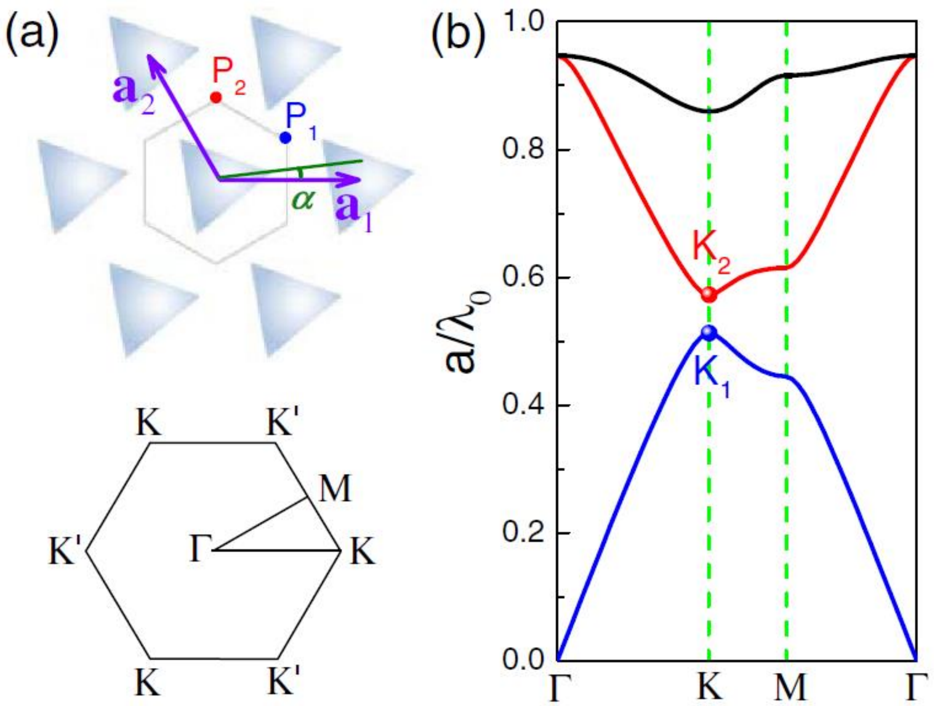
Acoustic topological circuitry in square and rectangular phononic crystals

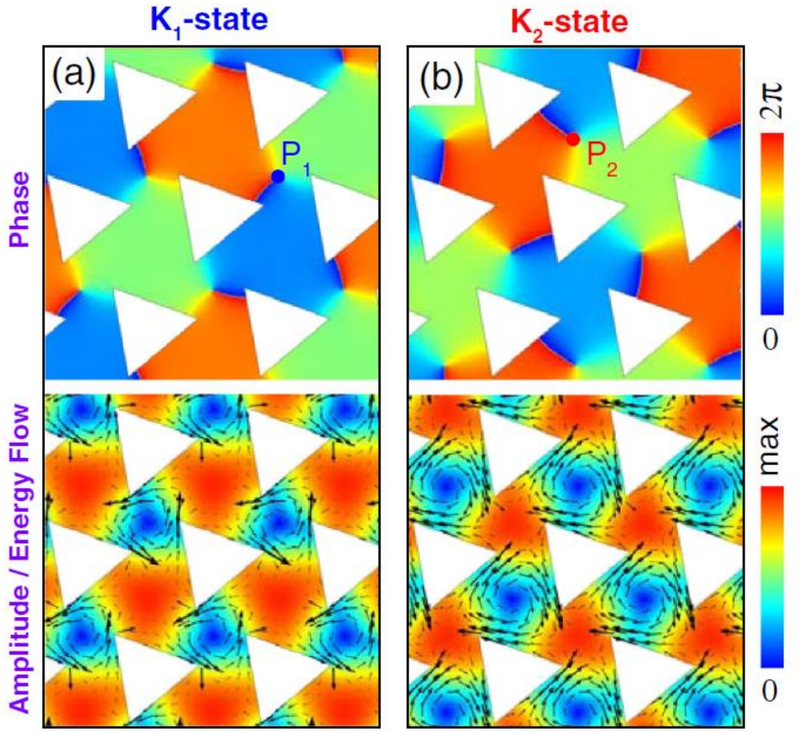
NICOLAS LAFORGE, RICHARD WILTSHAW, RICHARD V. CRASTER, VINCENT LAUDE, JULIO ANDRÉS IGLESIAS MARTINEZ, GUILLAUME DUPONT, SÉBASTIEN GUENNEAU, MUAMER KADIC AND **MEHUL P. MAKWANA**

Acoustic analog of quantum valley Hall effect



Lu *et al.*, Phys. Rev. Lett. 116, 093901 (2016).

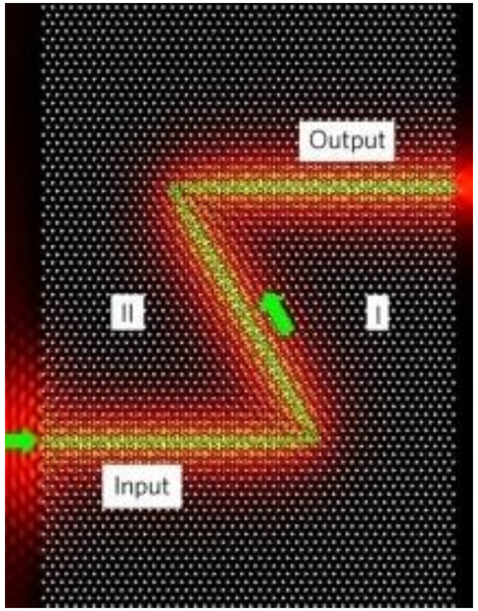
Lu *et al.*, Nat. Phys. 13, 369 (2017).



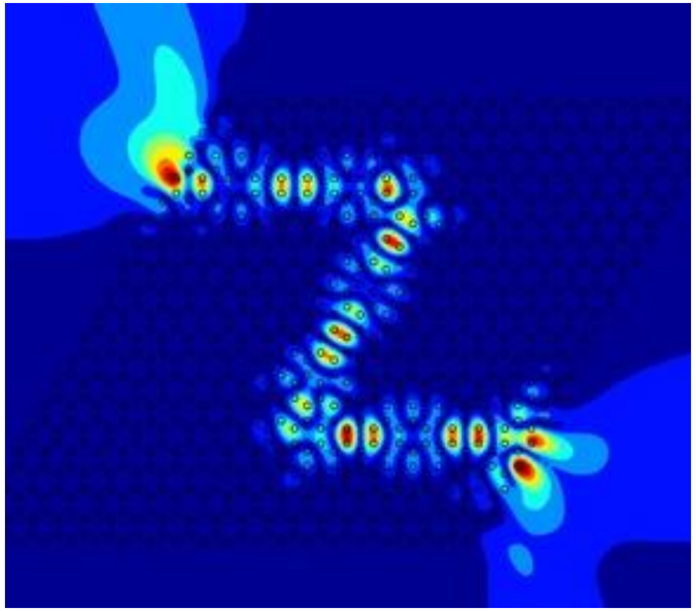
- (Bloch) vortex waves at the K point hold the topological *valley* invariant
- Edge modes guided at a domain wall are formed by combining crystals with angles $\pm\alpha$

