Empa

Materials Science and Technology

Experimental observation of topologically protected helical edge modes in patterned elastic plates

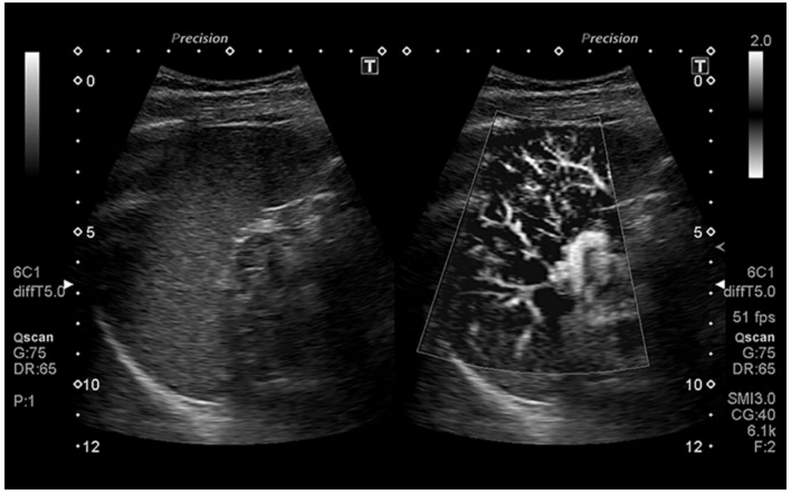
Marco Miniaci, Andrea Bergamini

MARIE CURIE ACTIONS

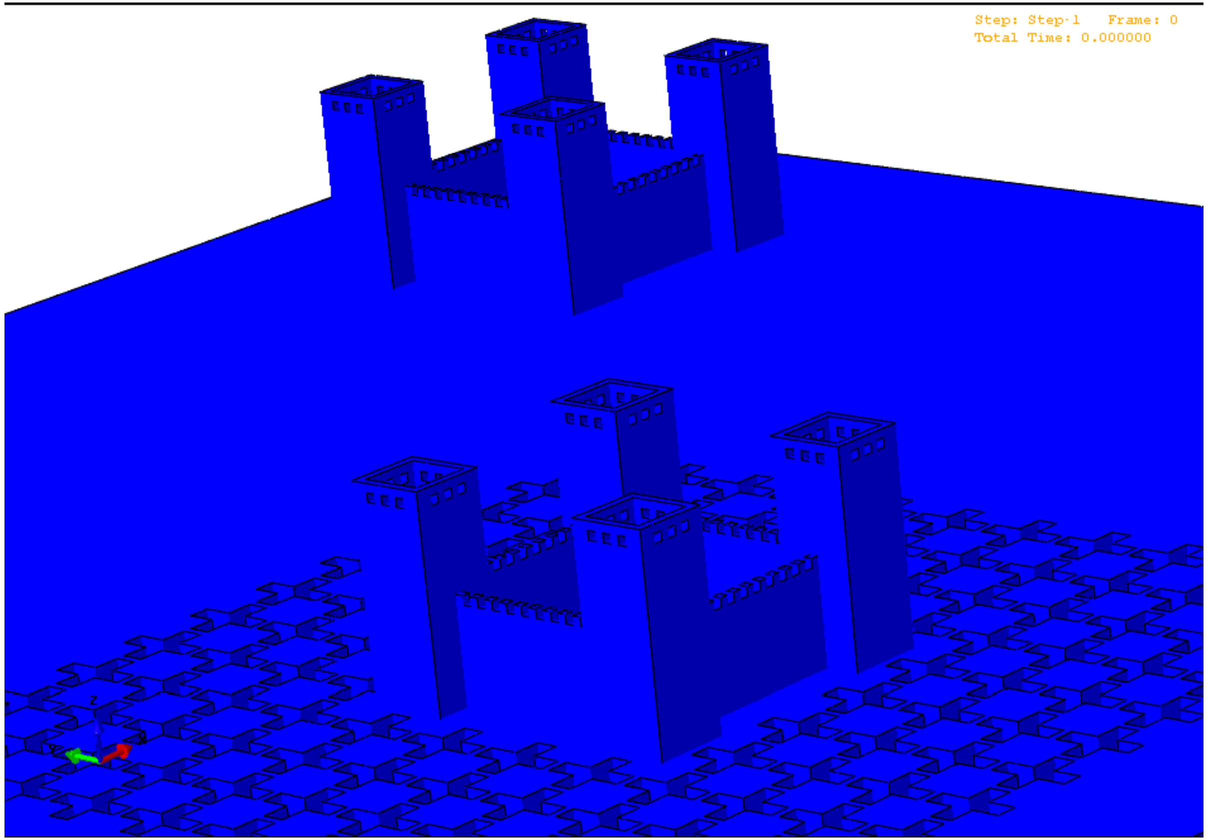
M. M. acknowledges the EMPAPOSTDOCS-II programme which has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement number 754364.

Motivations – Why controlling elastic wave propagation is important?

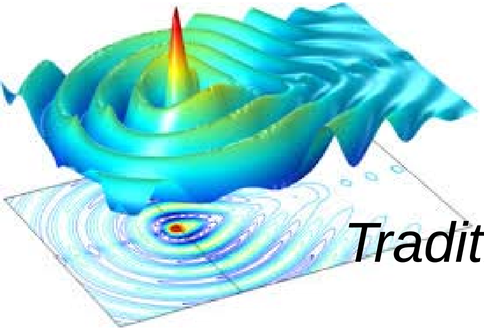
Acoustic and Noise Control Engineering



Medical applications



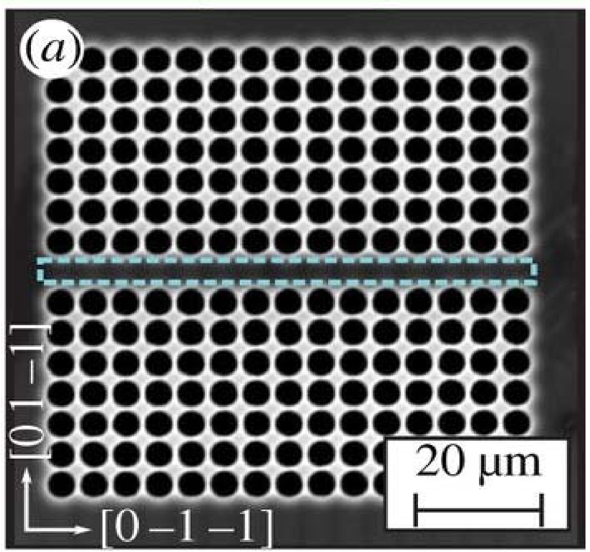
Seismic waves
Miniaci et al., NJP 18 (8), 083041, 2016



Transport energy from A → B

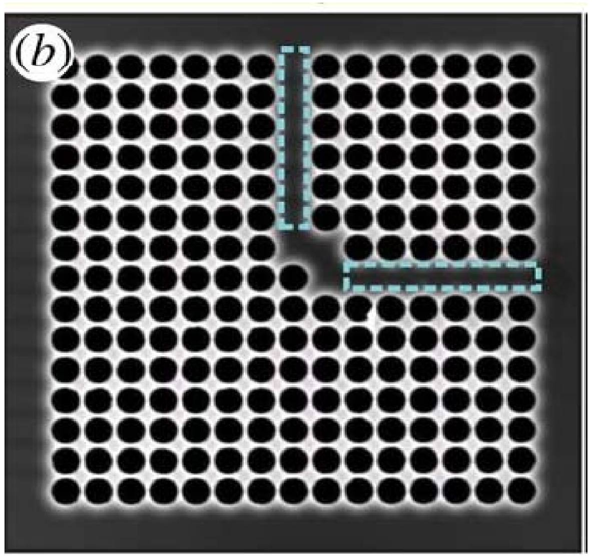
Traditional waveguides: **defects** **=** **losses** and **backscattering**

A



B

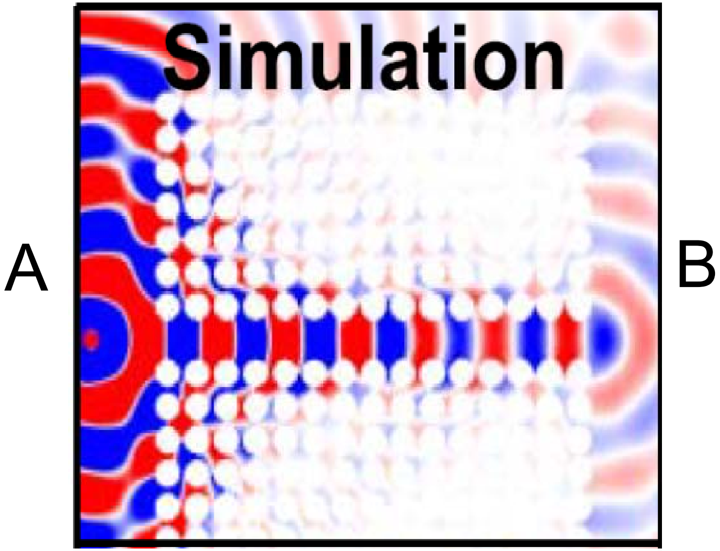
A

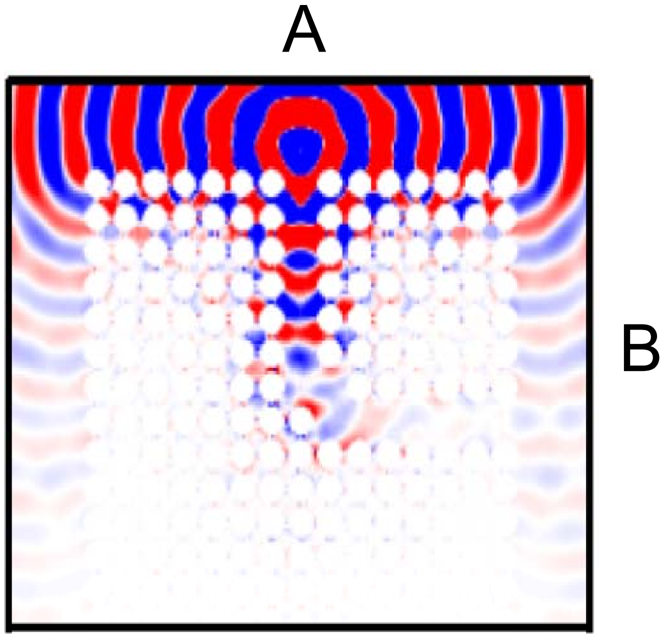


B

Otsuka et al., *Sci. Rep.*, 2013

Quest for **defect immune** and **scattering free** wave propagation

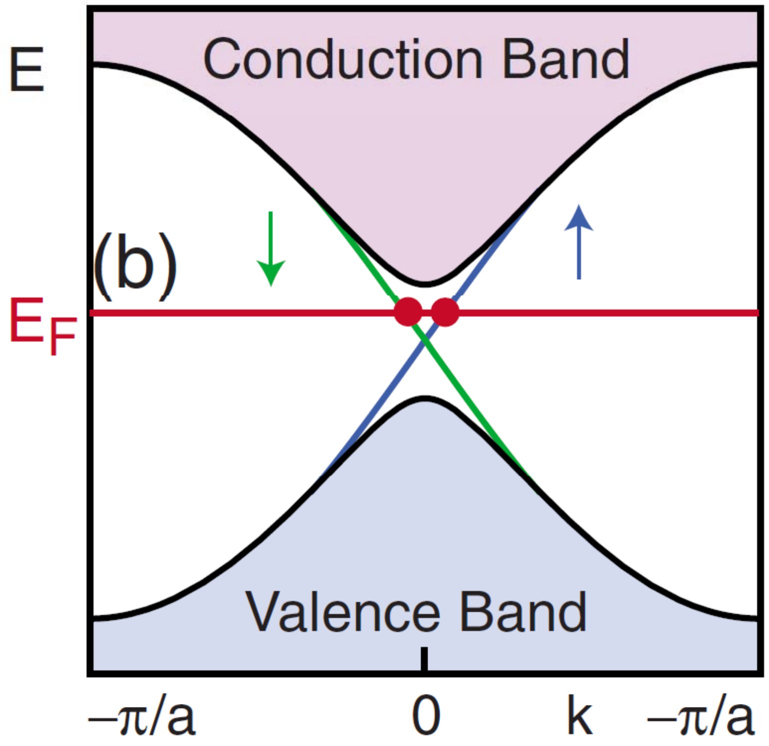




Otsuka et al., *Sci. Rep.*, 2013

Quantum Mechanics

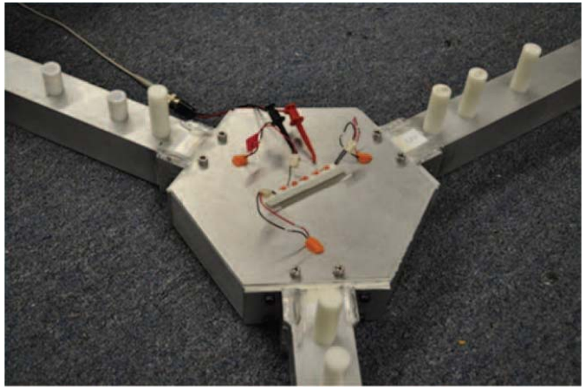
Topological insulator:
1. insulating in bulk, conducting at edges
2. scattering free, defect immune



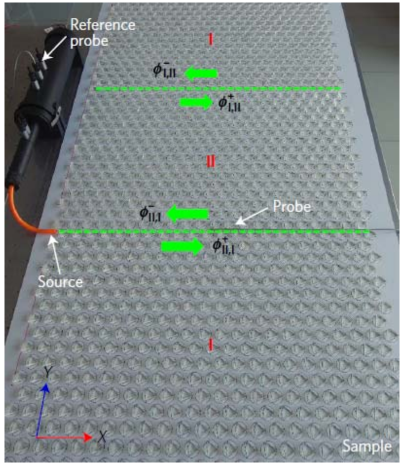
Kane and Hasan, Rev Mod Phys, 82, 2010

Topological insulation

Acoustics

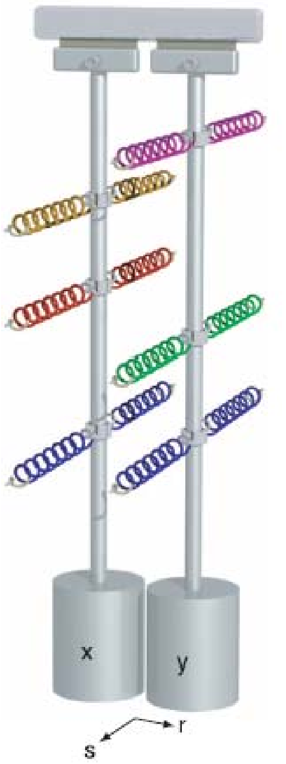


Fleury et al., Sceince 2013



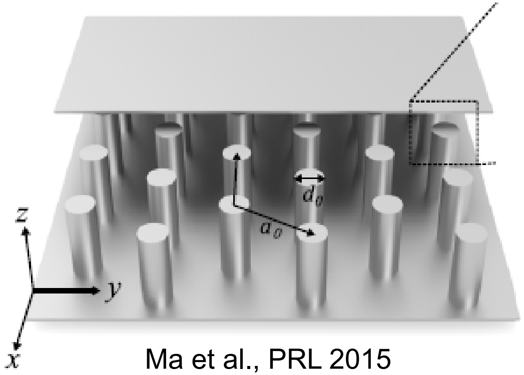
Lu et al., Nat. Phys. 2017

Elasticity



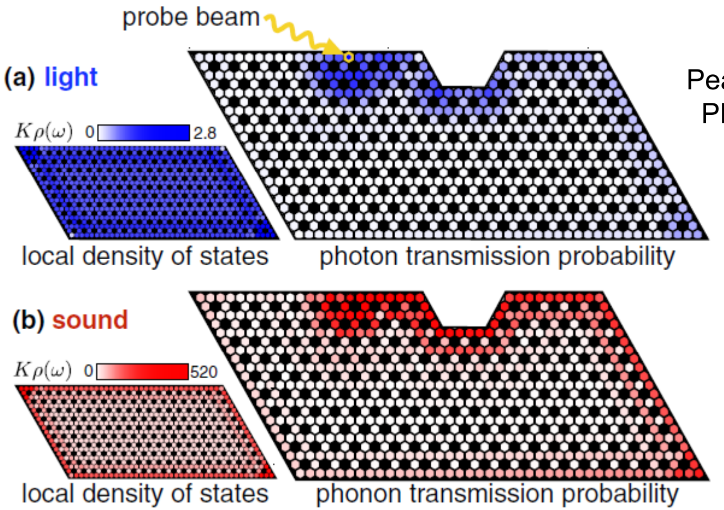
Susstrunk & Huber, Science 2015

Electromagnetisms



Ma et al., PRL 2015
Khanikaev et al., Nat. Mat. 2013

Opto-mechanics



Peano et al., PRX 2015

Topological insulation

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Approaches in elastic media

- Active systems capable of breaking the time reversal symmetry (→ Quantum Hall effect)

