Groupement de recherche
ARCHI-META
Architectured Metamaterials

Topological lattices for efficient light transport

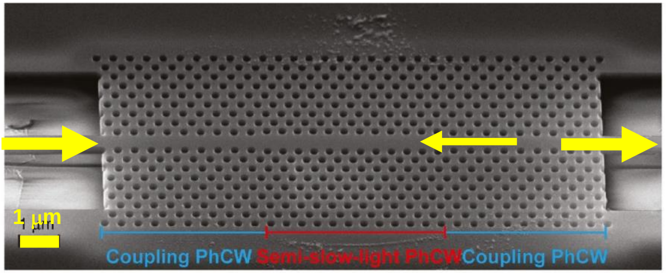
T. Ozawa, H. M. Price, A. Amo et al., Rev. Mod. Phys. 91, 15006 (2019)

Journée de lancement
27 novembre 2023

Alberto Amo
Laboratoire PhLAM – CNRS – Université de Lille

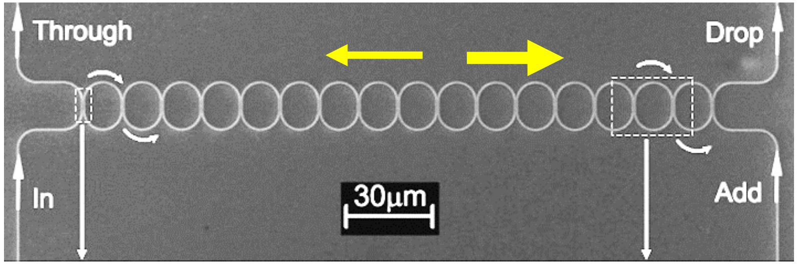
Transport of light at the microscale

Photonic crystal waveguides



Z. Cheng et al., Nanophotonics 9, 2377 (2020)

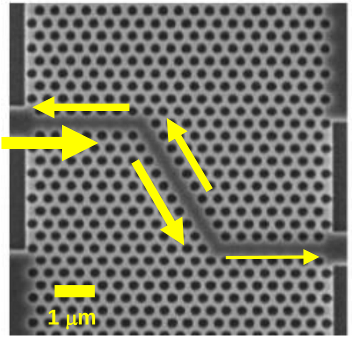
Coupled resonator waveguides (delay lines)



F. Xia et al., Appl. Phys. Lett. **89**, 041122 (2006)

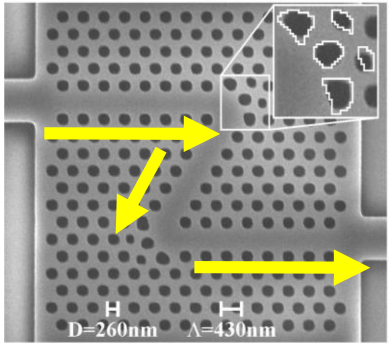
Problems

- Back scattering at imperfections
- **Very strong bending losses**



L. H. Frandsen et al.,Opt. Exp. **12**, 5916 (2004)

Inverse design using variational algorithms, deep learning etc.



P. I. Borel et al.,Opt. Exp. **12**, 1996 (2004)

Highly demanding

Topological invariants: a closed surface

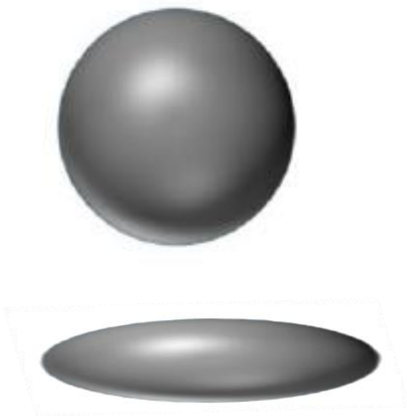
Properties that remain unaffected under smooth distortions

Genus

$$g = 1 - \frac{1}{4\pi}\int_S K(\boldsymbol{r})dA = 0, 1, 2, \ldots$$

- $K(\boldsymbol{r})$ local curvature
- Number of holes
- Global property
- **Robust to deformations**
- **Topological invariant**

$\boldsymbol{g = 0}$



$\boldsymbol{g = 1}$

Topological invariants: a lattice

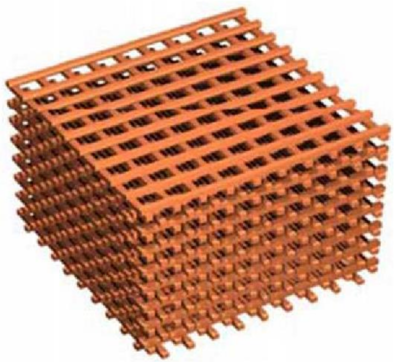
Properties that remain unaffected under smooth distortions

Chern number

$$C = \frac{1}{2\pi} \oiint_{BZ} \nabla_{\boldsymbol{k}} \times \langle \psi(\boldsymbol{k}) | i\nabla_{\boldsymbol{k}} | \psi(\boldsymbol{k}) \rangle \cdot d\boldsymbol{s}$$

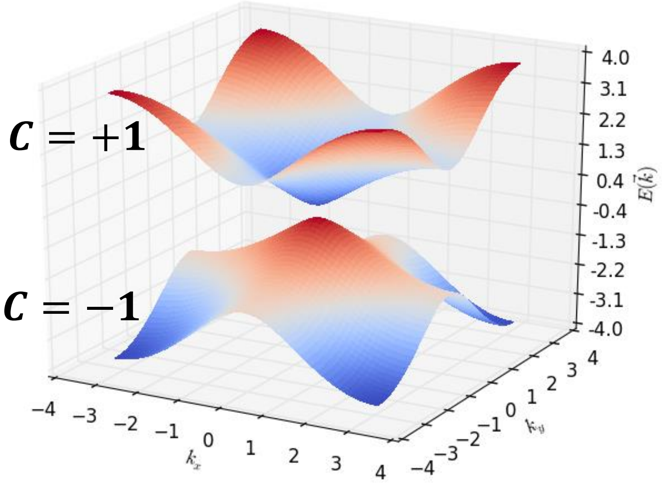
- $\boldsymbol{C = 0, \pm 1, \pm 2, \pm 3, \ldots}$
- Global property
- **Robust to deformations**
- **Topological invariant**