Three K Points: no backscattering in 3 directions

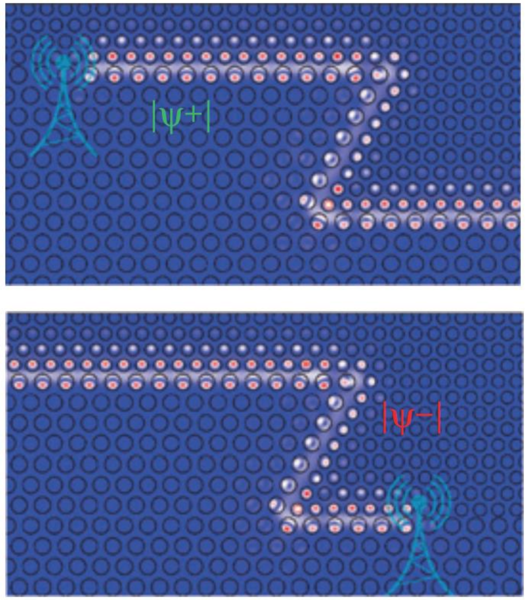
Acoustics



Elastic waves



Optics

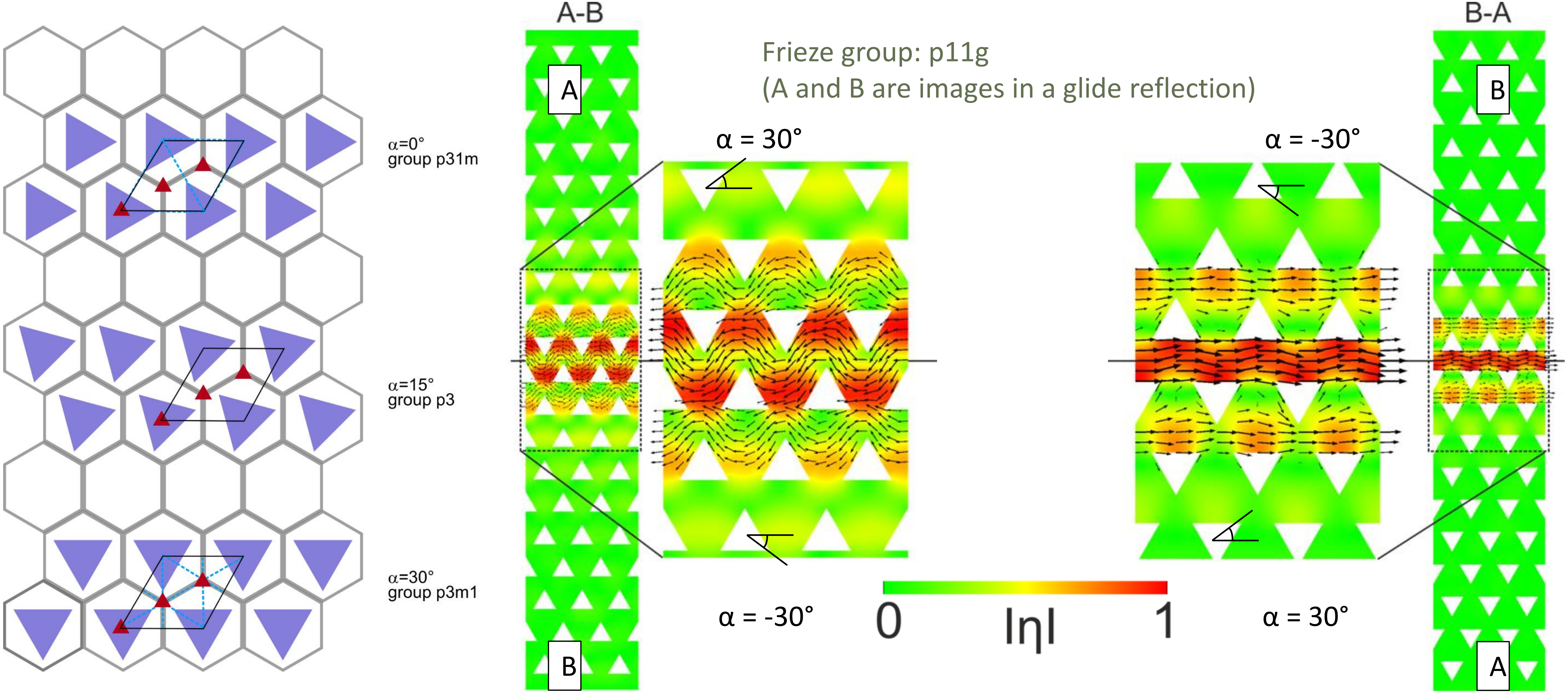


Lu *et al., Nat. Phys. 13* (2017) 369

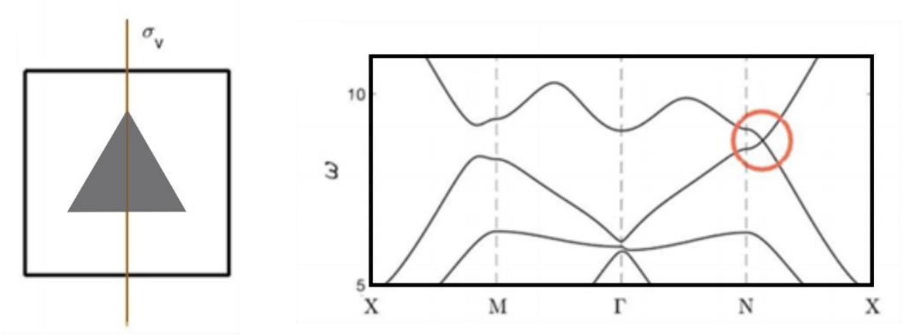
Pal *et al., New J. Phys. 19,2* (2017) 025001

Khanikaev *et al., Nat. Mater. 12* (2012) 223

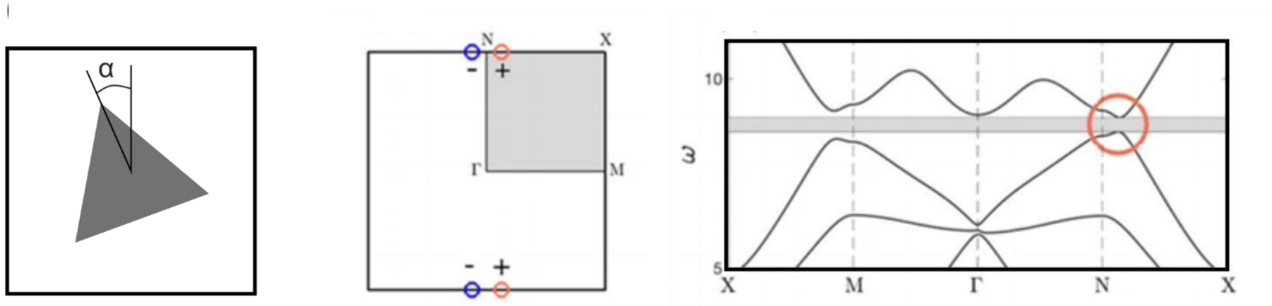
Space groups of the 2D crystal and the 1D waveguide



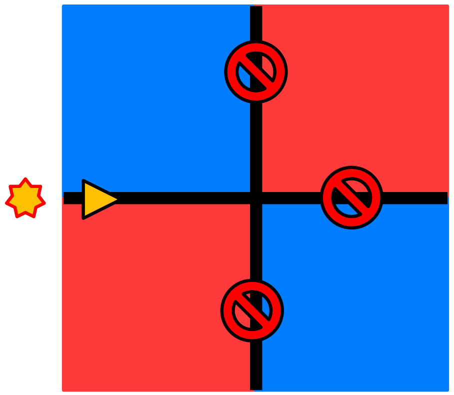
Dirac points in the square lattice? 3-way splitter?



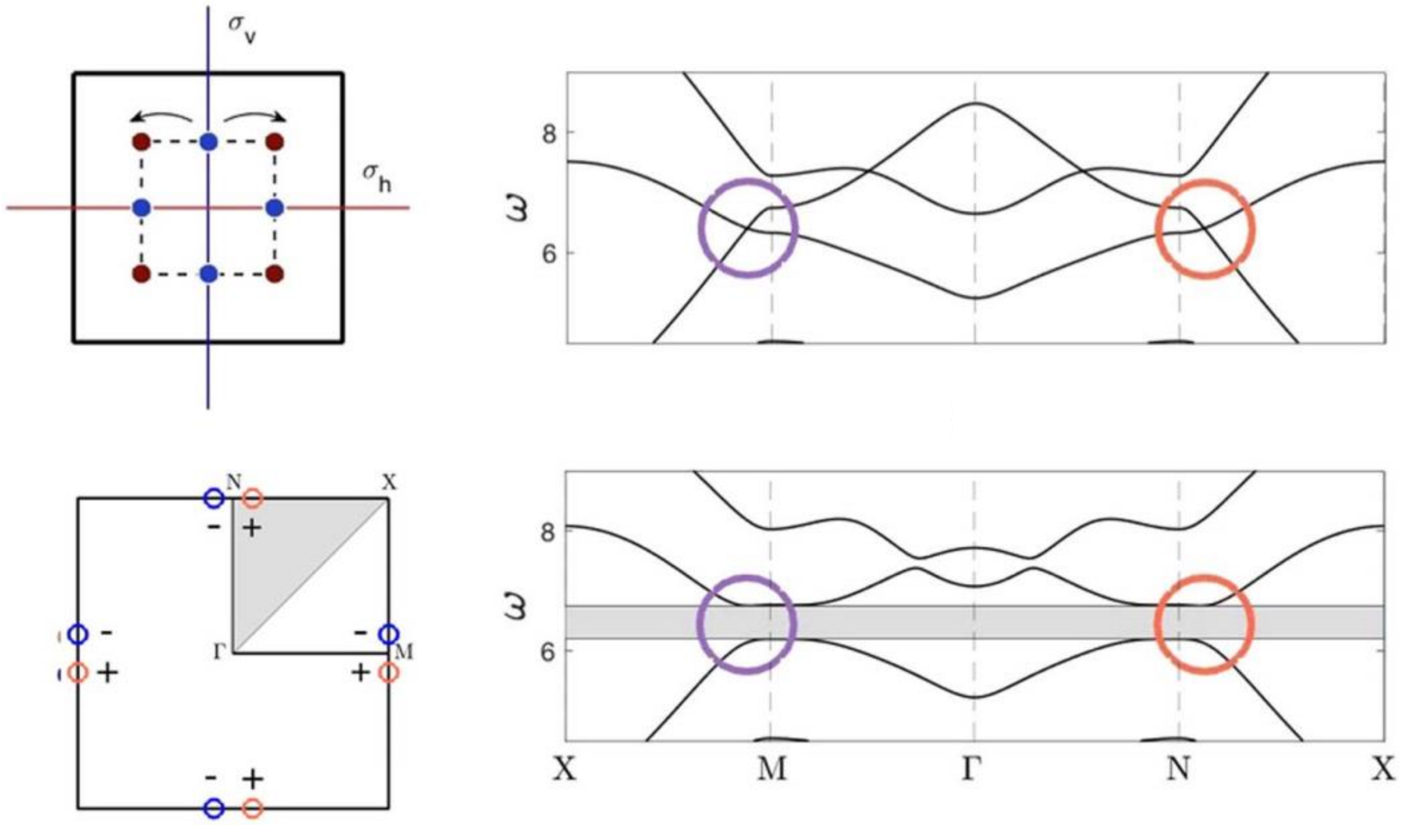
Makwana, M.P., Chaplain, G. Tunable three-way topological energy-splitter. *Sci Rep* **9,** 18939 (2019)



The sign of the Chern number associated with Dirac cones dictates if waves go along a domain wall or not