Susstrunk & Huber, PNAS 2016

QHE

Prodan^2, PRL 2009

- Dynamic instability of microtubules

- Rotational components Khanikaev, Nat. Comm. 2015 Wang et al., PRL 2015

- Active liquids Souslov et al., Nat. Phys. 2017

- Random media comprising spinning gyroscopes Mitchell et al., Nat. Phys. 2018

Topological insulation

Quantum Mechanics

Topological insulator:
1. insulating in bulk, conducting at edges
2. scattering free, defect immune

Approaches in elastic media

- Active systems capable of breaking the time reversal symmetry (→ Quantum Hall effect)

- Passive systems that break / preserve proper geometrical symmetries (→ Quantum Spin Hall effect)

Susstrunk & Huber, PNAS 2016

QHE

Prodan^2, PRL 2009

- Dynamic instability of microtubules

- Rotational components Khanikaev, Nat. Comm. 2015 Wang et al., PRL 2015

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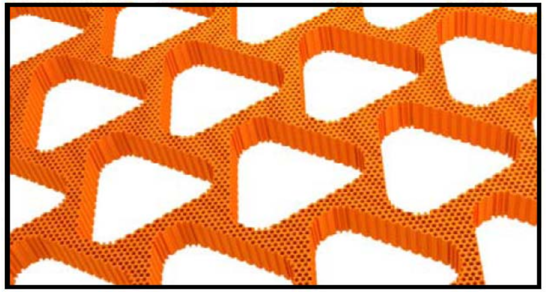
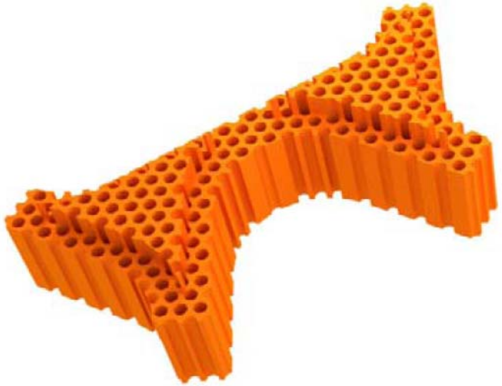
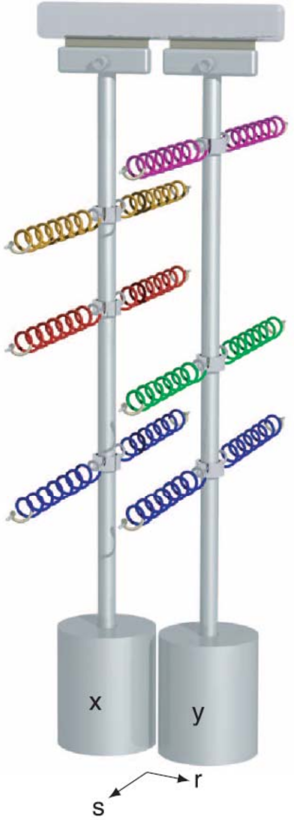
Deep sub-wavelength patterning in a dual-scale phononic slab





Khanikaev et al., Nat. Comm., 2015



Susstrunk and Huber, Science, 2015

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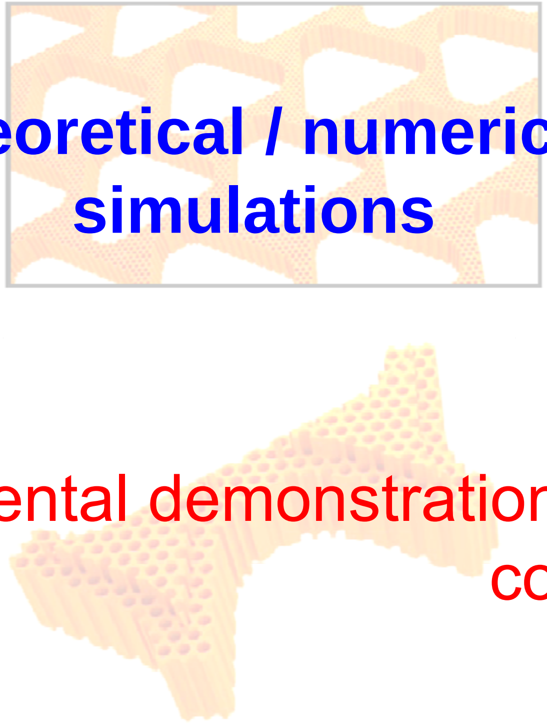


Theoretical / numerical simulations

Khanikaev et al., Nat. Comm., 2015

Discrete systems

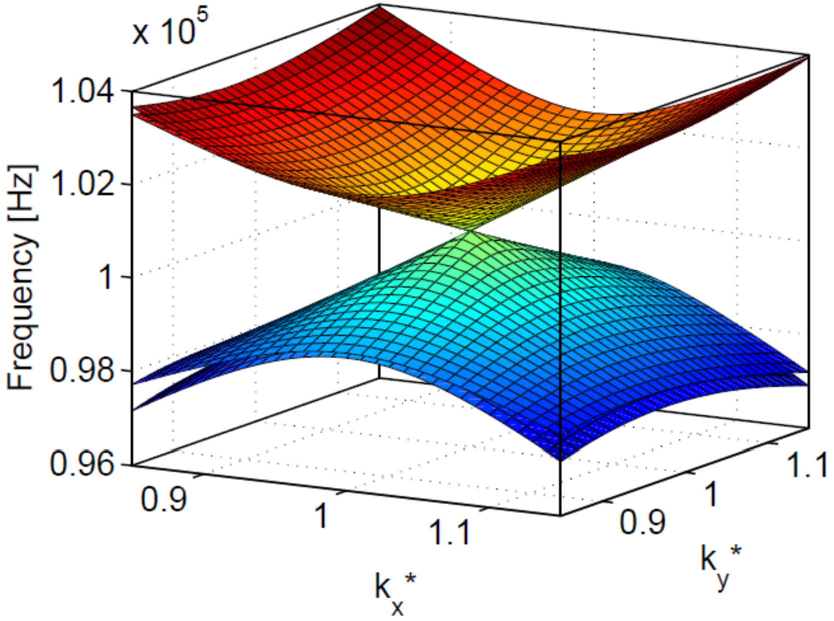
Susstrunk and Huber, Science, 2015

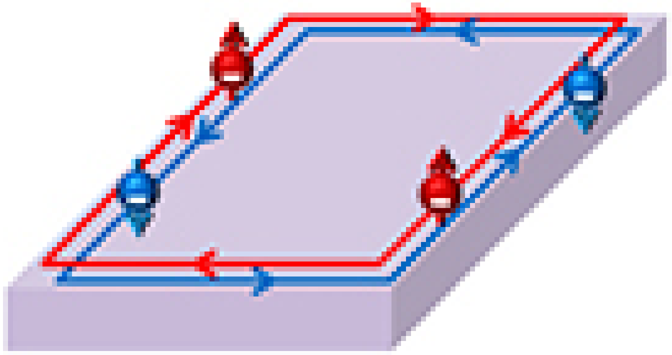
What is missing:

Experimental demonstration of topologically protected helical edge waves in continuous elastic media

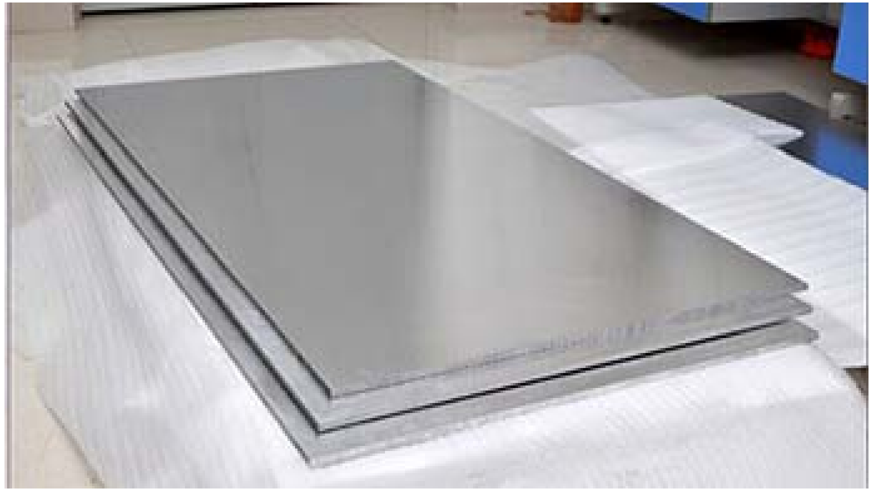
QSHE analogy:

- nucleation of a double Dirac cone
- coupling of two degenerate modes (emulating the two effective spins in the QSHE)





Elastic plates = excellent candidates



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

Aluminum plates (+)

a) ∞ number of mode shapes with distinct polarization

b) Coupled deformation mechanism

Aluminum plates (-)

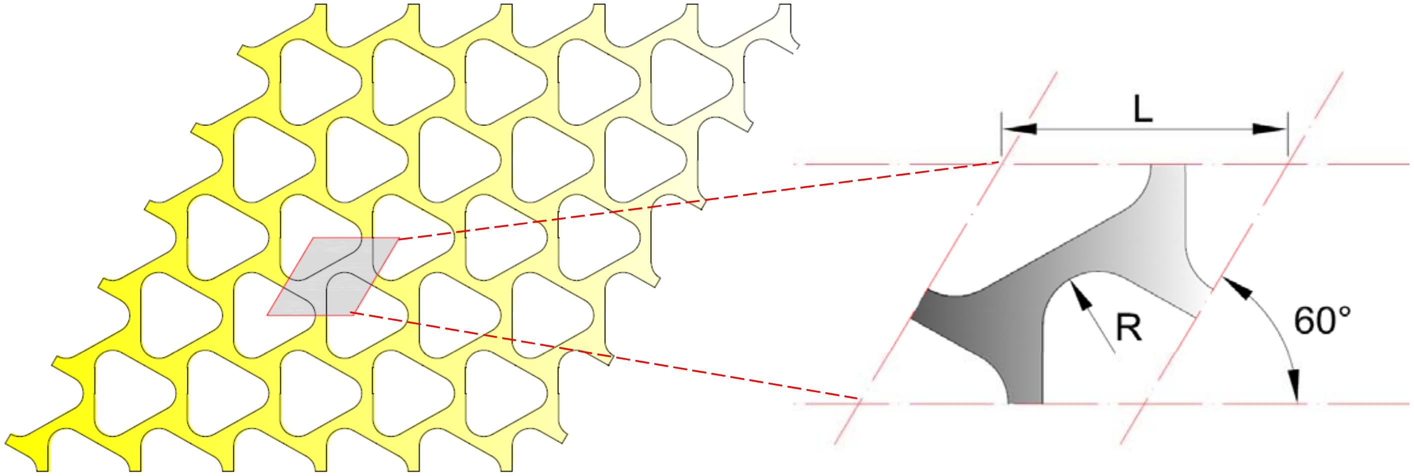
a) Crowding of the wave spectrum

b) Mode conversion at free boundaries and interfaces

Graff, *Wave motion in elastic solids*, 2012

Theory behind our approach - Engineering the dispersion bands

Step 1: Plate patterned according to a Kagome lattice (KL)



Geometrical parameters:

- L = 20.5 mm
- R = 10.7 mm
- ff = 31.9%

Nominal material properties:

- ρ = 2700 kg/m^3
- E = 70 GPa
- ν = 0.33

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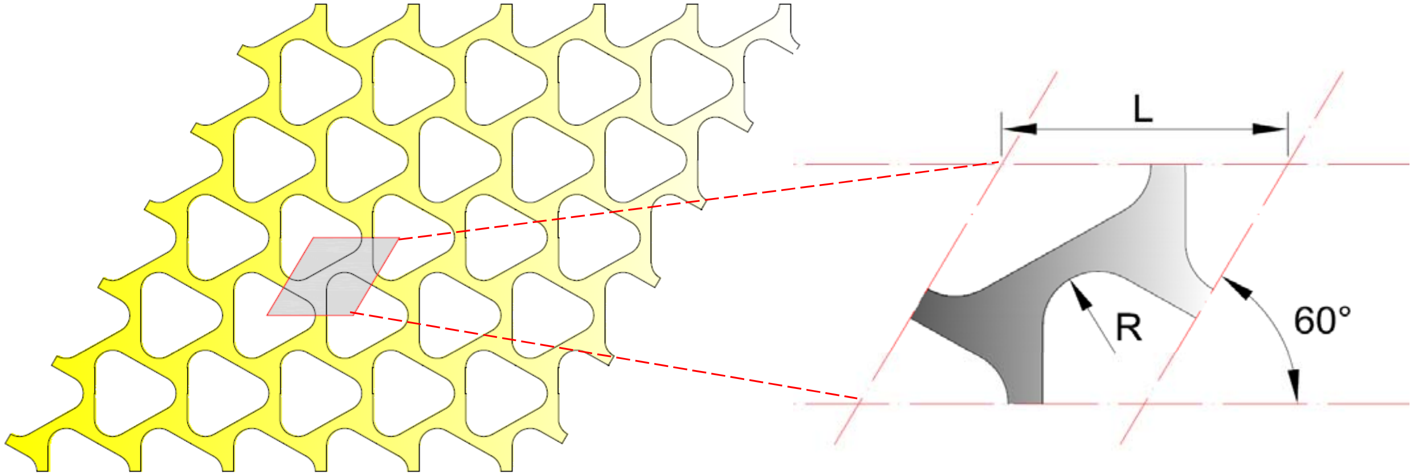