Electronic, phononic or photonic crystal



@ Intechopen

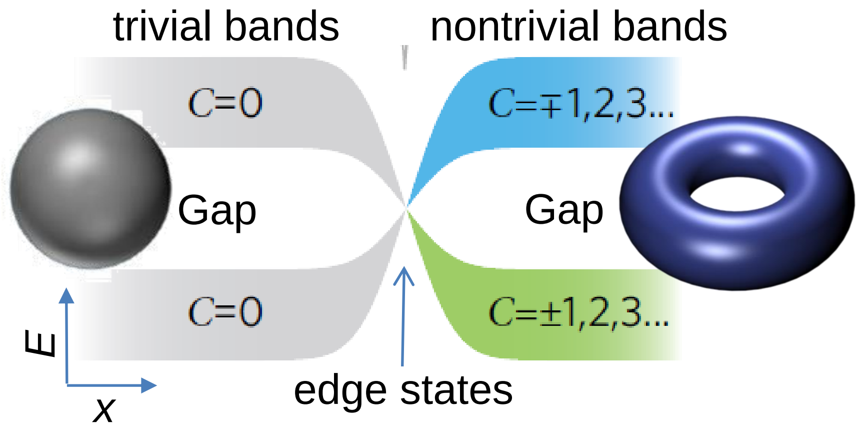
Bands



Topological invariants: edge states

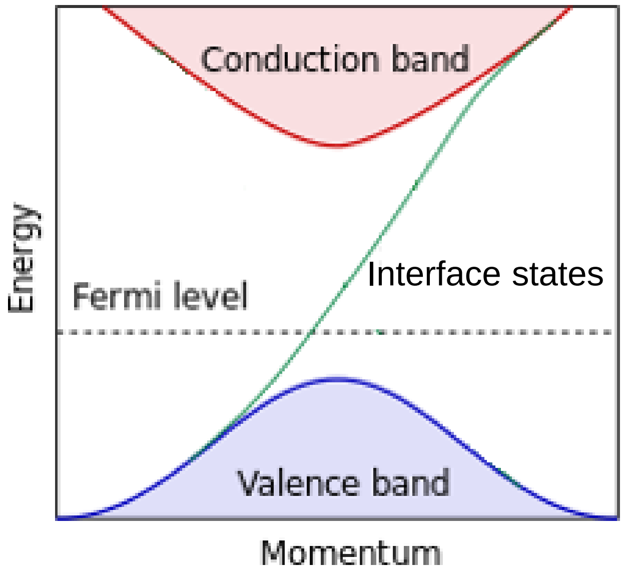
Topological invariant (Chern #)

$$C = \frac{1}{2\pi} \oiint \nabla_{\boldsymbol{k}} \times \langle u(\boldsymbol{k}) | i\nabla_{\boldsymbol{k}} | u(\boldsymbol{k}) \rangle \cdot d\boldsymbol{s}$$



Bulk-edge correspondence

Unidirectional transport



1D lattice: the Su-Schrieffer-Heeger Hamiltonian

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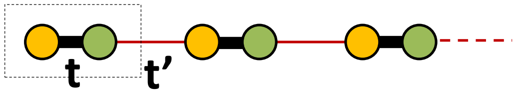
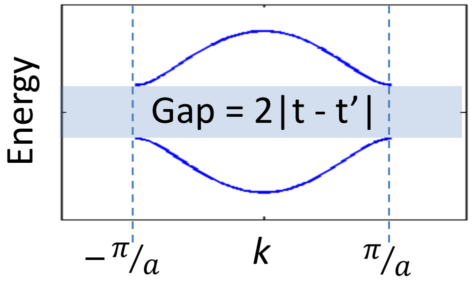
Dimerization 1

t > t'





Same dispersion

Eigenfunctions are different

$$|\pm\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ \pm e^{-i\phi(k)} \end{pmatrix}$$

$$\cot\phi(k) = \frac{t'/t}{\sin ka} + \cot ka$$

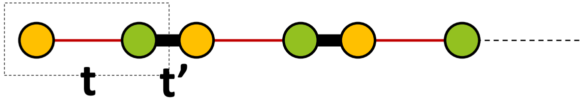
Winding number:

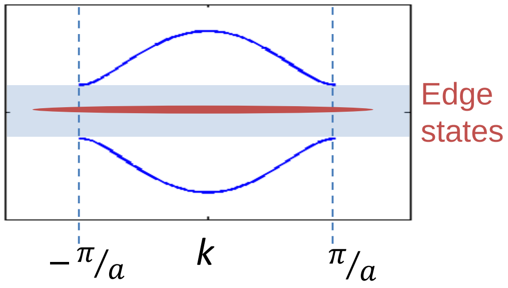
$$\mathcal{W} = \frac{1}{2\pi}\oint_{BZ} dk \langle \psi_\pm(k) | \frac{d}{dk} | \psi_\pm(k) \rangle = 0$$

NO edge state

Dimerization 2

t < t'





Winding number:

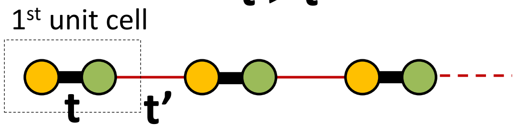
$$\mathcal{W} = 1$$

Edge states in the gap (E=0)

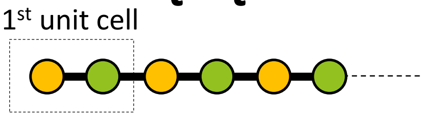
J. Asboth et al., A Short Course on Topological Insulators, arXiv:1509.02295

1D lattice: the Su-Schrieffer-Heeger Hamiltonian

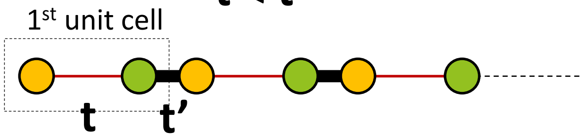
Dimerization 1 — **t > t’**

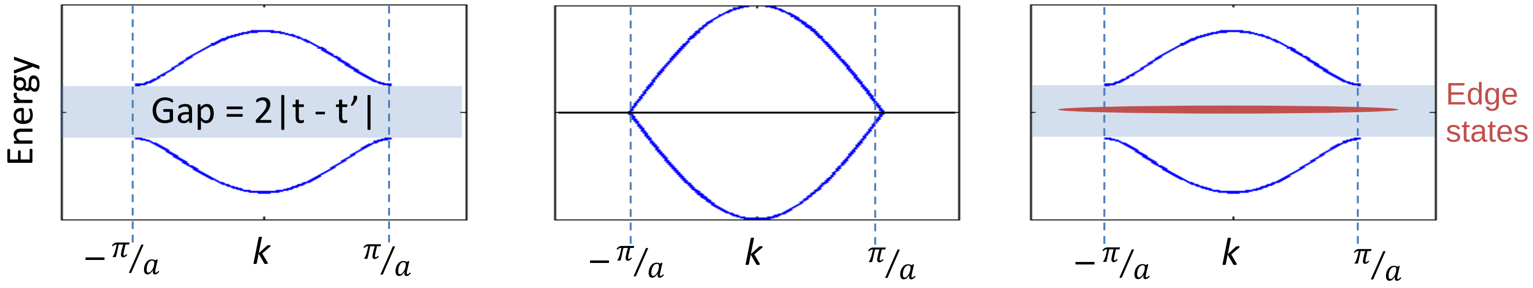


No dimerization — **t = t’**



Dimerization 2 — **t < t’**





Winding number:

$$\mathcal{W} = \frac{1}{2\pi}\oint_{BZ} dk\langle\psi_{\pm}(k)|\frac{d}{dk}|\psi_{\pm}(k)\rangle = 0$$

