Topological Insulators for Light and Sound

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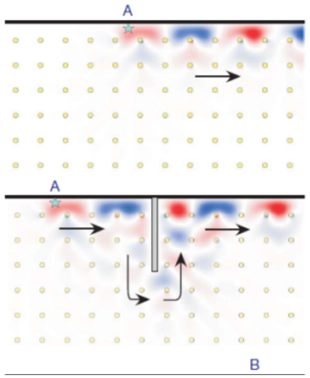
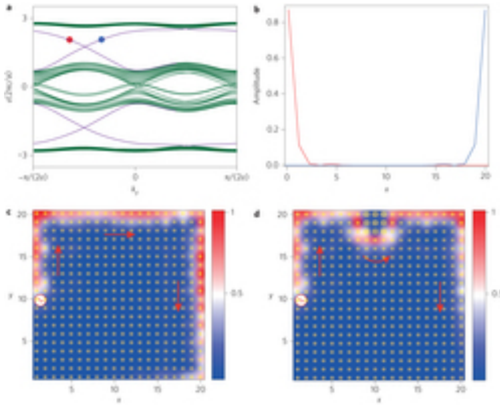
&The Center for Functional Nanomaterials,

Brookhaven National Laboratory, Upton, NY

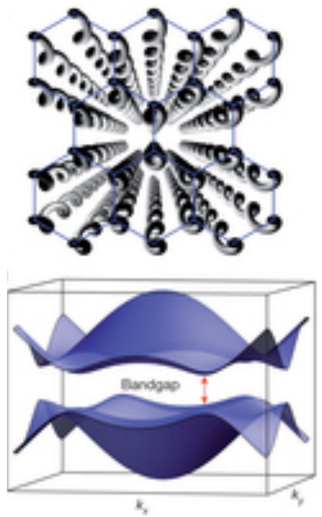
Topological order for photons

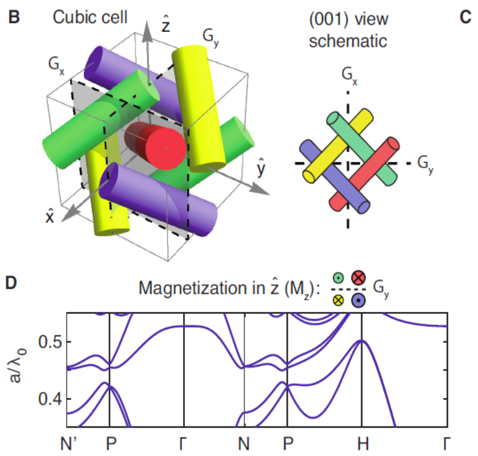
Broken TR symmetry





PRL **100**, 013904, (2008)
Nature 461, 772-775 (2009). *Nature Photon.* 6, 782–787 (2012)

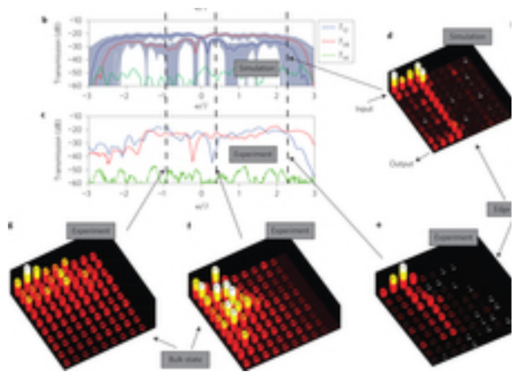


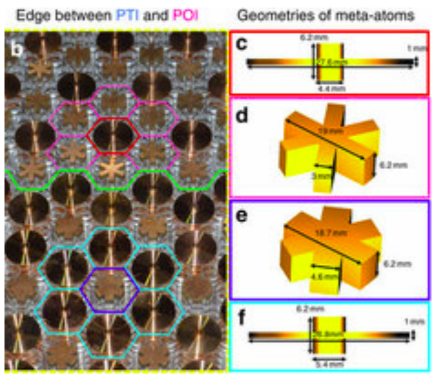


Nature 496,
196–200, (2013)

arXiv:1507.00337 (2015)
Nature Physics (2016)

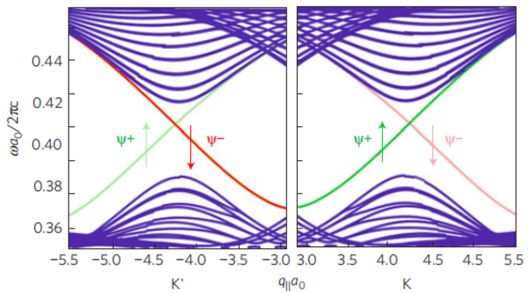
Preserved TR symmetry

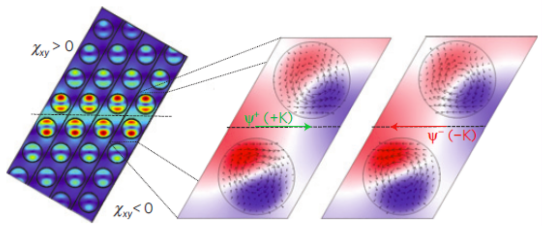


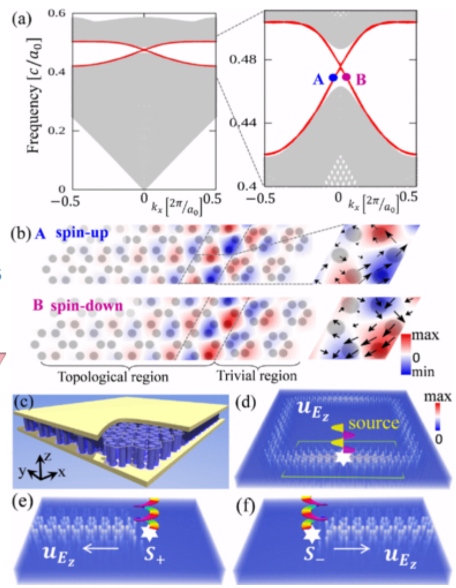


Nature Phys. **7**, 907–912 (2011).
Nature Photon. **7**, 1001–1005 (2013)

Nature Comm. 5, 5782, (2014)







arXiv:1401.1276 (2012)
Nature Mater. **12**, 233–239 (2013)

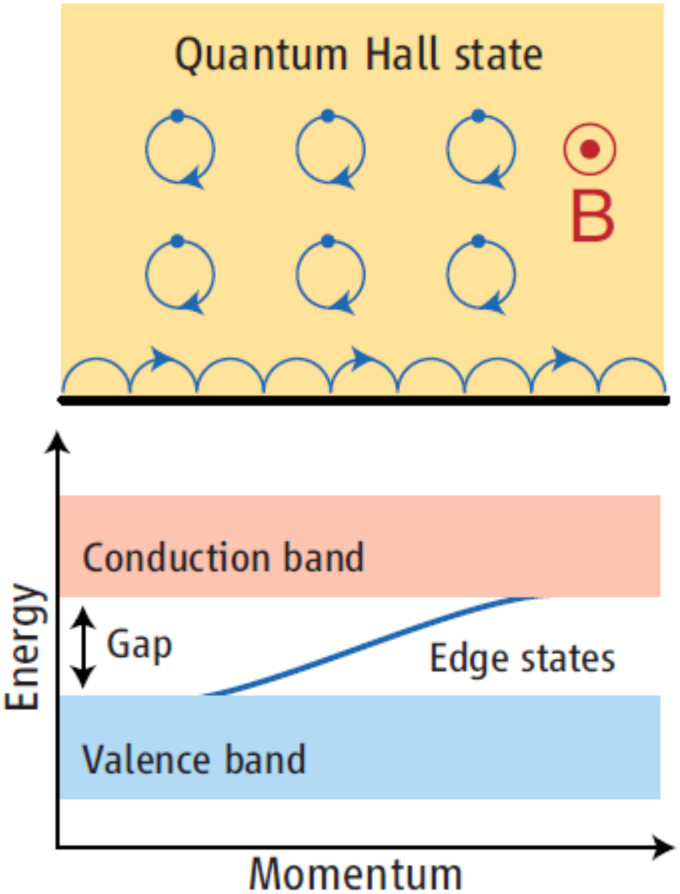
Phys. Rev. Lett. **114**, 223901 (2015)

Topological roadmap:
From Quantum Hall effect to Topological insulators

Broken TR symmetry

$$H = H_0 - \mu_B \boldsymbol{S}\cdot\boldsymbol{B}$$

One-way edge states



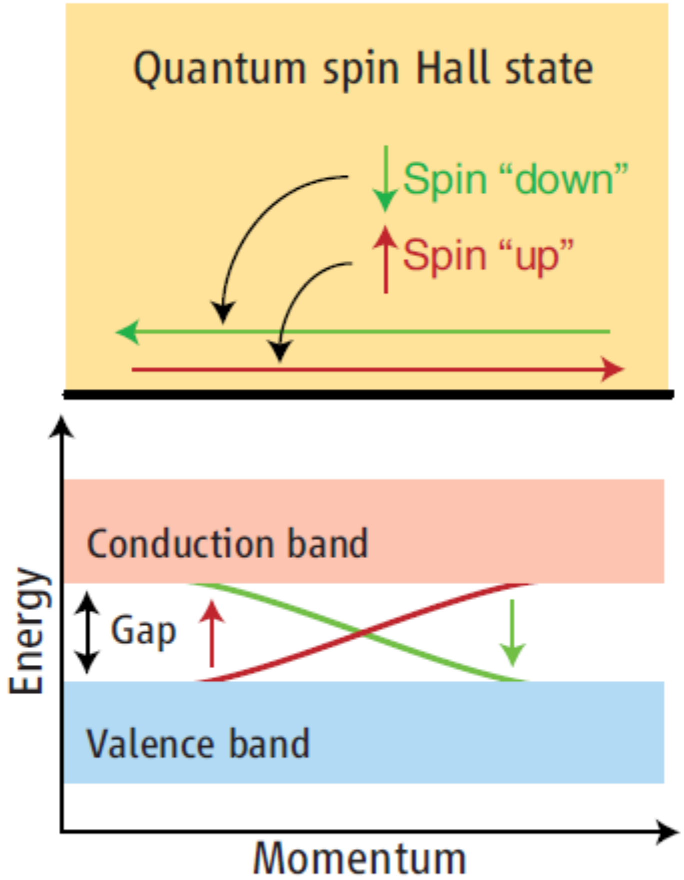
v. Klitzing, *Phys. Rev. Lett.* **45**, 494 (1980).
Nobel prize 1985

Robust edge states in the gap

Preserved TR symmetry

$$H = H_0 - \chi_{SO} \boldsymbol{S}\cdot\boldsymbol{L}$$

Spin-locked one-way edge states



Kane, C. L. & Mele, E. J.,
Phys. Rev. Lett. **95**, 146802 (2005).

Role of Symmetry and Gauge Potentials in Topological Phases

Preserved TR symmetry ensures the presence of Kramer's TR partners (two spins/ helicities) in fermionic systems but no in bosonic.

Fermions

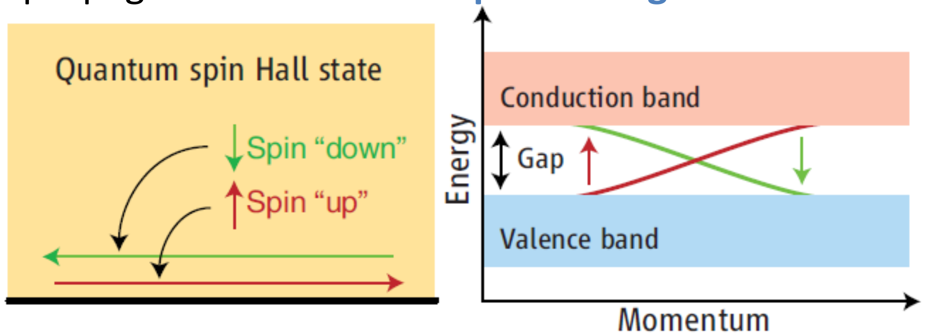
$$\mathcal{H} = \mathcal{H}_0 + V_{SO}$$

$\mathcal{H}_0$ - unperturbed fermionic lattice potential

$V_{SO} = -\chi_{SO}\, \boldsymbol{S} \cdot \boldsymbol{L}$ - gauge (SO) potential inducing topological transition (band crossing)

$$\mathcal{T}_f \mathcal{H} \mathcal{T}_f^{-1} = -\mathcal{H} \text{ and } \mathcal{T}_f^2 = -1$$

Robustness is insured by TR symmetry (no magnetic defects are allowed).
Doublets generated by TR are locked to their propagation directions – **spin-locking.**



Kane, C. L. & Mele, E. J., *Phys. Rev. Lett.* **95**, 146802 (2005).
Hasan, M. Z. & Kane, C. L., Rev. Mod. Phys. 82, 3045-3067 (2010).
Qi, X.-L. & Zhang, S.-C., Rev. Mod. Phys. 83, 1057-1110 (2011).