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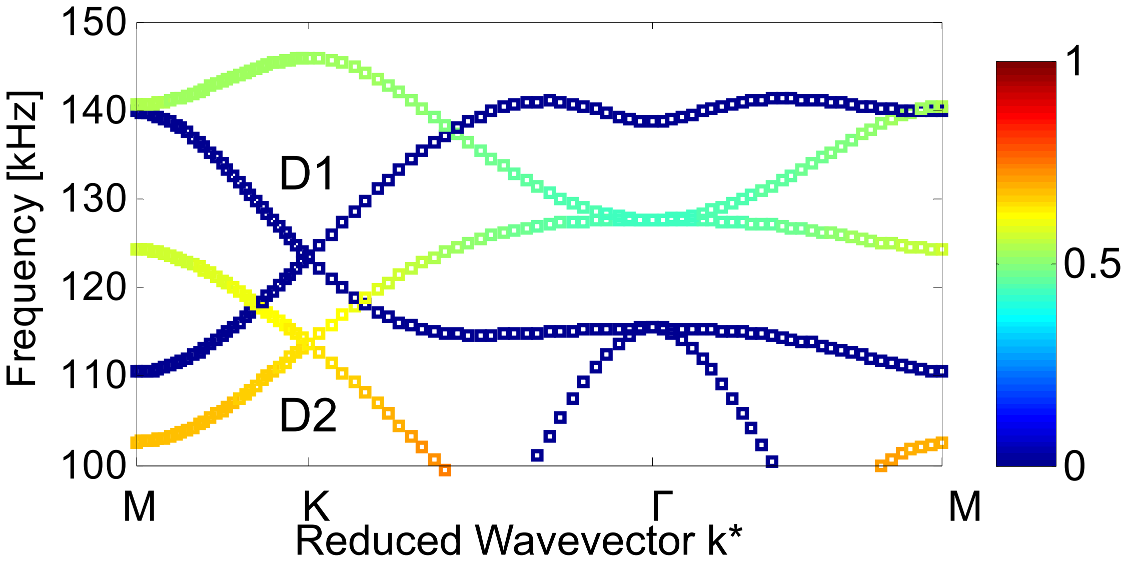
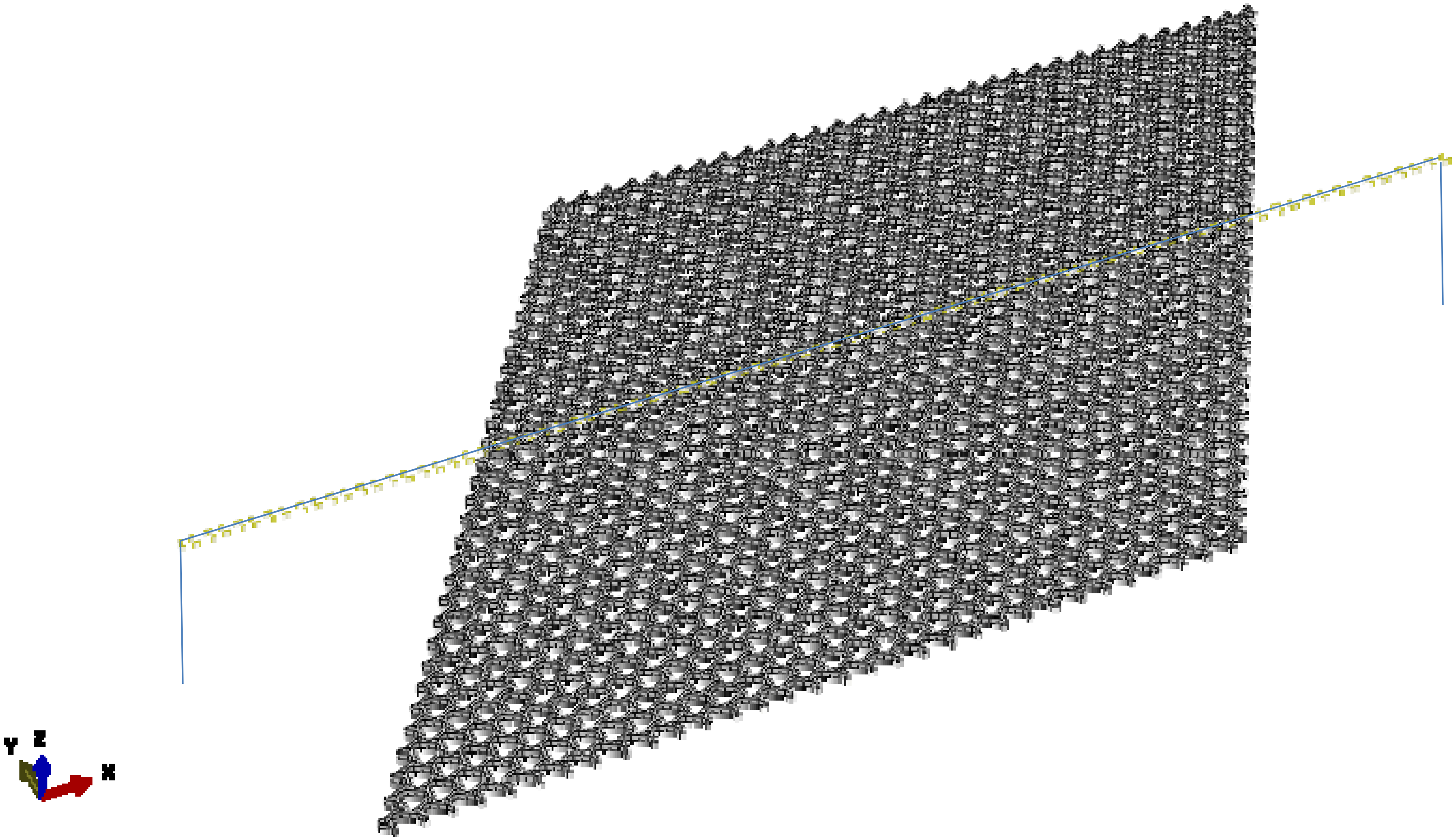
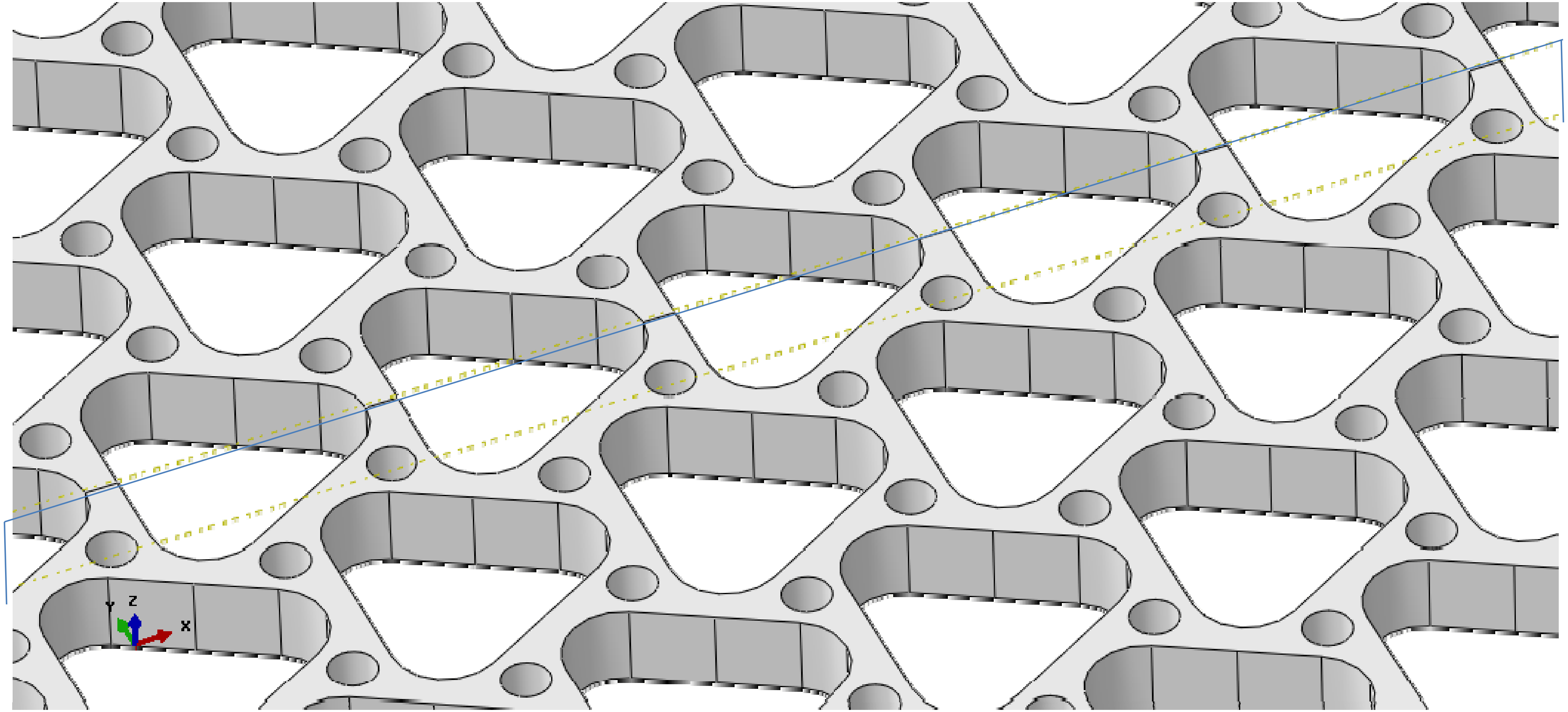


1) Dirac Points = Degeneracy of modes arising from the D3h (C3, σ_v, σ_h) symmetry