NO edge state

Winding number:

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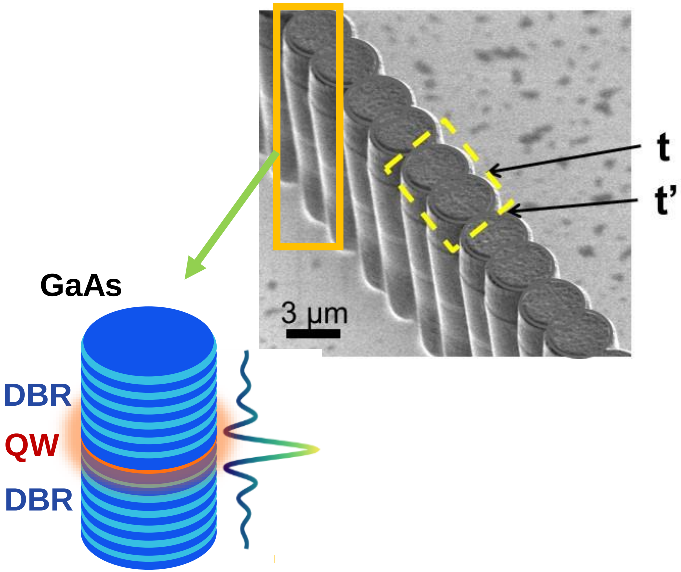
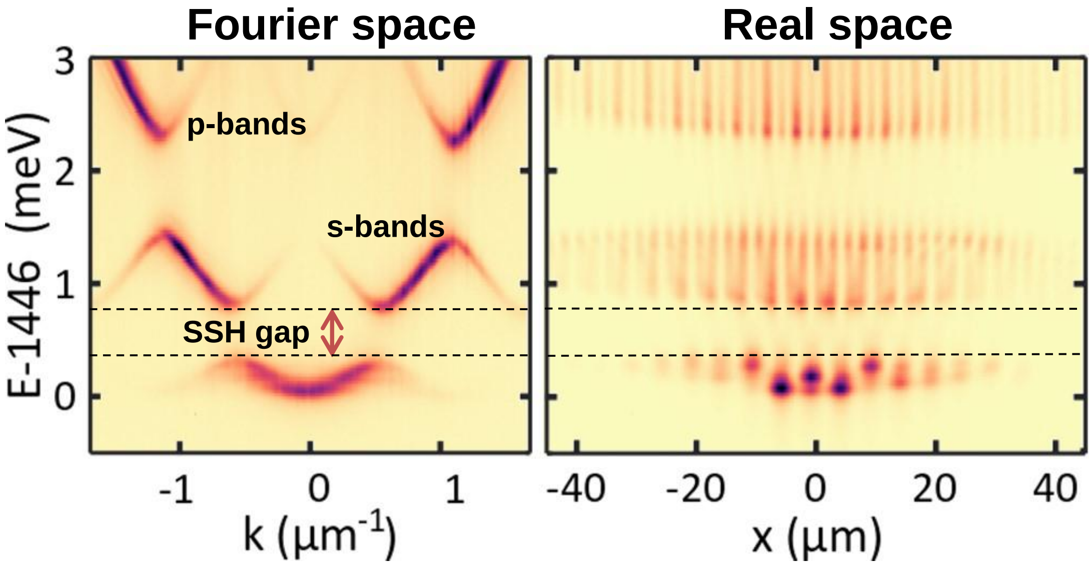
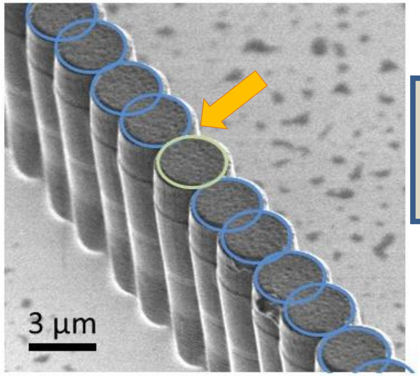
SSH lattice of photonic resonators