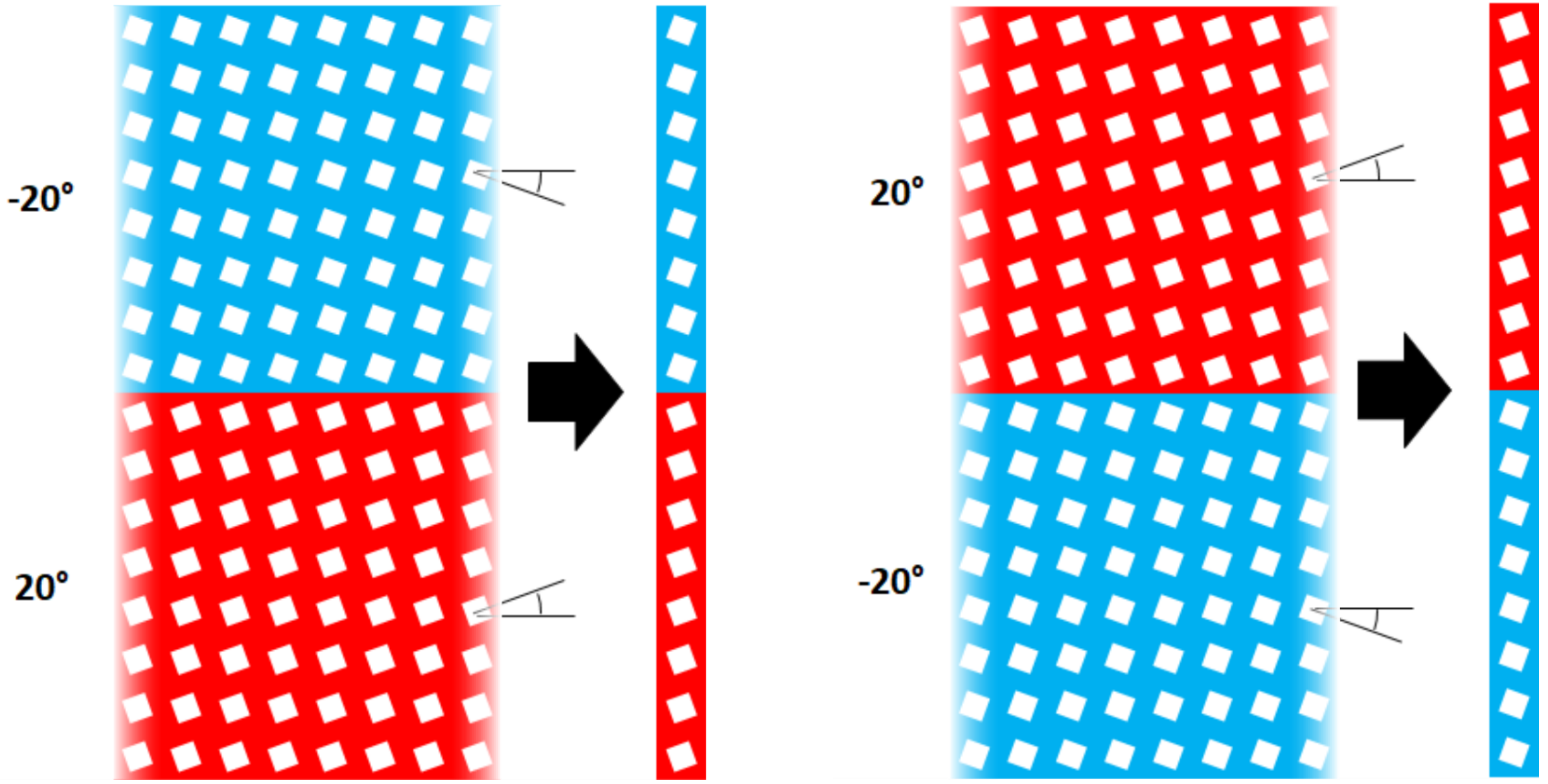
Square inclusion in square-lattice



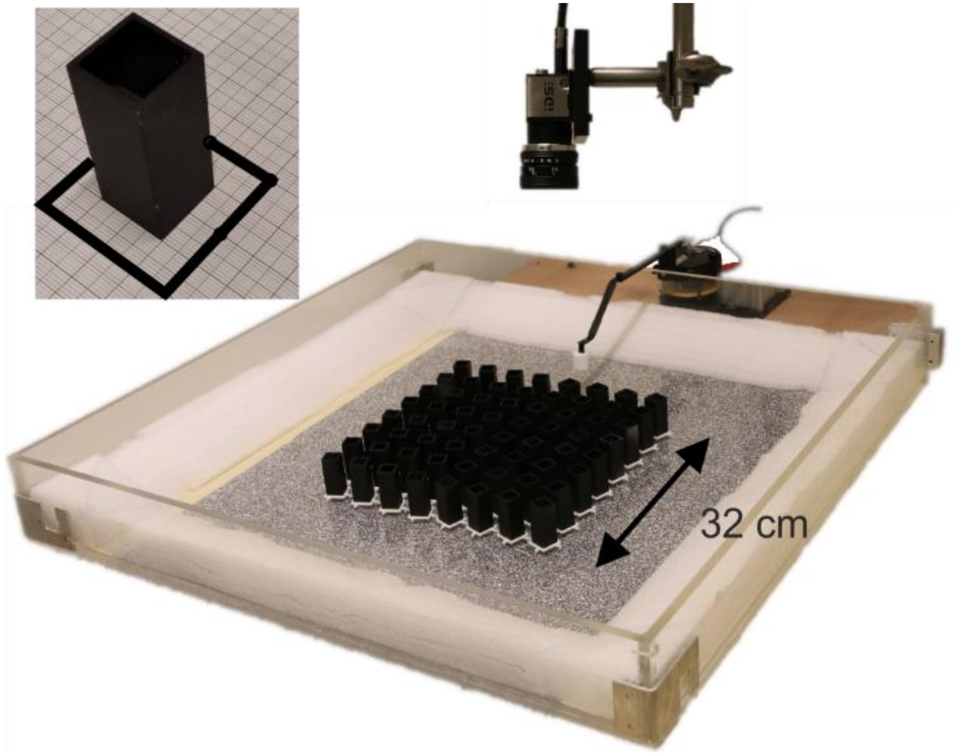
A pair of Dirac points is needed along each direction

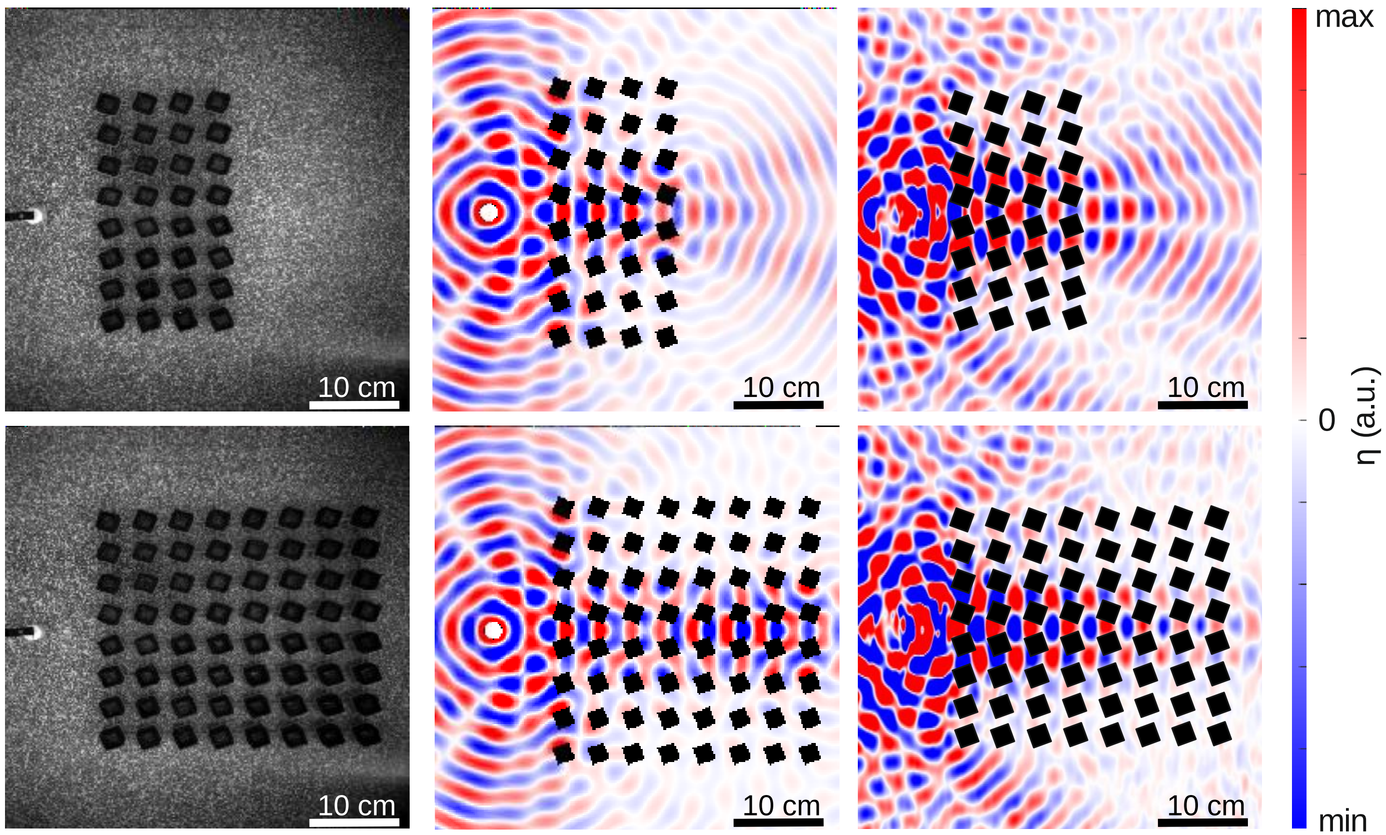
Makwana, M.P., Chaplain, G. Tunable three-way topological energy-splitter. *Sci Rep* **9,** 18939 (2019)

Domain walls with square-lattice crystal



Square-lattice topological crystal: water waves

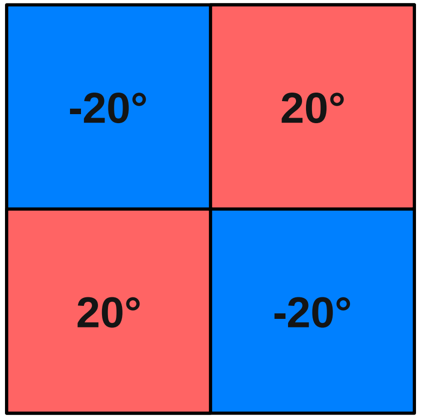


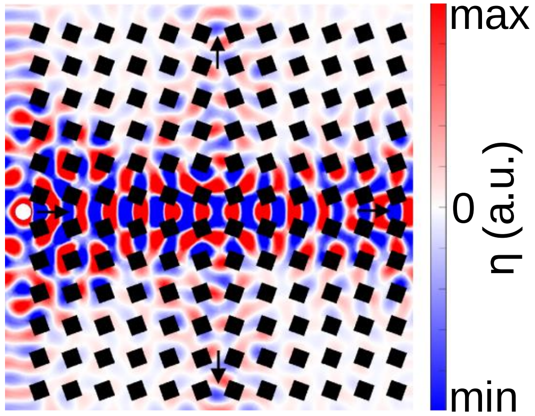


Makwana, Mehul P., et al. "Experimental observations of topologically guided water waves within non-hexagonal structures." Applied Physics Letters 116.13 (2020): 131603.