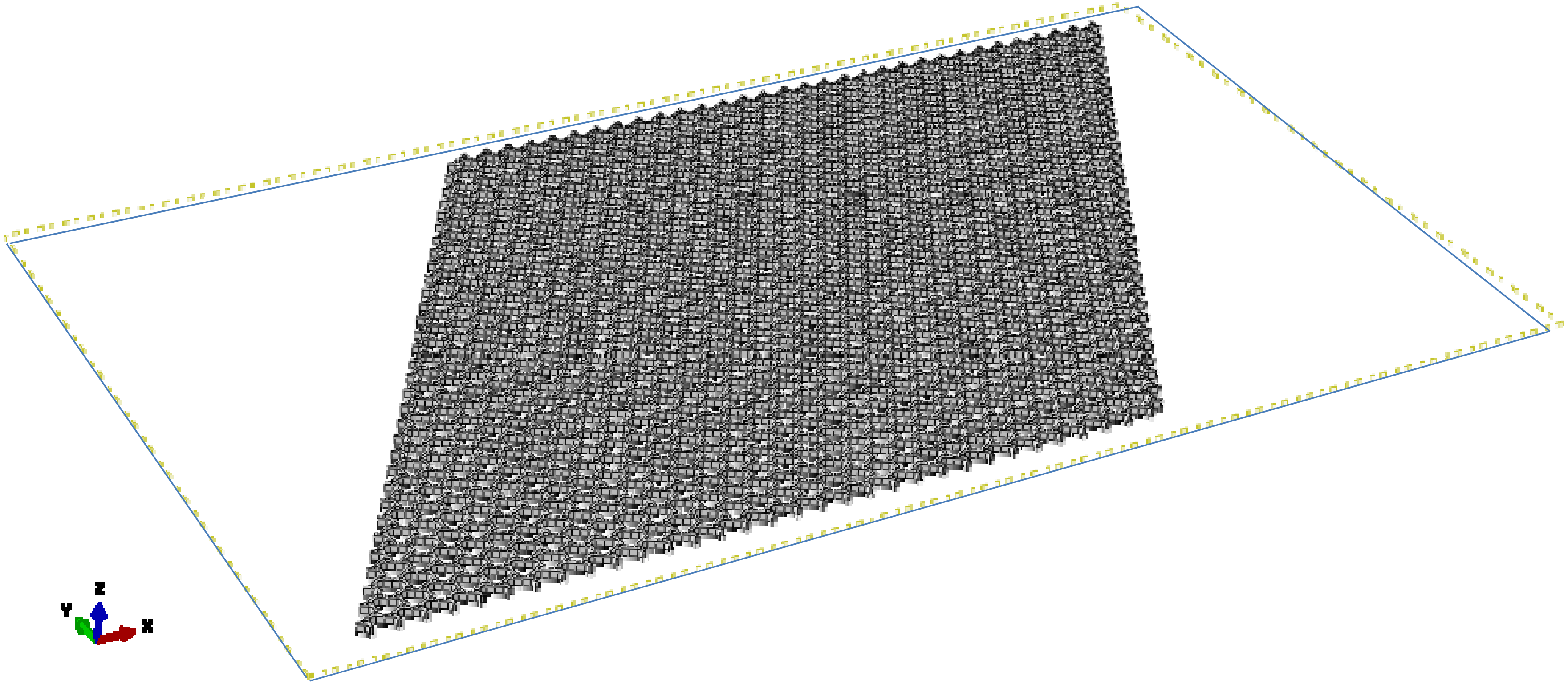
σ_v symmetry



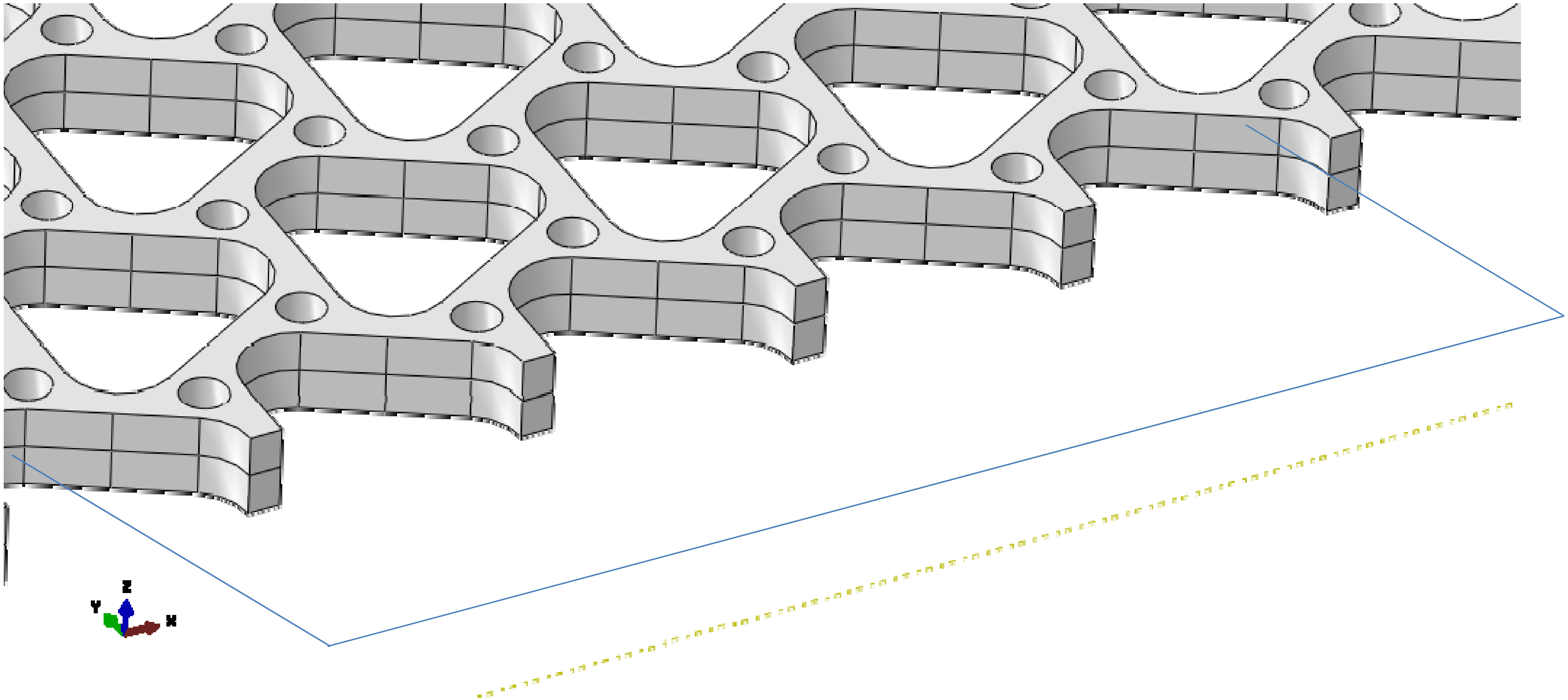
σ_v symmetry



σ_h symmetry

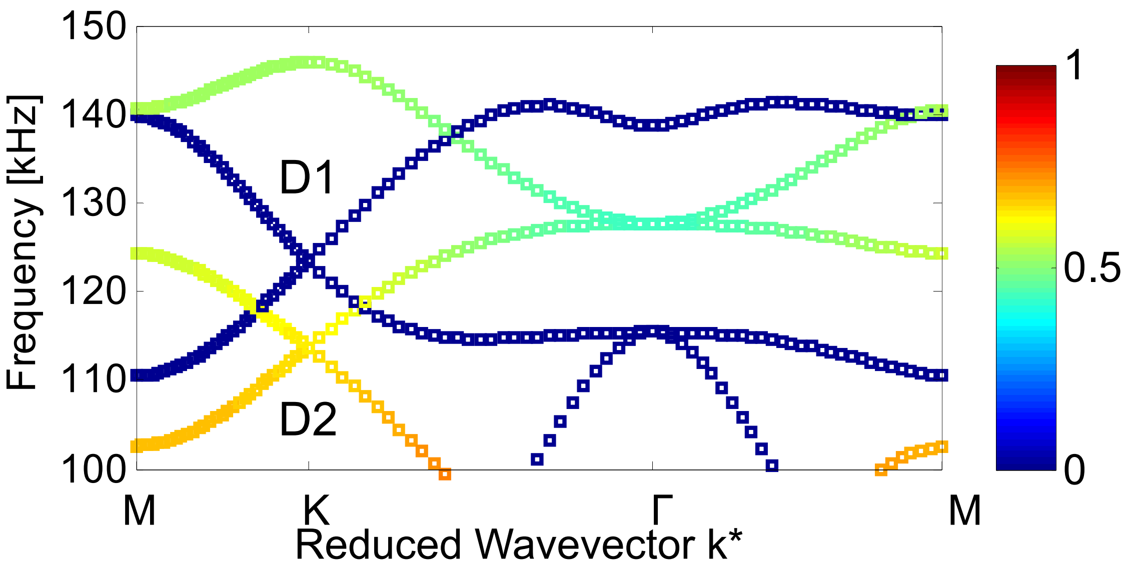


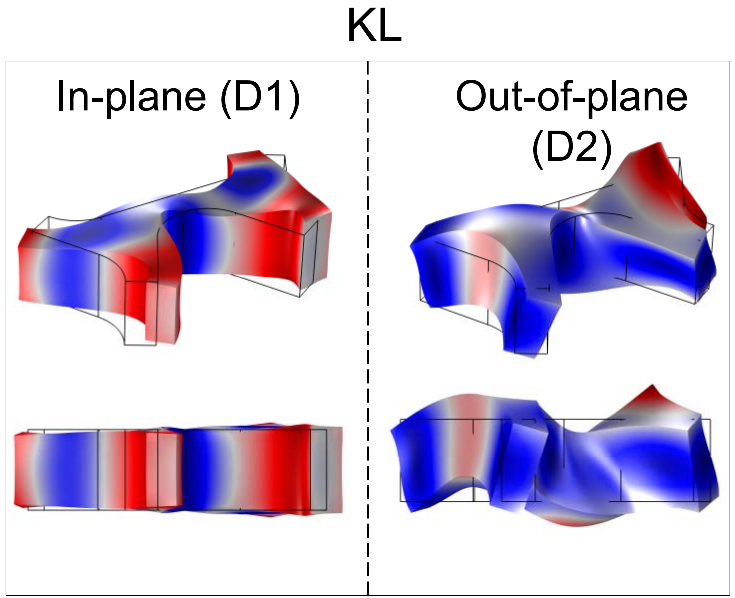
σ_h symmetry



The colors in the figure indicate the polarization *p* of each mode, calculated as:

$$p = \frac{\int_V (|u_z|)^2 dV}{\int_V (|u_x|^2 + |u_y|^2 + |u_z|^2) dV}$$





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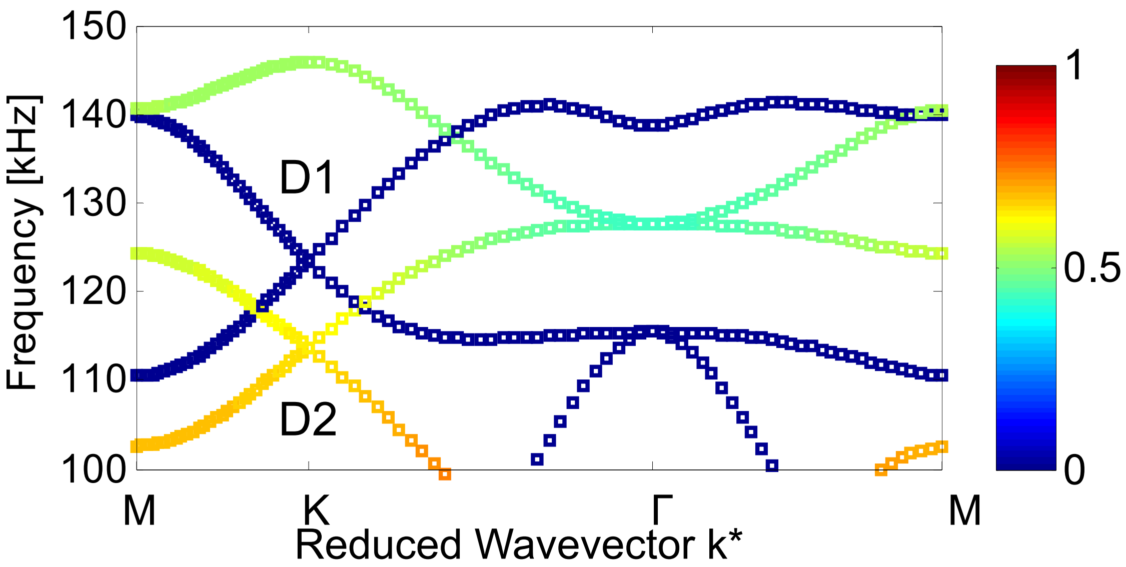
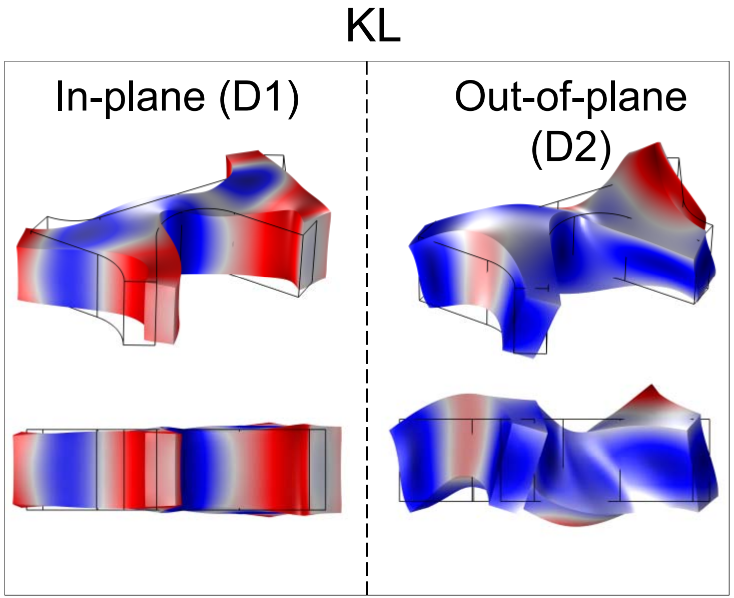


1) Dirac Points = Degeneracy of modes arising from the D3h (C3, σ_v, σ_h) symmetry;

2) Modes = Span subspaces associated to E' and E'' irreducible representations of the reciprocal lattice group at the K point.



Rationale

1) Merge the two Dirac cones (preserving D_{3h} symmetry)

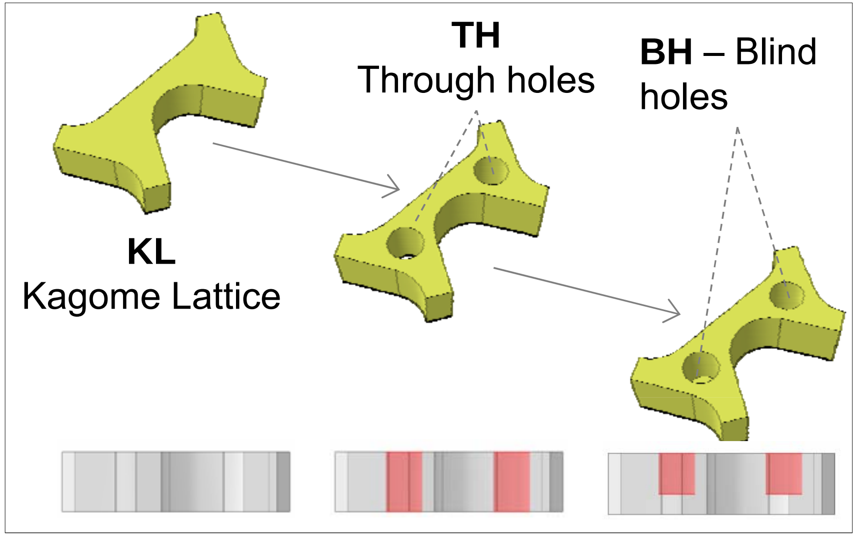
2) Isolate the remaining bands

3) Open a topological bandgap (by breaking σ_h symmetry)

4) Hybridize the modes (by matching the two modes at the K point)

5) Create an interface supporting the protected modes

Super-positioning of the two Dirac cones D1 et D2



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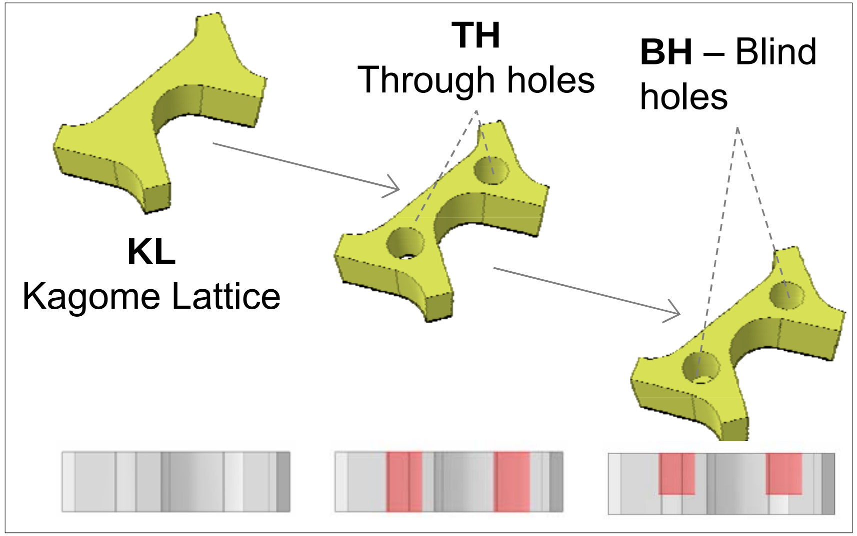
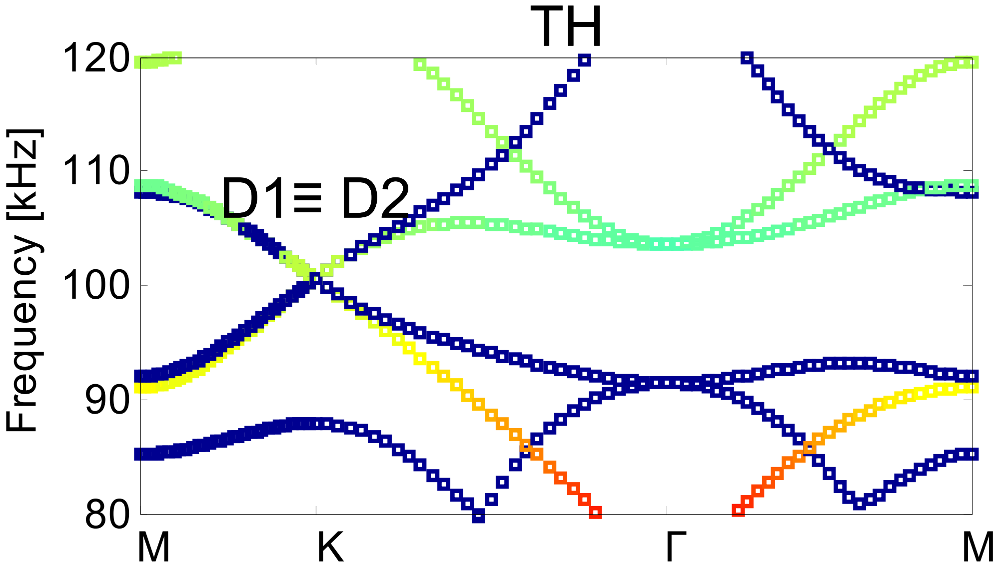
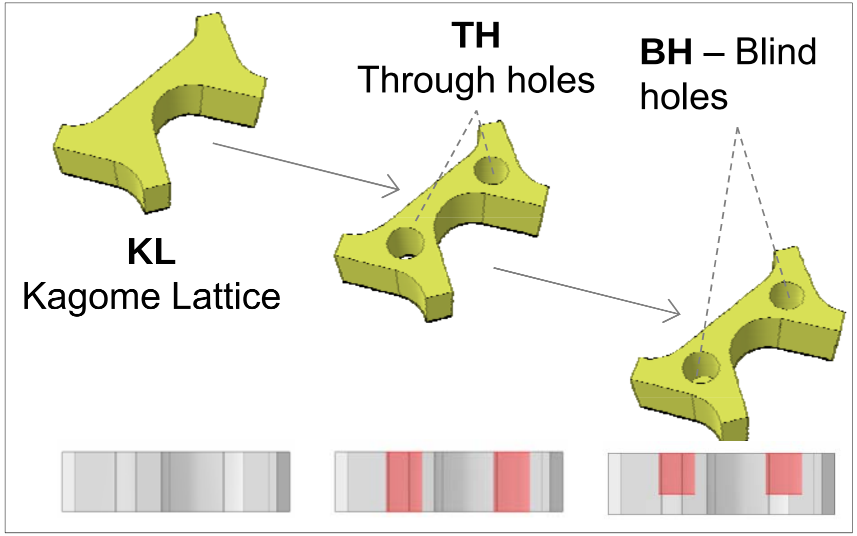
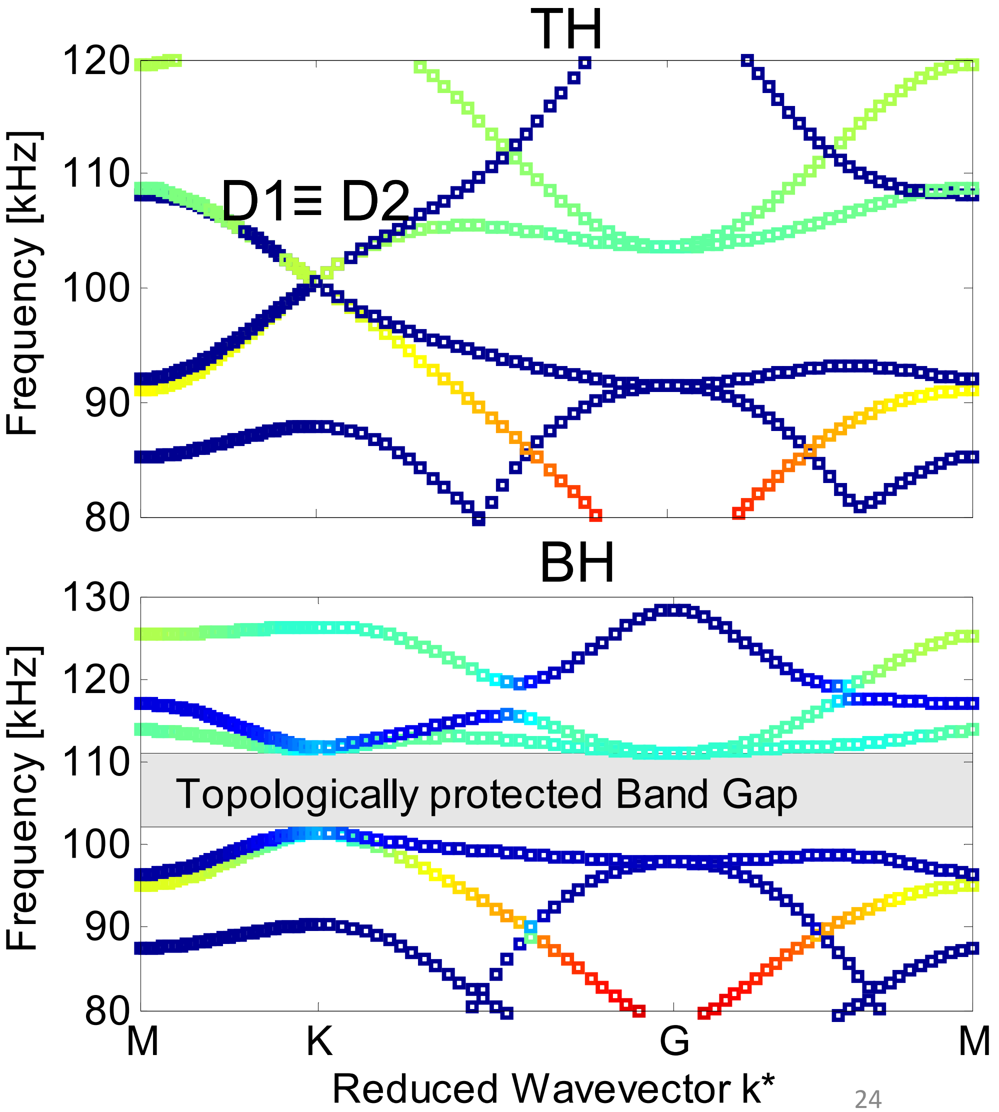