Bosons

$$\mathcal{H} = \mathcal{H}_0 + V_{gauge}$$

$\mathcal{H}_0$ - unperturbed bosonic lattice potential

$V_{gauge} =$ **Photonic** gauge potential (SO or pseudo-magnetic) inducing topological transition

$$\mathcal{T}_b \mathcal{H} \mathcal{T}_b^{-1} = \mathcal{H} \text{ and } \mathcal{T}_b^2 = 1$$

Consequence: TR alone is not sufficient for topological order for bosons, i.e. no topological phase analogous to fermionic TR phase is possible.

Solution: non-TR symmetry protected phases.

$$C_b \mathcal{H} C_b^{-1} = -\mathcal{H} \text{ and } C_b^2 = -1$$

Where C_b is a spatial or internal symmetry operator generating a doublet state – **pseudo-spin degree of freedom**.

$$\mathcal{T}_b\, \psi_{\uparrow(\downarrow)}(\boldsymbol{k}) = \mathcal{T}_b\, \psi_{\downarrow(\uparrow)}(-\boldsymbol{k})$$

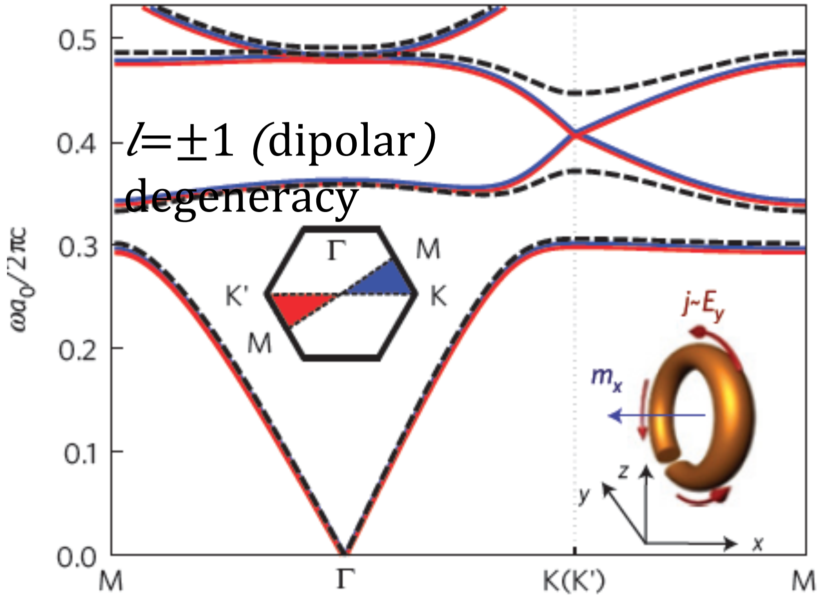
Role of Symmetry and Gauge Potentials in Topological Phases

Photonic topological insulator:
I. Duality of EM field as the pseudo-spin generating symmetry

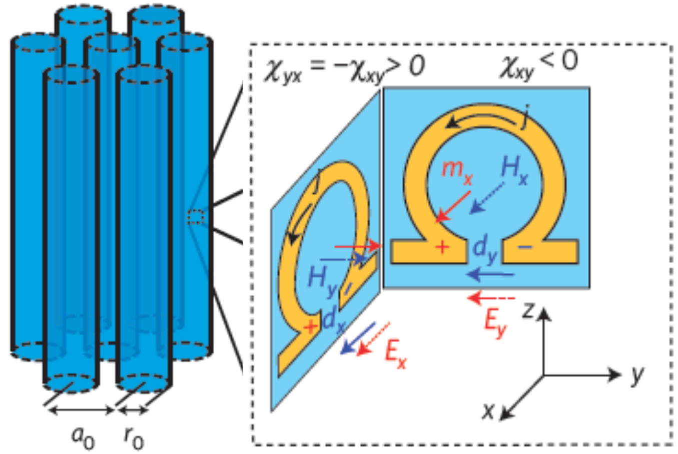
Duality in free space follows by the symmetry of Maxwell equations with respect to electric and magnetic fields: $D\,(\boldsymbol{E},\boldsymbol{H}) \rightarrow (-\boldsymbol{H},\boldsymbol{E})$

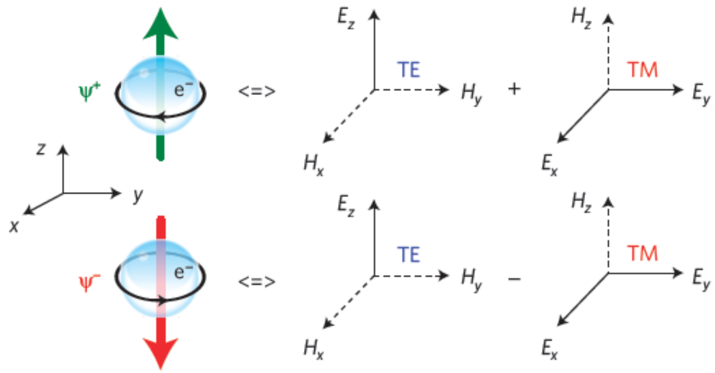
Broken by materials response $\epsilon \neq \mu$, it can be restored by (meta-)material's design.

In dual material $\epsilon_{zz} = \mu_{zz}$, $\epsilon_{\perp} = \mu_{\perp}$, duality transformation operator, which satisfies $D^2 = -1$, allows emulating spin degree of freedom.



Khanikaev *et al.*, Nat. Mater. **12**, 233 (2013).





$$\psi^{\pm}(\boldsymbol{r},\boldsymbol{k}) = E_z(\boldsymbol{r},\boldsymbol{k}) \pm H_z(\boldsymbol{r},\boldsymbol{k})$$

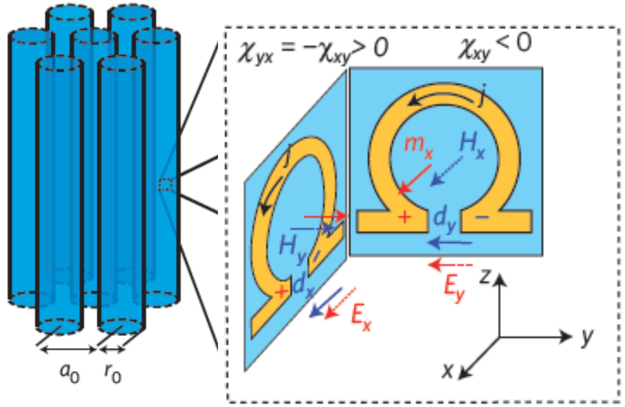
$$\mathcal{T}_b\, \psi^{\pm}(\boldsymbol{r},\boldsymbol{k}) = \psi^{\mp}(\boldsymbol{r},-\boldsymbol{k})$$

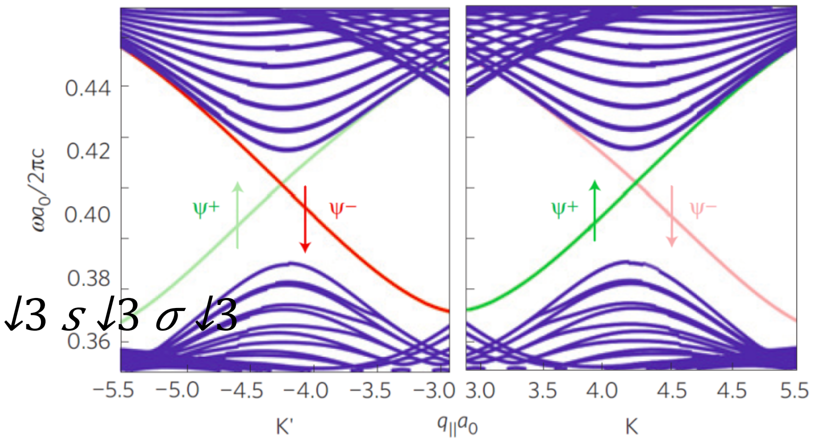
Role of Symmetry and Gauge Potentials in Topological Phases

Photonic topological insulator:
II. Bianisotropy as the gauge field

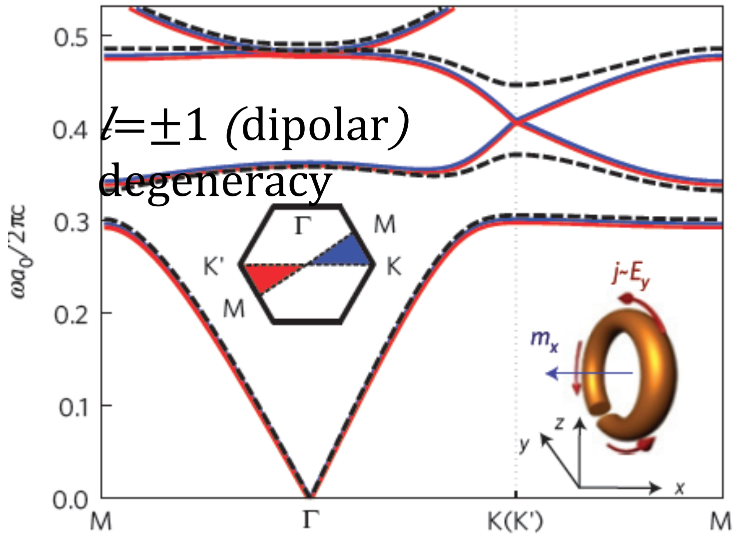
$\chi=(\blacksquare 0\&\chi\&0@-$

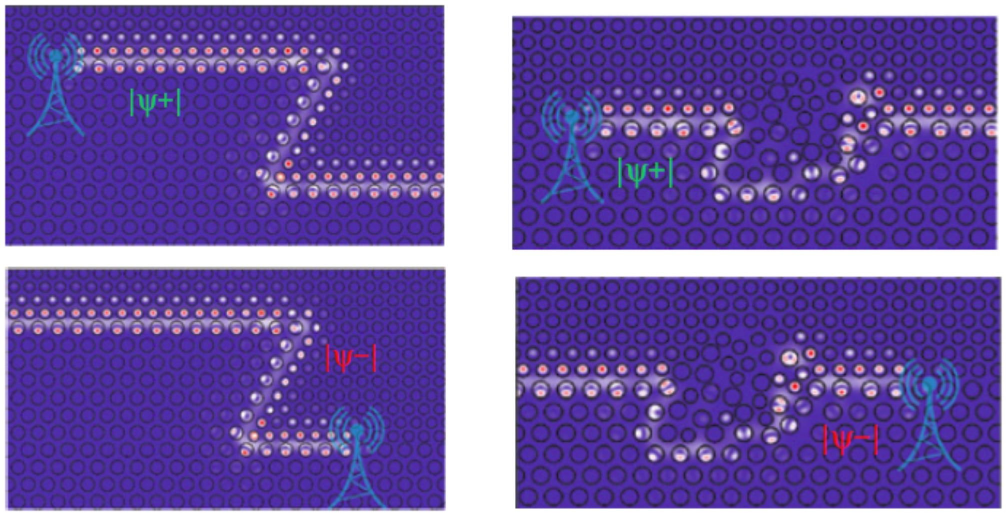
$\boldsymbol{D}=\epsilon\,\boldsymbol{E}+i\chi\,\boldsymbol{H}$ and $\boldsymbol{B}=\mu\,\boldsymbol{H}-i\chi^{T}\boldsymbol{E}$, where





$\mathcal{H}_{\uparrow/\downarrow}=v_D\,\tau_0\,s_0\,\boldsymbol{\sigma}_{\|}\cdot\delta\boldsymbol{k}_{\|}+m\tau_3\,s_3\,\sigma_3$