$f = 7.3\ Hz$

3-way splitter with water waves?





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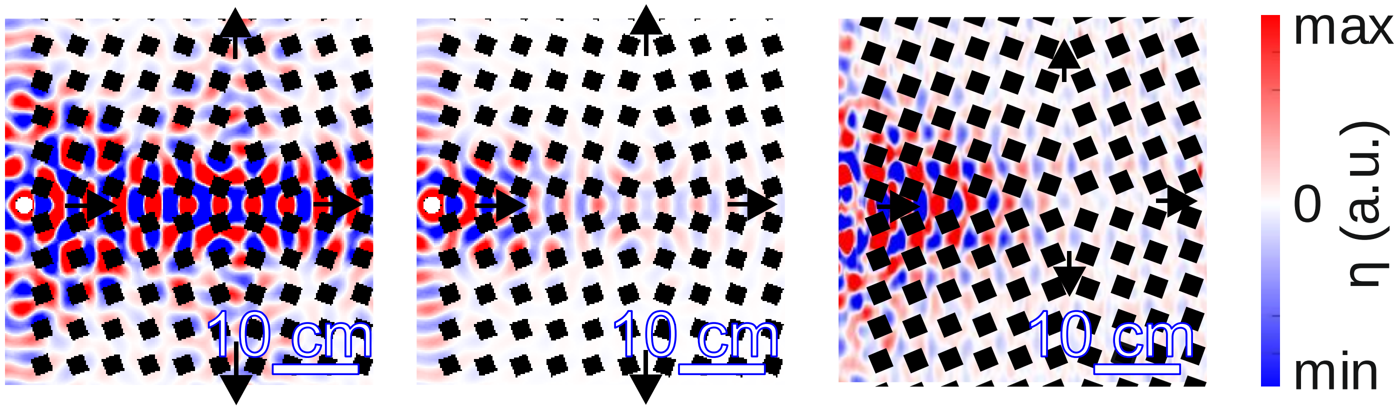
$f = 7.3\ Hz$