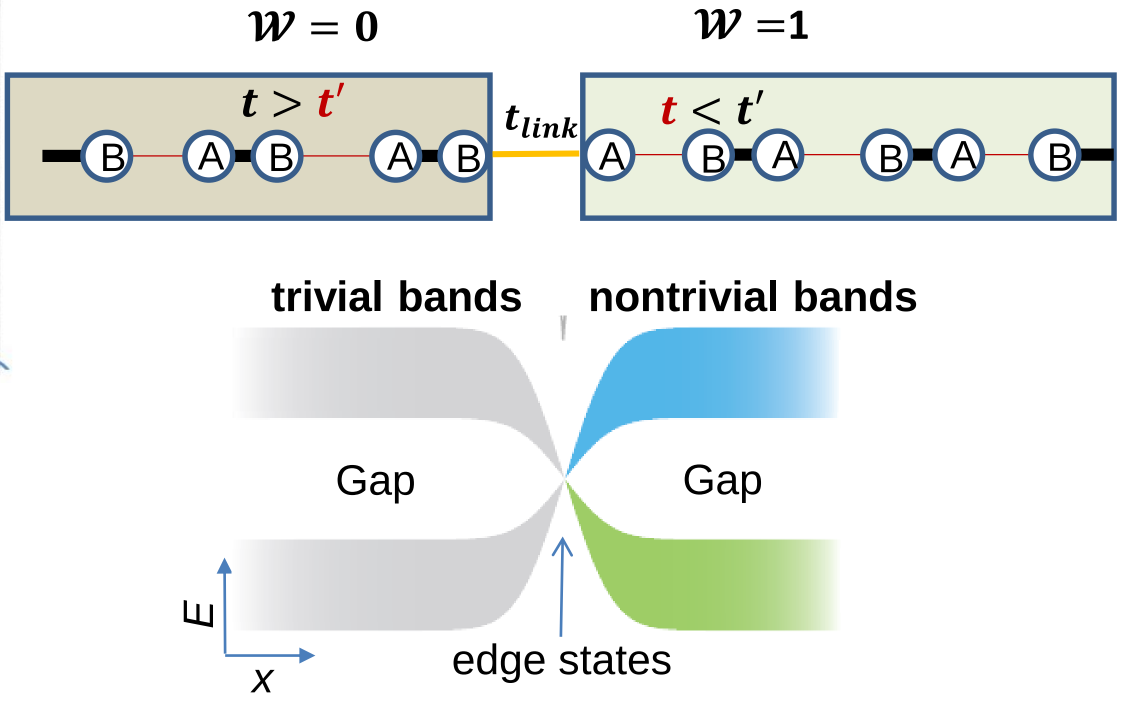




N. Pernet et al., Nat. Phys. **18**, 678 (2022)

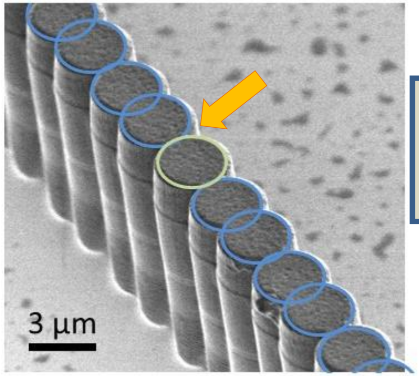
SSH lattice of photonic resonators

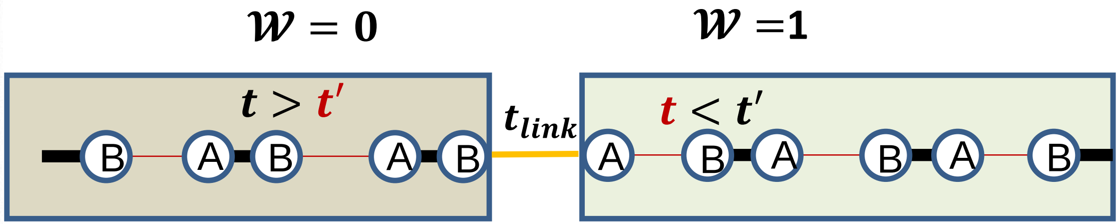


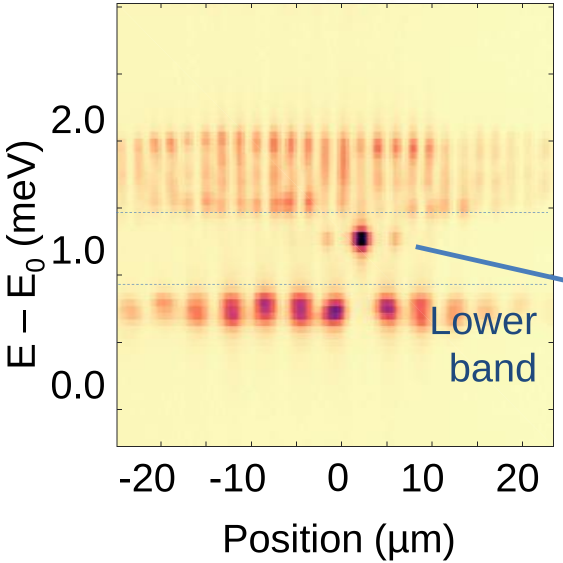


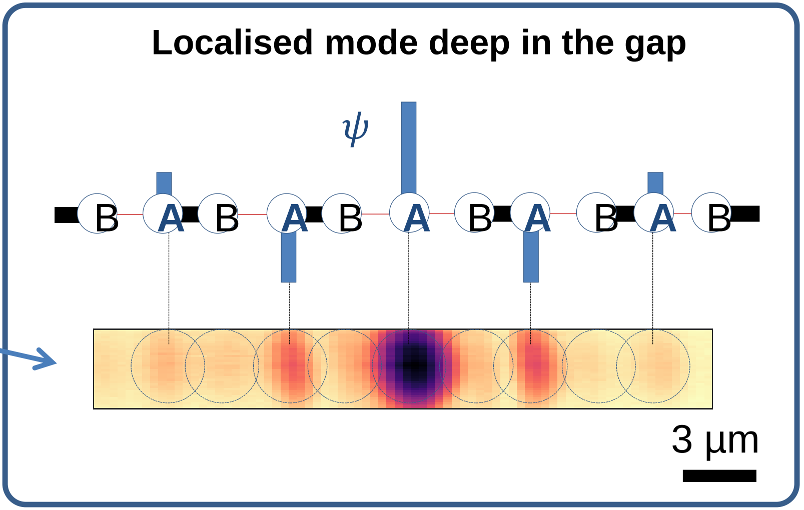
N. Pernet et al., Nat. Phys. **18**, 678 (2022)

SSH lattice of photonic resonators









N. Pernet et al., Nat. Phys. **18**, 678 (2022)

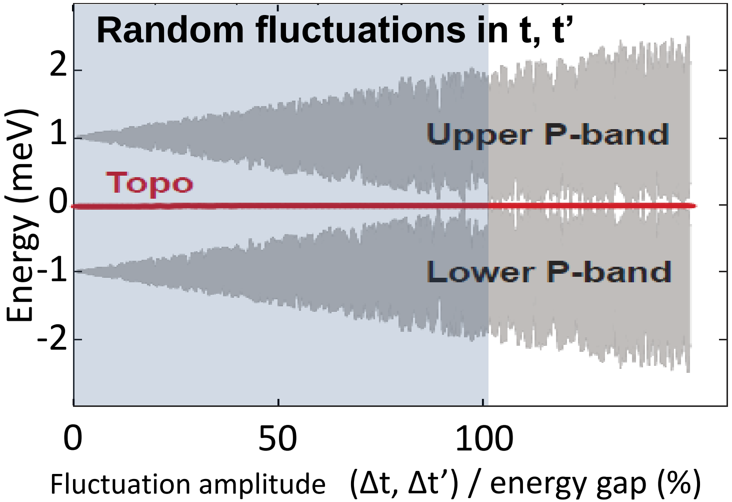
Topological robustness

$\{H, \sigma_z\} = 0$ (chiral symmetry)