Double Dirac Point is achieved by means of an accidental degeneracy (r = 0.085L with L = 20.5 mm)

Opening of a topologically protected band gap





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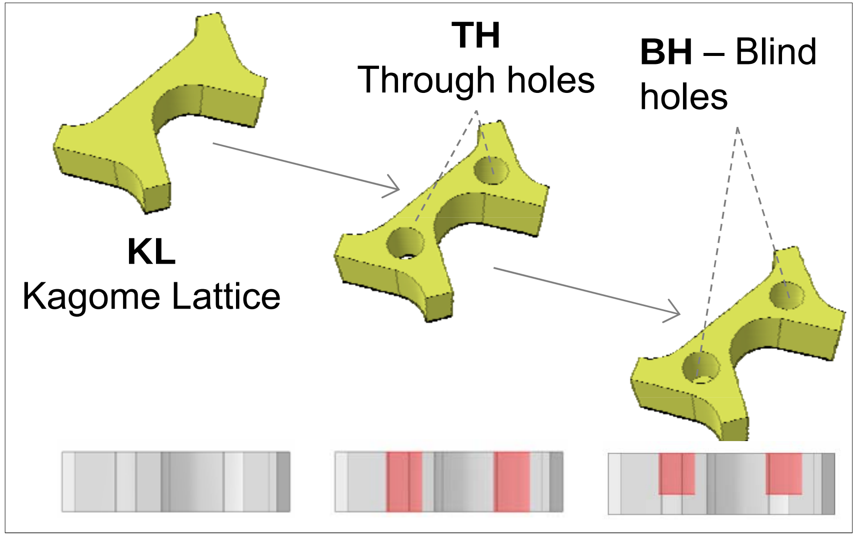

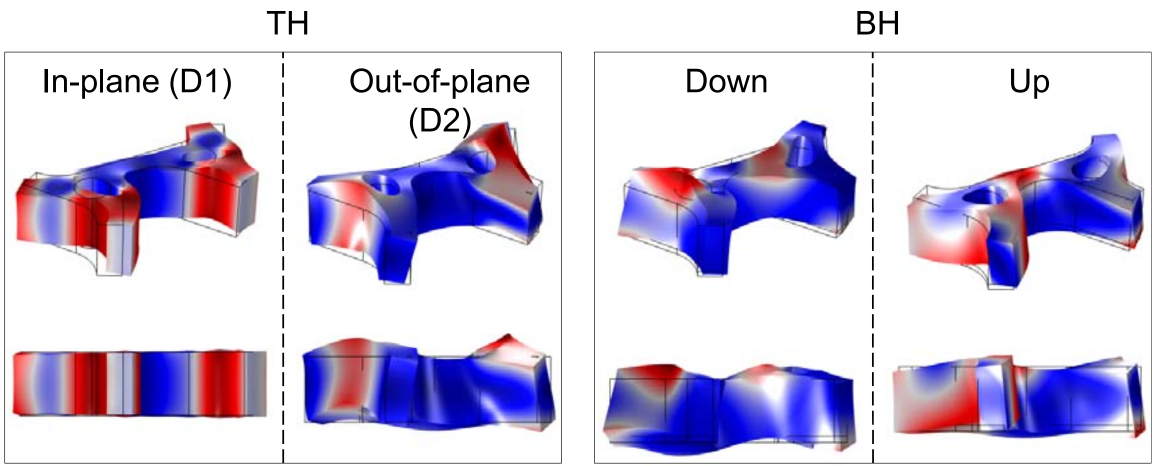

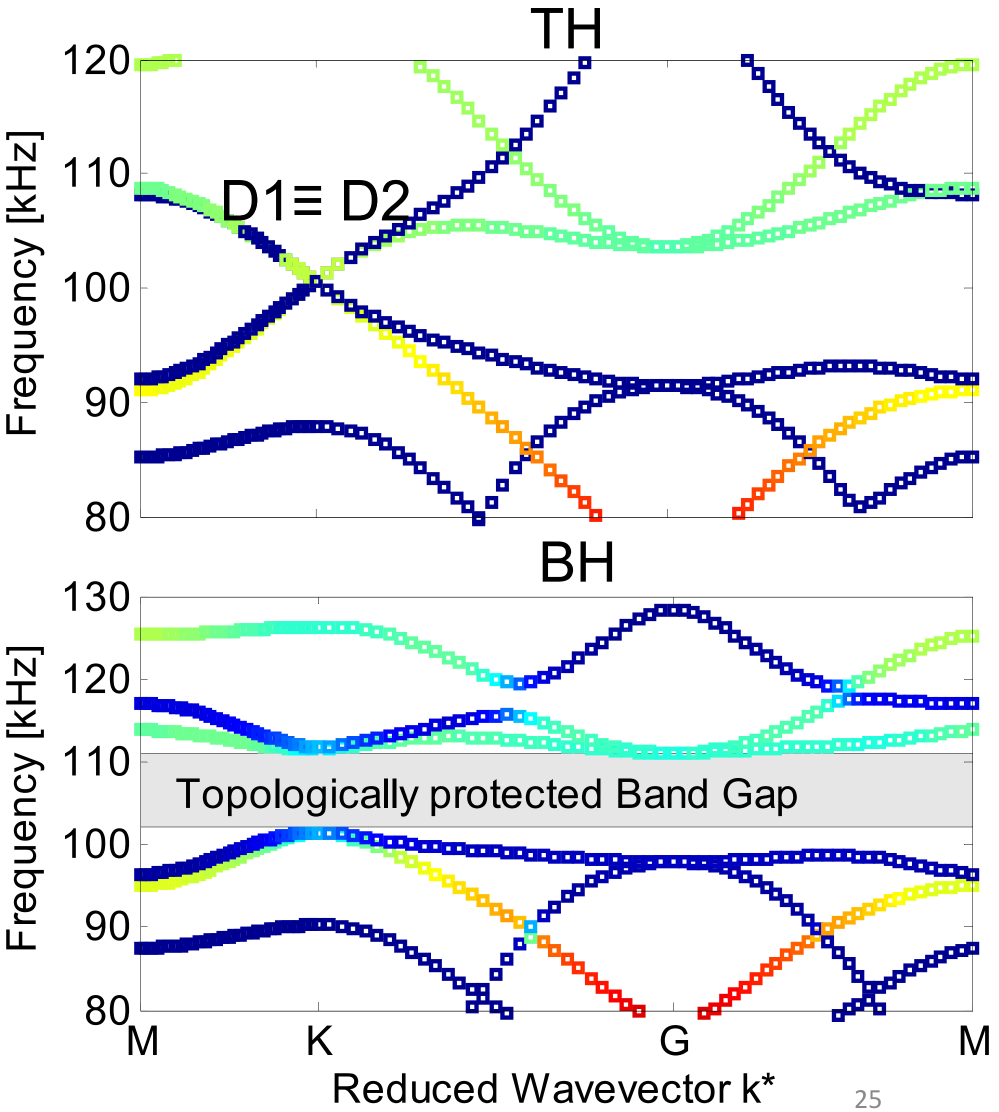

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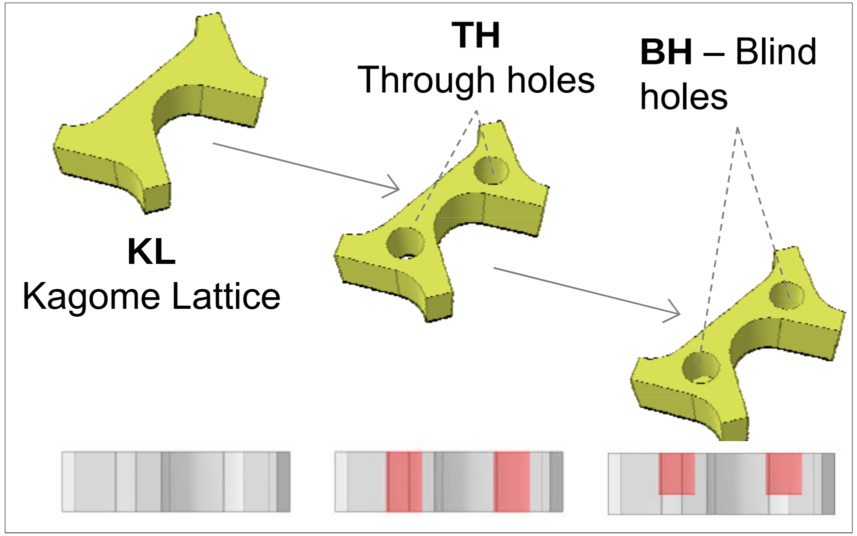
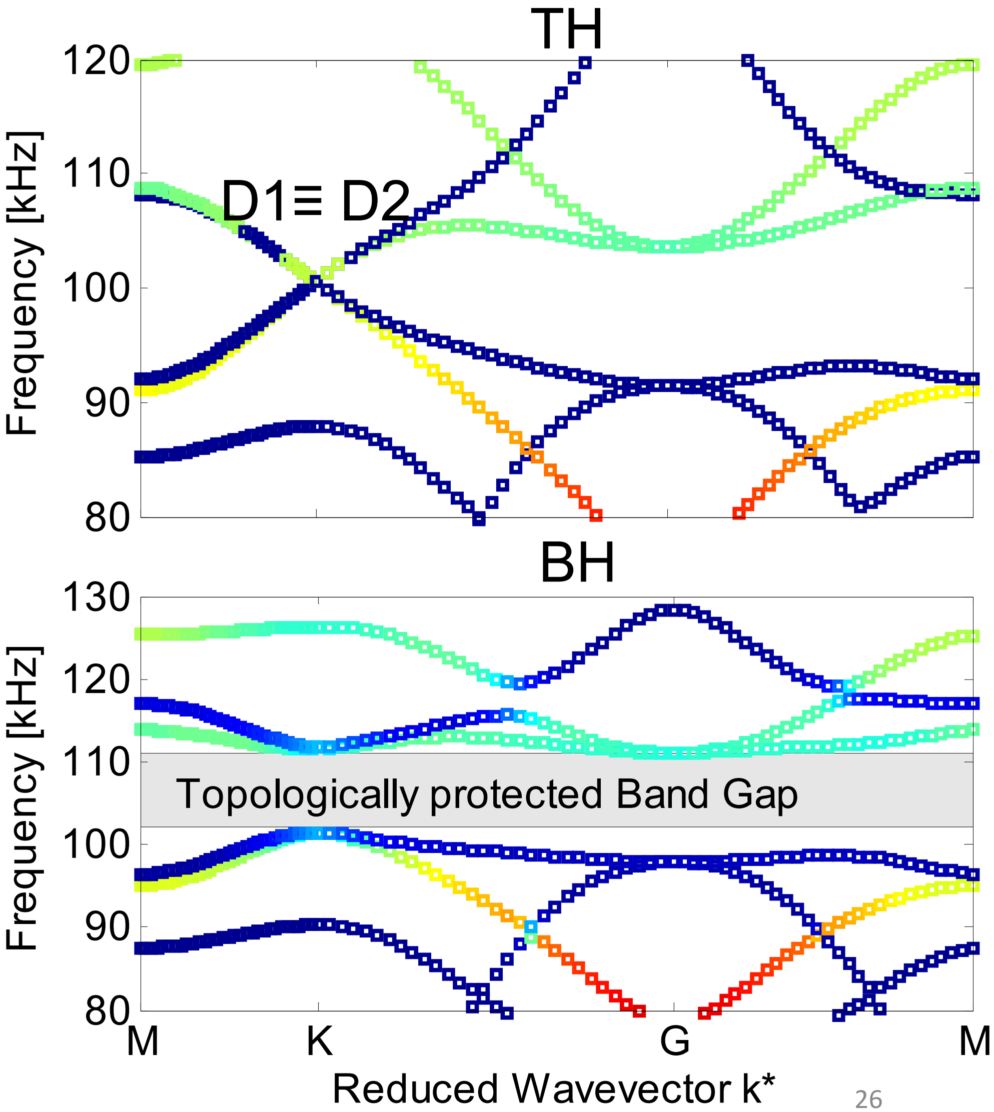
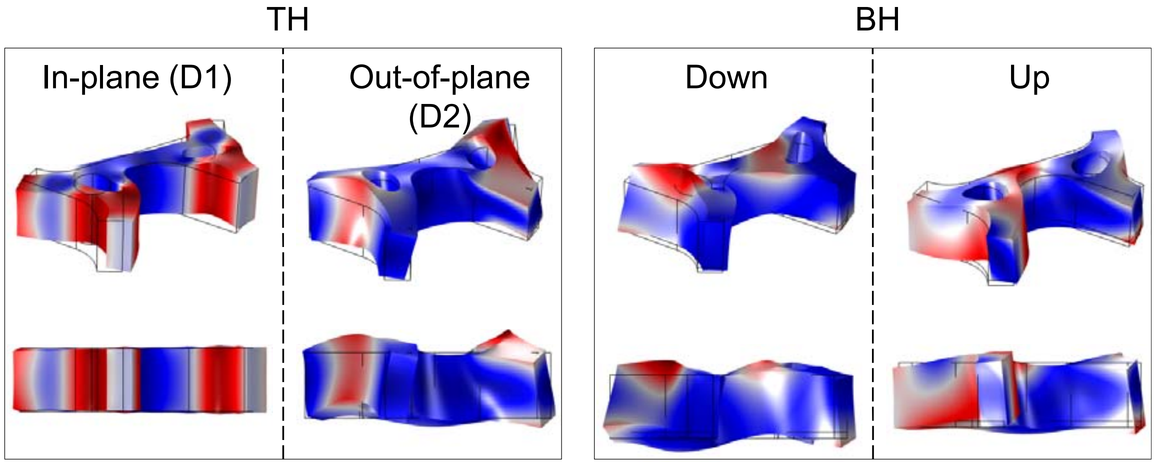
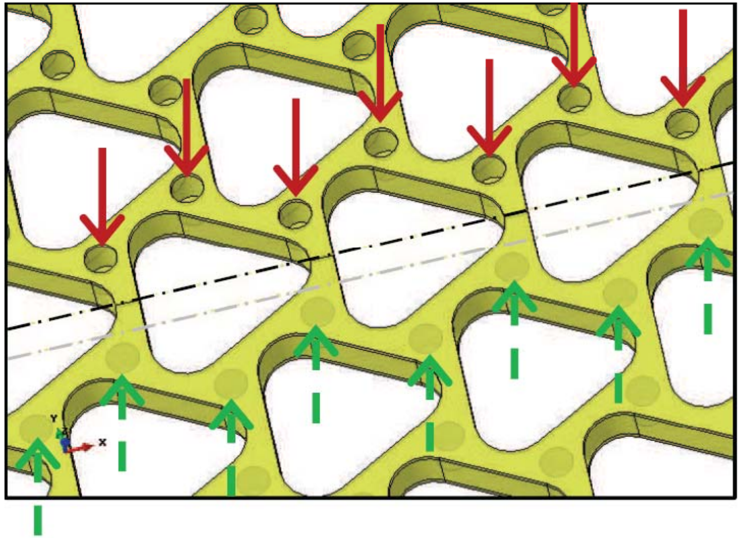


