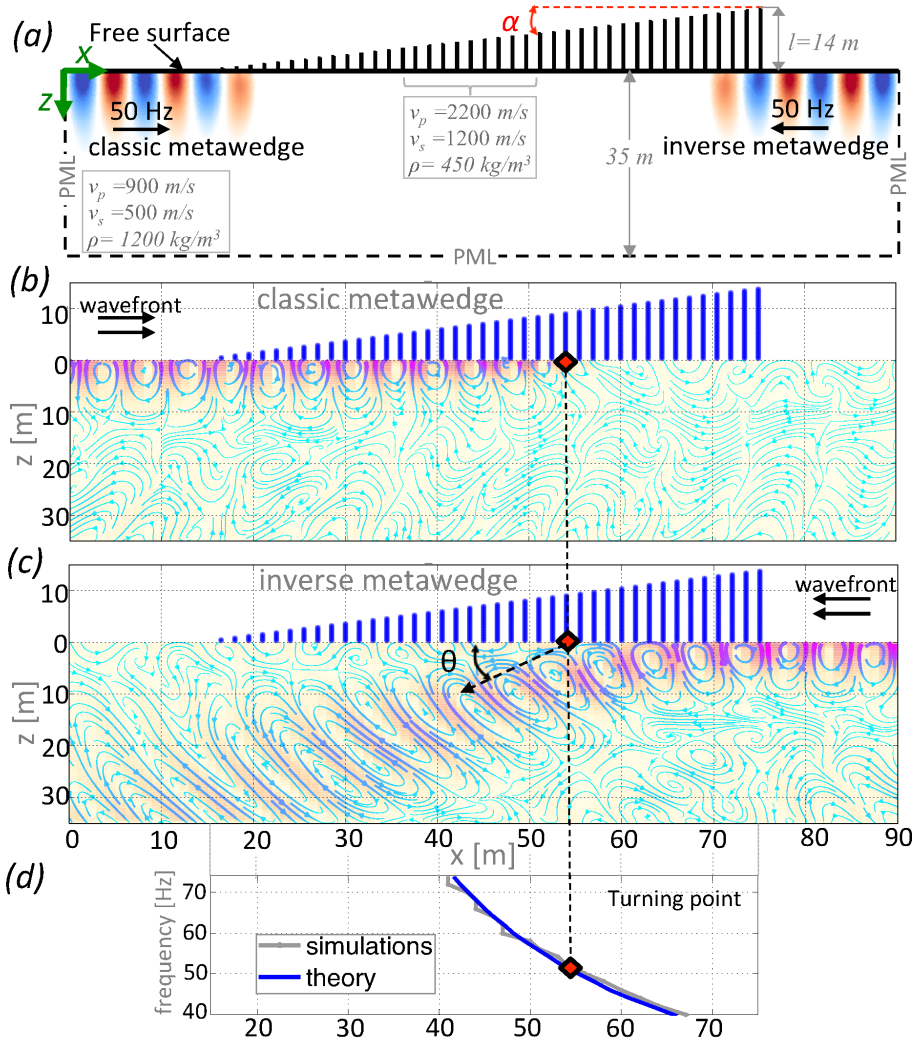


Above the stop-band



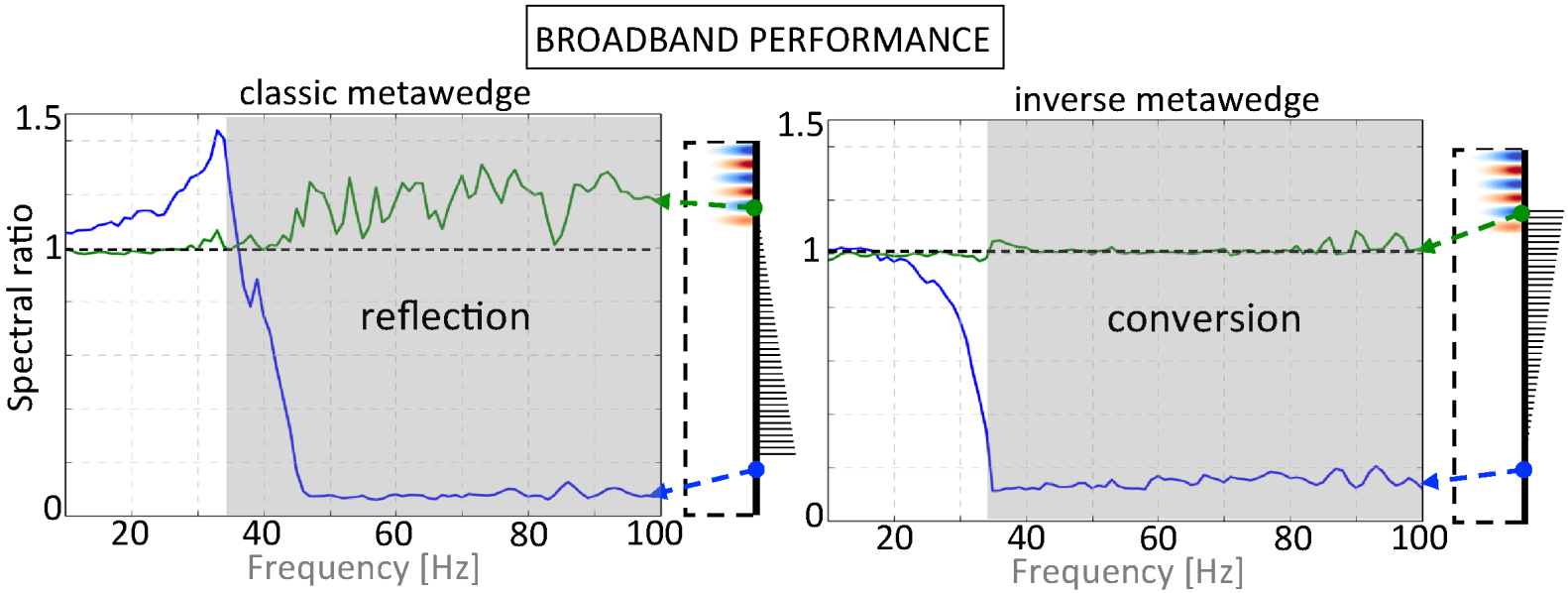
Surface wave mode converter - Metawedge

Start animation

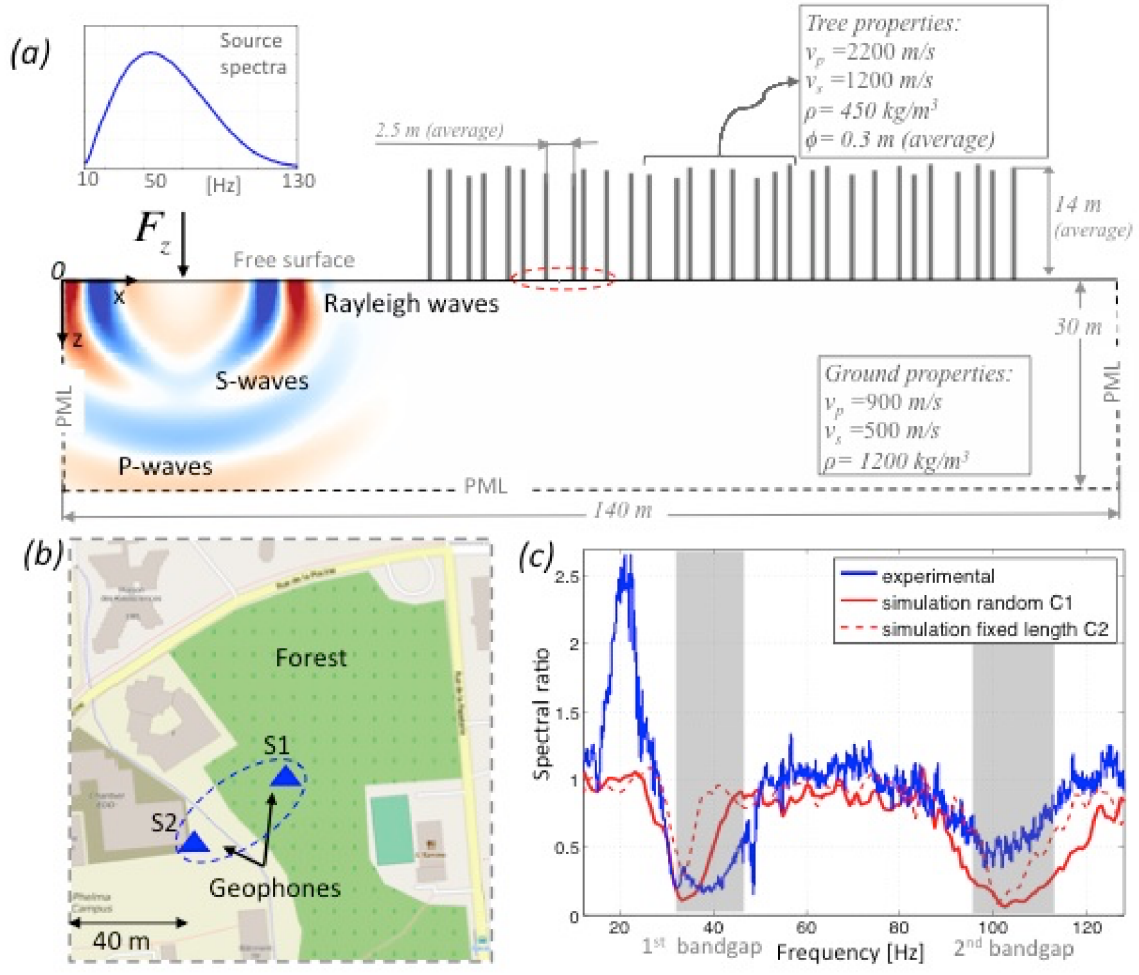