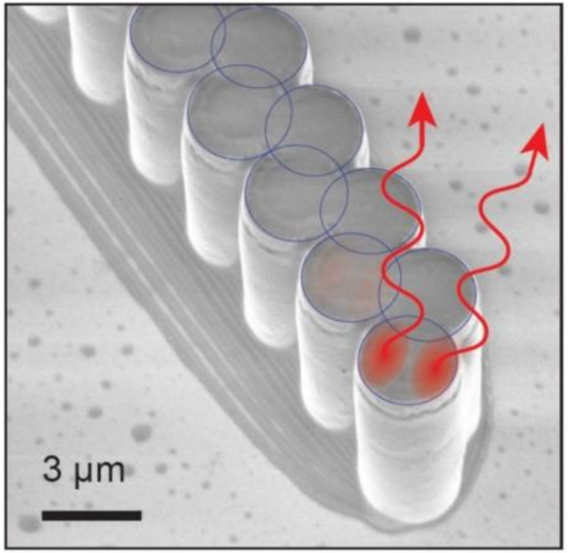
Eigenspectrum is symmetric around E=0

Preserved even if t and t' fluctuate

Simulation



Lasing at an edge state



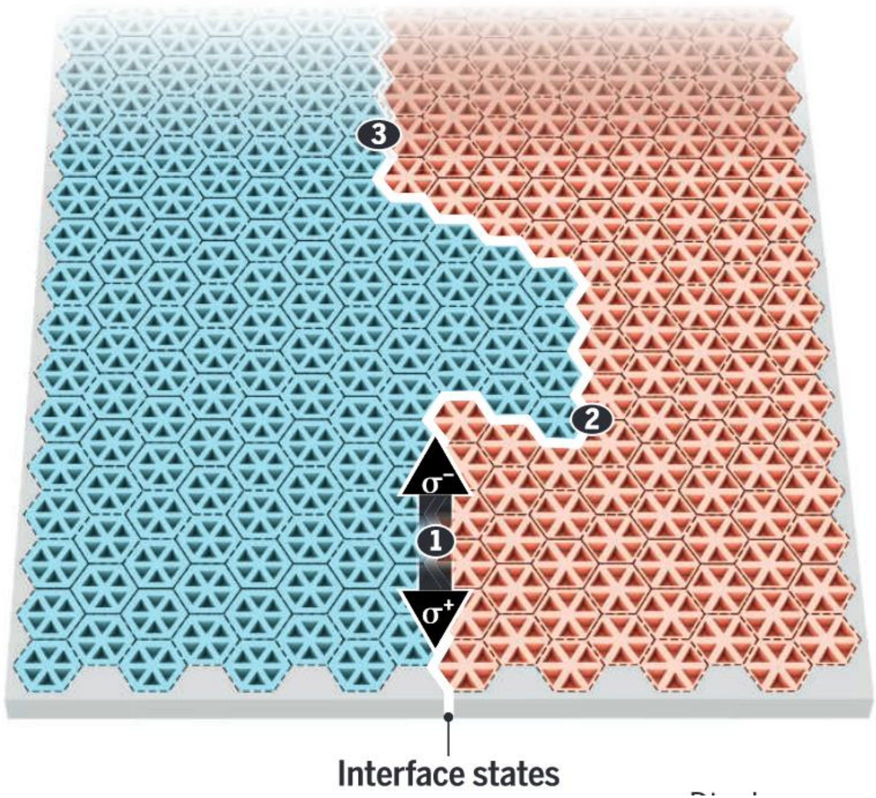
P. St-Jean et al., Nat. Photon. **11**, 651 (2017)

See also:

1D:
- H. Zhao et al., Nat. Comm. **9**, 981(2018)
- M. Parto et al., PRL **120**, 113901 (2018)

2D:
- B. Bahari et al., Science **358**, 636 (2017)
- M. A. Bandres et al., Science **359** aar4005 (2018)
- S. Klembt et al., Nature **562**, 552 (2018)

Topology in 2D photonic crystals



A. Amo, Science **359**, 638 (2018)

Is it possible to create a topological 2D material?

$$C = \frac{1}{2\pi} \oiint_{BZ} \underbrace{\nabla_{\boldsymbol{k}} \times \langle \psi(\boldsymbol{k}) | i\nabla_{\boldsymbol{k}} | \psi(\boldsymbol{k}) \rangle}_{} \cdot d\boldsymbol{s}$$

$\boldsymbol{\Omega}(\boldsymbol{k})$ **Berry curvature**

- **Time-reversal symmetry** ➡ $\boldsymbol{\Omega}(\boldsymbol{k}) = -\boldsymbol{\Omega}(-\boldsymbol{k})$

See: Z. Wang et al., Nature 461, 772 (2009)

- **Inversion symmetry** ➡ $\boldsymbol{\Omega}(\boldsymbol{k}) = \boldsymbol{\Omega}(-\boldsymbol{k})$

⬇

$C = 0$

Valley Hall topology in photonic crystals

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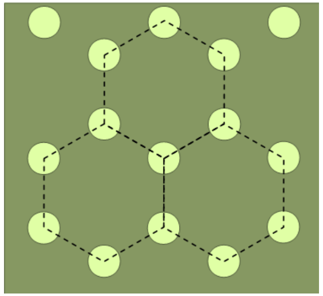
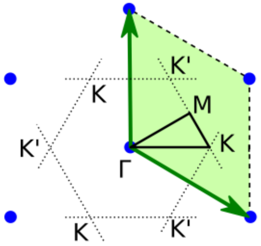
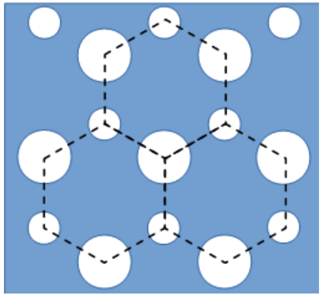
Honeycomb lattice