BH = 0.9H
↓
10% BG



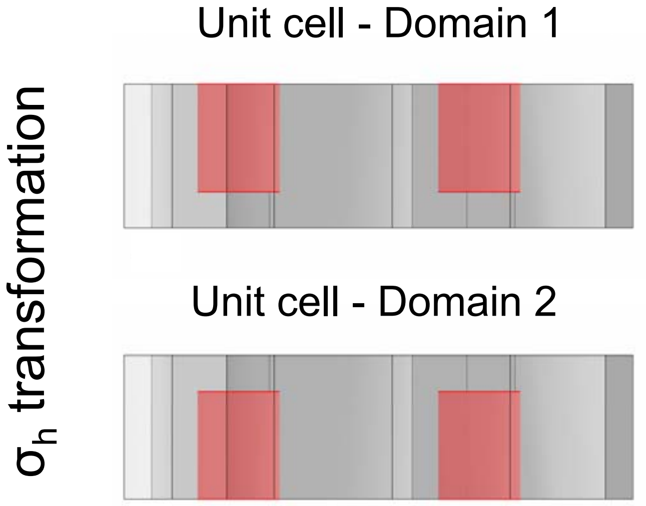


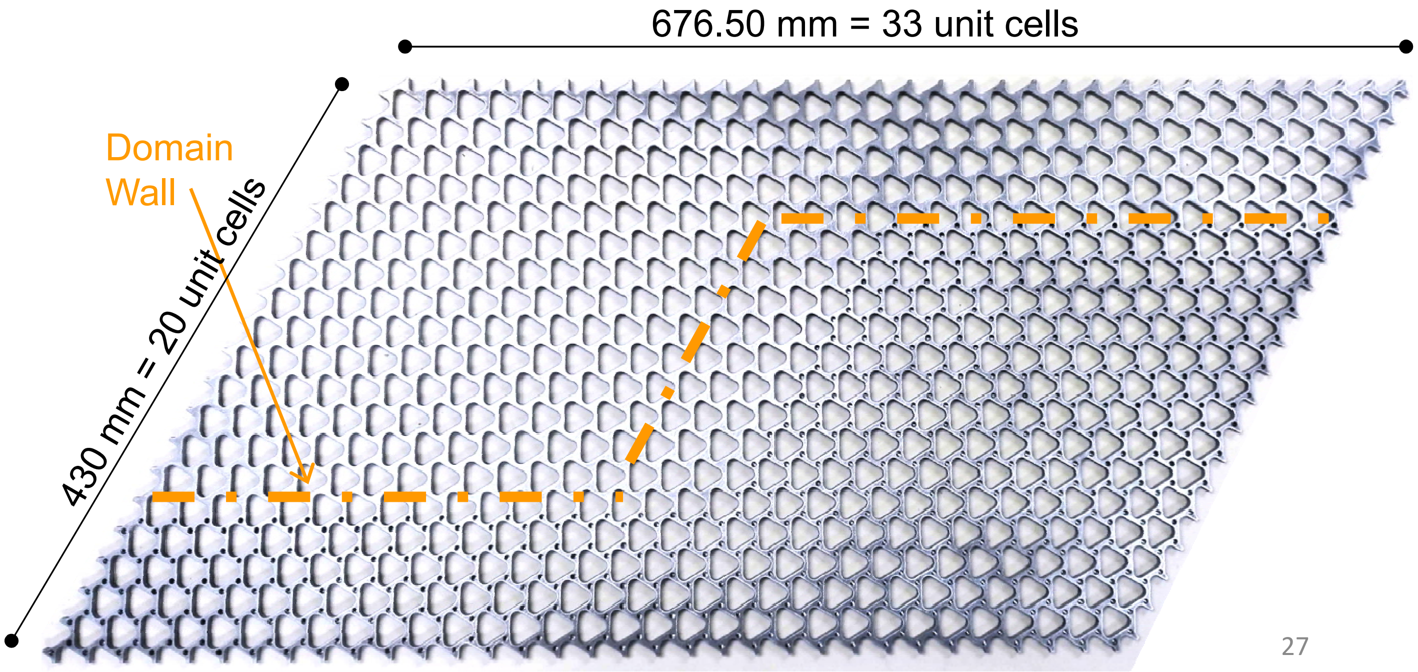
Design of the topological edge through the inversion of the structure in point 2



Topologically protected edge = drilling inverted blind holes along a zigzag path (to prove the **lack of backscattering**)

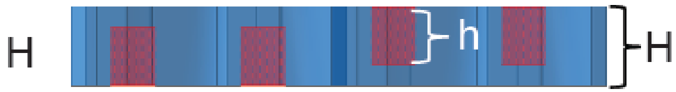
Bulk boundary correspondence principle → the hybridized modes exist (distinct and related by a σ_h transformation) on either side.

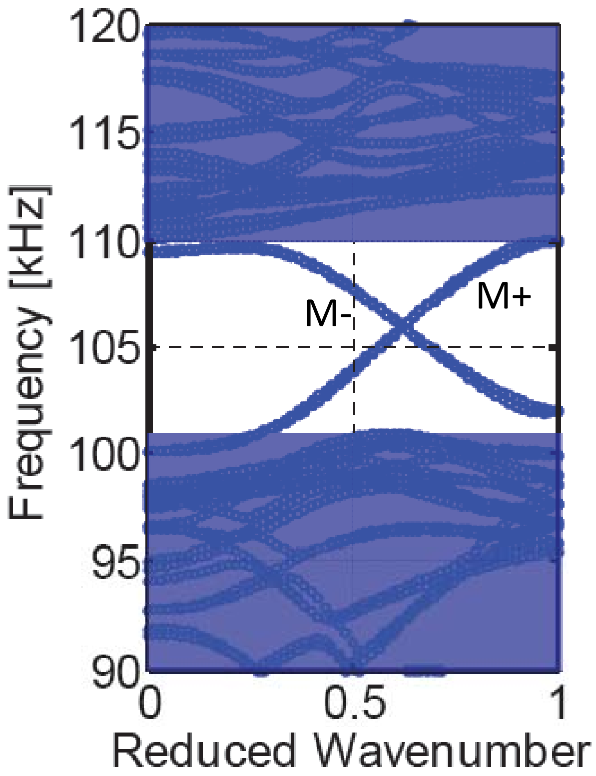




Numerical prediction of the topologically protected edge modes

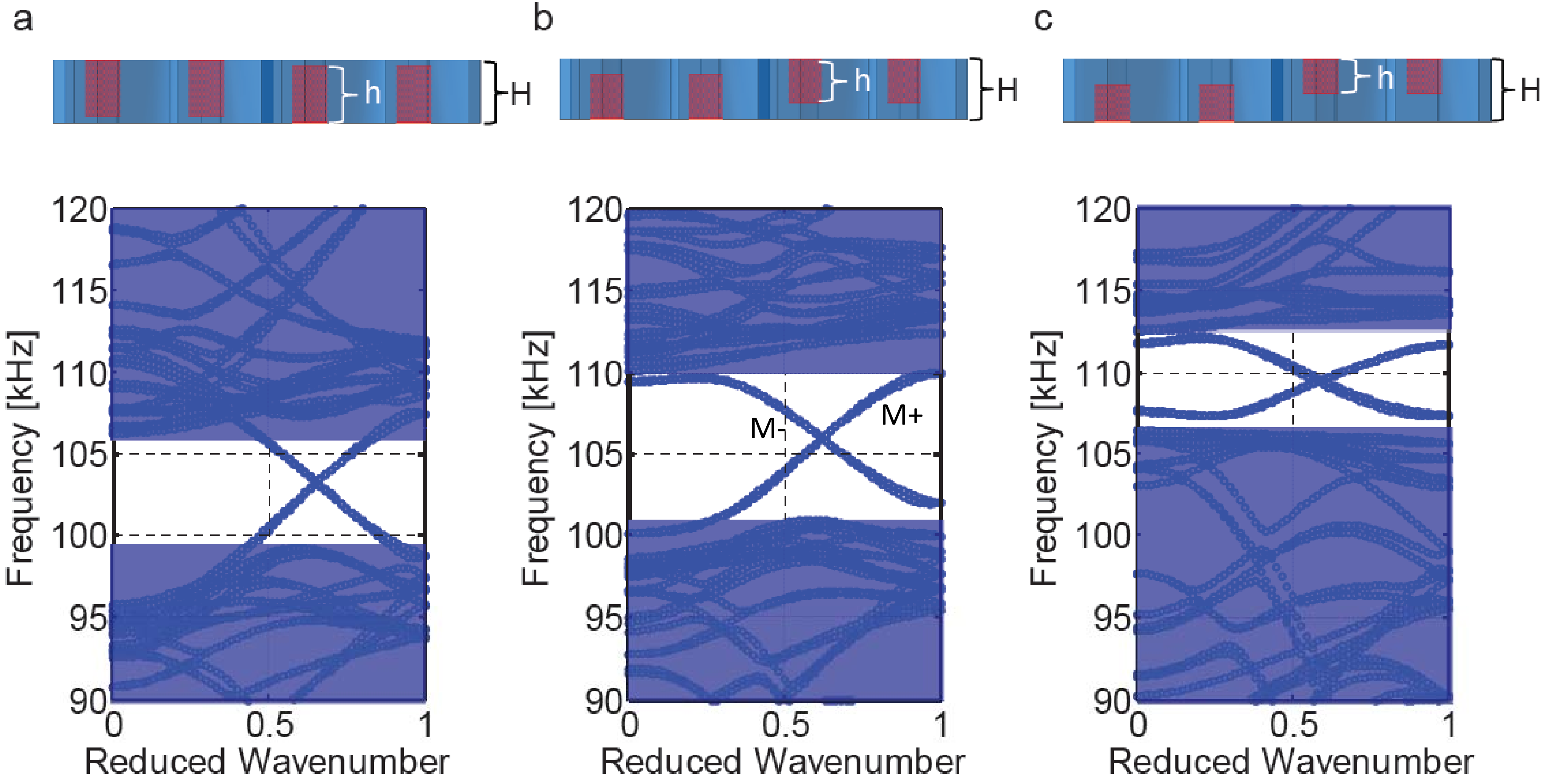
10×1 strip periodic in the $\mathbf{a_1}$ direction





Modes do not merge into the bulk spectrum --> Our system is a perfect analogue in the limit of small perturbations of the double Dirac cone

Numerical prediction of the topologically protected edge modes



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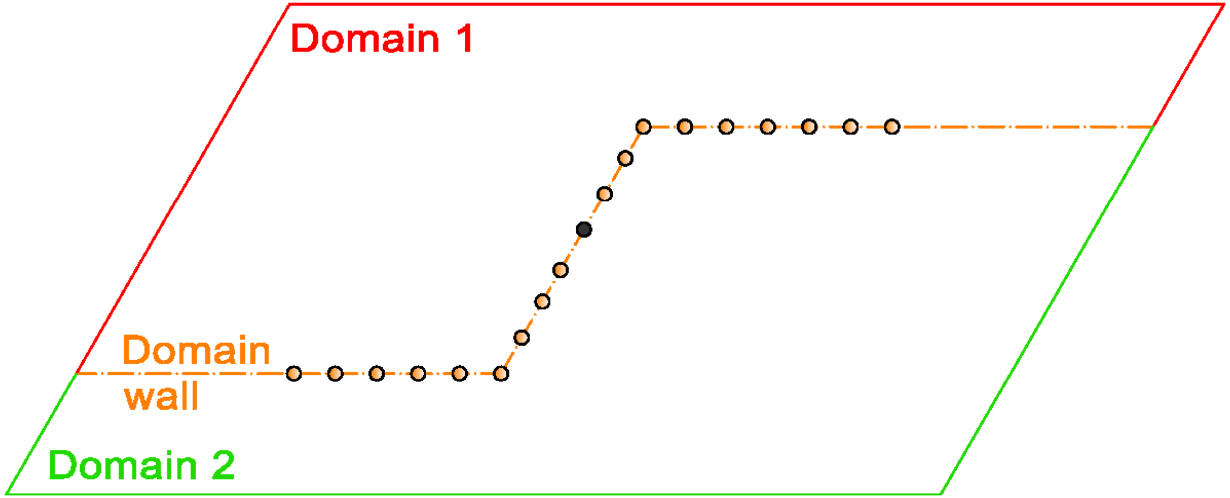
Experimental observation of the edge modes – Z scan