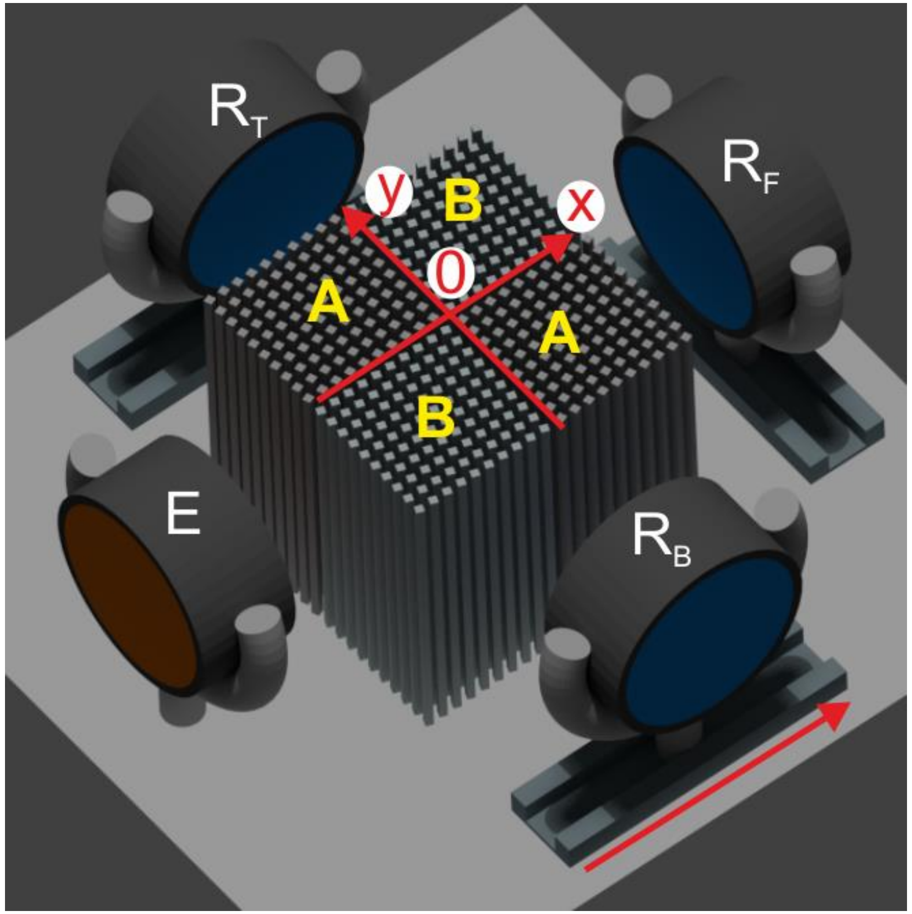
Simulation without dissipation

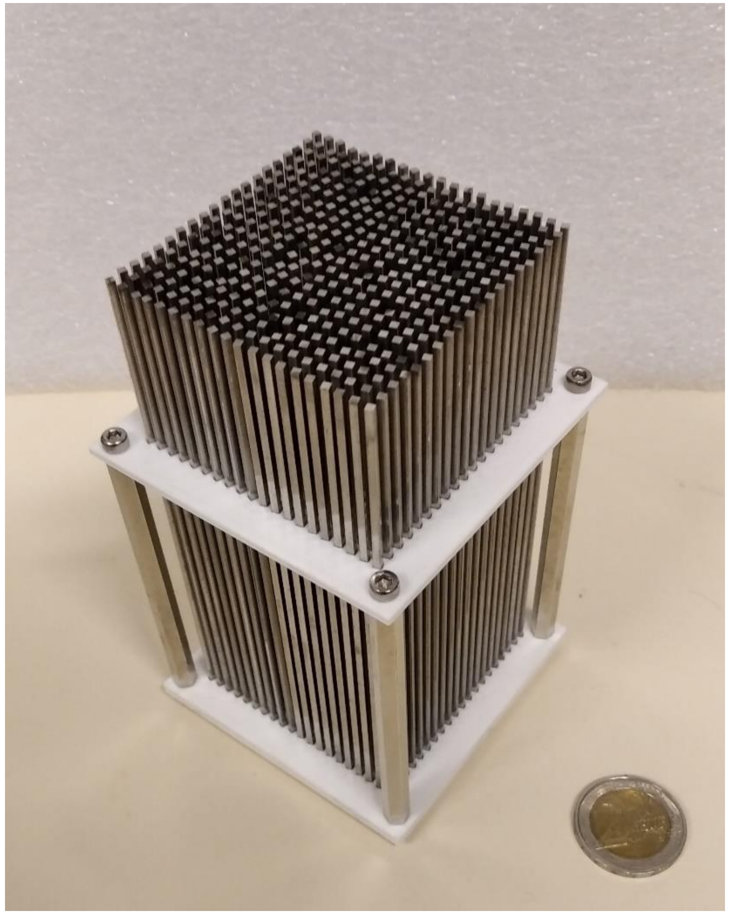
Simulation with dissipation

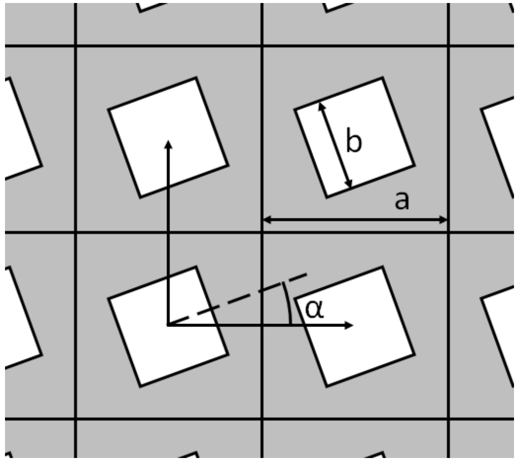
Experiment



Square lattice topological crystal: acoustic waves





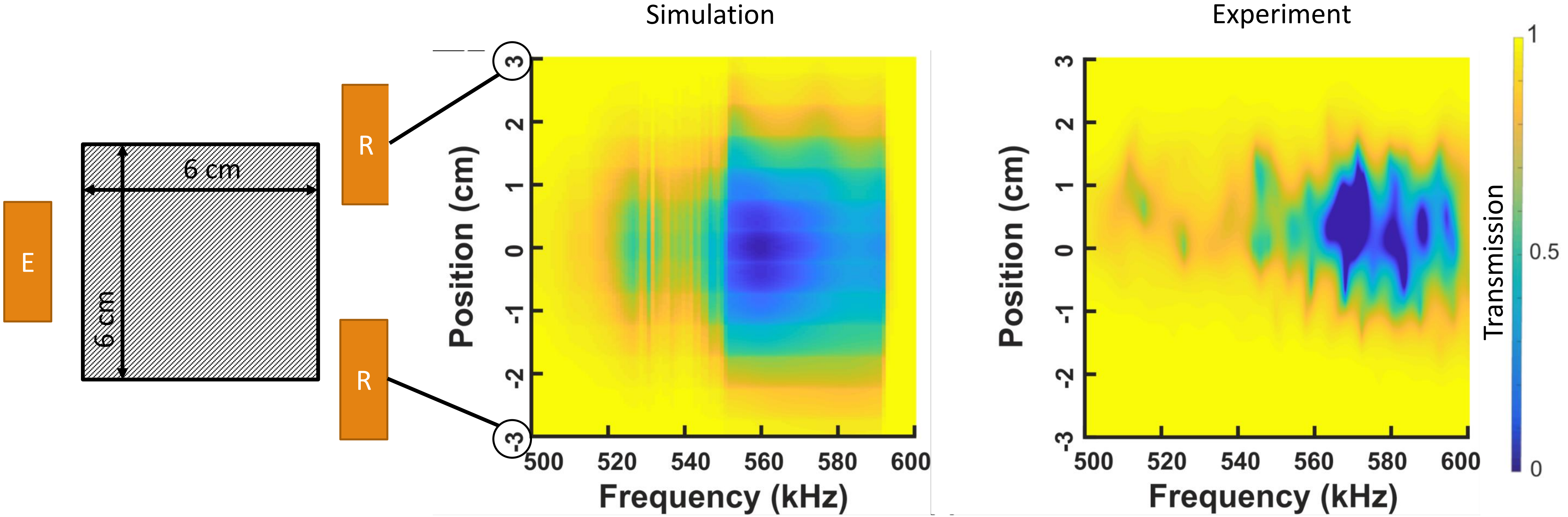


$a = 3$ mm, $b = 1.5$ mm

$f \sim 500$ kHz

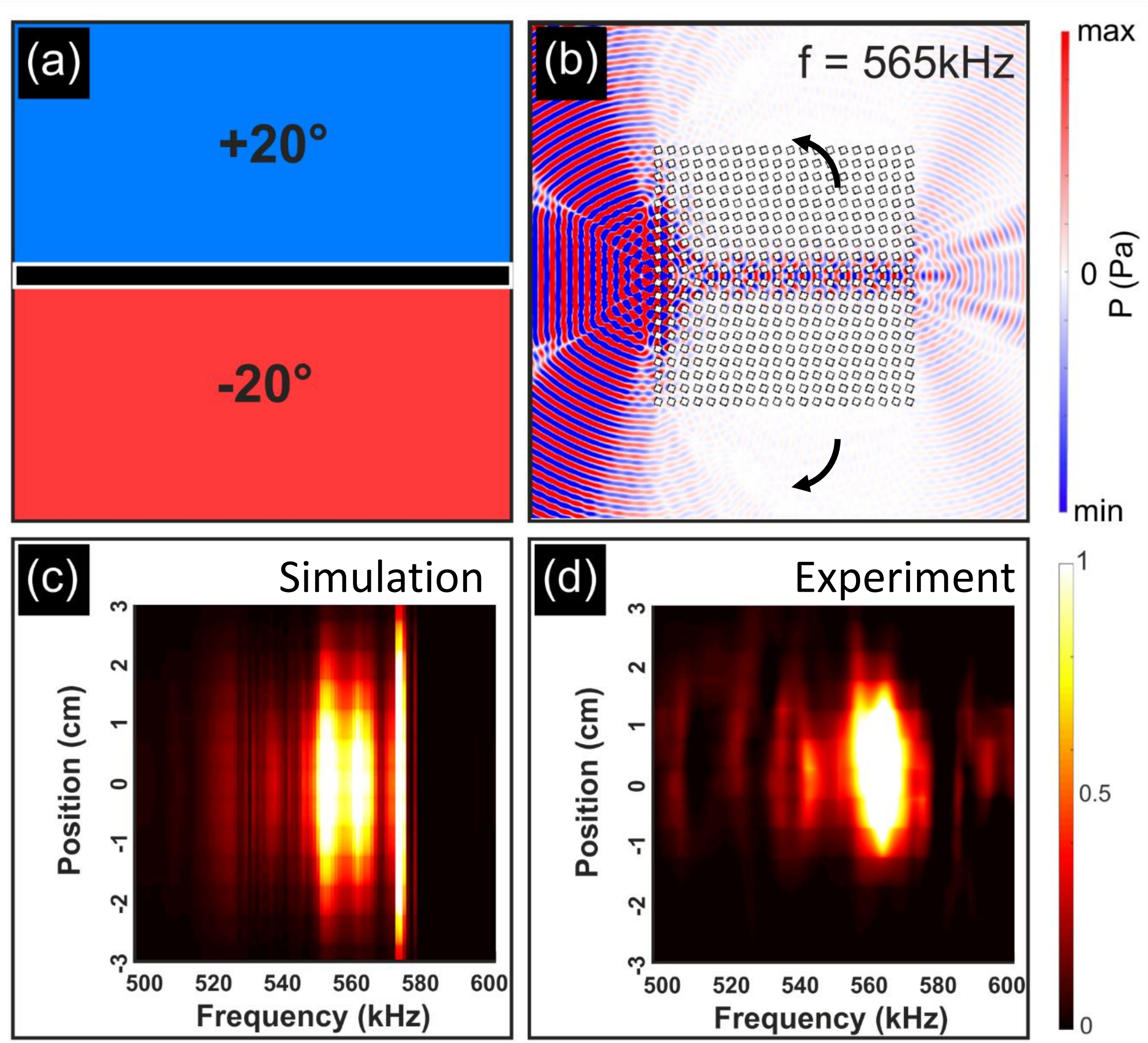
Laforge, Nicolas, et al. "Acoustic topological circuitry in square and rectangular phononic crystals." arXiv preprint arXiv:2012.08014 (2020).

Measuring the phononic band gap



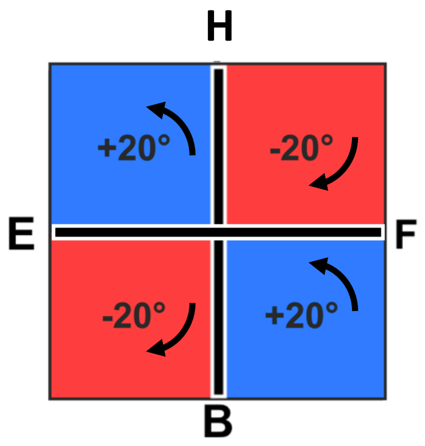
Laforge, Nicolas, et al. "Acoustic topological circuitry in square and rectangular phononic crystals." arXiv preprint arXiv:2012.08014 (2020).

Measuring the domain wall waveguide



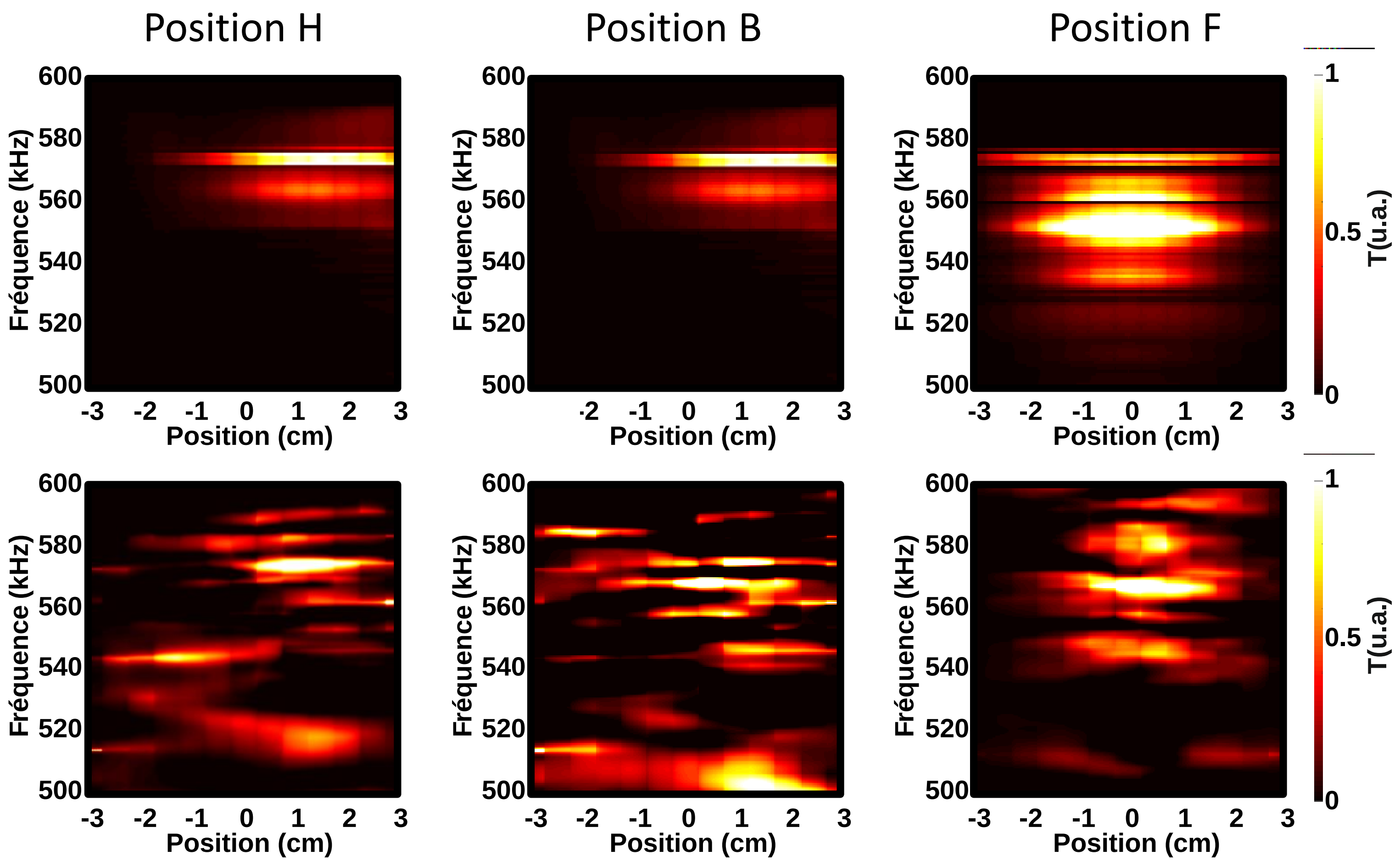
Laforge, Nicolas, et al. "Acoustic topological circuitry in square and rectangular phononic crystals." arXiv preprint arXiv:2012.08014 (2020).