A. Colombi, D. Colquitt, P. Roux, S. Guenneau, R. V. Craster *Scientific Reports*, **6**, 27717, 2016

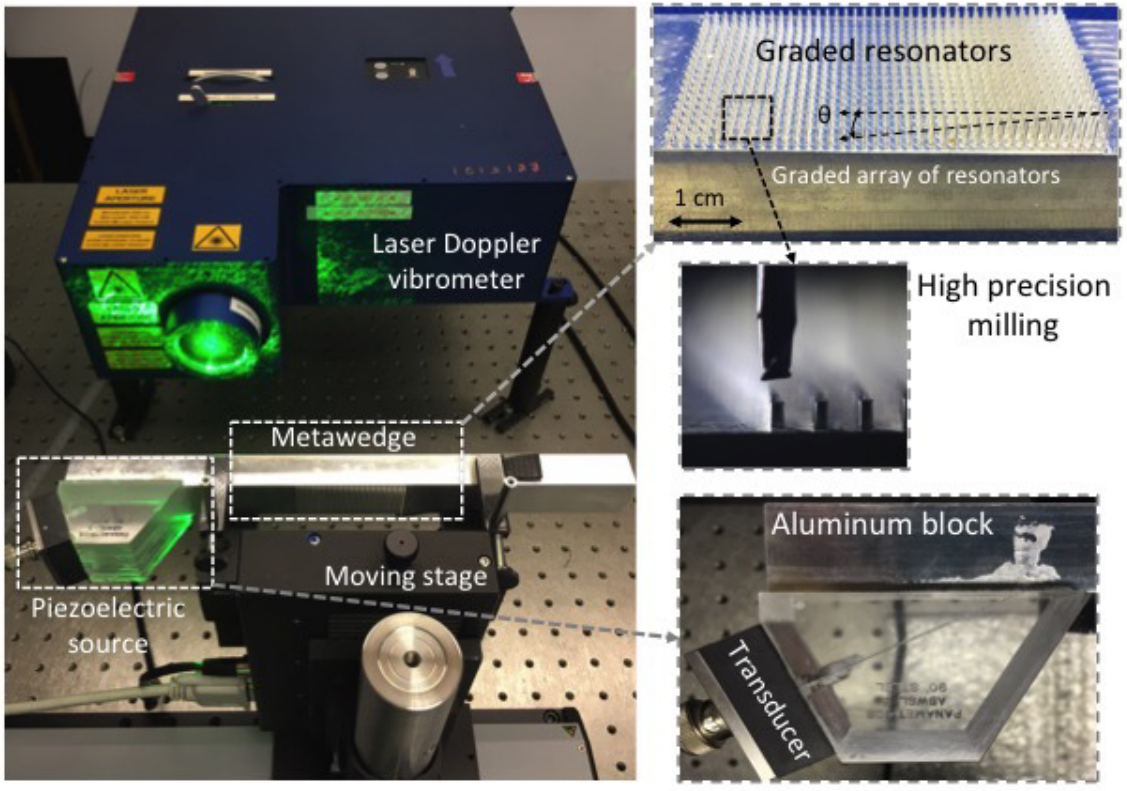
Broadband performance



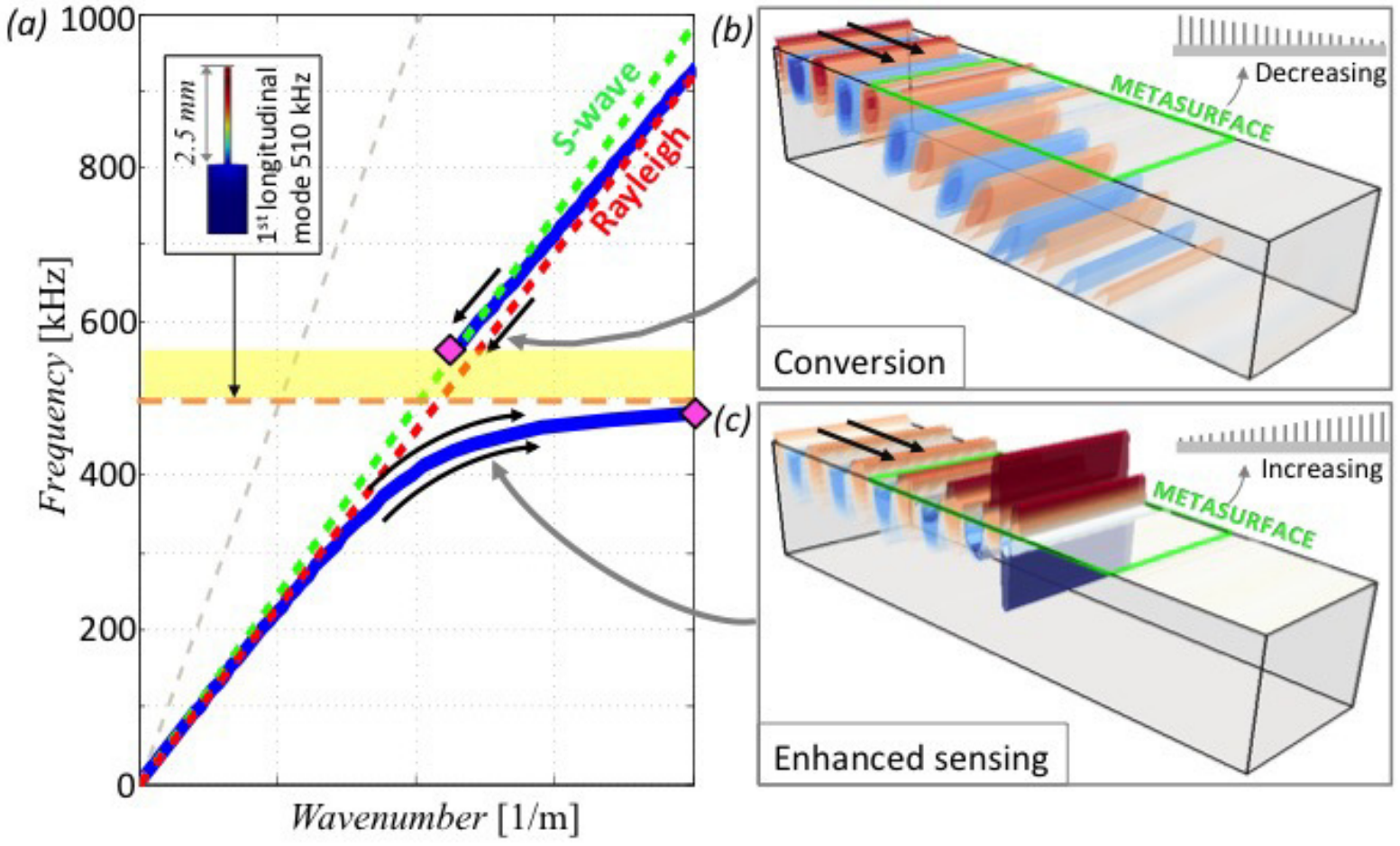
A natural metamaterial. Does weak disorder matter?