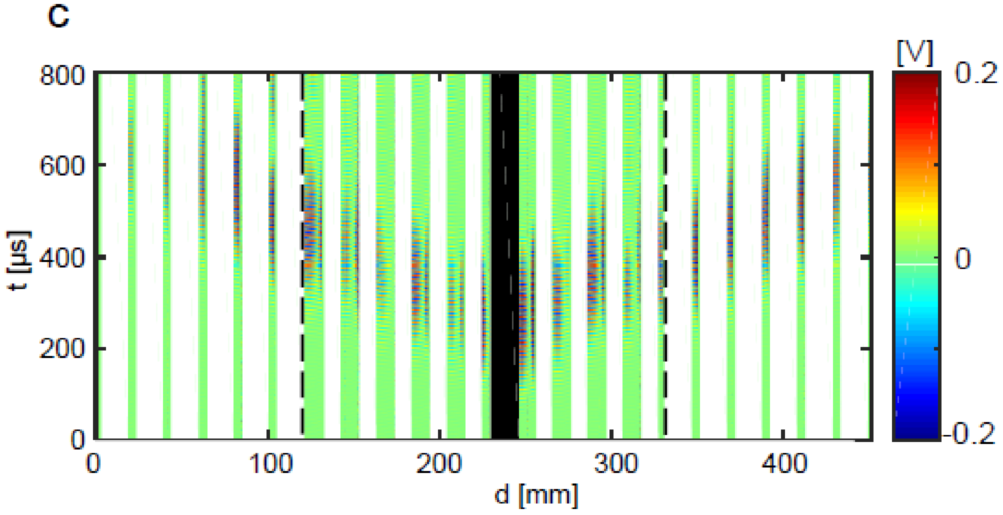
Excitation:

- Piezoelectric transducer glued to the plate
- 51 sine cycles (Hanning windowed) centered at 107 kHz

Acquisition:

- Scanning Laser Doppler Vibrometer Polytec OFV 505 (10mm/s/V)
- 0.2 mm





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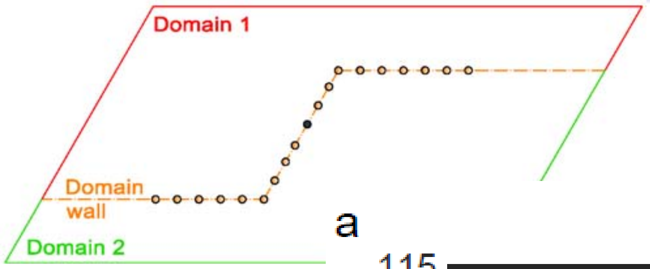

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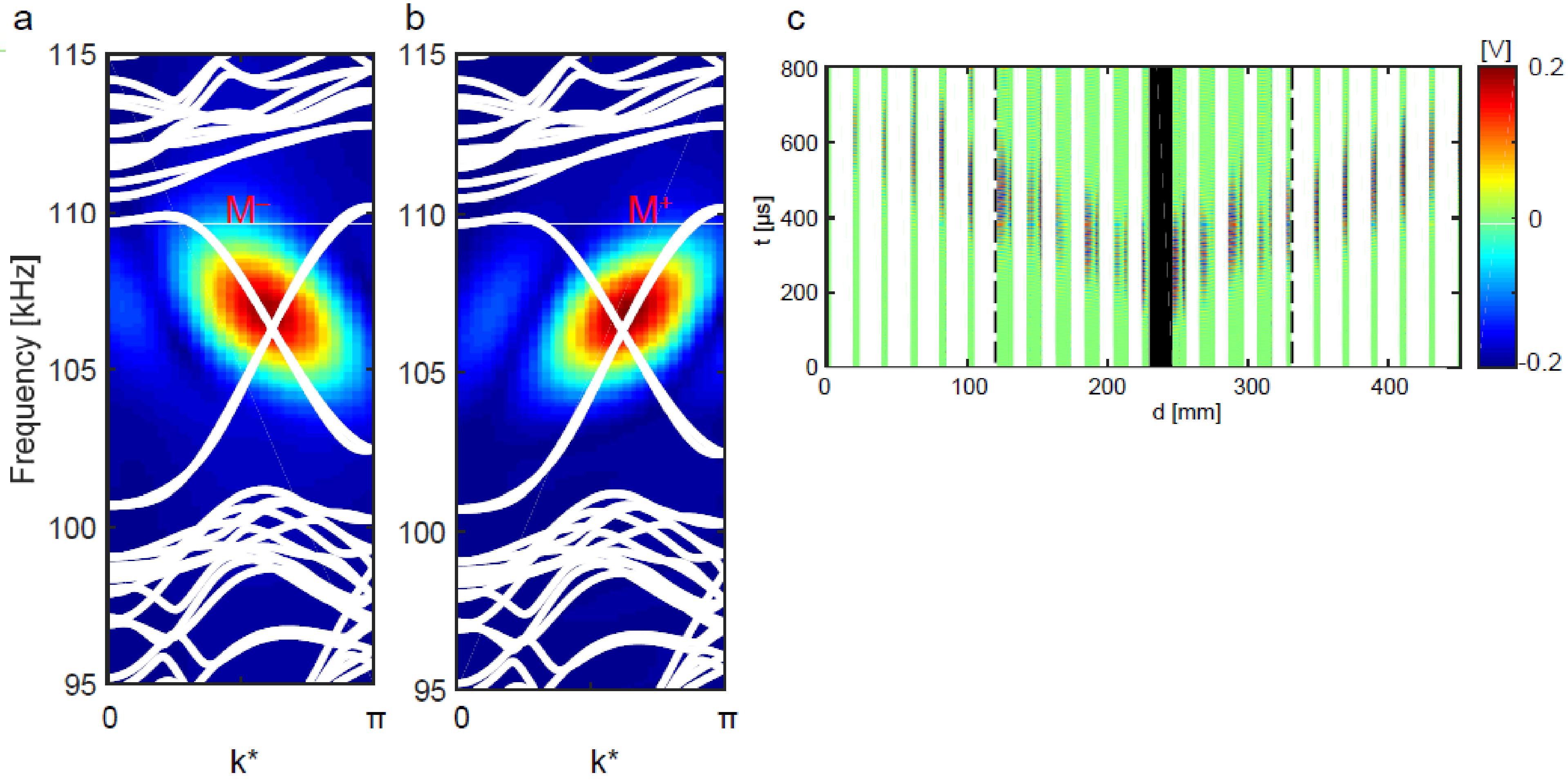
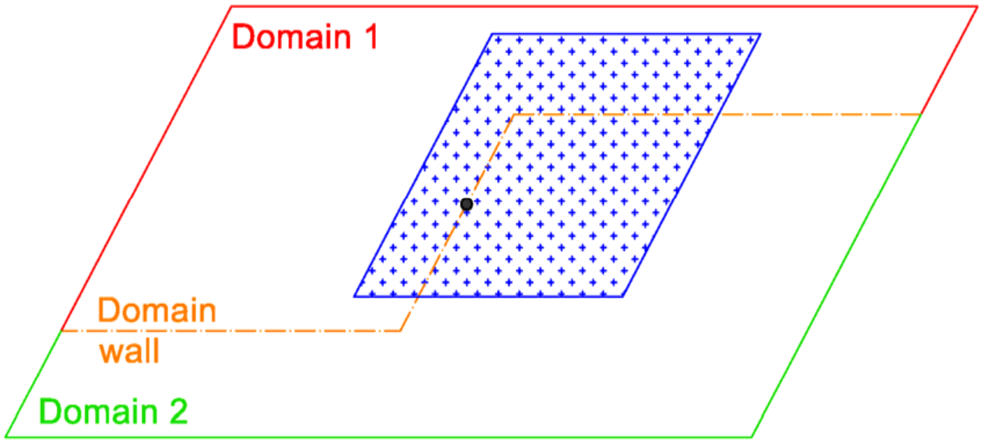
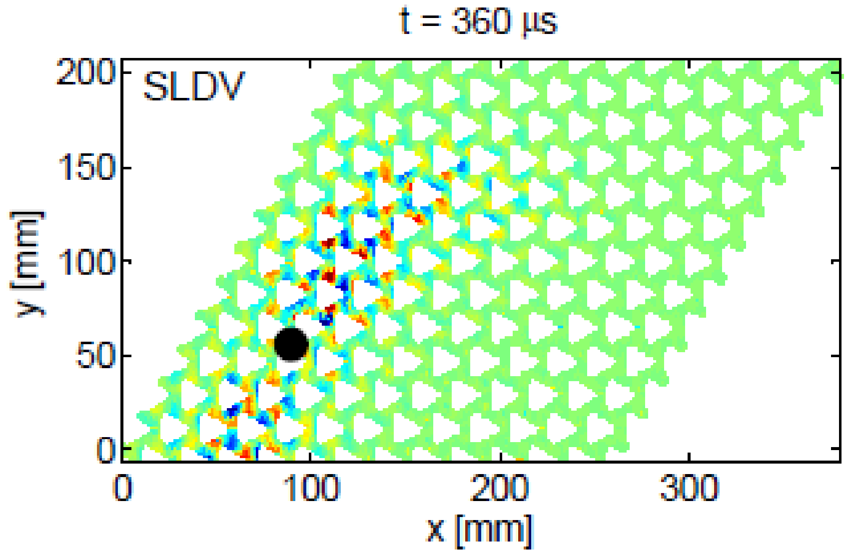
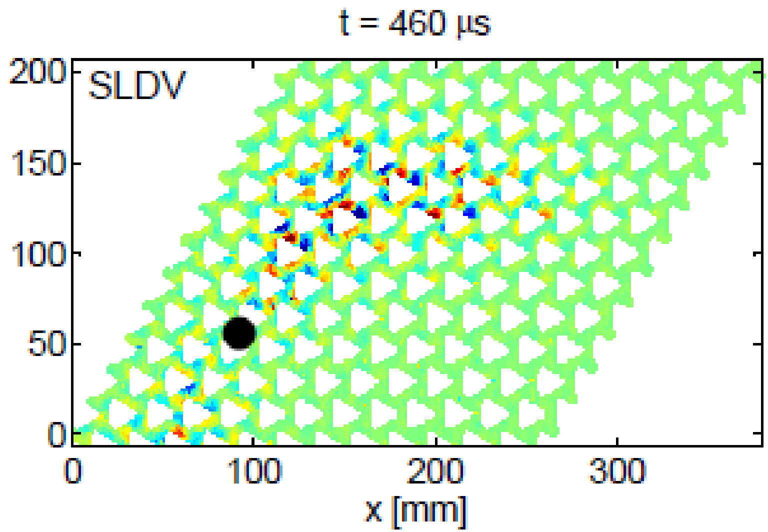
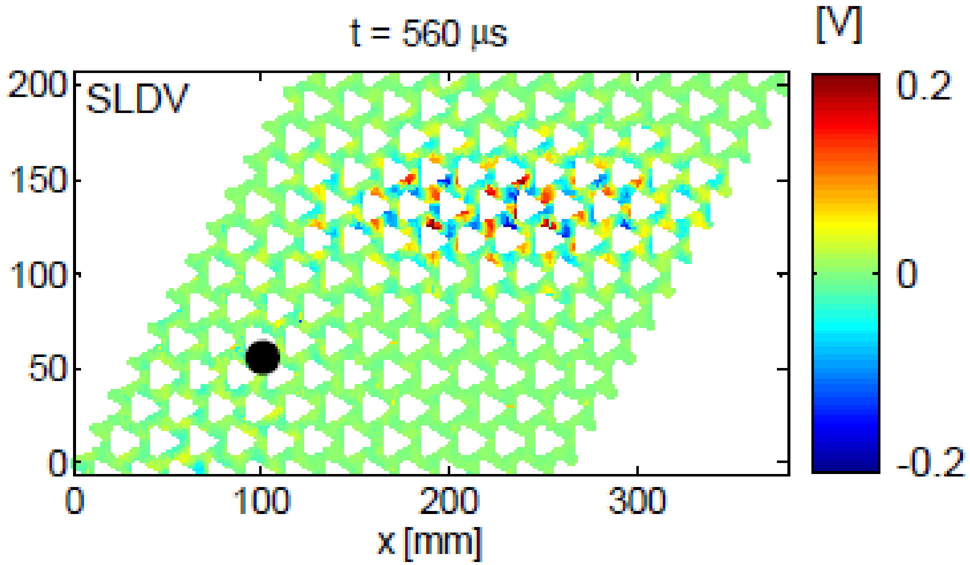


Experimental observation of the edge modes – Large scan









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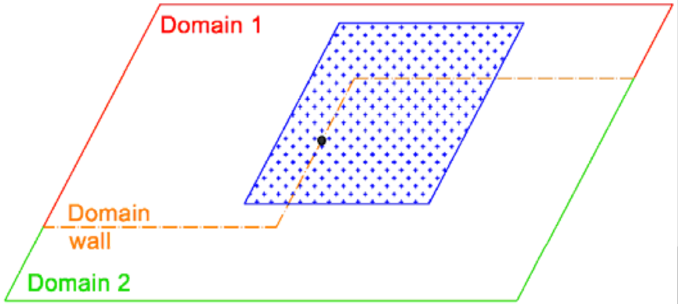