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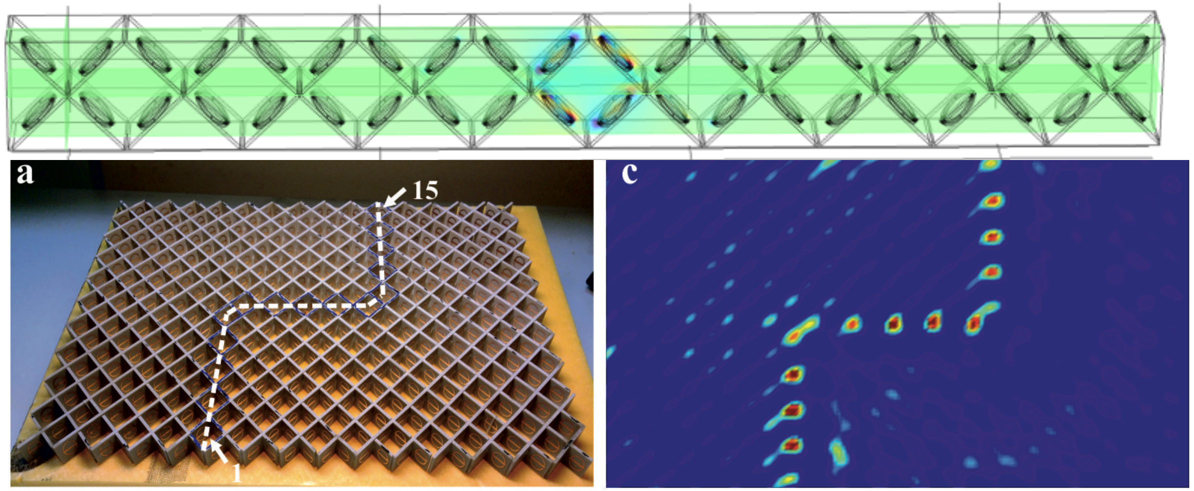
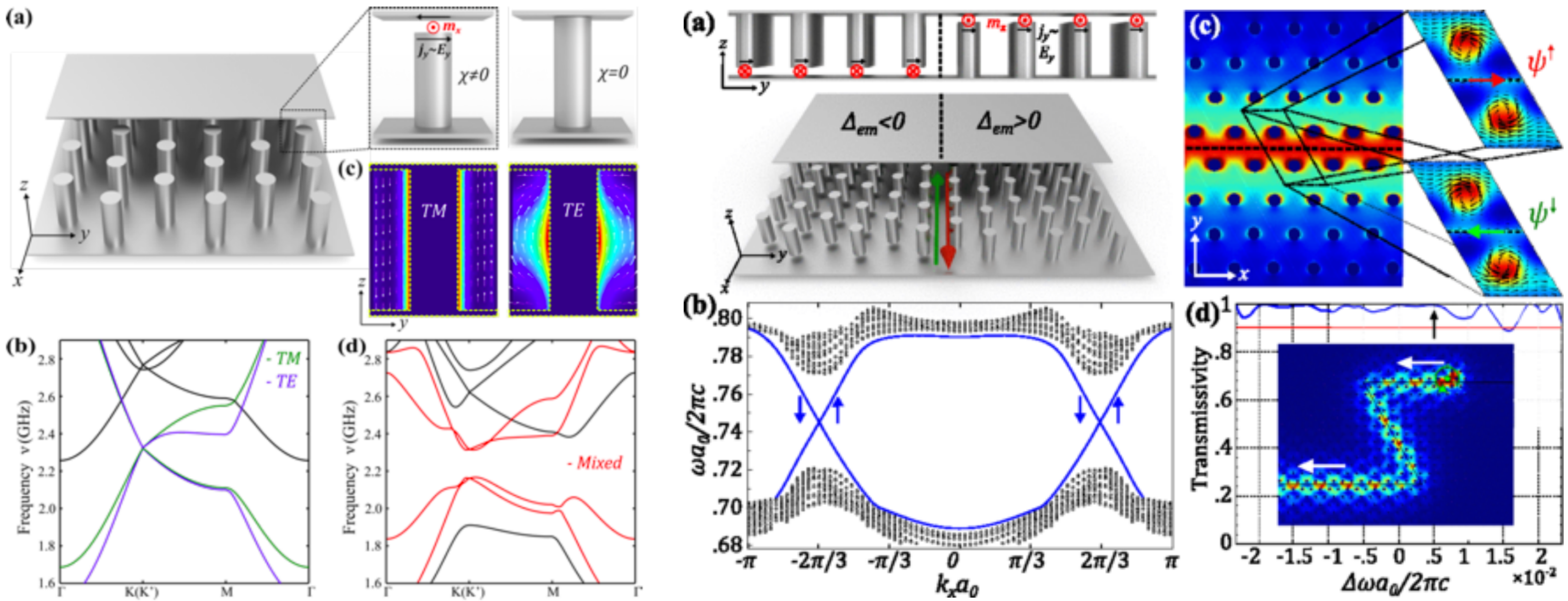
Practical designs of photonic topological insulators



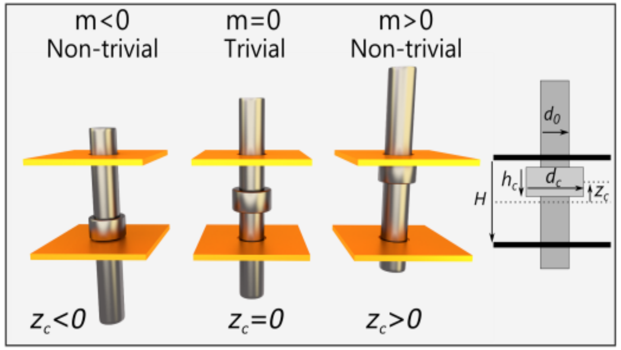
A. P. Slobozhanyuk, A. B. Khanikaev, D. S. Filonov, D. A. Smirnova, A. Miroshnichenko, Y. S. Kivshar, arXiv:1507.05158 (2015).

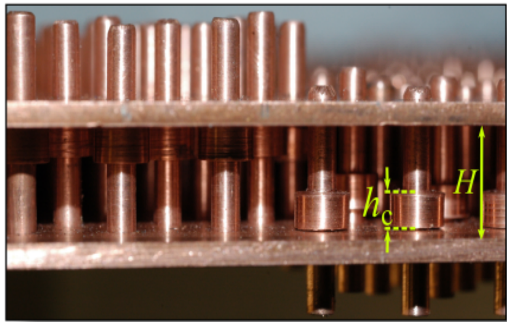


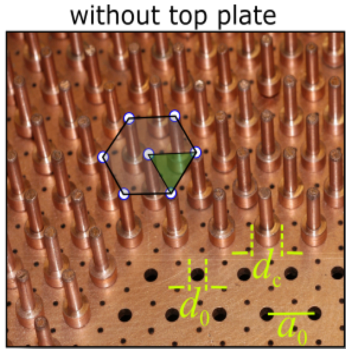
T. Ma, A. B. Khanikaev, S. H. Mousavi, and G. Shvets, arXiv:1401.1276 (2014) and Phys. Rev. Lett. **114**, 127401 (2015).

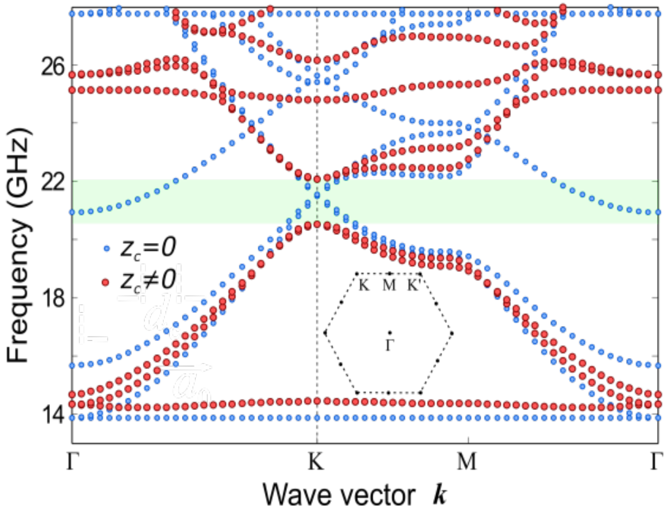
Reconfigurable photonic topological insulator

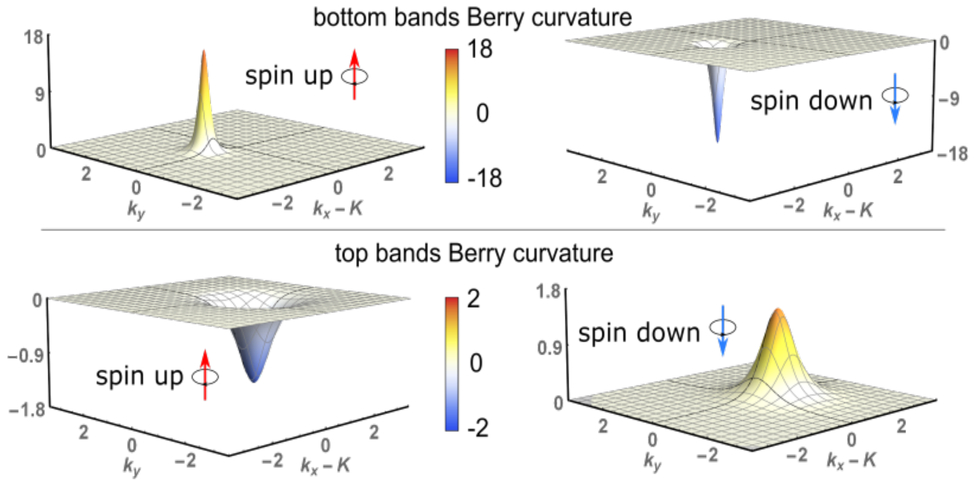
X. Cheng, C. Jouvaud, X. Ni, S. H. Mousavi, A. Z. Genack, and **A. B. Khanikaev**, *Robust propagation along reconfigurable pathways within a photonic topological insulator*, Nature Materials (2016). DOI:10.1038/nmat4573.











Effective Kane-Mele-like Hamiltonian

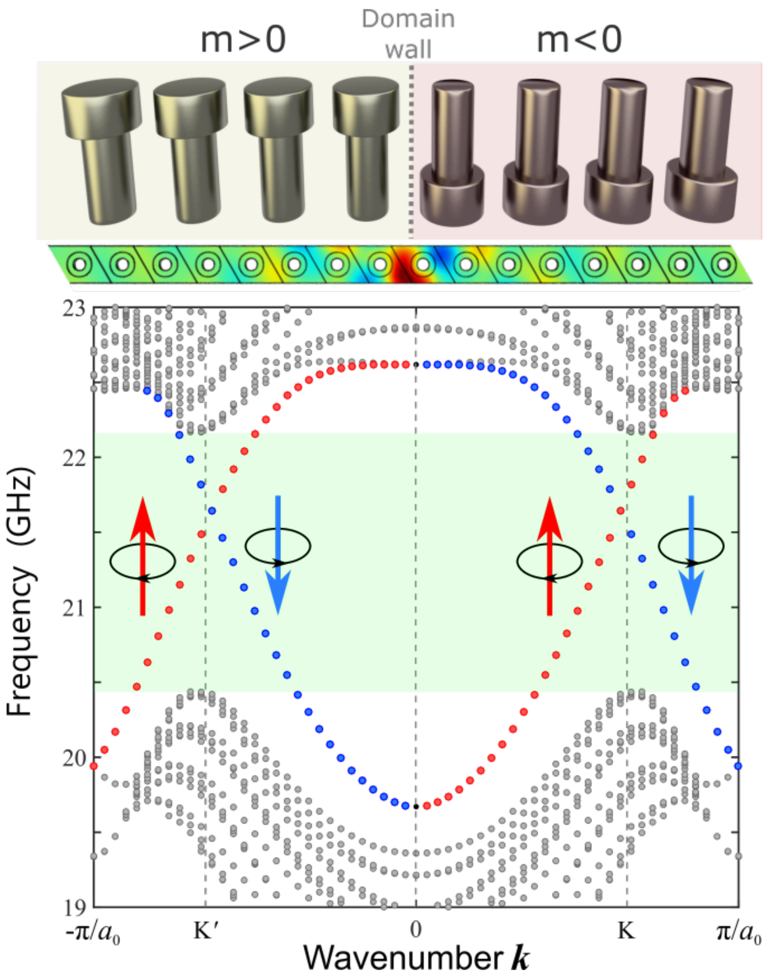
$$\mathcal{H}_{\uparrow/\downarrow} = v_D \tau_0 s_0 \boldsymbol{\sigma}_{\parallel}\cdot\delta\mathbf{k}_{\parallel} + m\tau_3 s_3 \sigma_3$$