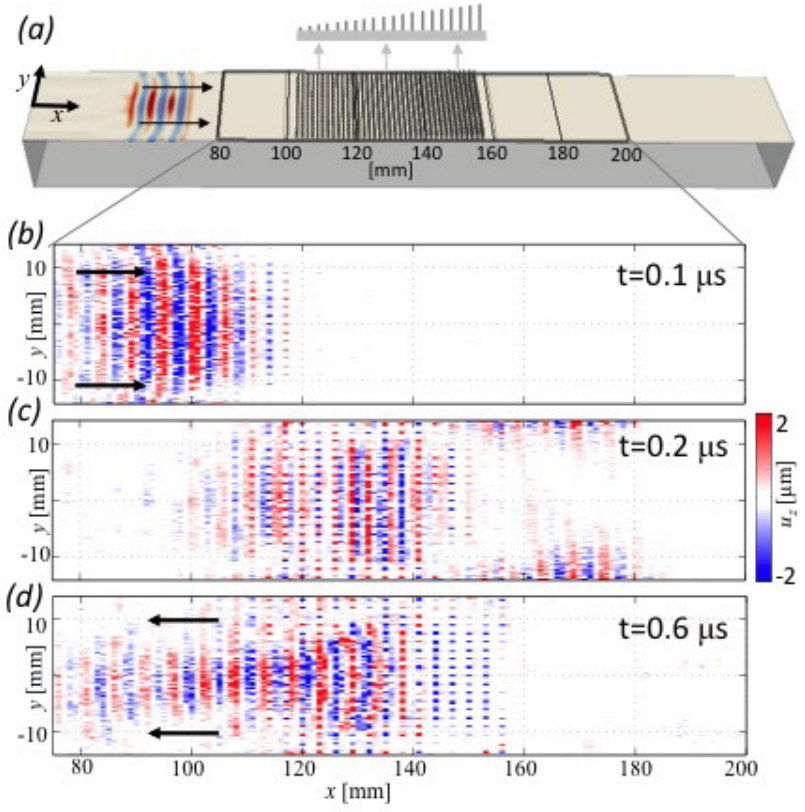


Ultrasonic experiments - scaled down in size

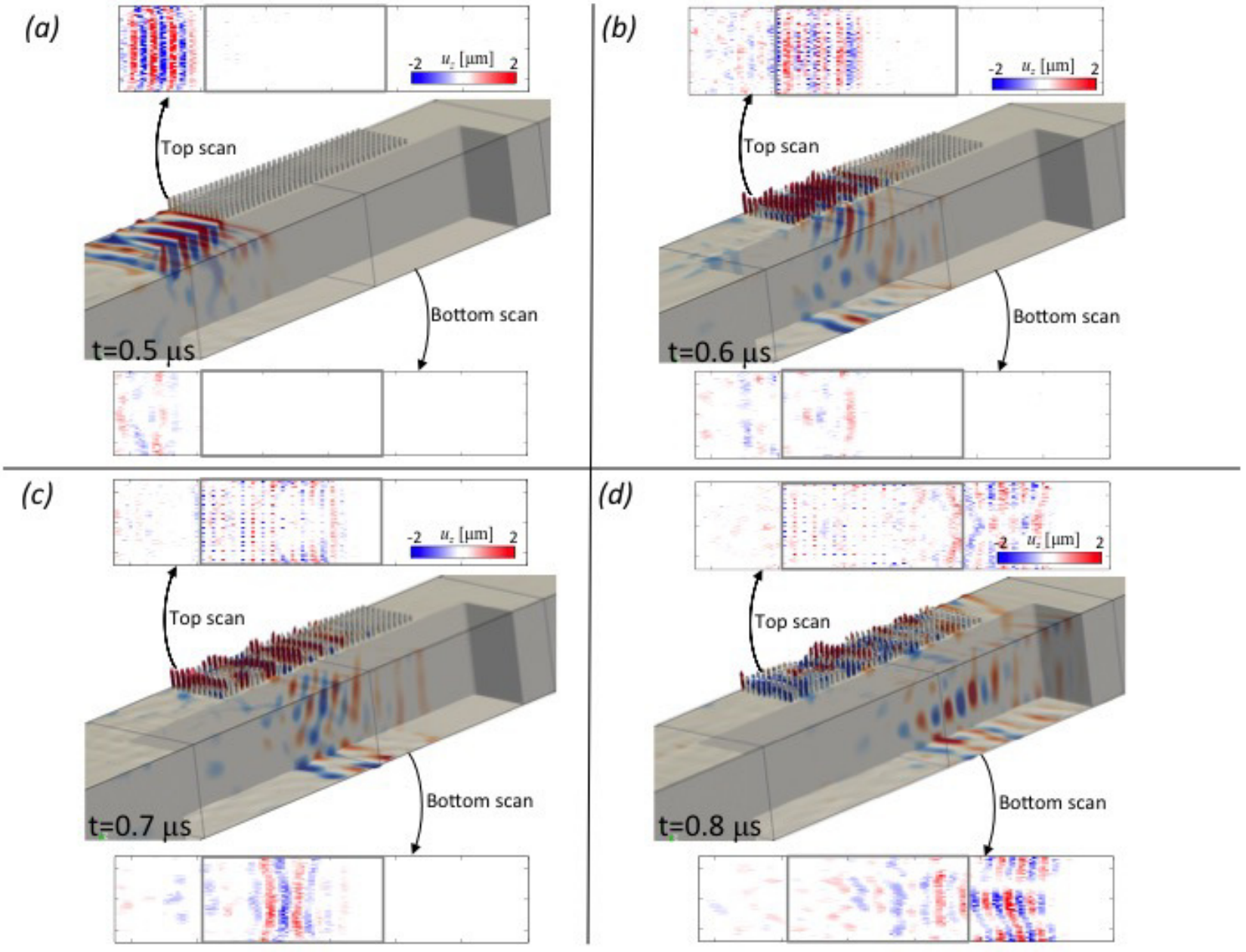


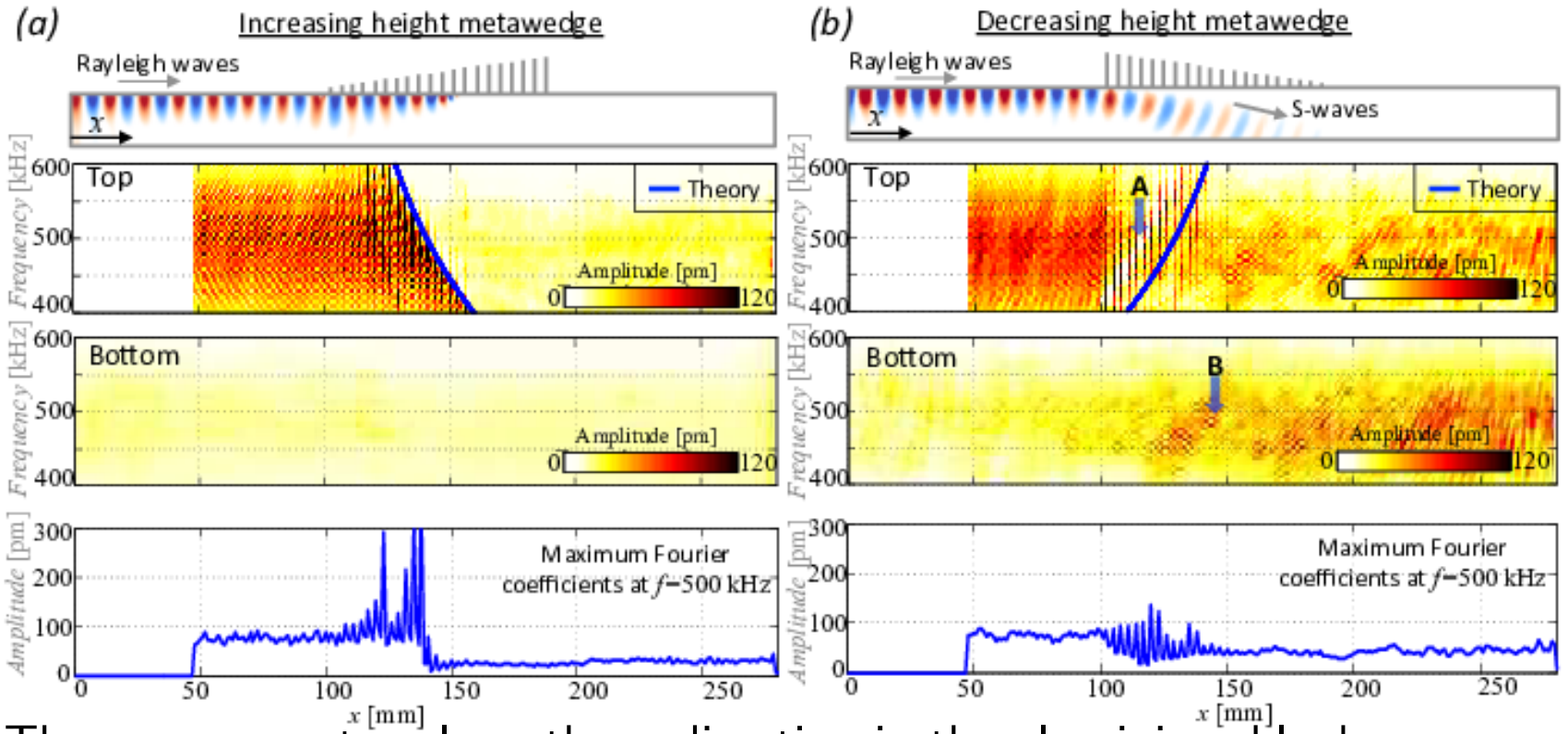
Experimental setup - laser doppler vibrometer scanning aluminium block created by micro-milling Colombi, Clarke et al *Sci Reps* 2017


(a)
1000
800
600
400
200
0
Frequency [kHz]
Wavenumber [1/m]
2.5 mm
1st longitudinal mode 510 kHz
S-wave
Rayleigh
(b)
Decreasing
METASURFACE
Conversion
(c)
Increasing
METASURFACE
Enhanced sensing



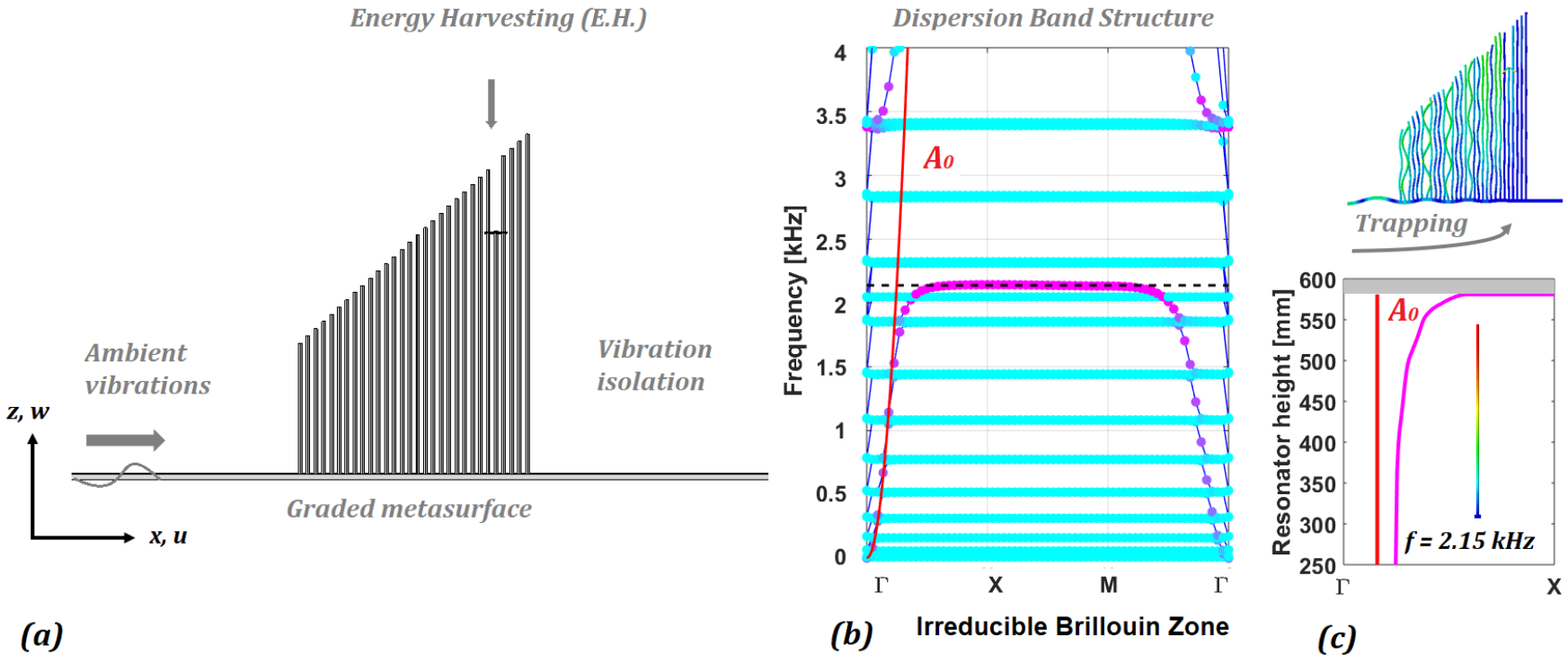
Experimental results showing the reflection of the surface wave (filtered at 450-600 kHz) Start animation