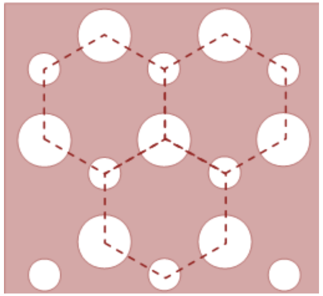


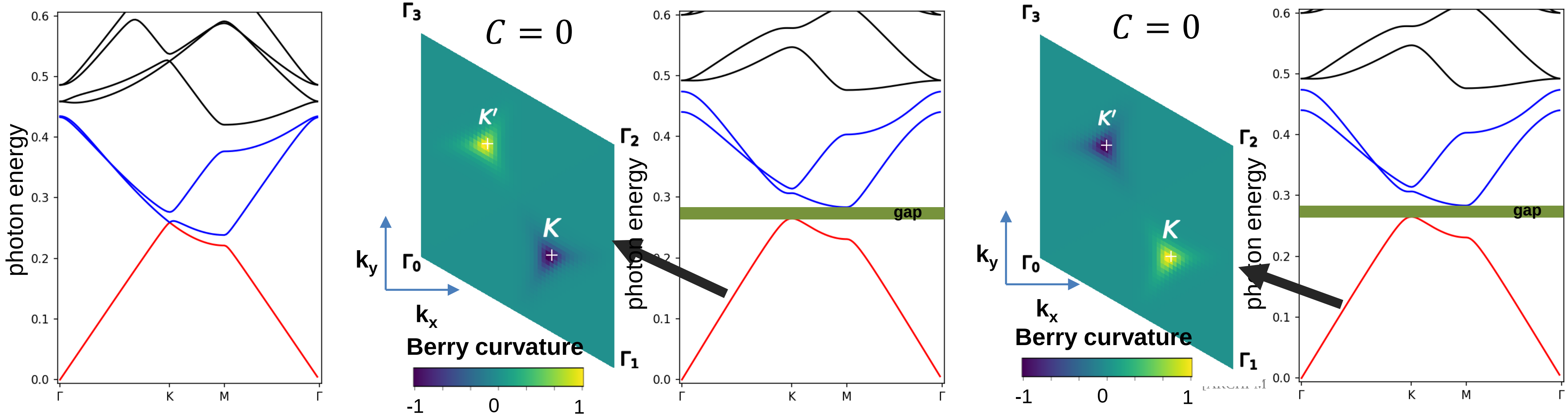
Brillouin zone

Boron nitride - 1



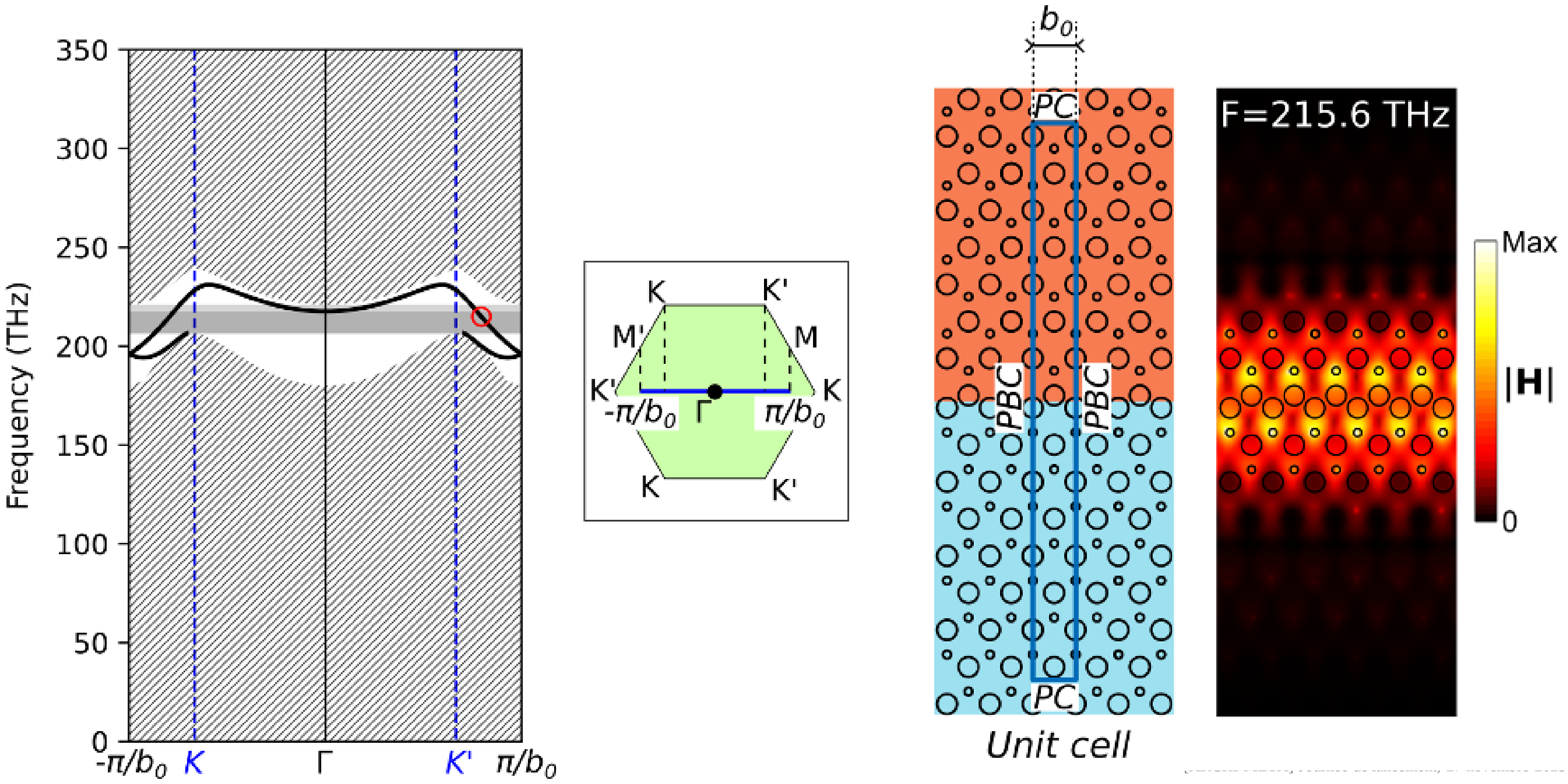
Boron nitride - 2





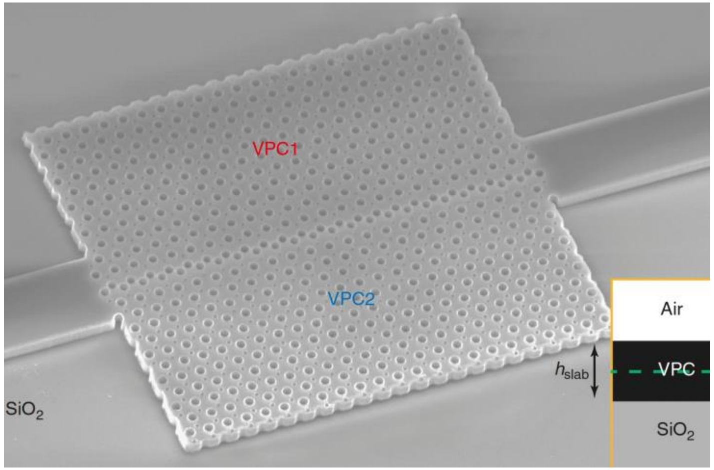
Valley Hall topology in photonic crystals