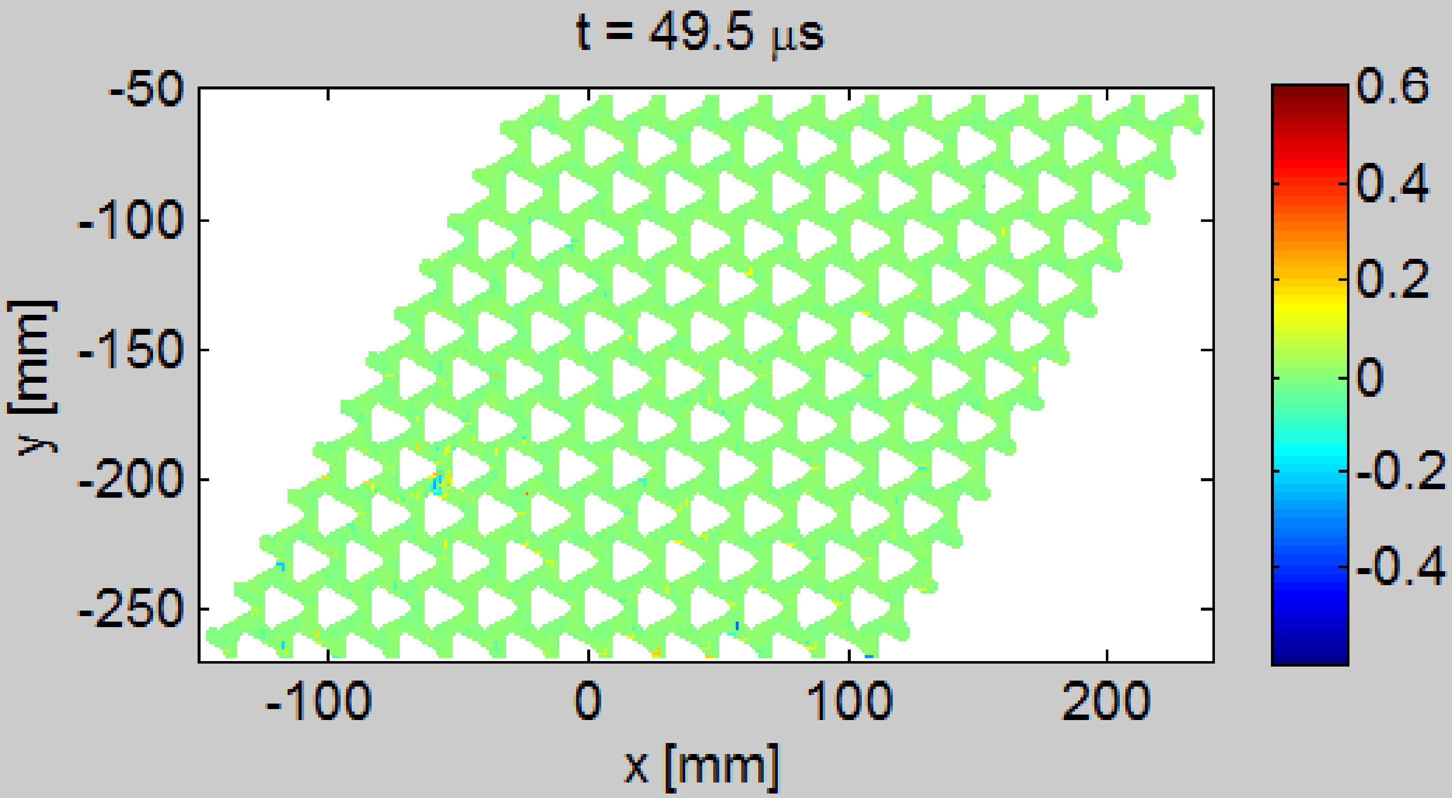

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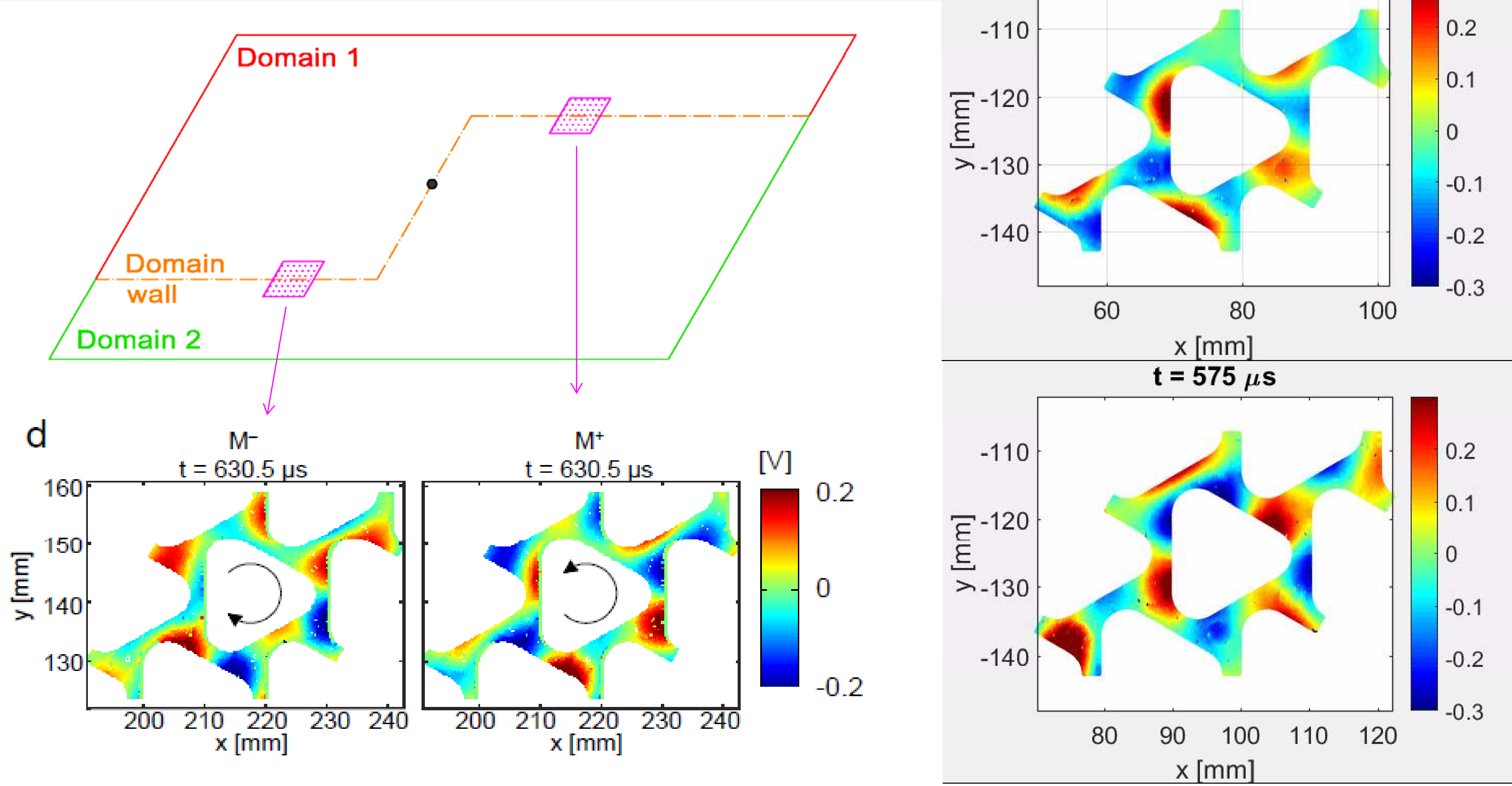
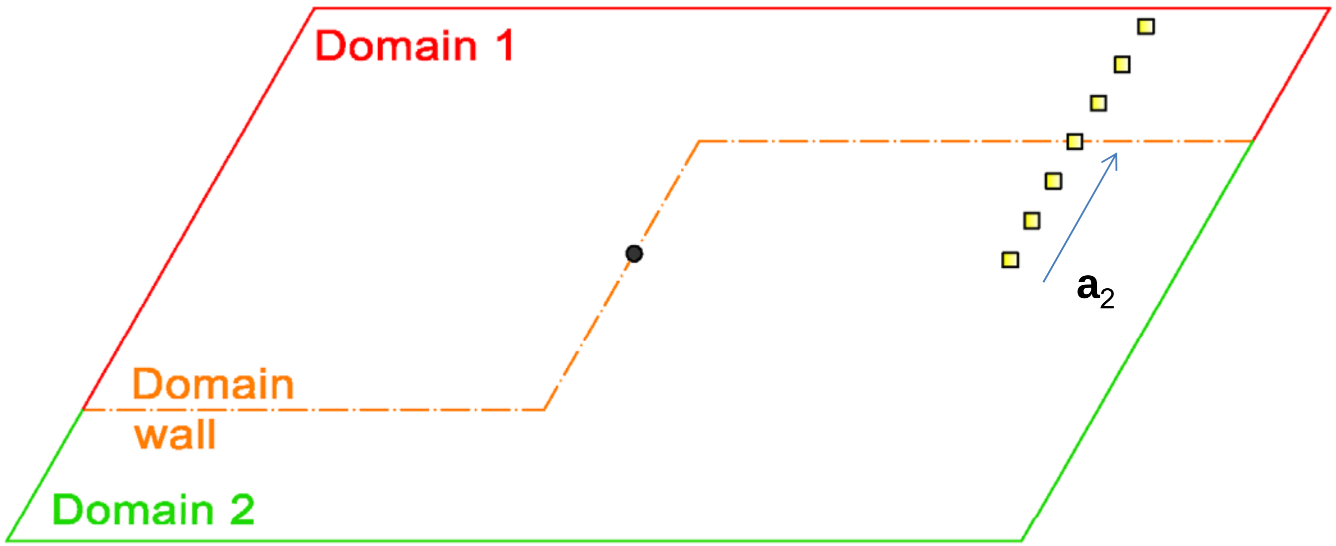
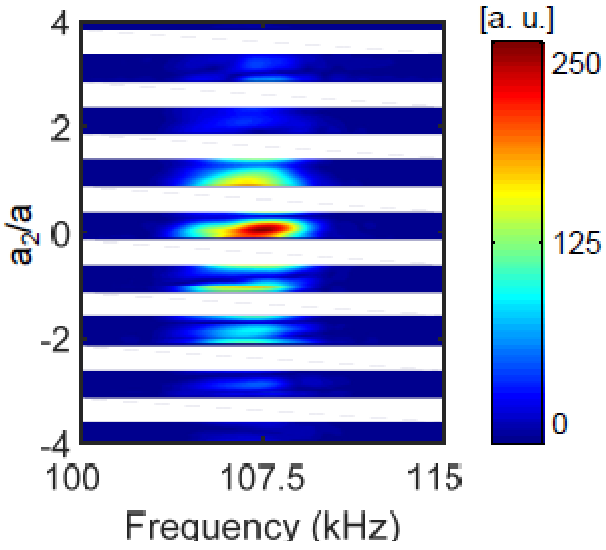
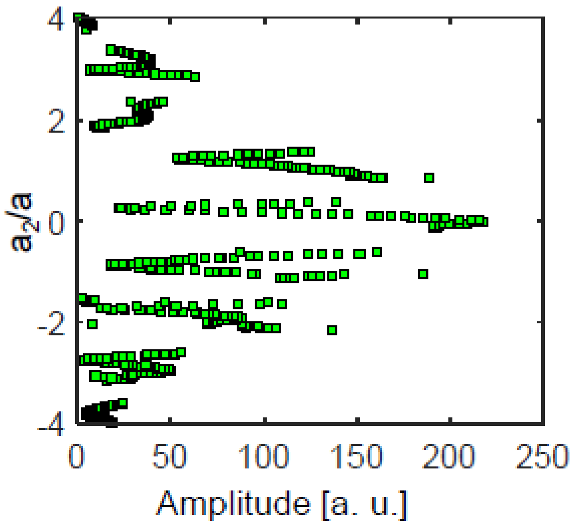


Decay of the edge mode energy along a 1D transversal scan



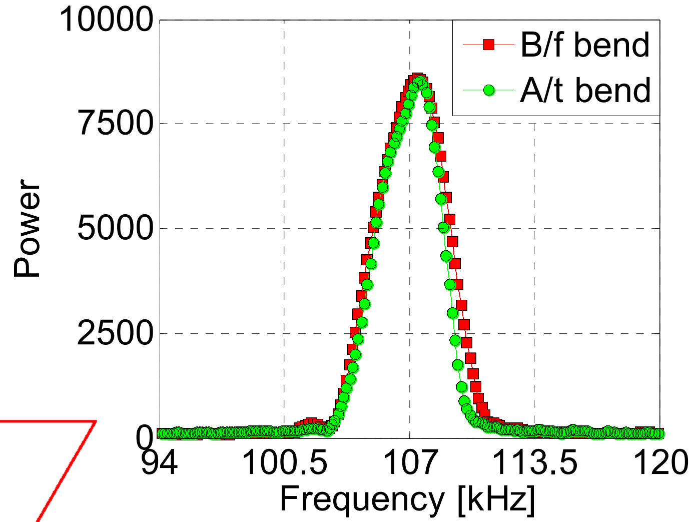


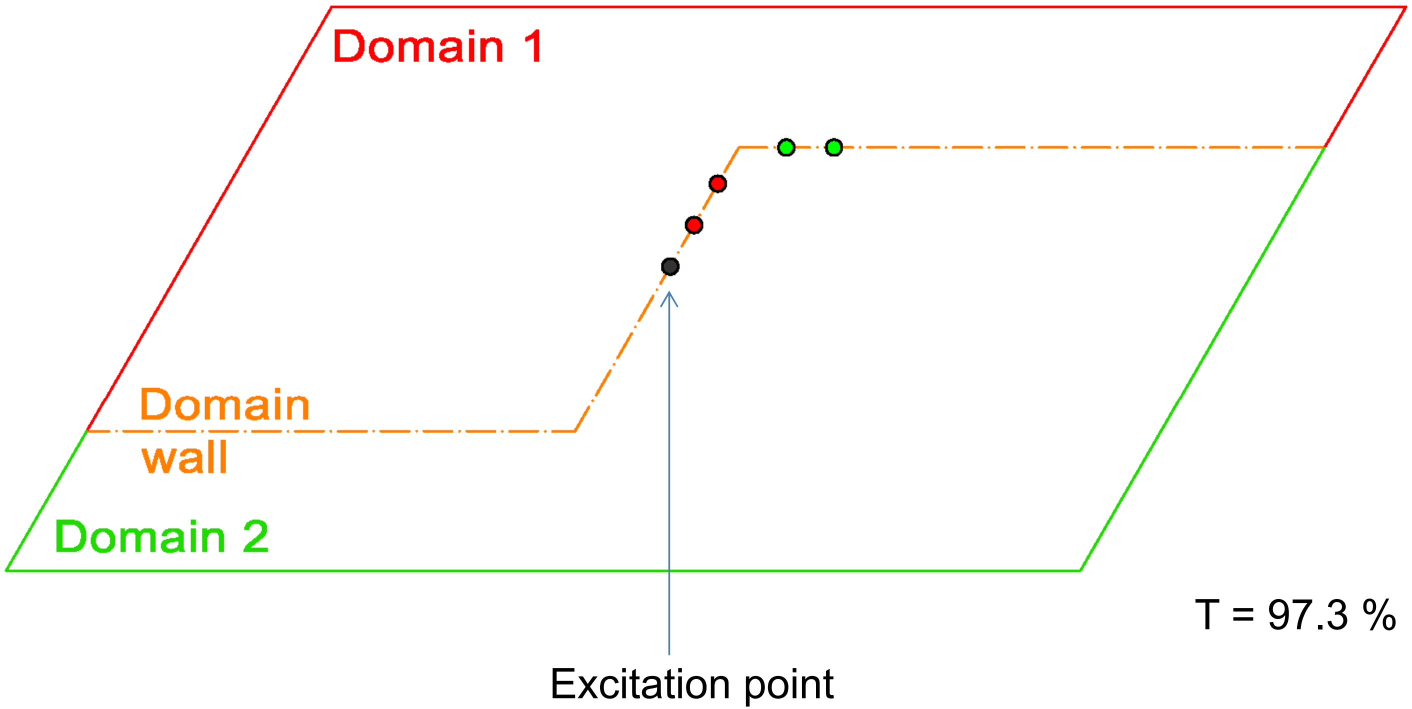
Cut @107 kHz

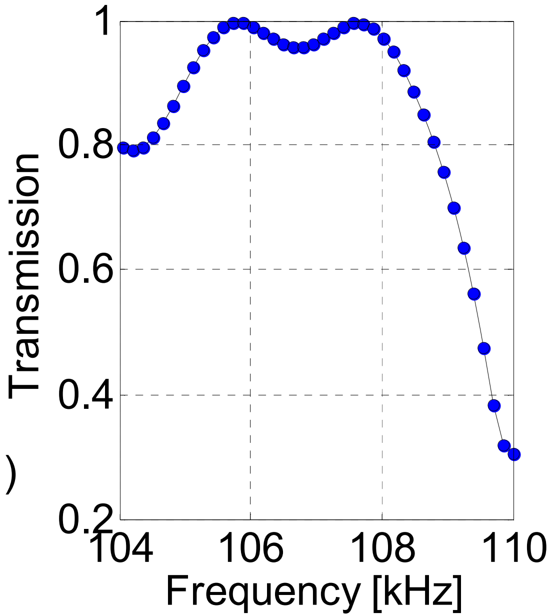


Attenuation of the edge mode before and after the bend

Comparison of the energy of the wave **before** and **after** the turn is obtained by performing a FFT-2D on scans of the same length located on both sides of the bend.







T = 97.3 % (!)

THANK YOU FOR YOUR ATTENTION