(a)
-2 u_z [μm] 2
Top scan
Bottom scan
t=0.5 μs
(b)
-2 u_z [μm] 2
Top scan
Bottom scan
t=0.6 μs
(c)
-2 u_z [μm] 2
Top scan
Bottom scan
t=0.7 μs
(d)
-2 u_z [μm] 2
Top scan
Bottom scan
t=0.8 μs



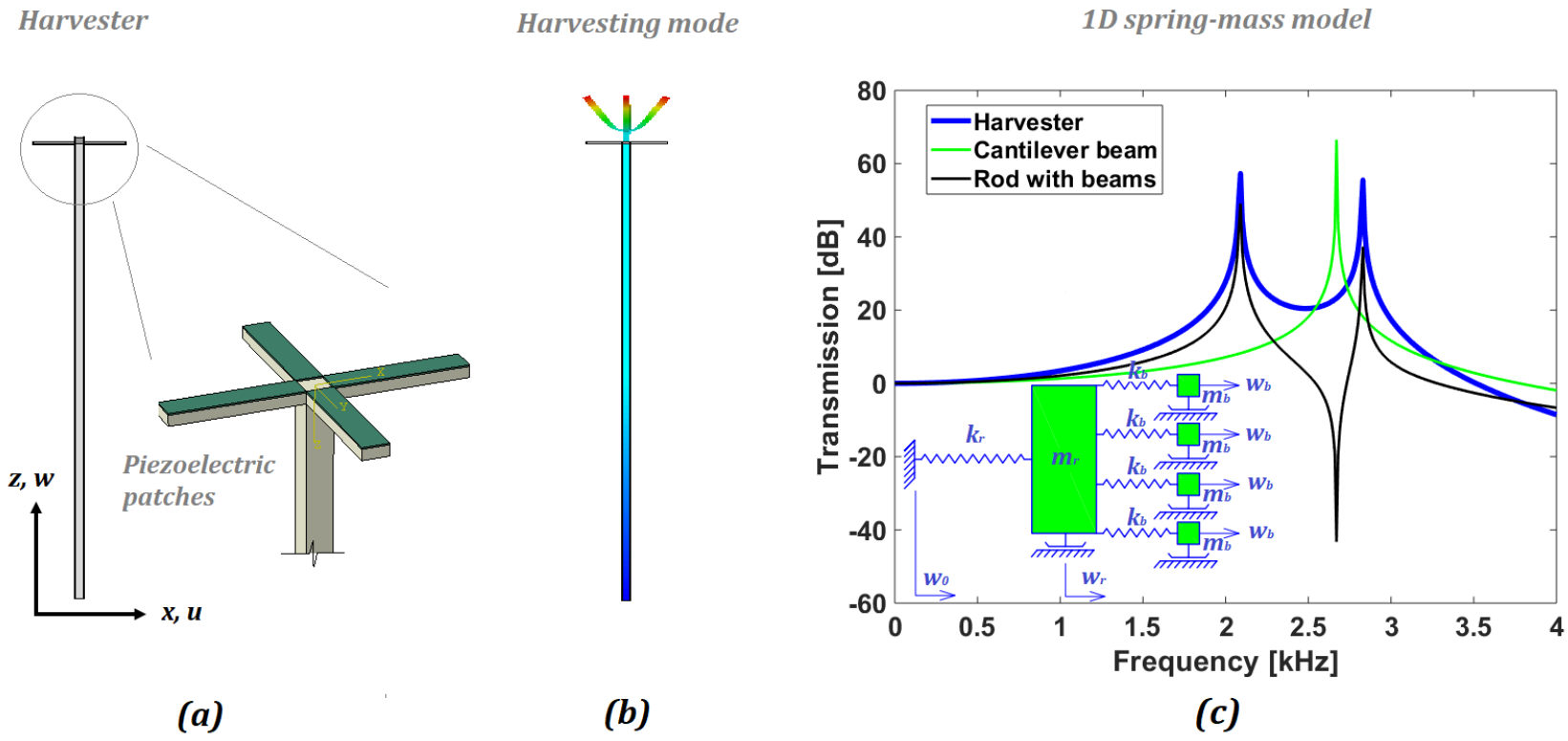
The power spectra along the x-direction in the aluminium block measured at the centreline. Maximum value of the Fourier coefficients at 500 kHz. (b) Same as (a) but for the inverse metawedge.

An application: Harvesting simplified for an elastic plate



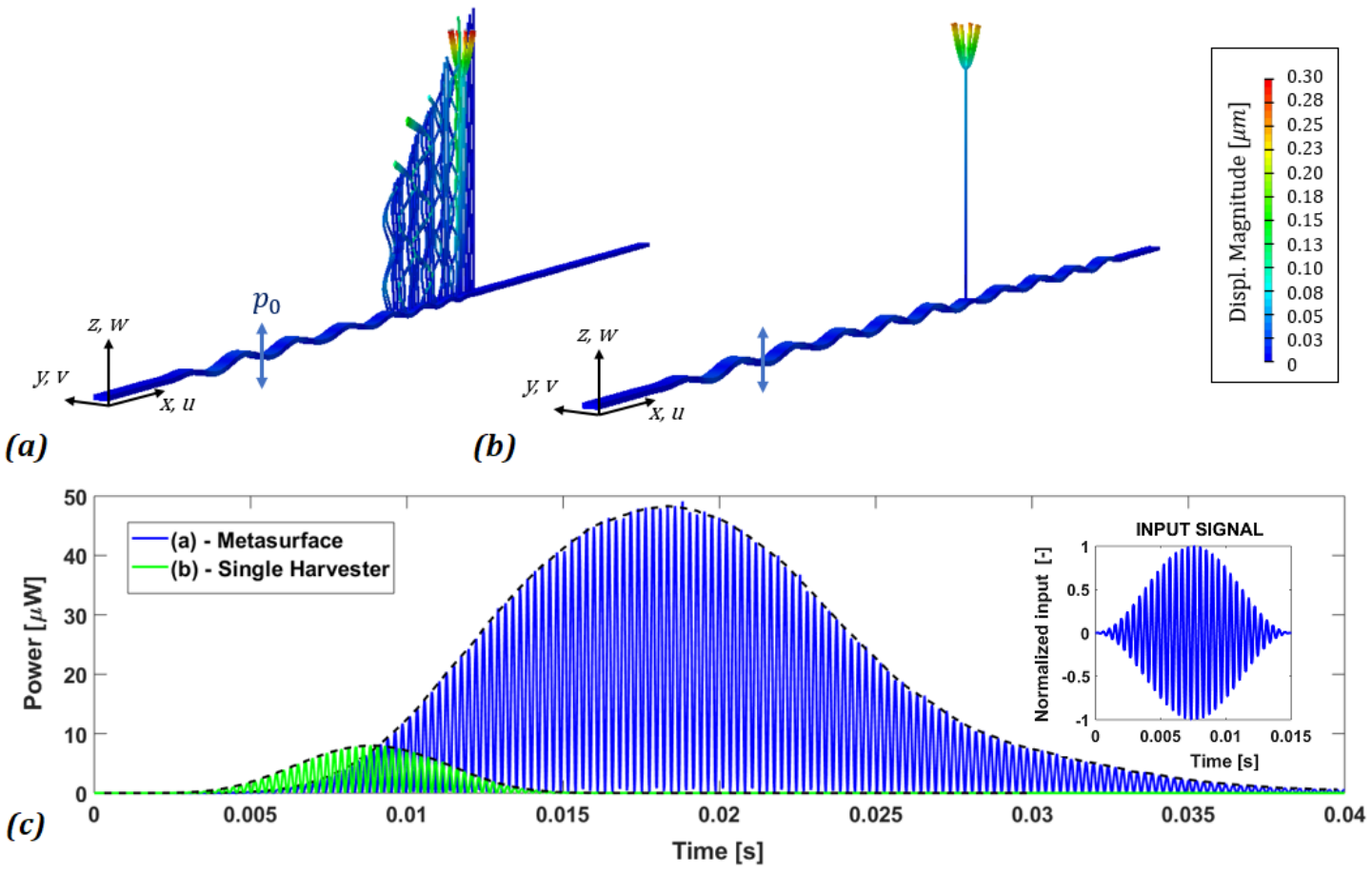
(a) metasurface, (b) dispersion curves for fixed height 581 mm. De Ponti, J. et al *New J. Phys.* 2019

The harvester



Harvester with piezoelectric patches (a), the harvesting fundamental mode (b). (c) the transmission spectrum.