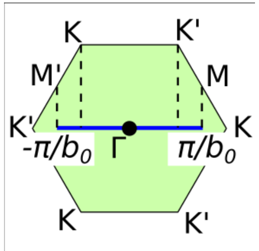
Interface modes



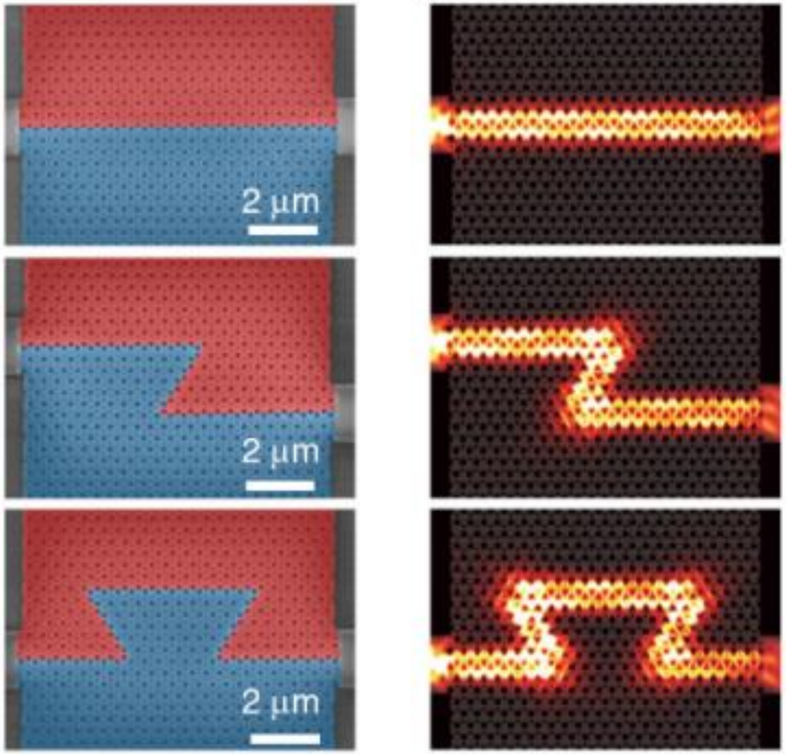
Valley Hall topology in photonic crystals

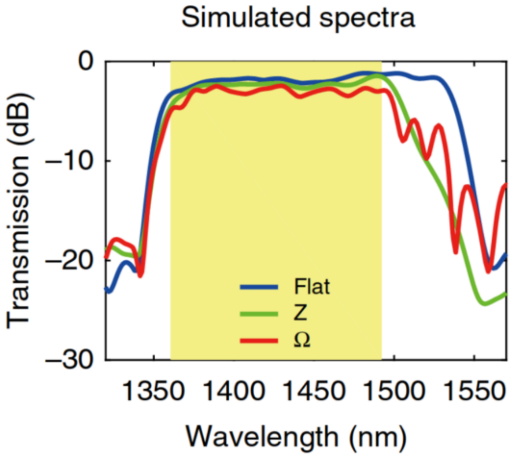
Interface modes





Go around corners with high transmission!!



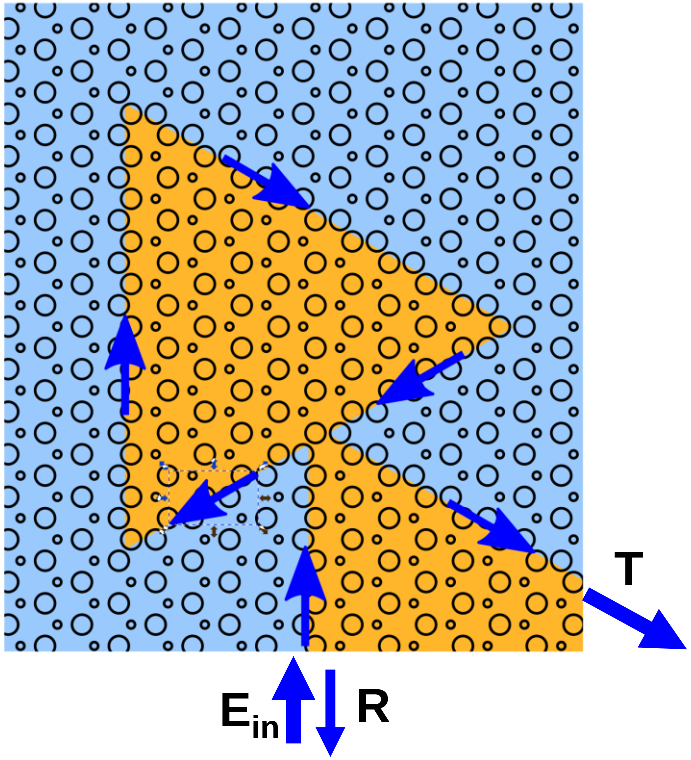


As long as valley is preserved (60º turns)

X.-T. He et al.,
Nat. Commun. **10**, 872 (2019)