Non-vanishing spin-Chern numbers

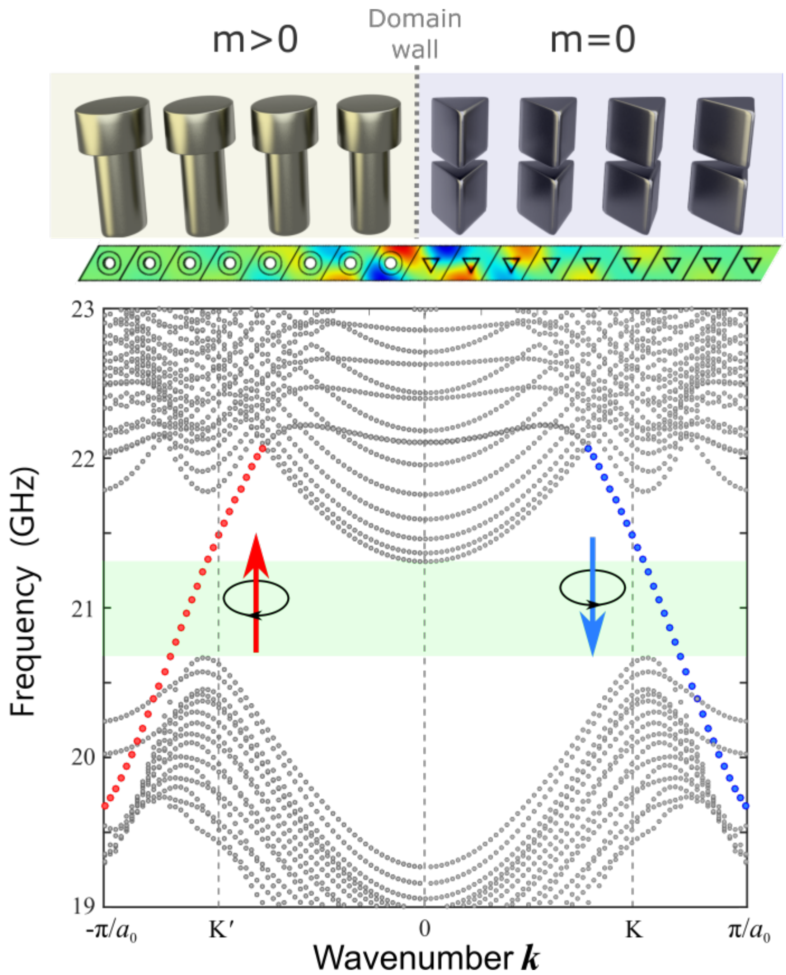
$C_{u/l}^{\uparrow} = \pm m/|m|$ and $C_{u/l}^{\downarrow} = \mp m/|m|$

Topological edge states

Reconfigurable domain wall

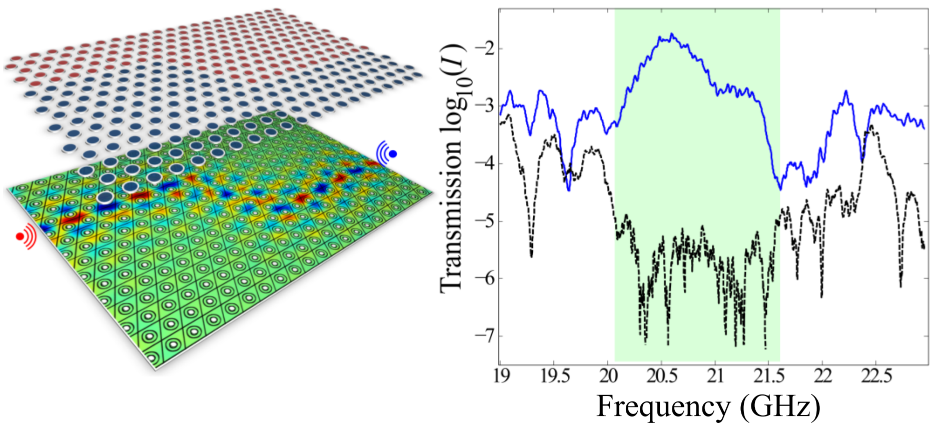


Static non-reconfigurable interface

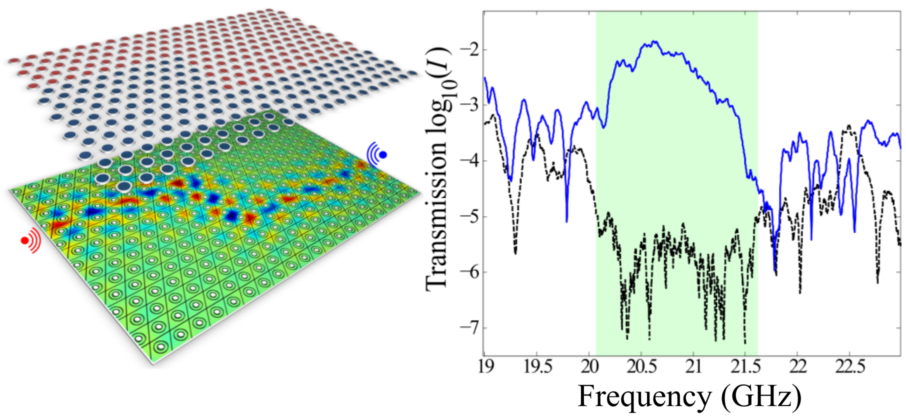


Reconfigurable guiding along arbitrarily shaped pathways

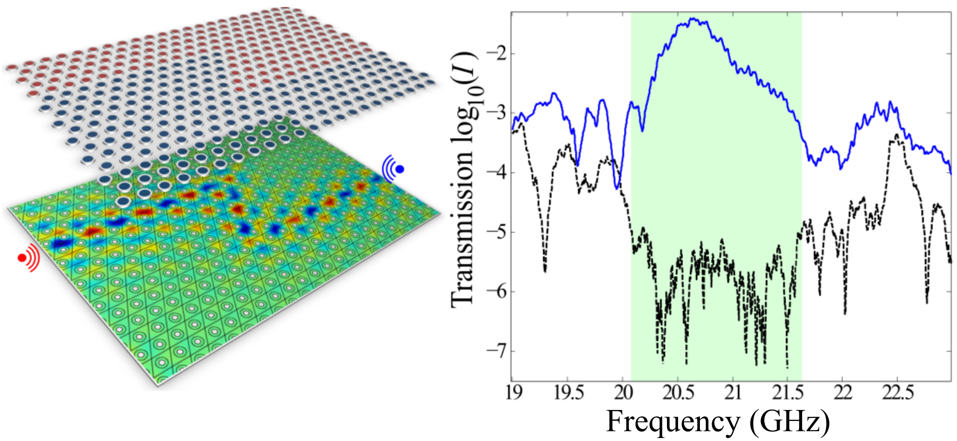
Two 60 deg. bends



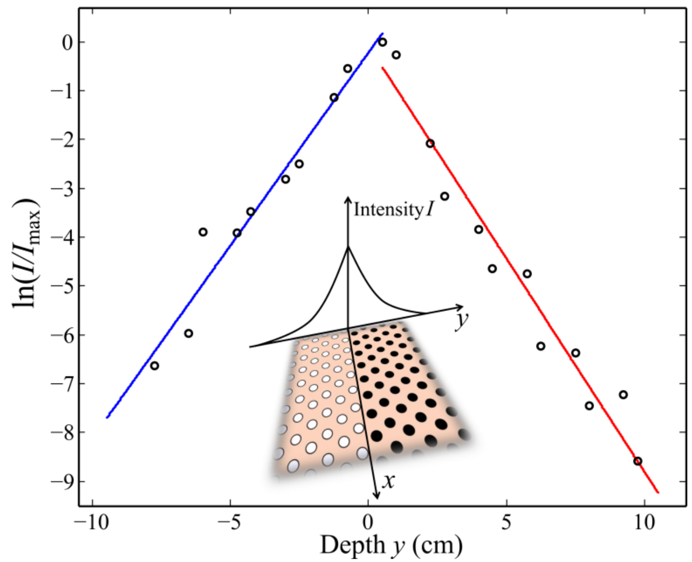
Two 90 deg. bends



Two 120 deg. bends



Exponential localization of the edge states

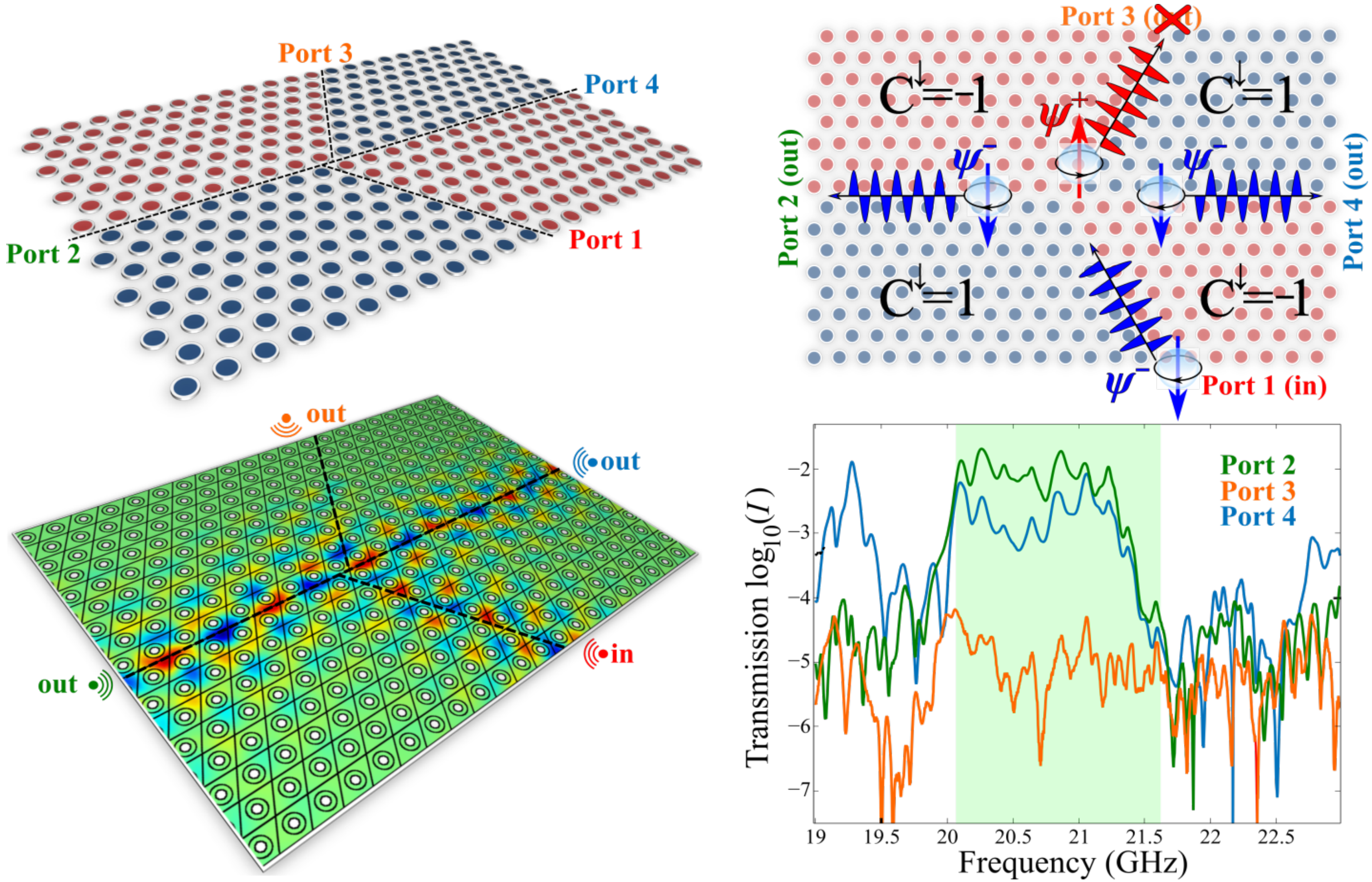


- - - - - - Transmission through the bulk

——— Transmission through the domain wall

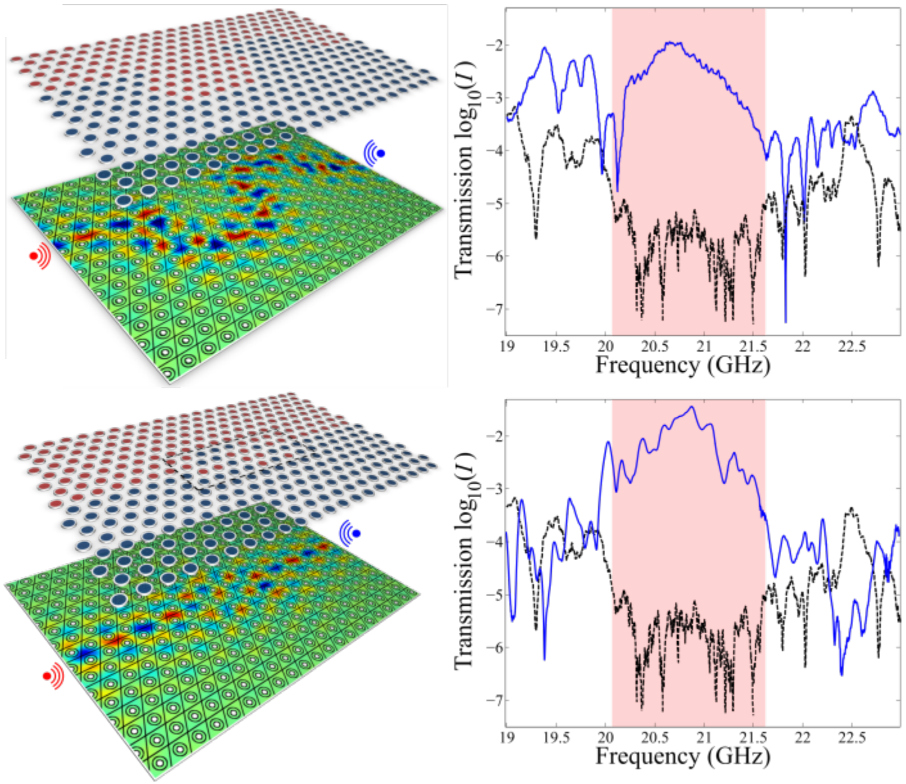
Demonstration of spin-locking of the topological edge states