Power



Harvester on a plate strip with (a), and without (b), the metasurface at 10 ms. Power with, and without, the metasurface (c).

Umklapp (flip-over) processes

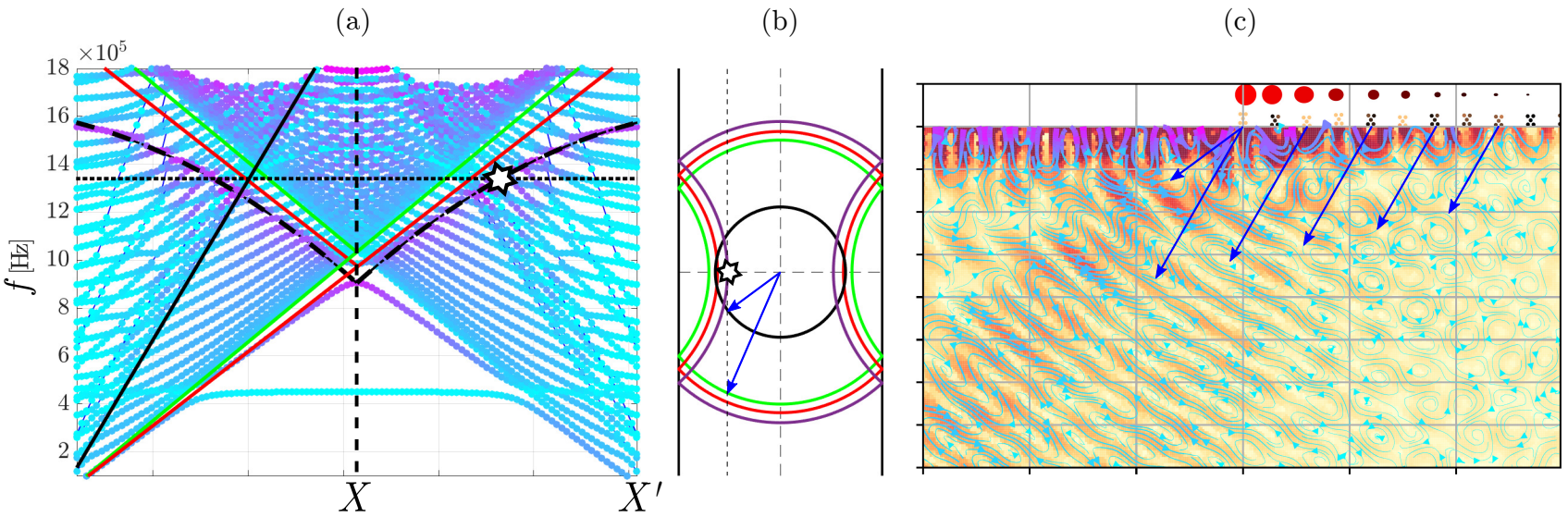
Thus far we have trapped (or at least slowed down waves) and mode converted to forward-propagating S waves.

- What about converting to P-waves?
- Can we direct converted bulk waves "backwards"?

Yes, can do both. Need ideas from solid-state physics.

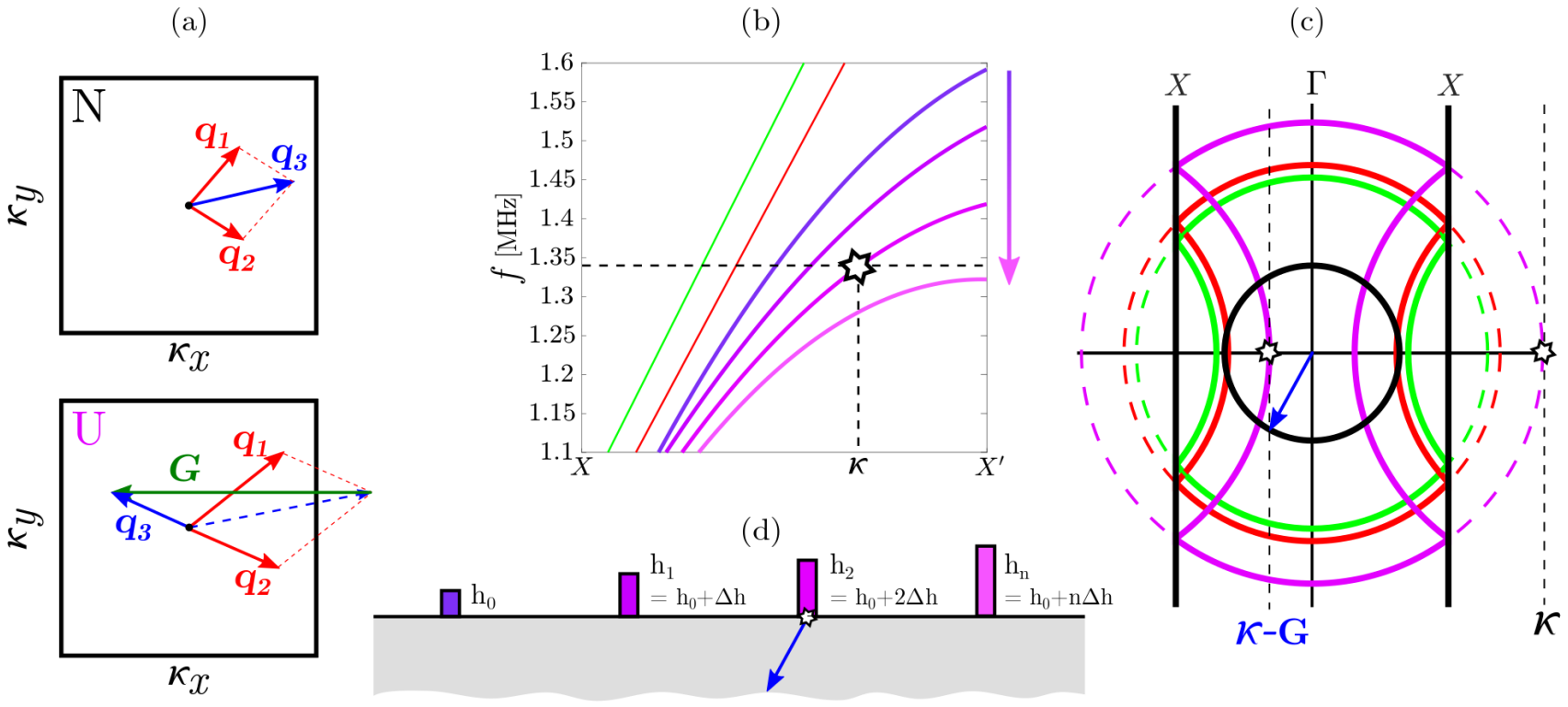
Chaplain, De Ponti, Colombi, Fuentes-Dominguez, Dryburg, Pieris, Smith, Clare, Clark and Craster *Tailored elastic surface to body wave Umklapp conversion, Nature Comms 2020*

An ungraded array



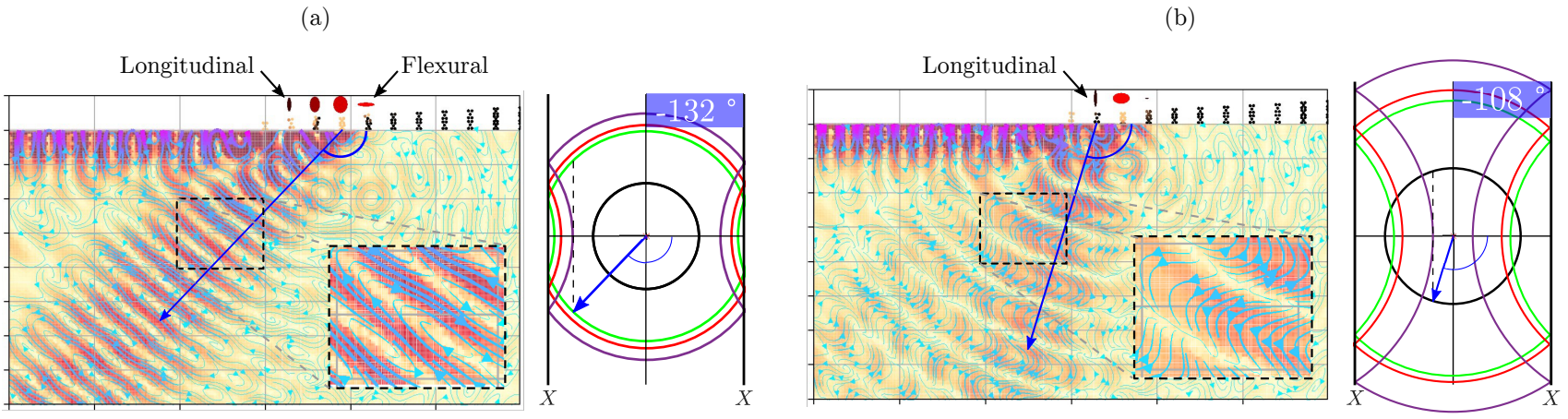
Excites both P and S waves into the bulk, no distinct beaming and acts as a self-phased leaky wave antenna.