3-way splitter, square-lattice



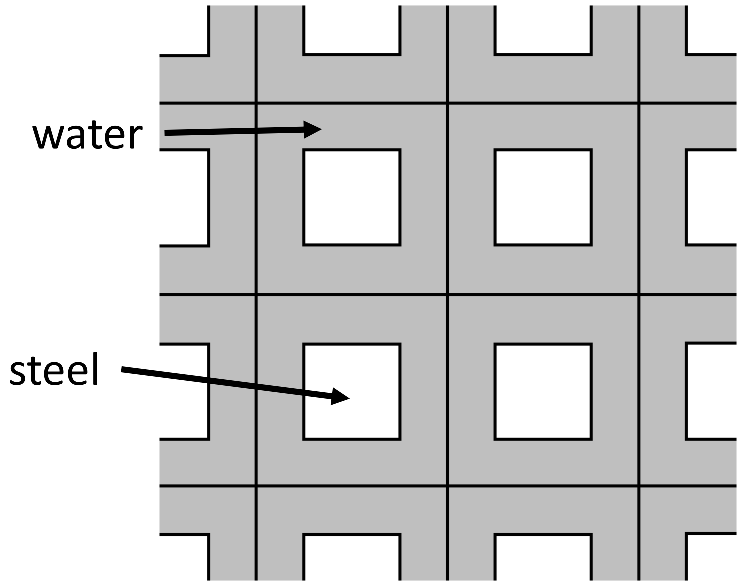
Simulations

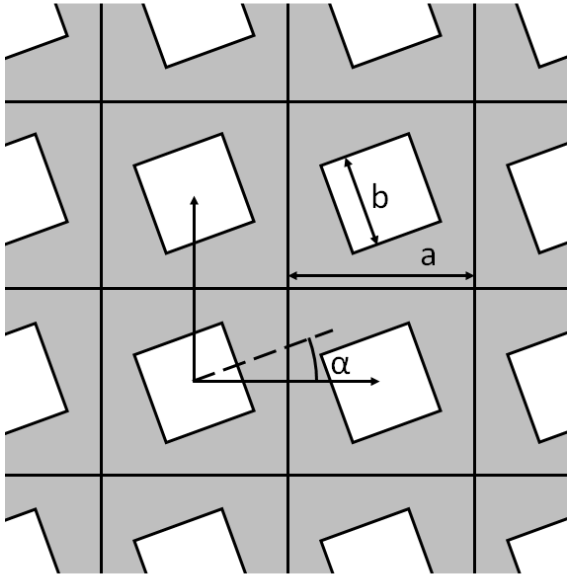
Experiment



Laforge, Nicolas, et al. "Acoustic topological circuitry in square and rectangular phononic crystals." arXiv preprint arXiv:2012.08014 (2020).

Coupling of acoustic and elastic waves





$$\nabla \cdot (\rho_1^{-1} \nabla p) = \frac{1}{\kappa} \frac{\partial^2 p}{\partial t^2}$$

$$\nabla \cdot [\mathbb{C} : \nabla \boldsymbol{u}] = \rho_2 \frac{\partial^2 \boldsymbol{u}}{\partial t^2}$$

<u>Acoustoelastic coupling:</u>

$$T = \mathbb{C} : \nabla \boldsymbol{u}$$

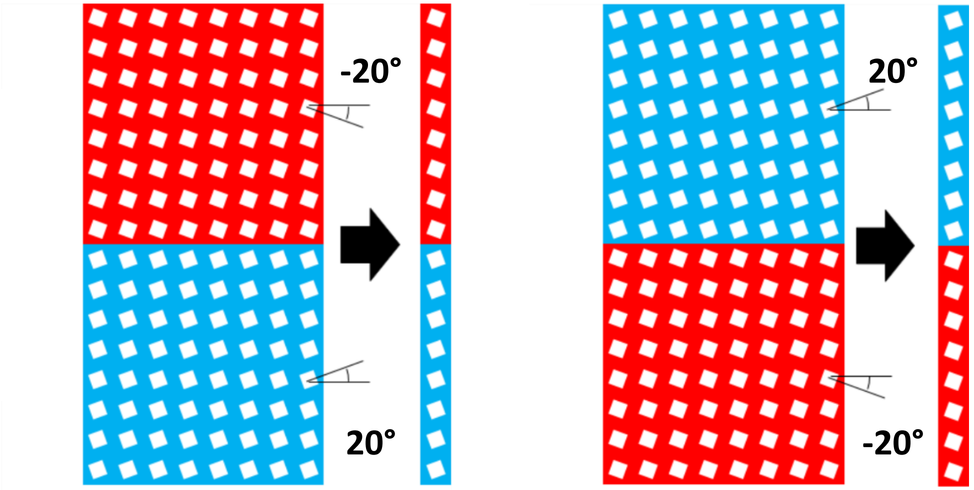
$$T_{ij} n_j = -p n_i$$

$$\boldsymbol{n} \cdot (\rho_1^{-1} \nabla p) = -\boldsymbol{n} \cdot \frac{\partial^2 \boldsymbol{u}}{\partial t^2}$$

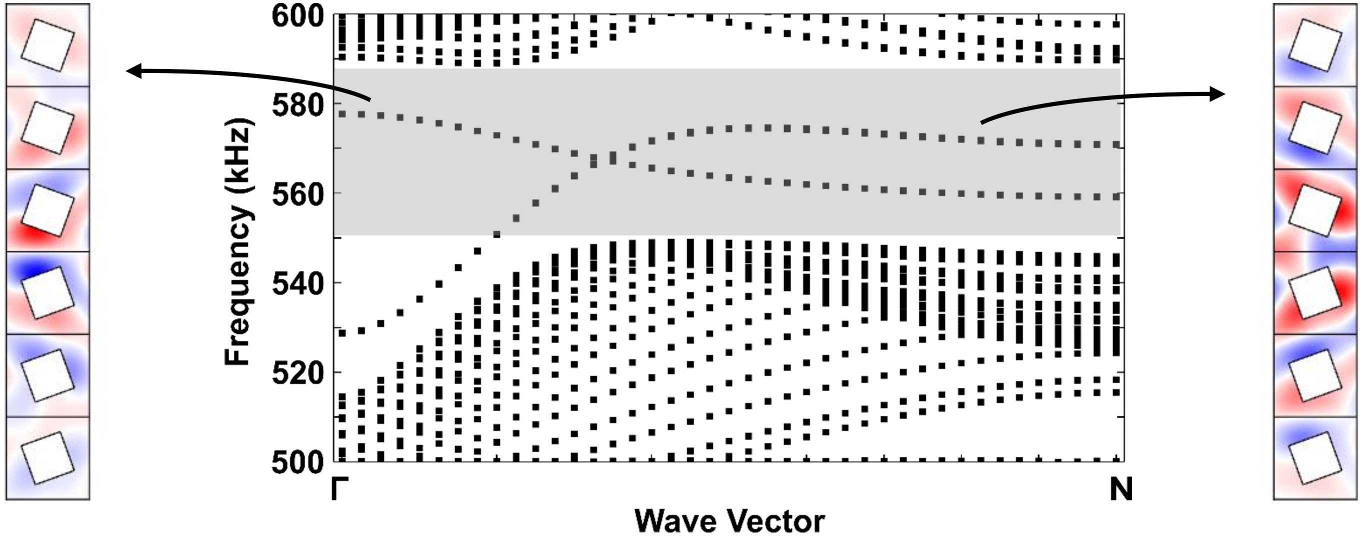
$$a = 3 \text{ mm}, b = 1.5 \text{ mm}$$

Dispersion of guided waves

Laforge, Nicolas, et al. "Acoustic topological circuitry in square and rectangular phononic crystals." arXiv preprint arXiv:2012.08014 (2020).