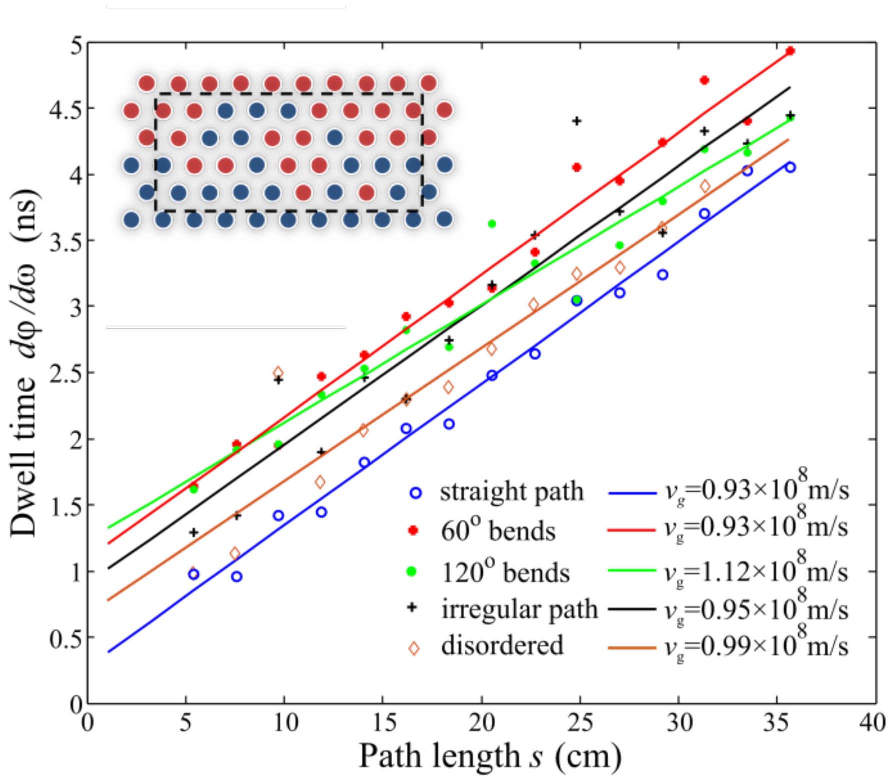
Experimental proof of spin-locked wave-division of an edge mode at
a four-port topological junction.



Robustness against disorder

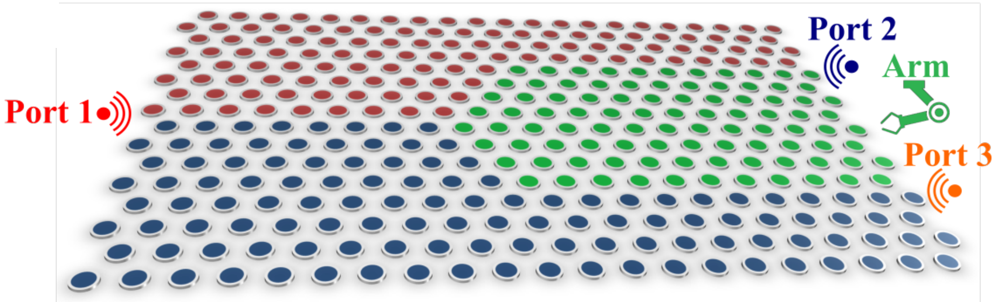
Experimental demonstration of ballistic transport of the topological edge modes through randomly shaped domain walls and disordered regions

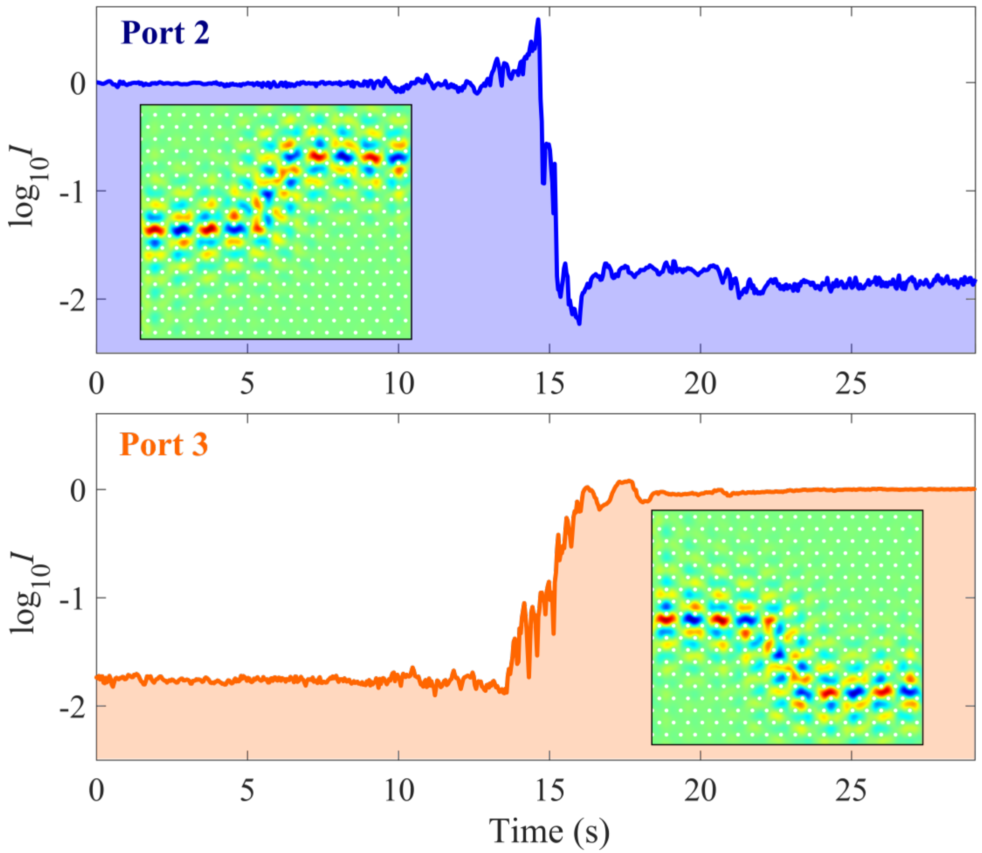




Reconfigurable topological switch: Dynamical steering of topological edge states

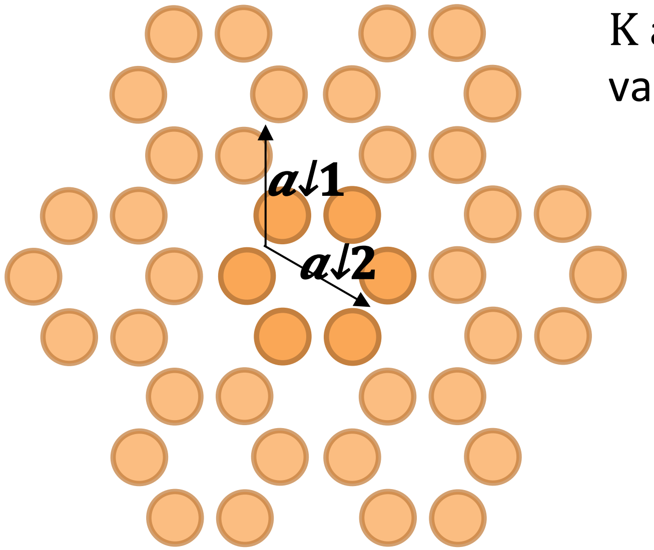
Reconfigurable topologically robust switching and its time-resolved dynamics



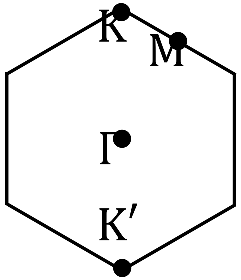


All-dielectric lattice symmetry protected topological metasurfaces

Lattice symmetry protected photonic topological metasurface (PTM)

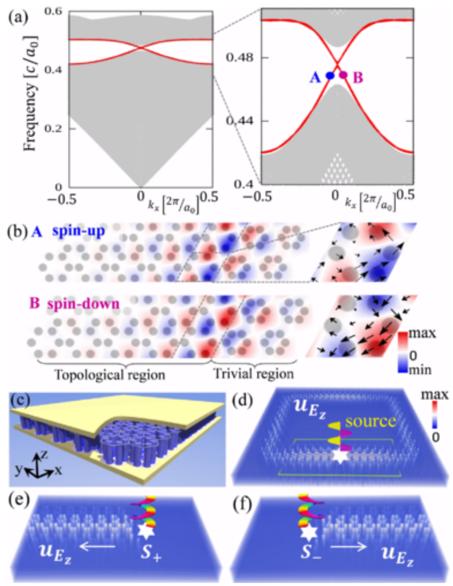


K and K′ valleys as pseudo-spin:
valley Chern insulator

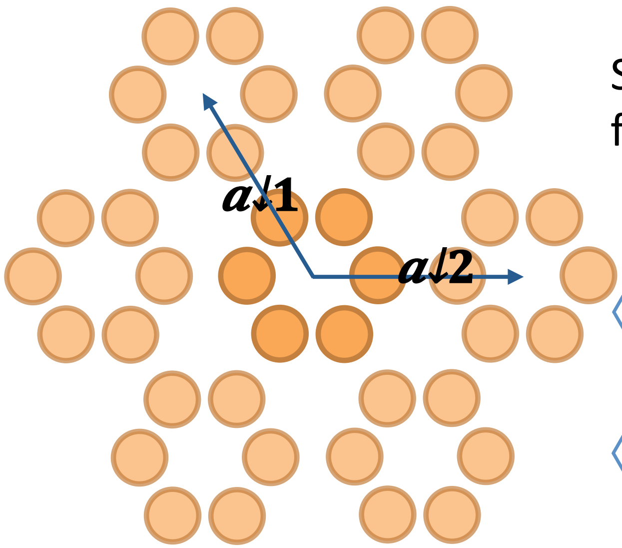


$$K=(0, 4/3\ \pi/a_0)$$

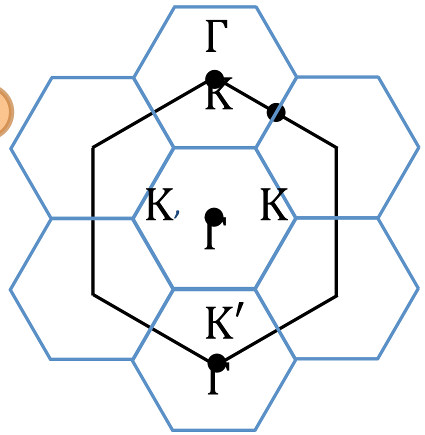
$$K'=(0, -4/3\ \pi/a_0)$$



Phys. Rev. Lett. **114**, 223901 (2015)



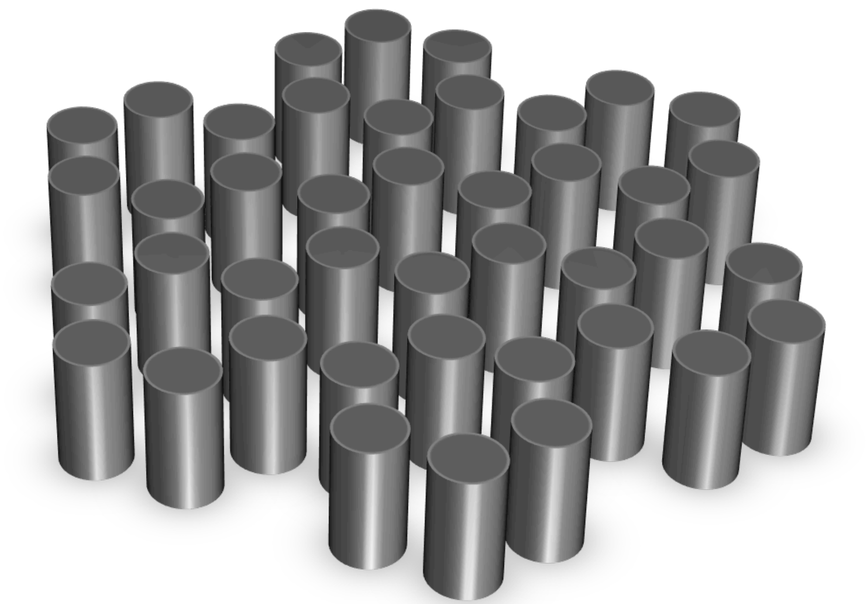
Shrinking/Expanding the "hexamer" leads to
folding of K and K' points to Γ point of the new lattice.