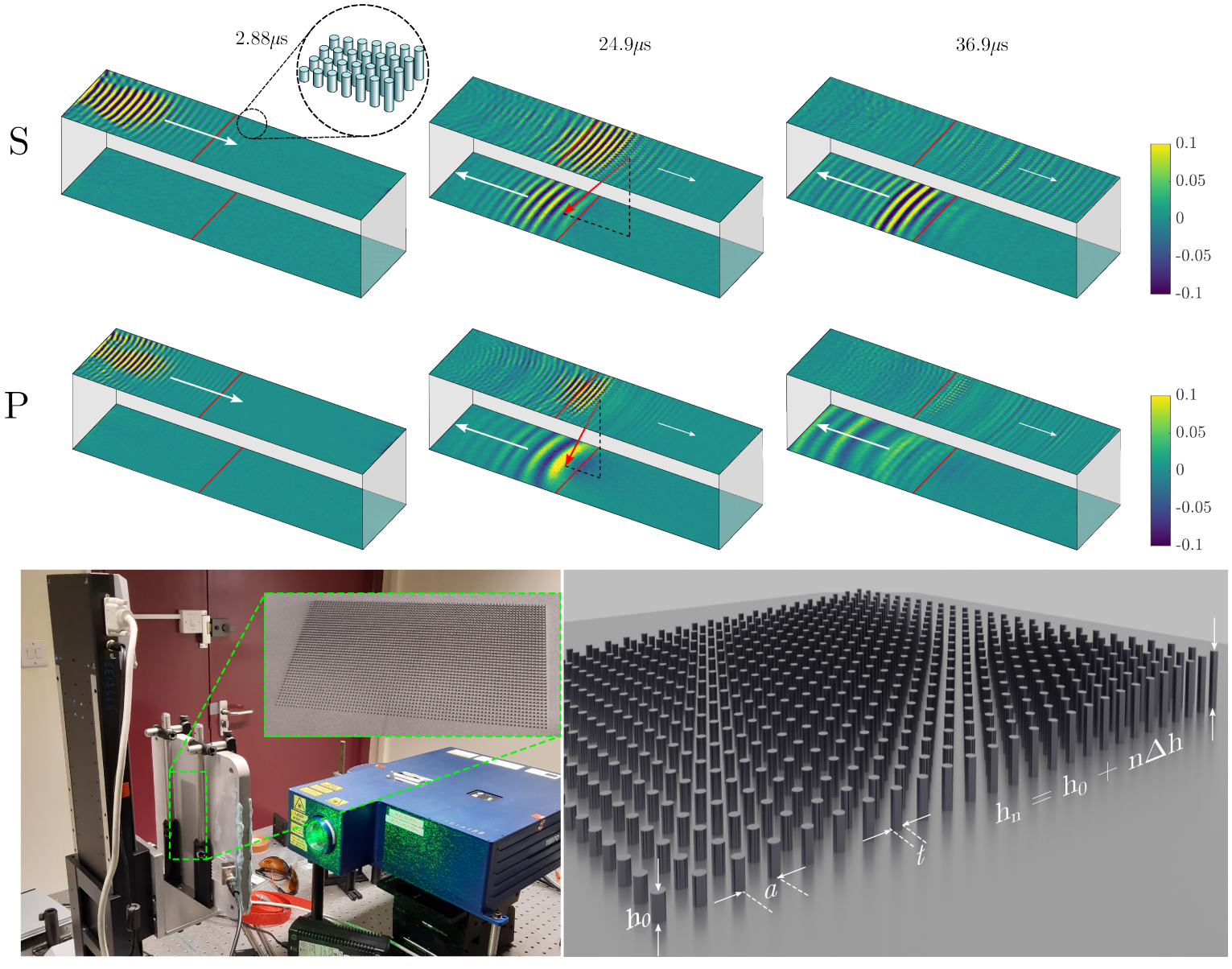
Grading the array



Note the band-gap and longitudinal resonance.