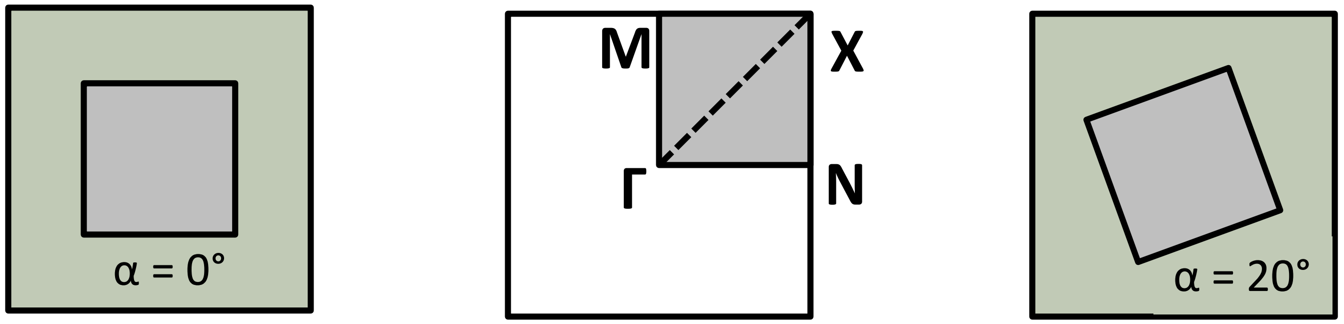


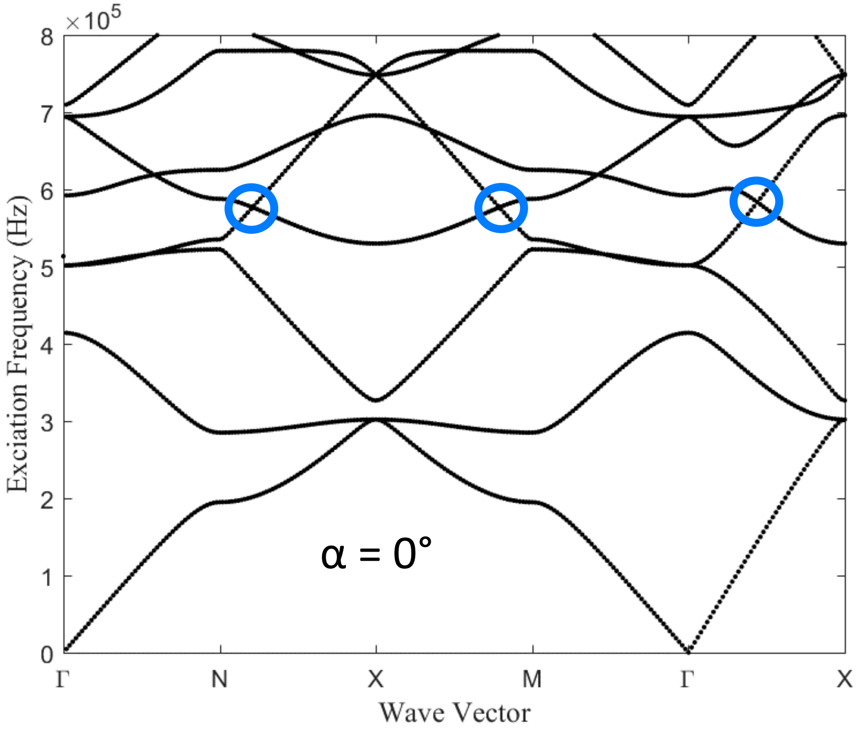
Antisymmetric mode

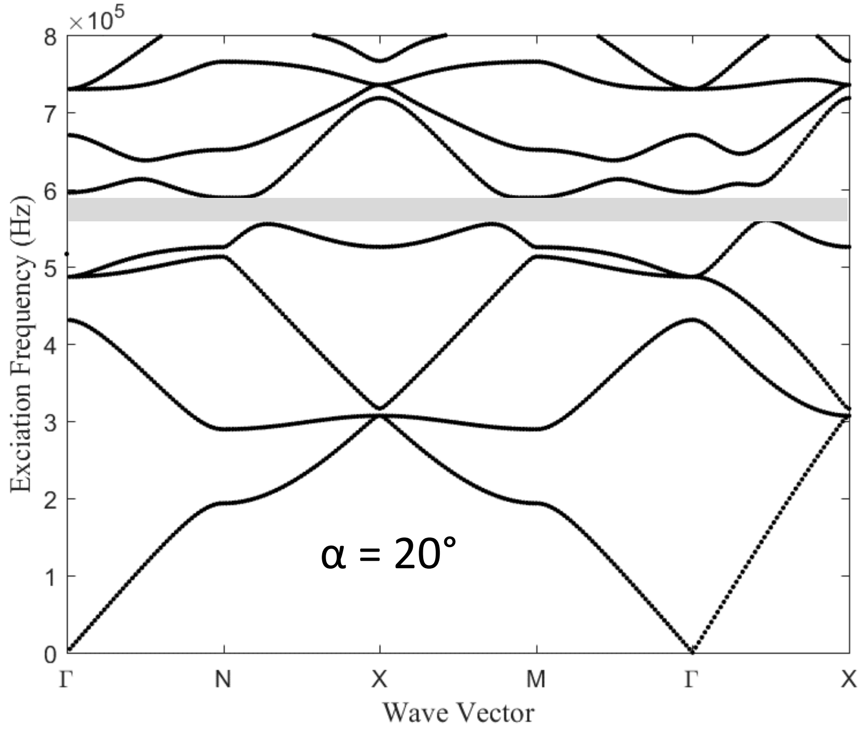


Symmetric mode

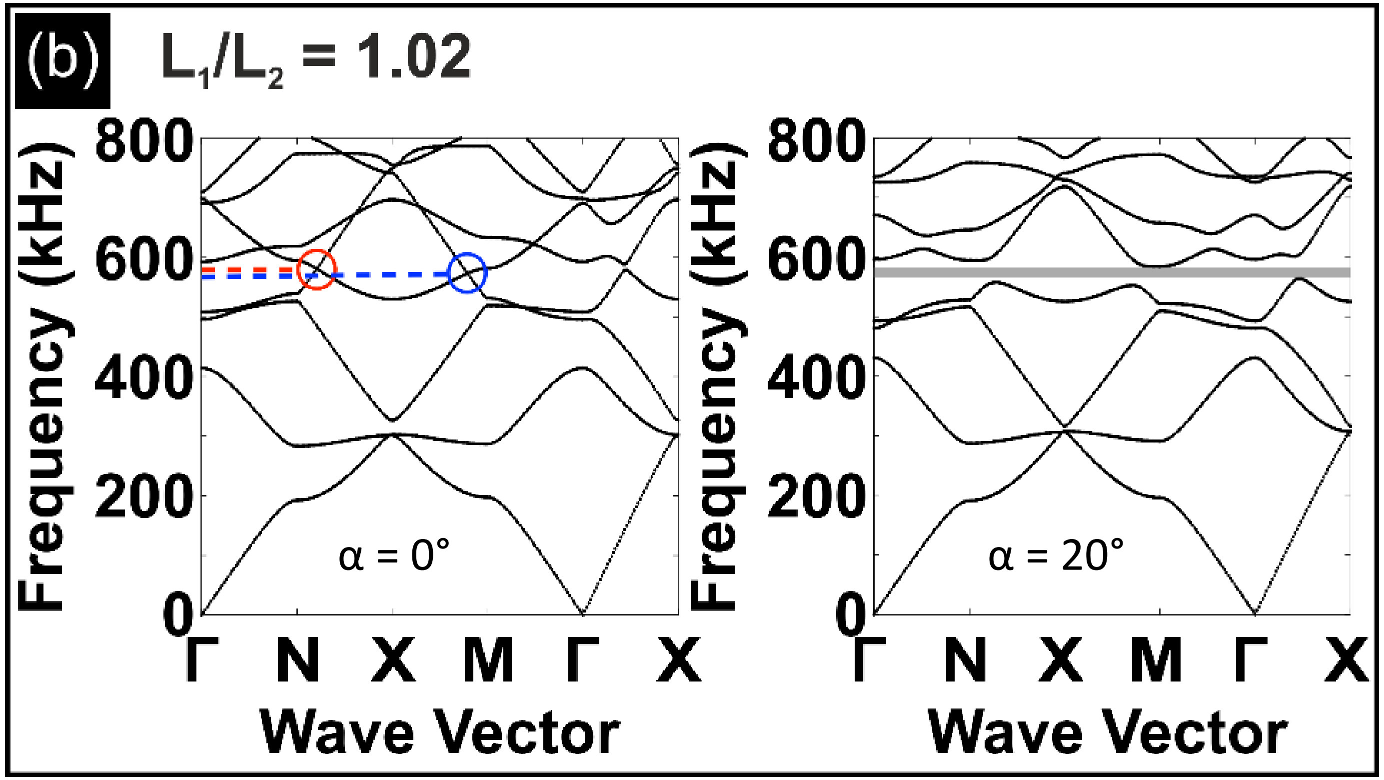
Trouble is… there's a third Dirac point!

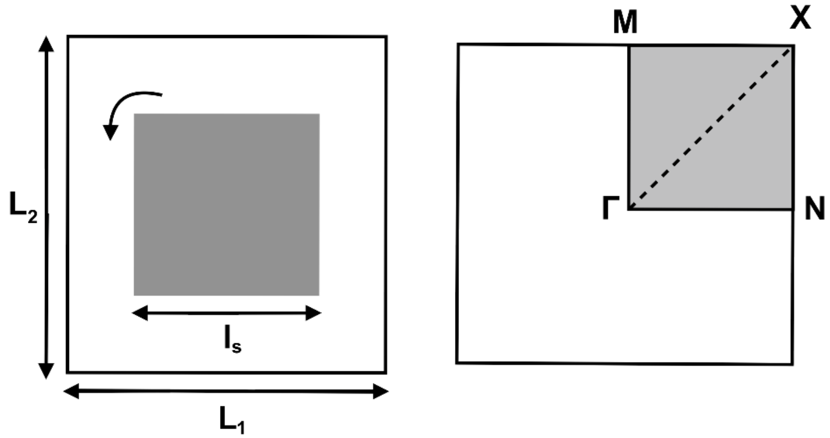






Breaking diagonal symmetry removes the third Dirac point





It also results in a slight frequency shift of the main Dirac points
And a slight reduction in band gap width

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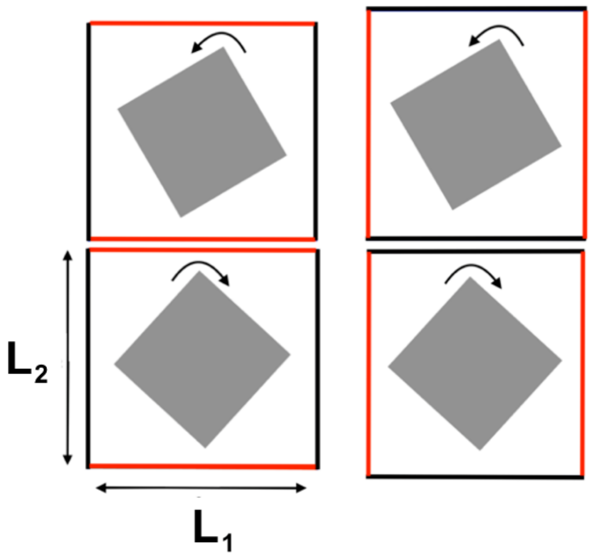
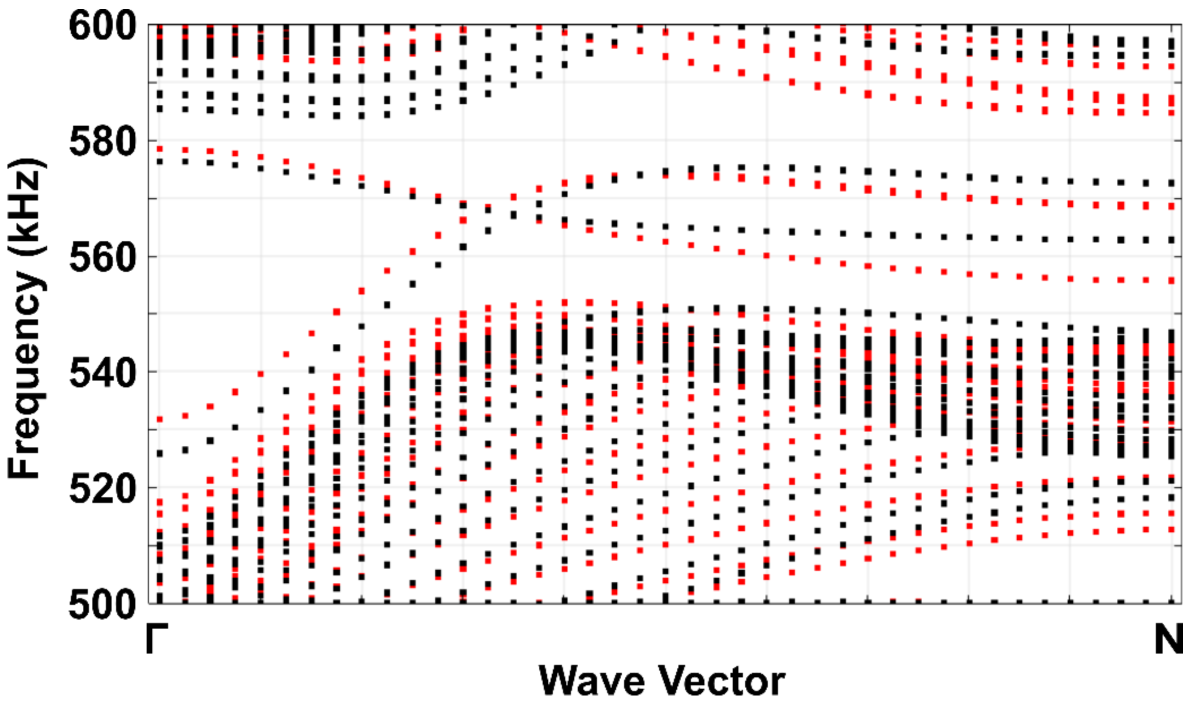
Dispersion of the guided waves shifts