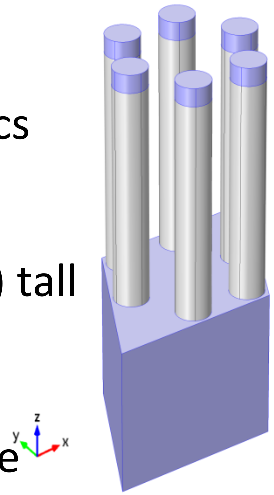
As a result of such symmetry reduction, valleys/pseudo-spins mix leading to the topological transition

Phys. Rev. Lett. **114**, 223901 (2015)

SOS (Silicon on Sapphire) implementation of all-dielectric PTM: modeling



The unit cell modeled in COMSOL® Multiphysics

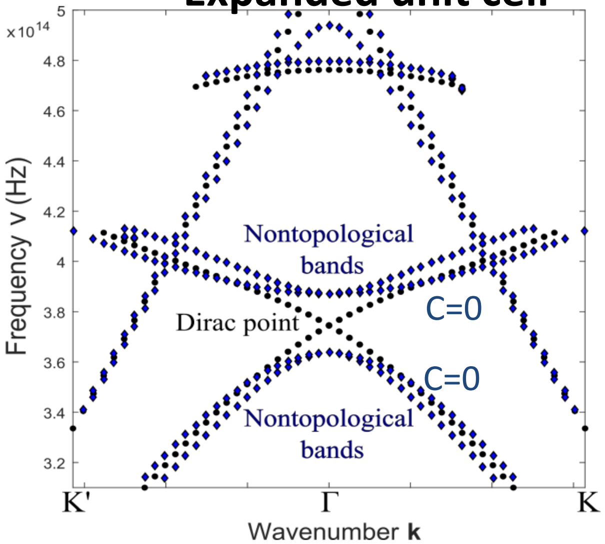


Al_2O_3 mask

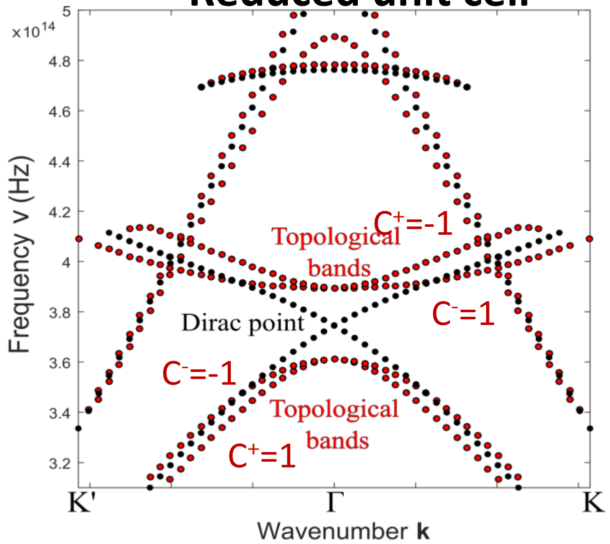
Si pillars (600 nm) tall

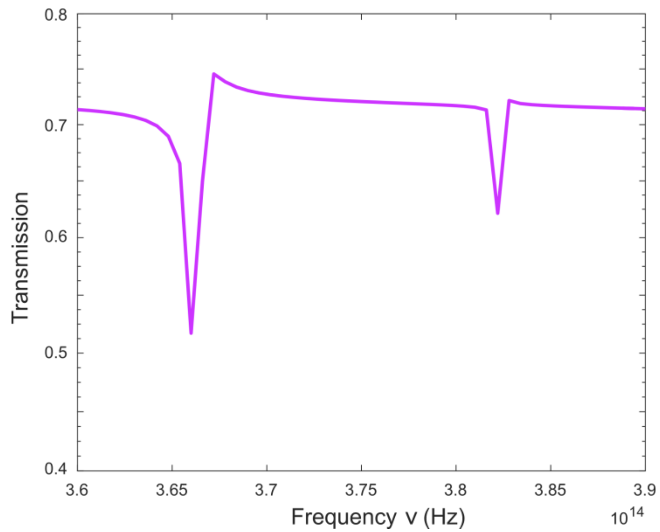
Al_2O_3 substrate

Expanded unit cell

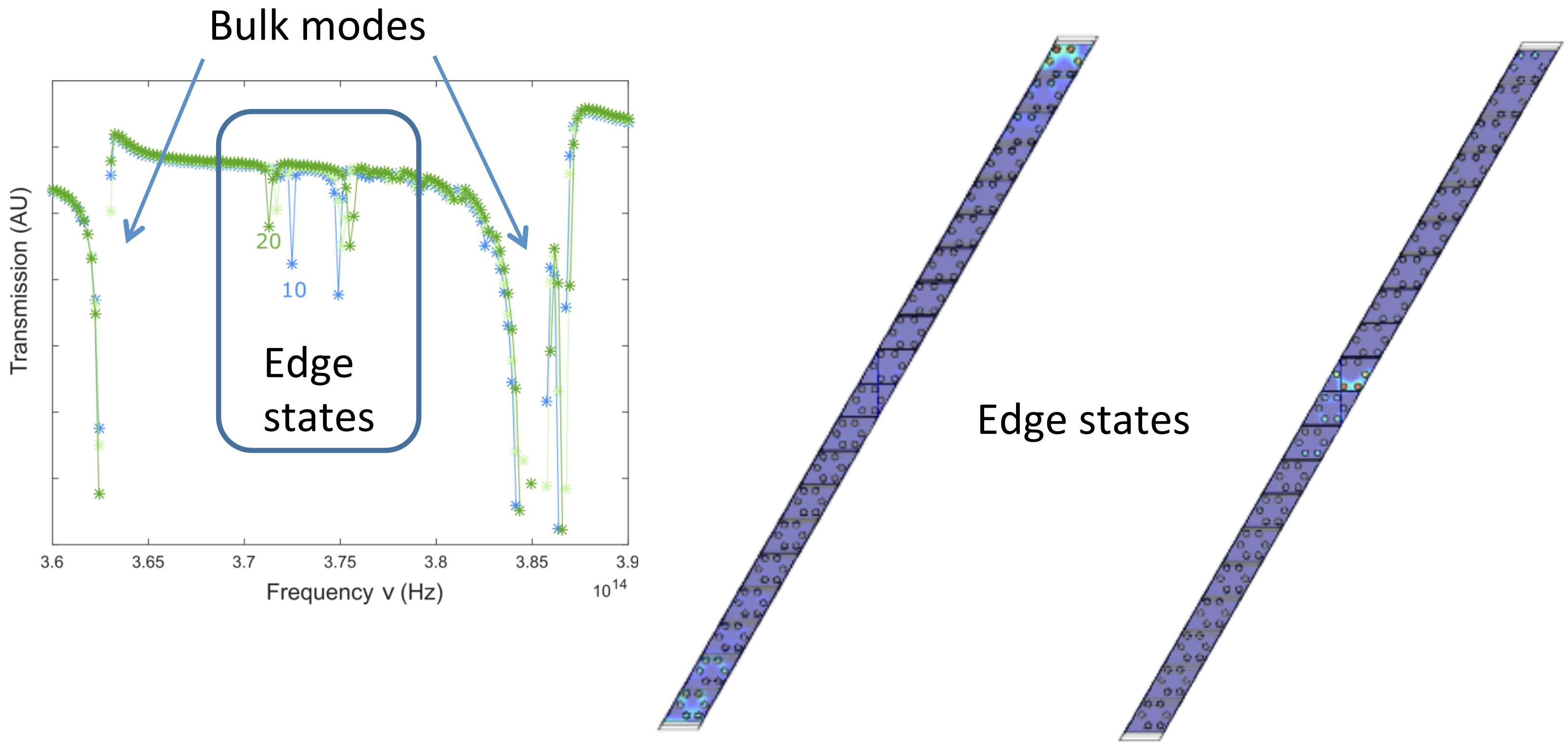


Reduced unit cell



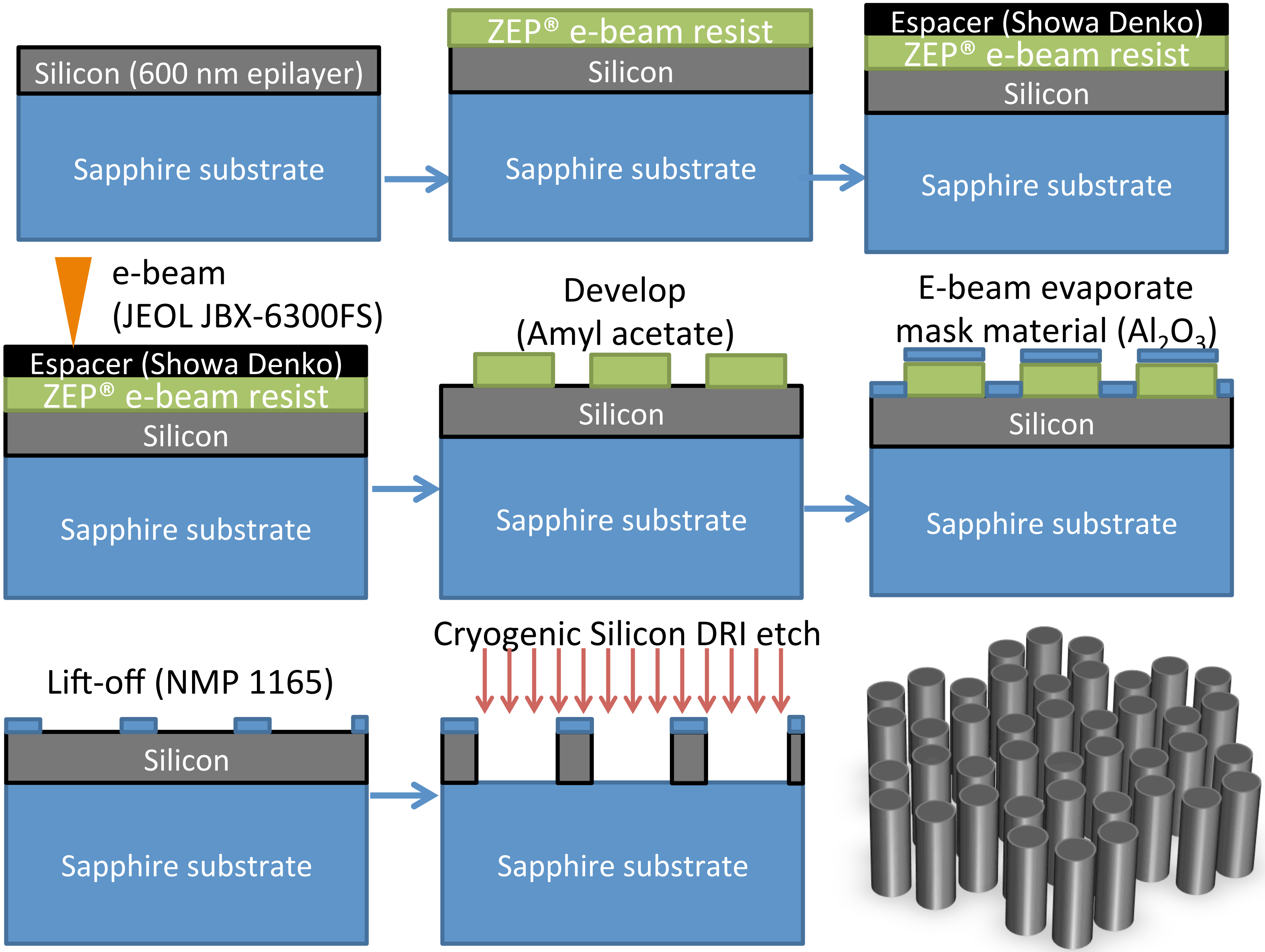


Direct excitation of topological edge states in all-dielectric topological metasurface: modeling

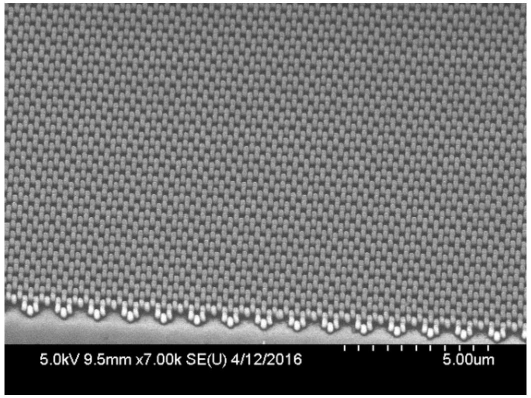


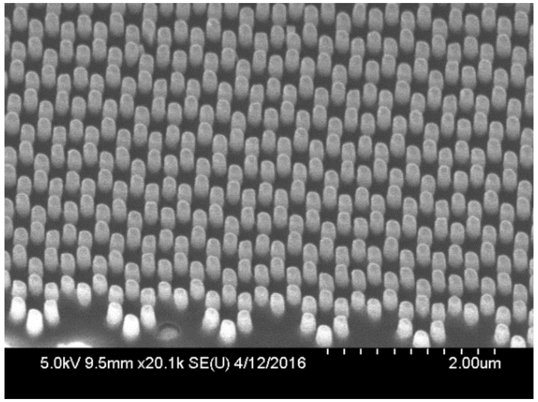
The large scale simulations of the supercell formed by 20 unit cells of 10 topologically trivial cells and 10 topologically nontrivial cells. The excitation of the edge states is evidenced by both the transmission spectra and field profiles under oblique incidence.