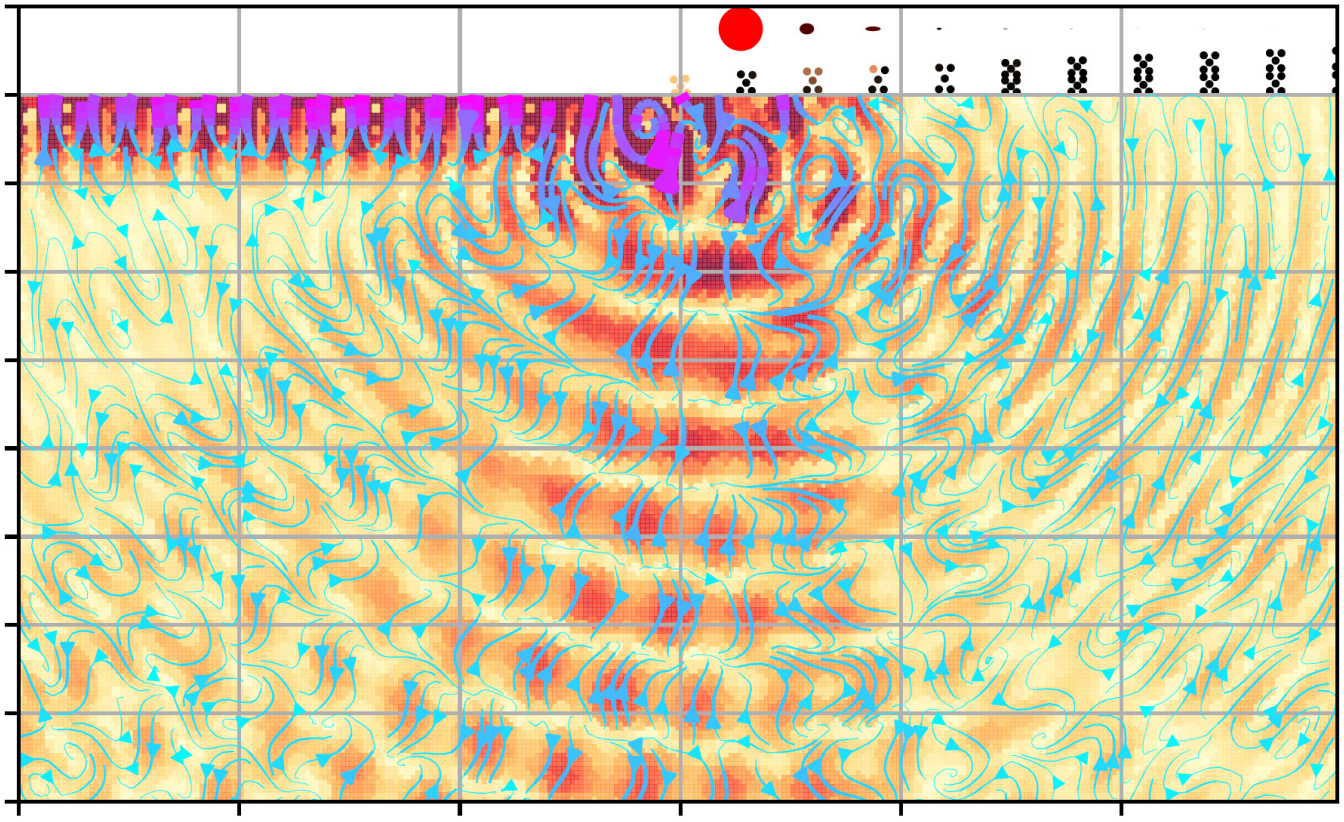
Separating S and P





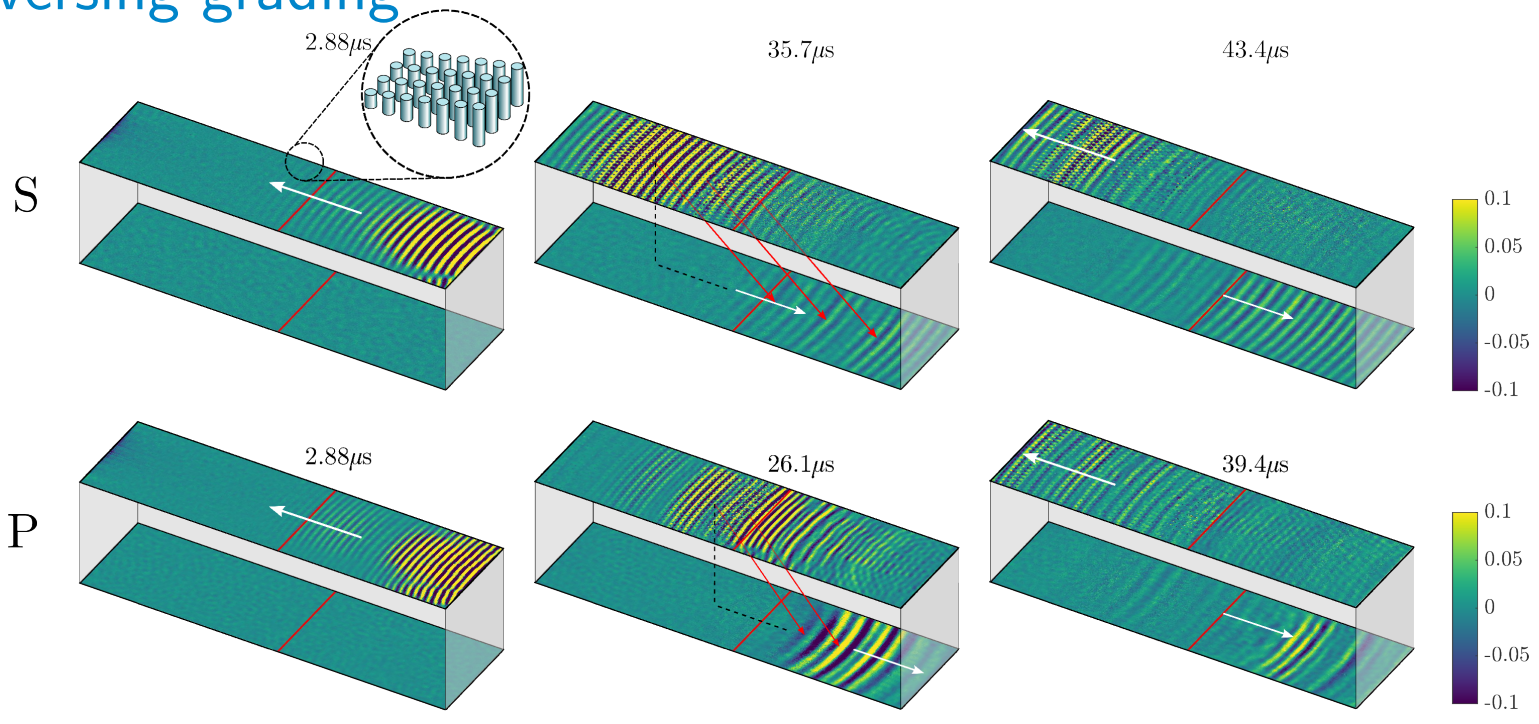
Start animation

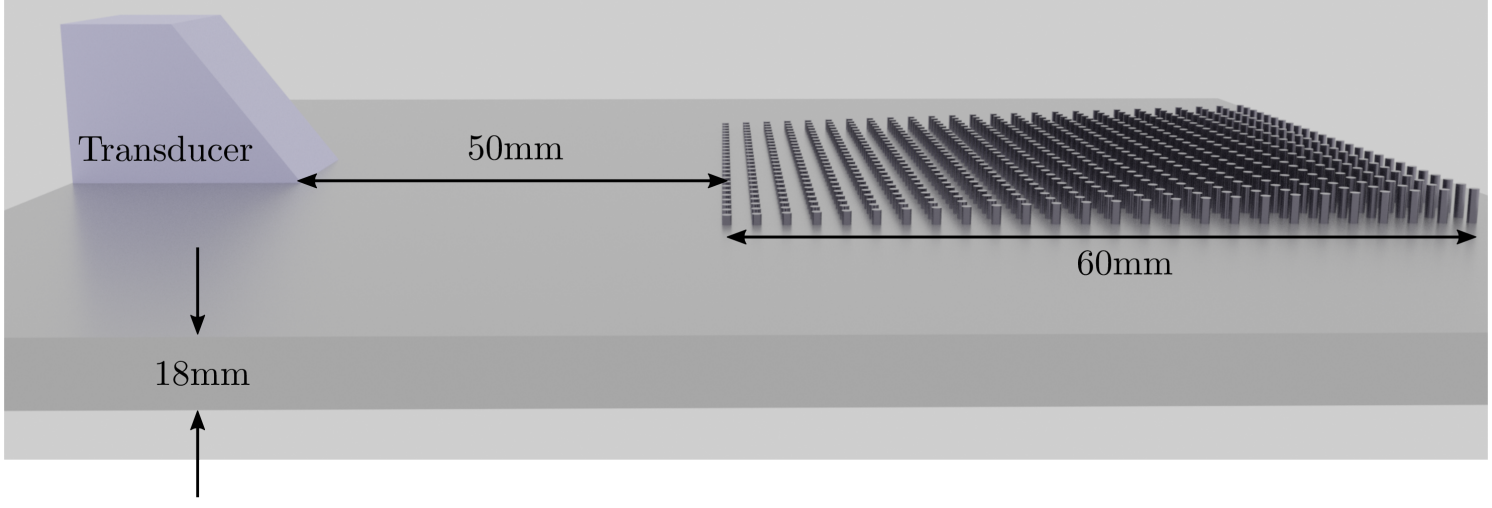
Tunable control



Launching a P wave at right-angles.

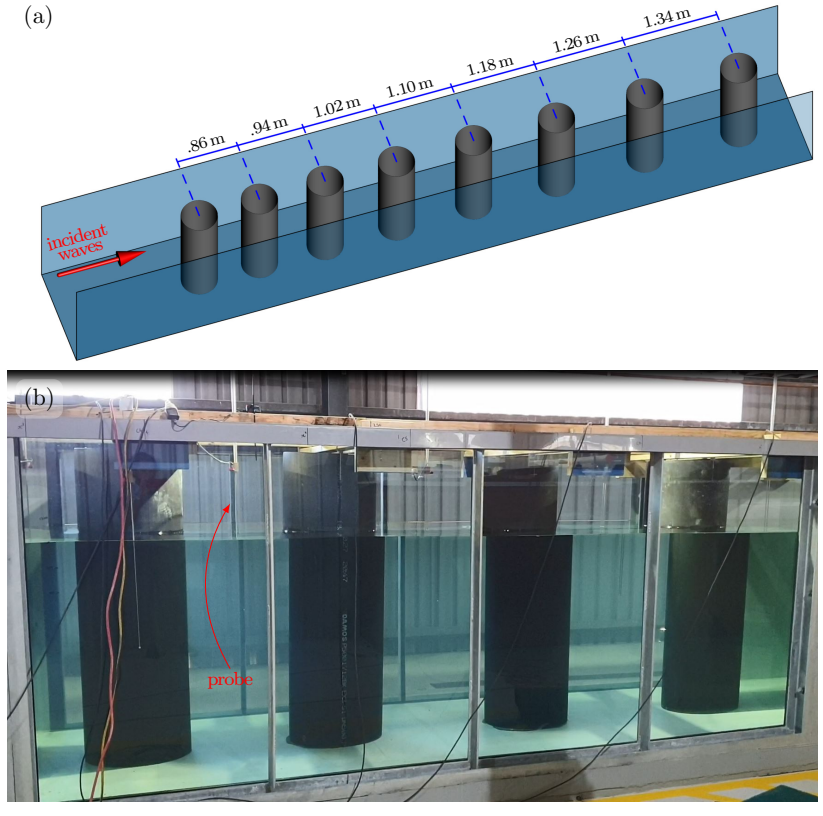
Reversing grading





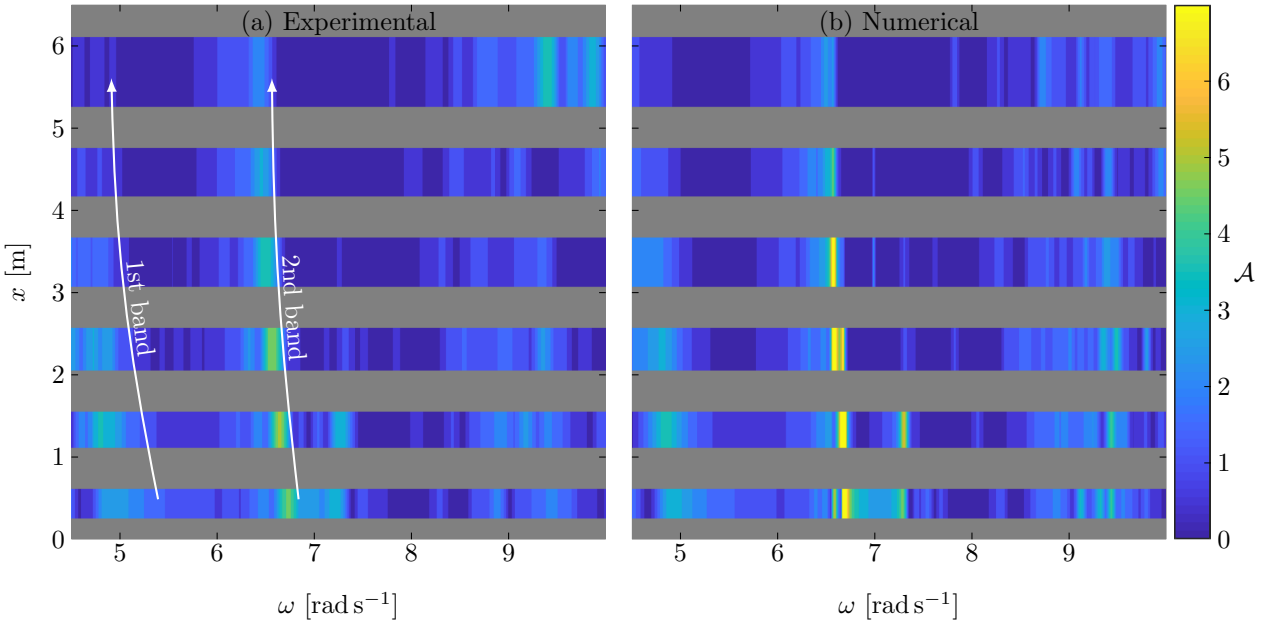
Generic ideas - applications to water waves

Water waves - nonlinear, surface tension, viscous etc not immediately clear the linear ideas from earlier carry across.



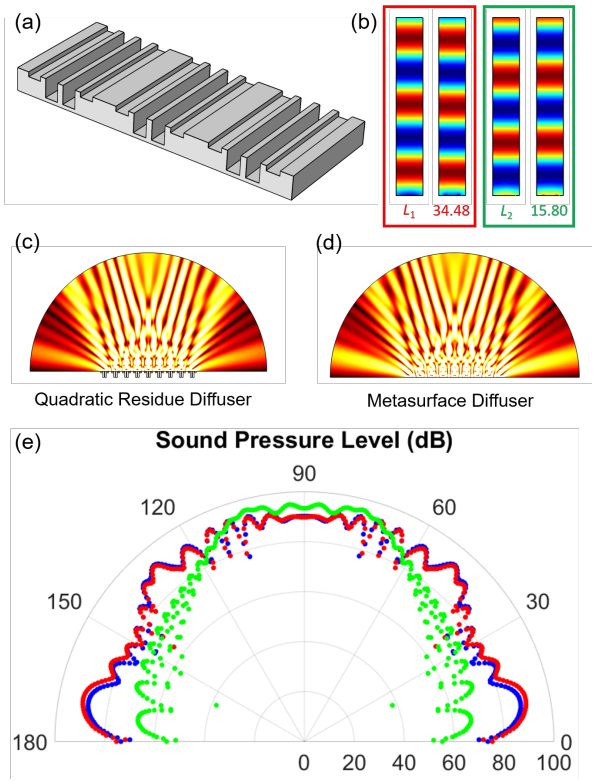
A. J. Archer, H. A. Wolgamot, J. Orszaghova, L. G. Bennetts, M. A. Peter & R. V. Craster, Experimental realisation of broadband control of water-wave-energy amplification in chirped arrays, Phys Rev Fluids, 2020

Simulations of the linear problem versus the full experiments.