Quantifying topological protection: simulations

Triangular cavity



If perfect topological protection

no backscattering

T=1 all over the gap

G. Lévêcque et al.,
PRA **108**, 043505 (2023)

Quantifying topological protection: simulations

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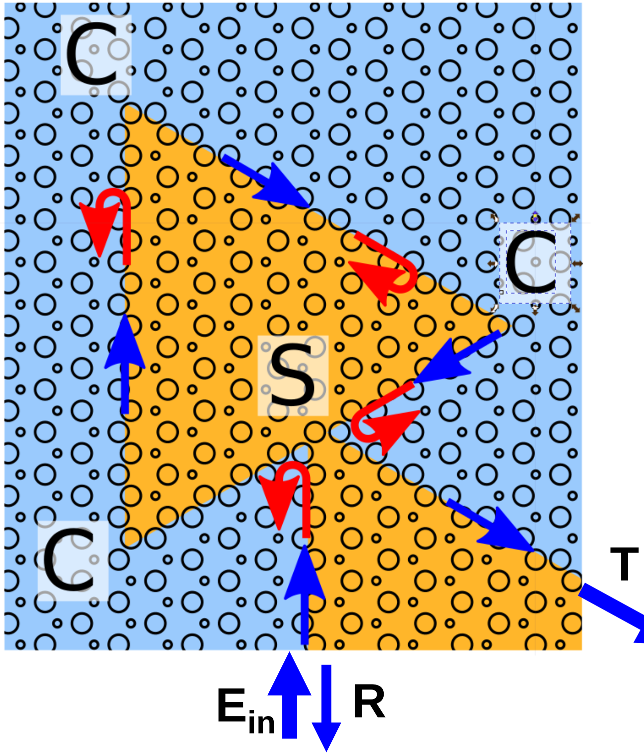
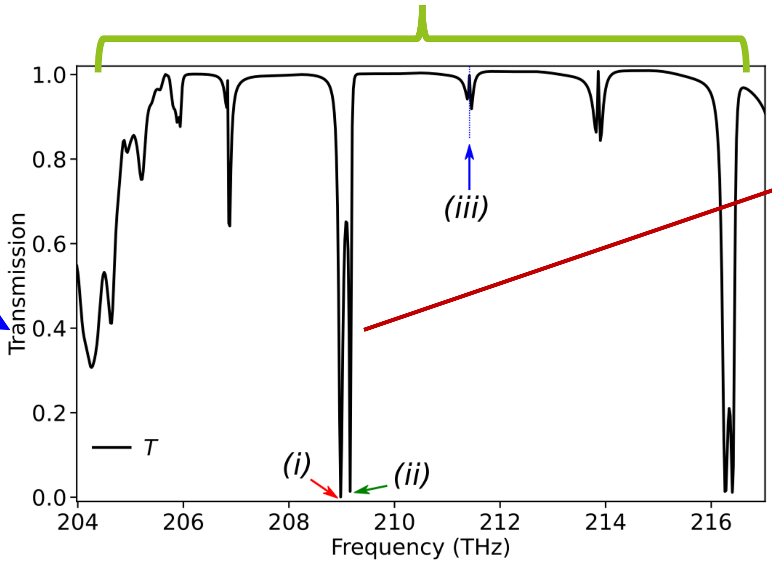
Triangular cavity

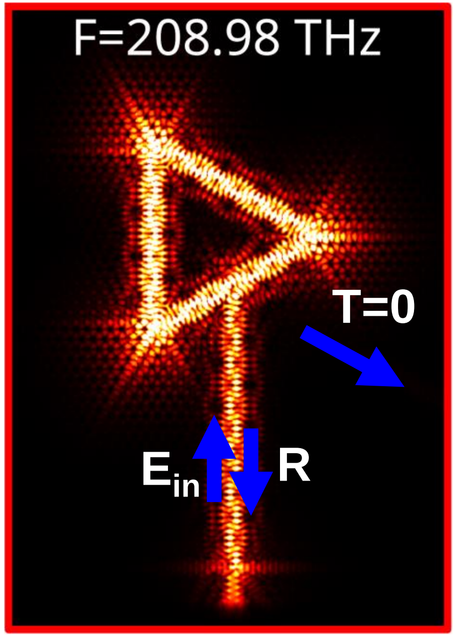


From finite element simulations: backreflection at corners ~ 1-2%

Triangular holes: 0.01%



simulation



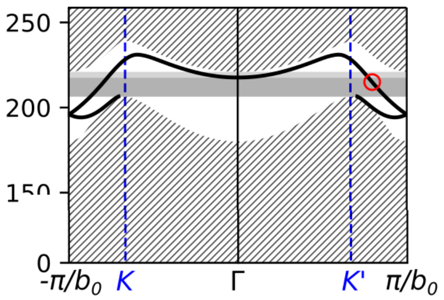
G. Lévêcque et al.,
PRA **108**, 043505 (2023)

Valley Hall effect

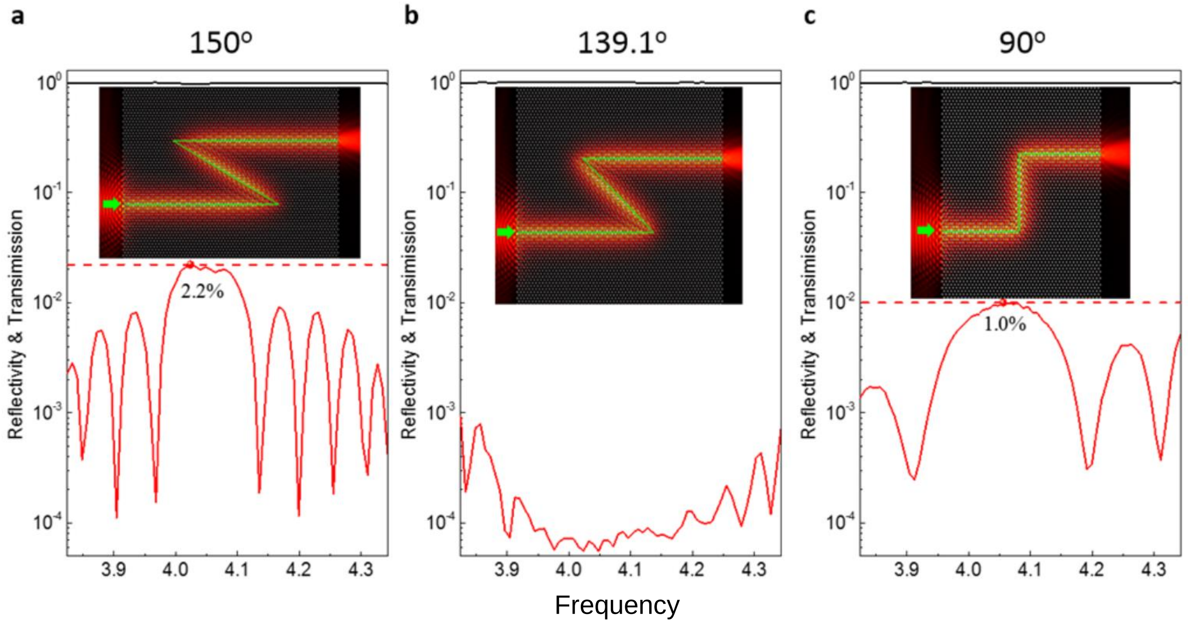
Topological protection is not perfect

G. Lévêcque et al., PRA **108**, 043505 (2023)

See also: S. Arora et al., LSA **10**, 9 (2021)
C. A. Rosiek et al., Nat. Photon. 17, 386 (2023)



K-valley conservation is not required!!



Is topology the right framework to understand these channels?

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

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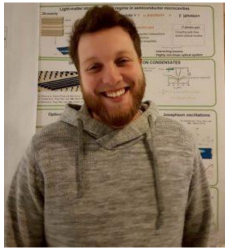
Palaiseau
(France)

Lattices of micropillars


Nicolas Pernet


Philippe St-Jean


Nicola Carlon Zambon


Jacqueline Bloch


Sylvain Ravets

Sample fabrication


Martina Morassi


Aristide Lemaître


Luc LeGratiet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Photonic crystals


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