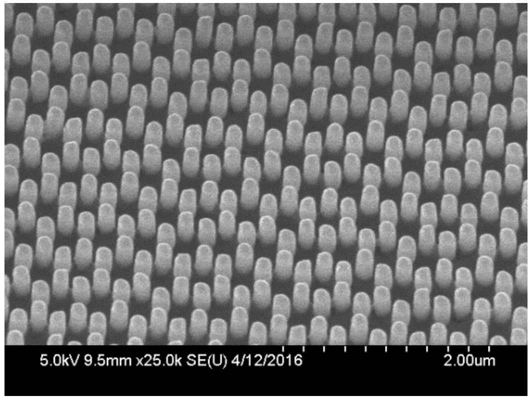
SOS (Silicon on Sapphire) implementation - recipe

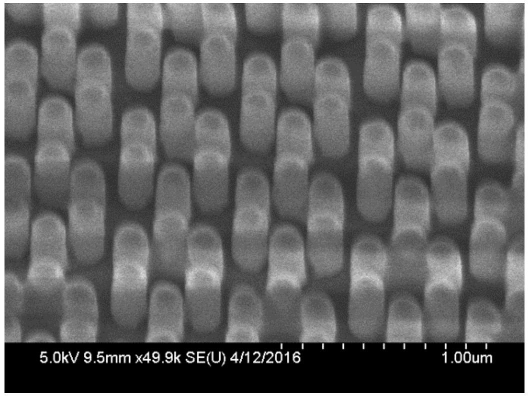


SOS (Silicon on Sapphire) implementation-result



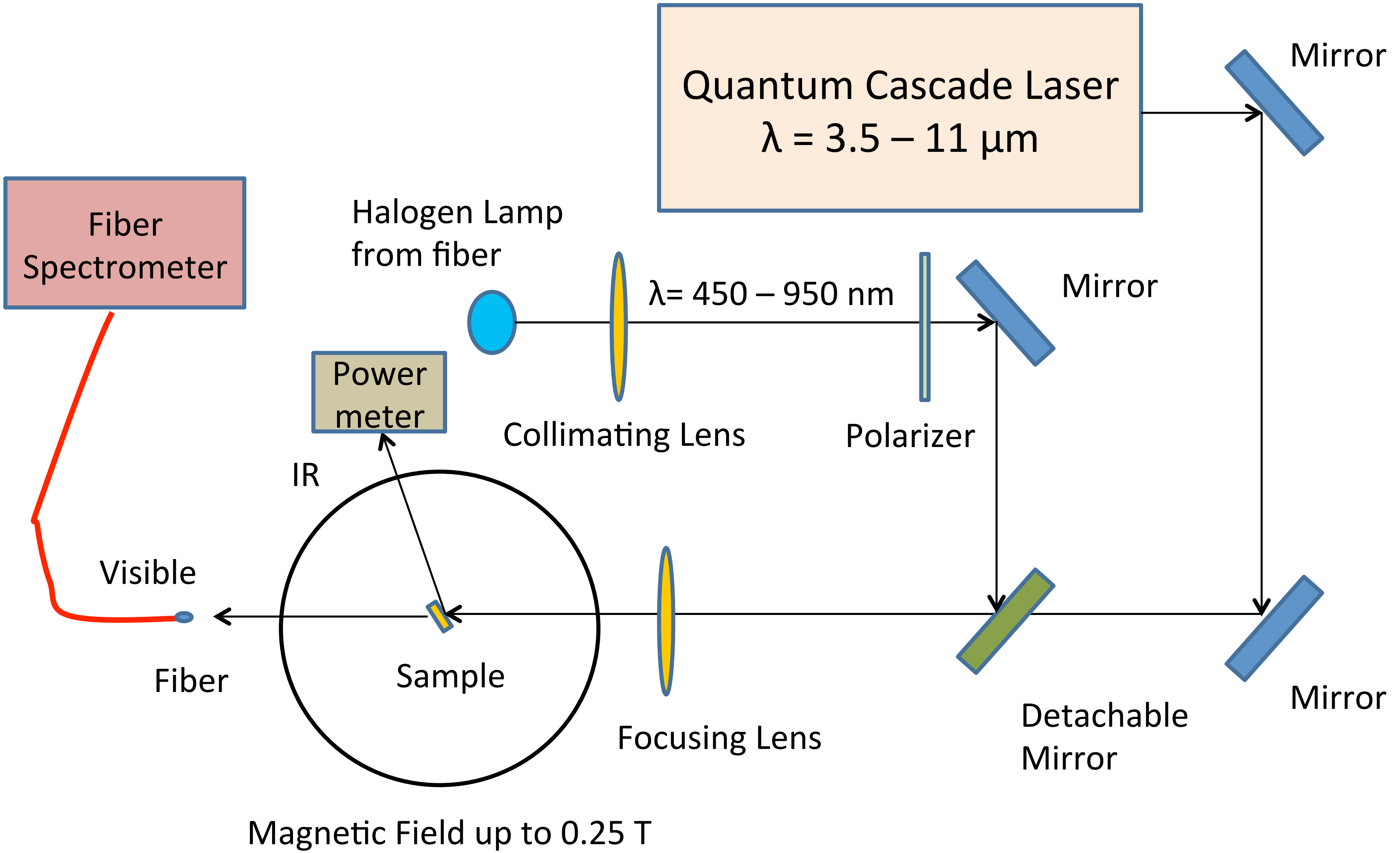




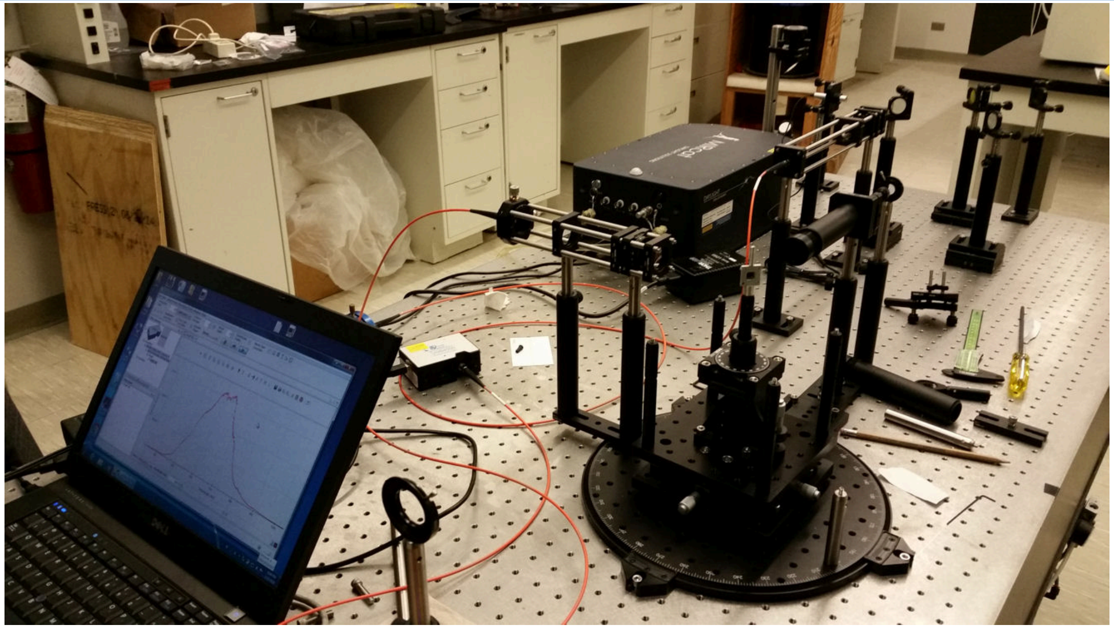


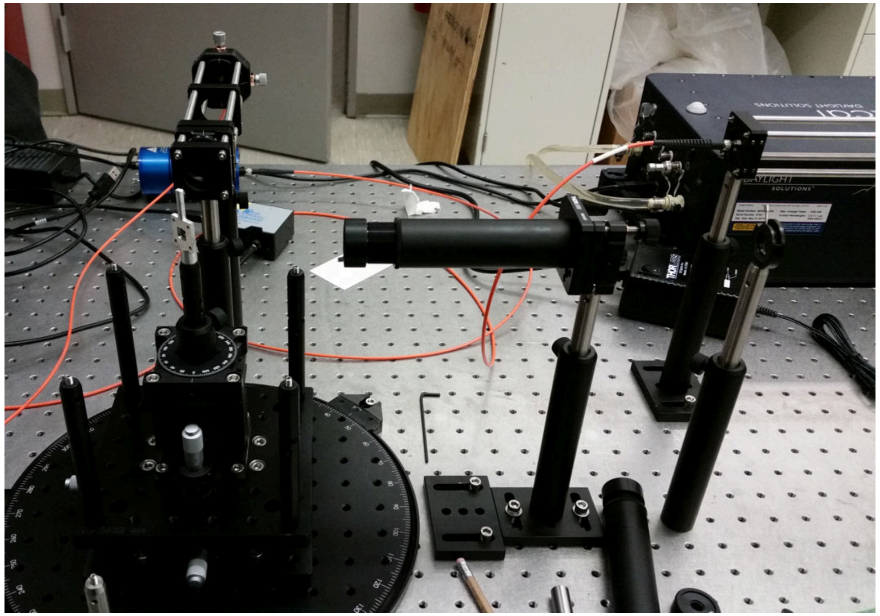
(Nano-fabrication and SEM imaging was performed in the Center for Functional Nanomaterials of Brookhaven National Laboratory)

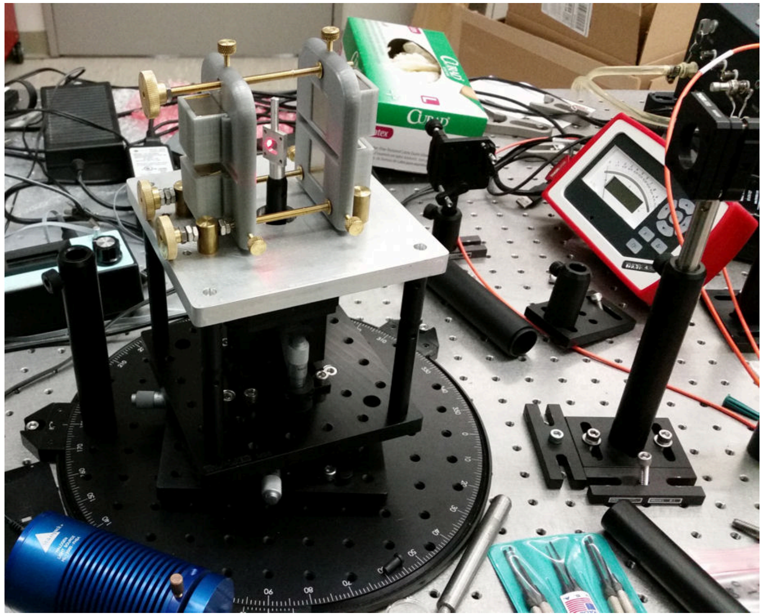
Experimental Set-up of the IR and Visible Spectroscopy



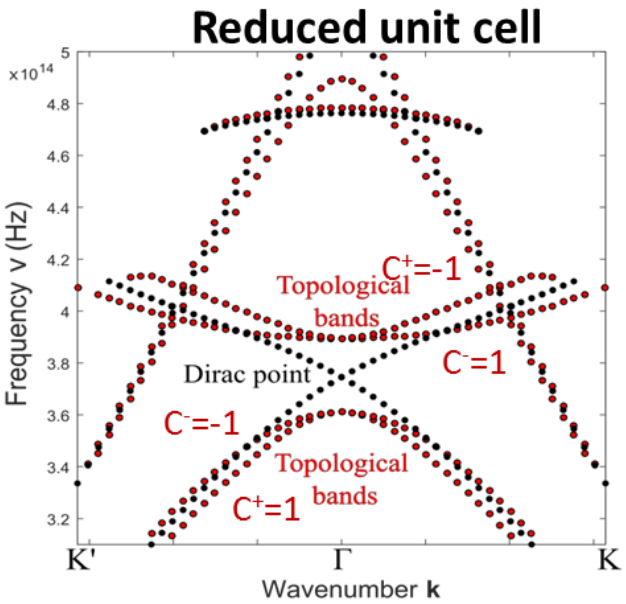
Experimental Set-up for IR and Visible Spectroscopy