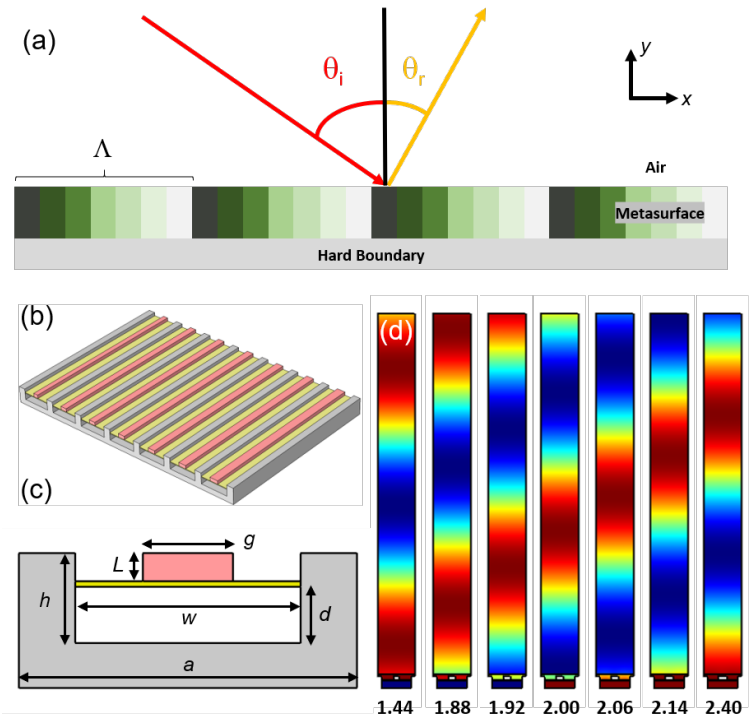
Amplitude enhancement in the cylinder spacings before propagation ceases increase by an order of magnitude, i.e., factors 9 and 17

Metasurfaces for wave control/ diffusers

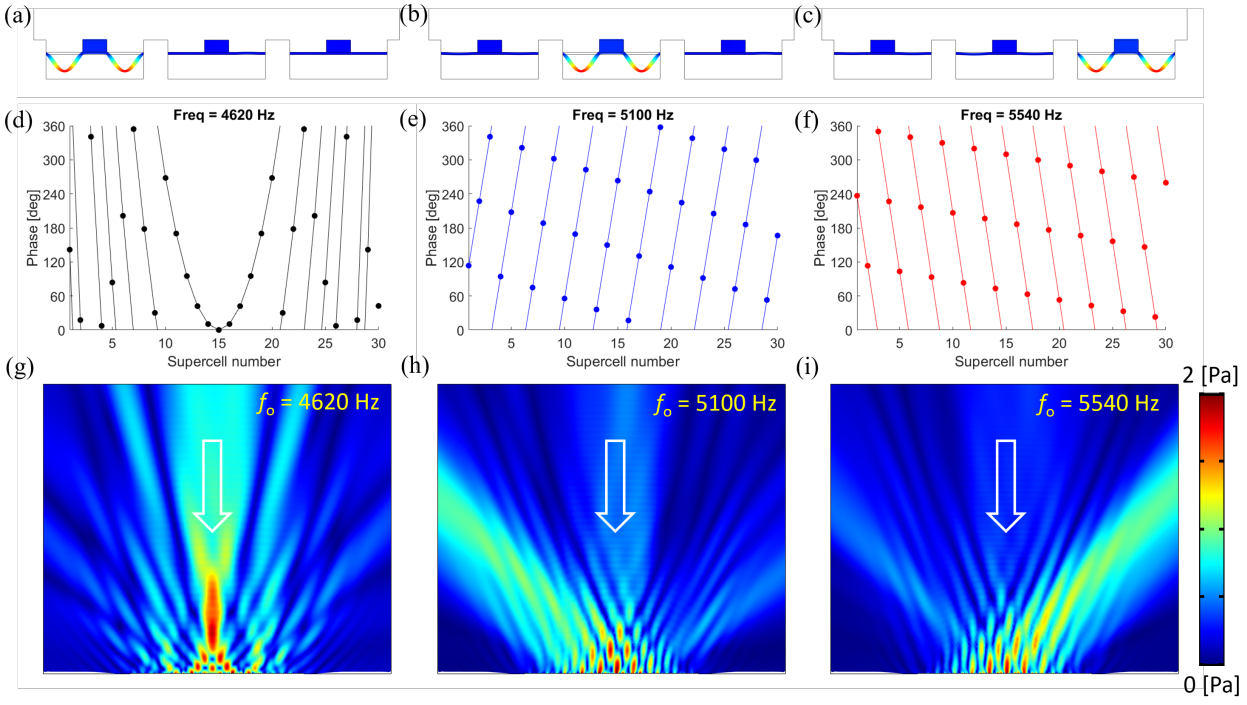


Mainly developed for air acoustics - this is a Schroeder diffuser with a deeply subwavelength metasurface (2mm) compared to a traditional diffuser (6cm). This is at 1.5kHz and thickness down to $\lambda/100$.
Joint work with Yao-Ting Wang and supported by UKRI Physics of Life (this is a grant about the "stealth" properties of moths to avoid bats).
Uses resonators to adjust the phase along the surface to create effects of our choosing.

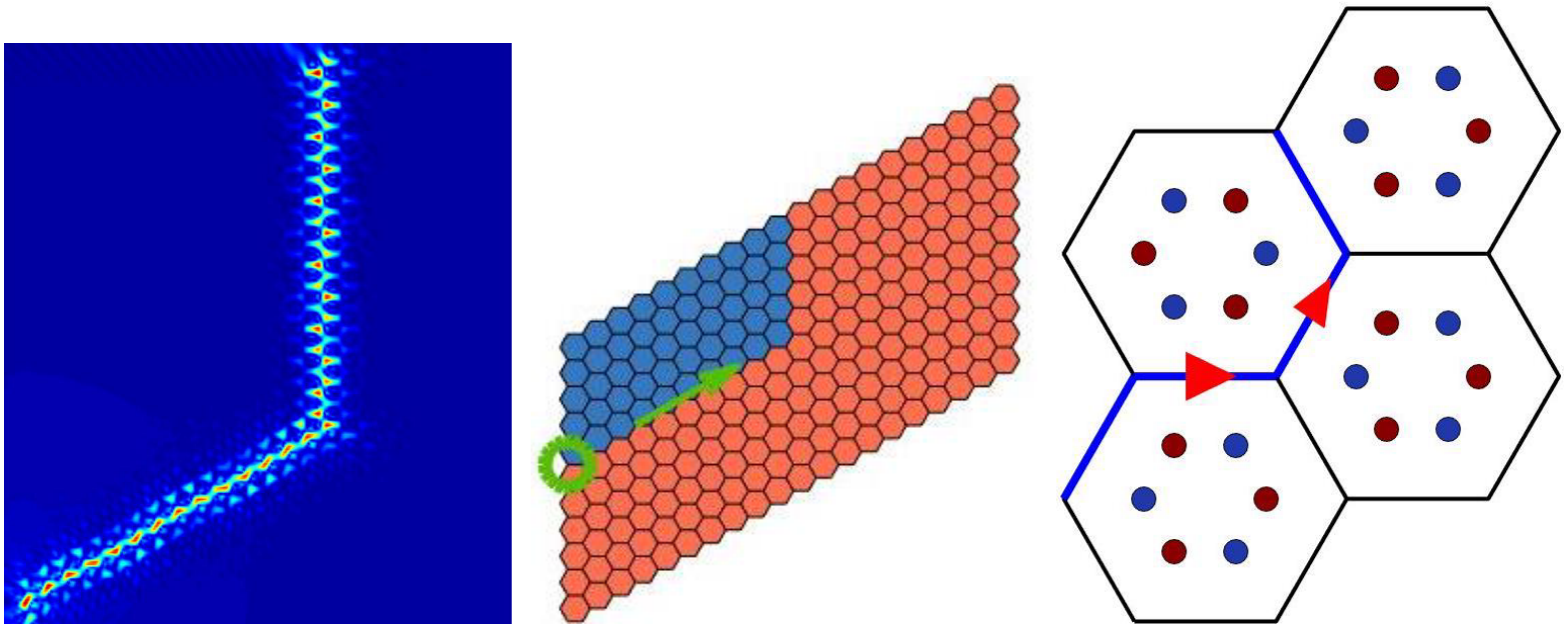
Designed changes in phase



Multifunctional surfaces



A little topology



Example of (broadband) passive wave-control using just shape i.e. topology (left) to minimise backscatter for waves around corners.

Makwana & RVC "Geometrically navigating topological plate modes around gentle and sharp bends" *Phys. Rev. B* **98**, 184105, 2018

Acknowledgements

Thanks to the Leverhulme Trust, EPSRC, EU Marie-Curie, ERC, French ANR & CNRS, ERC, US Air Force, Multiwave Technologies, Menard, DSTL, QinetiQ for their support.
UK Acoustics Network: www.acoustics.ac.uk (1000+ members, 15 SiGs, Early Career Group)
This work was partially supported by funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 863179.

And thanks for listening - questions?