L_1/L_2 = 1.02



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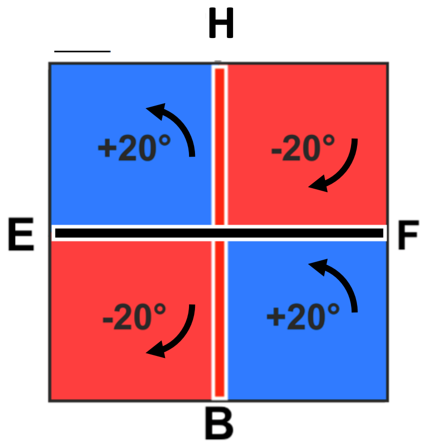
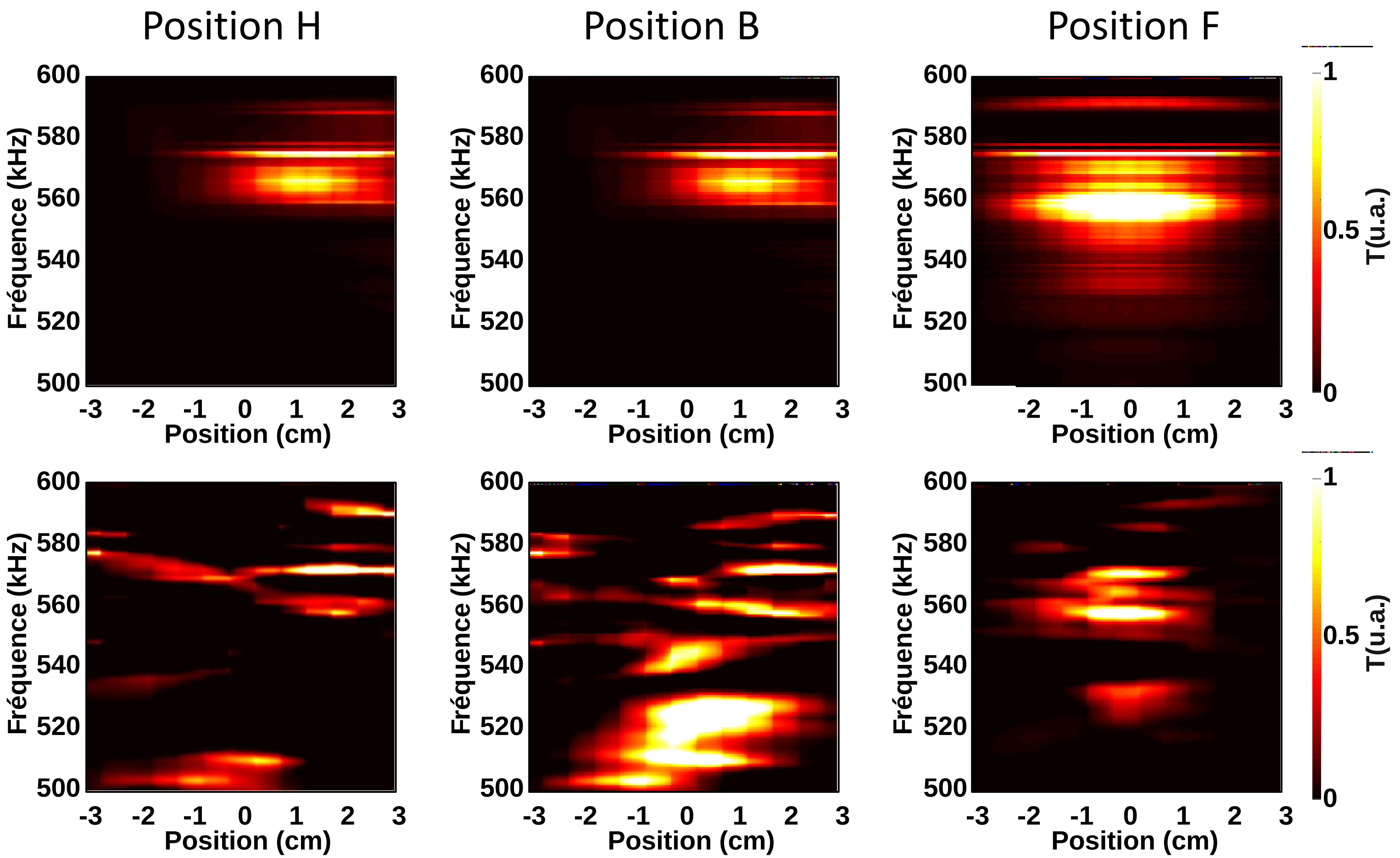
3-way splitter with the rectangular-lattice



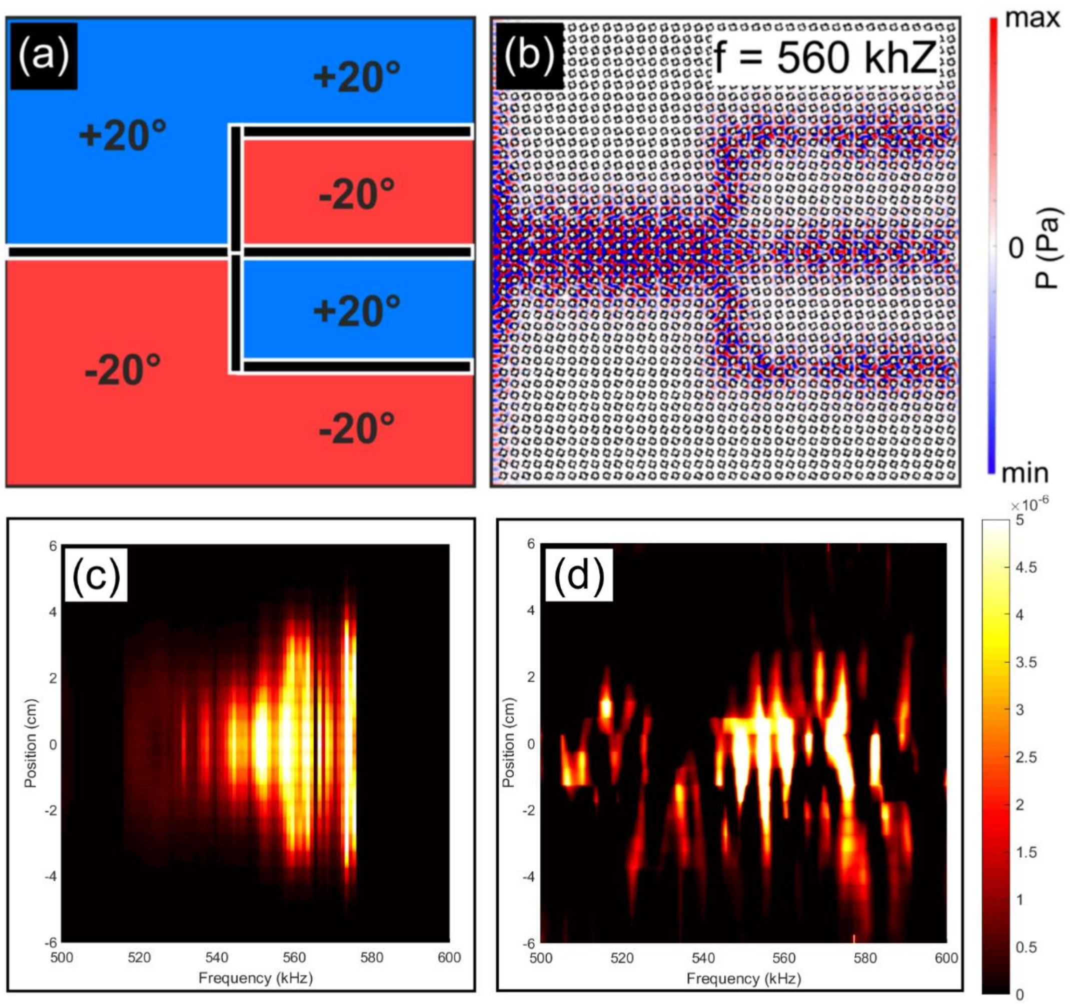
Simulation

Experiment



Laforge, Nicolas, et al. "Acoustic topological circuitry in square and rectangular phononic crystals." arXiv preprint arXiv:2012.08014 (2020).

And finally, a ‘trident’ circuit!



Simulation

Experiment

Laforge, Nicolas, et al. "Acoustic topological circuitry in square and rectangular phononic crystals." arXiv preprint arXiv:2012.08014 (2020).

Summary and conclusion

- Dirac points exist not only in the hexagonal (graphene) lattice, but with other symmetries, including the square and the rectangular lattices
- We have implemented topological phononic crystal circuits both with water waves and ultrasonic acoustic waves
- The rotated square inclusion in square-lattice crystal has ‘spurious’ Dirac points that can be removed considering the rectangular lattice
- Square and rectangular lattices are compatible with 3-way splitters and more general phononic circuits