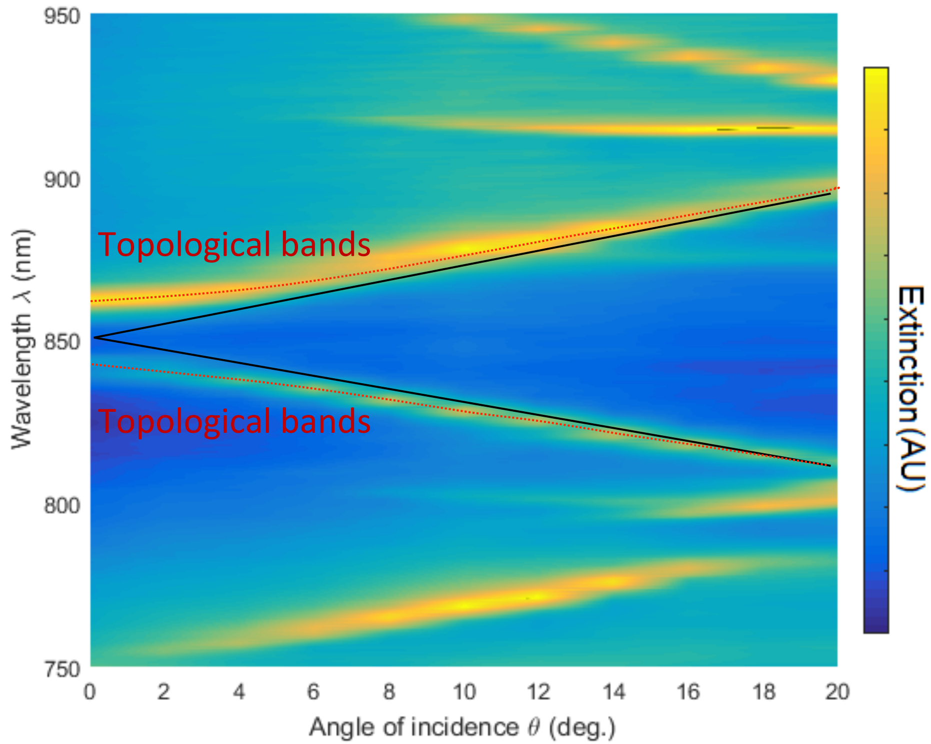






Optical characterization of the all-dielectric topological metasurface



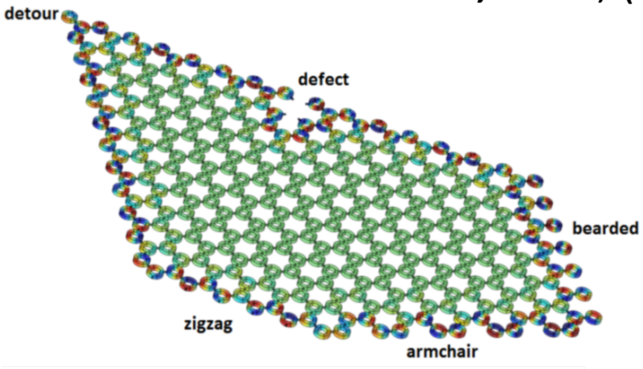


Next step – fabrication of samples with domain walls and observation of the edge states!

Acoustic and elastic topological states

1) Acoustic analogue of Quantum Hall effect

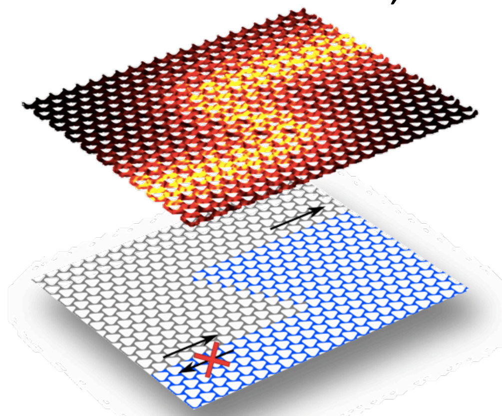
Nature Communications **6,** 8260, (2015).



In collaboration with Andrea Alu (UT Austin)

2) Acoustic analogue of Quantum Spin Hall Effect

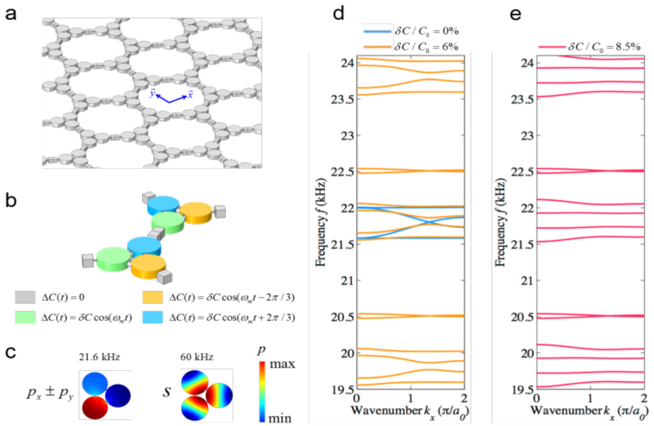
Nature Communications **6**, 8682 (2015).



In collaboration with Hossein Mousavi and Zheng Wang (UT Austin)

3) Floquet Topological Insulators for Sound

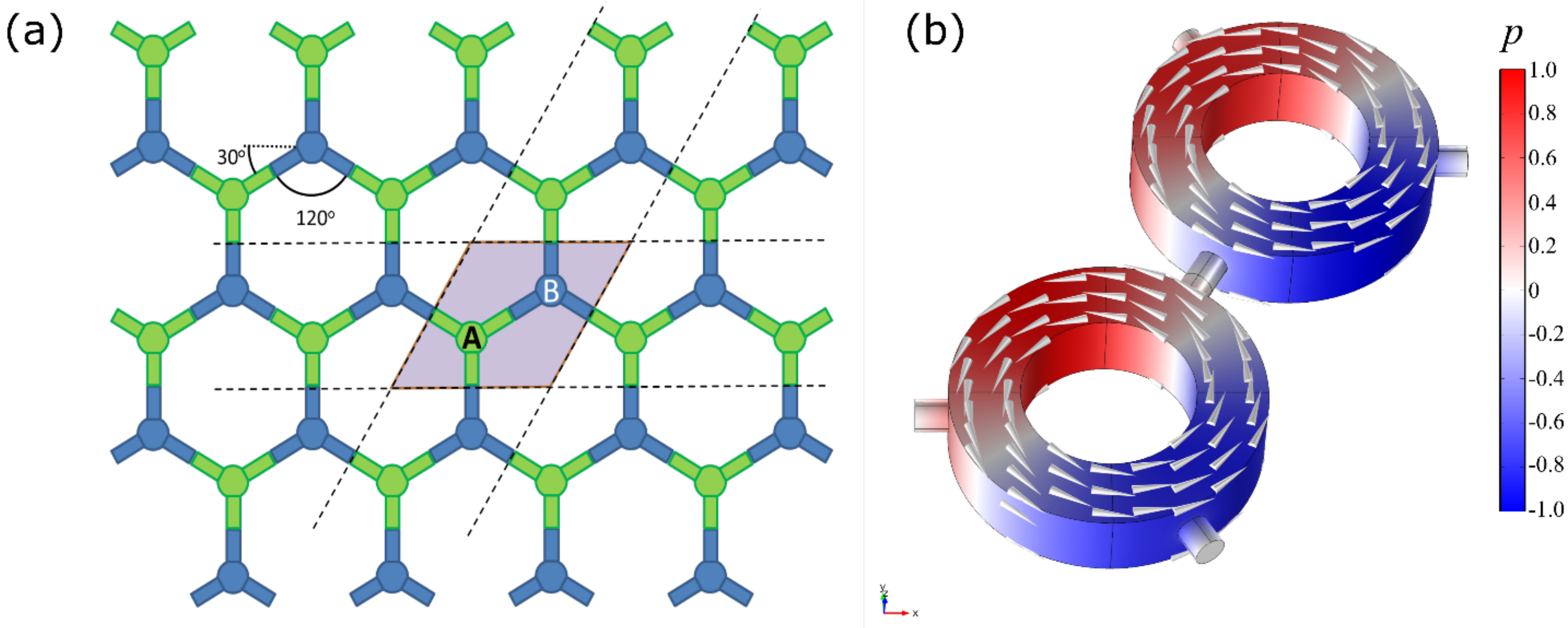
Nature Communications **7**, 11744 (2016).



Acoustic analogue of QHE

Nature Comm. 6, 8260 (2015).

See also: Yang, et al., Topological Acoustics Phys. Rev. Lett. **114**, 114301 (2015).

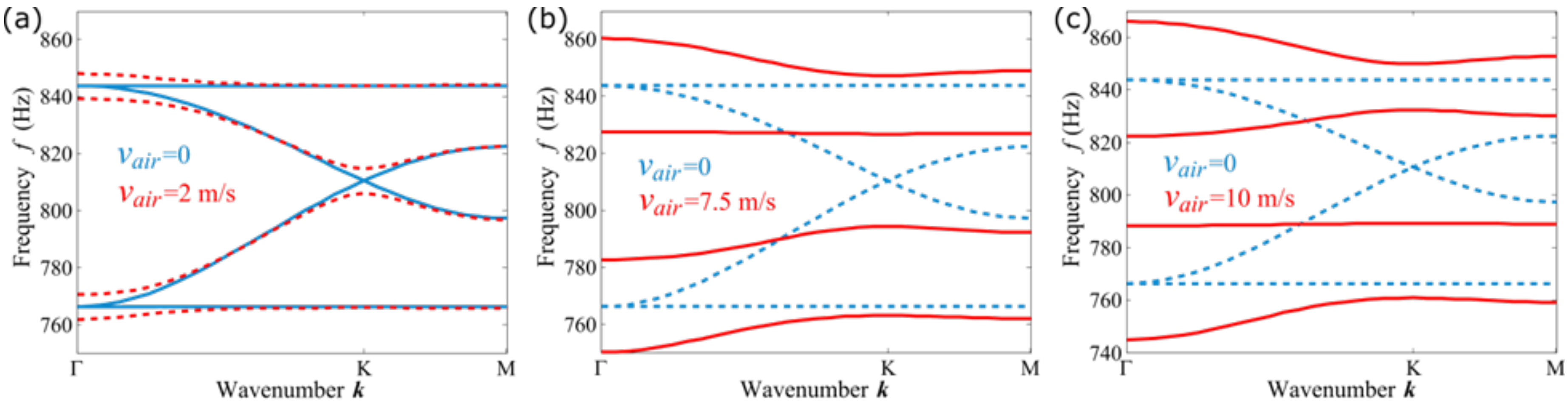


A diatomic hexagonal array to form the acoustic analogue of a graphene layer. (a) Lattice with two rotated Y-junctions/atoms (A and B, respectively) per unit cell (shaded region). (b) One unit cell of the lattice modelled in COMSOL Multiphysics, with acoustic pressure distribution shown in color for one of the Dirac modes of interest. The gray arrows indicate the direction of air flow in the resonators.

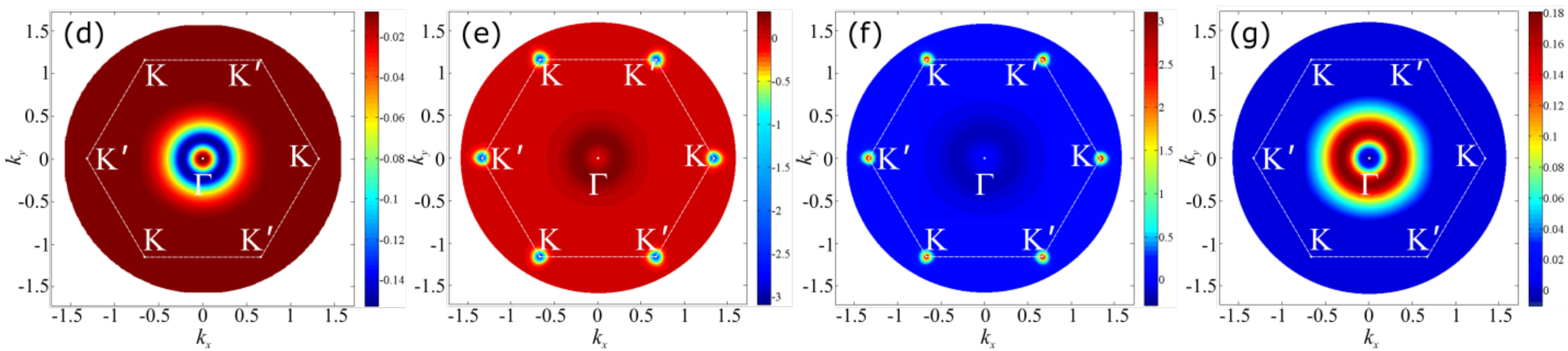
Acoustic analogue of QHE

Band structure of acoustic graphene with increasing air velocity inside the resonators.

Band diagrams obtained using first-principle numerical calculations.

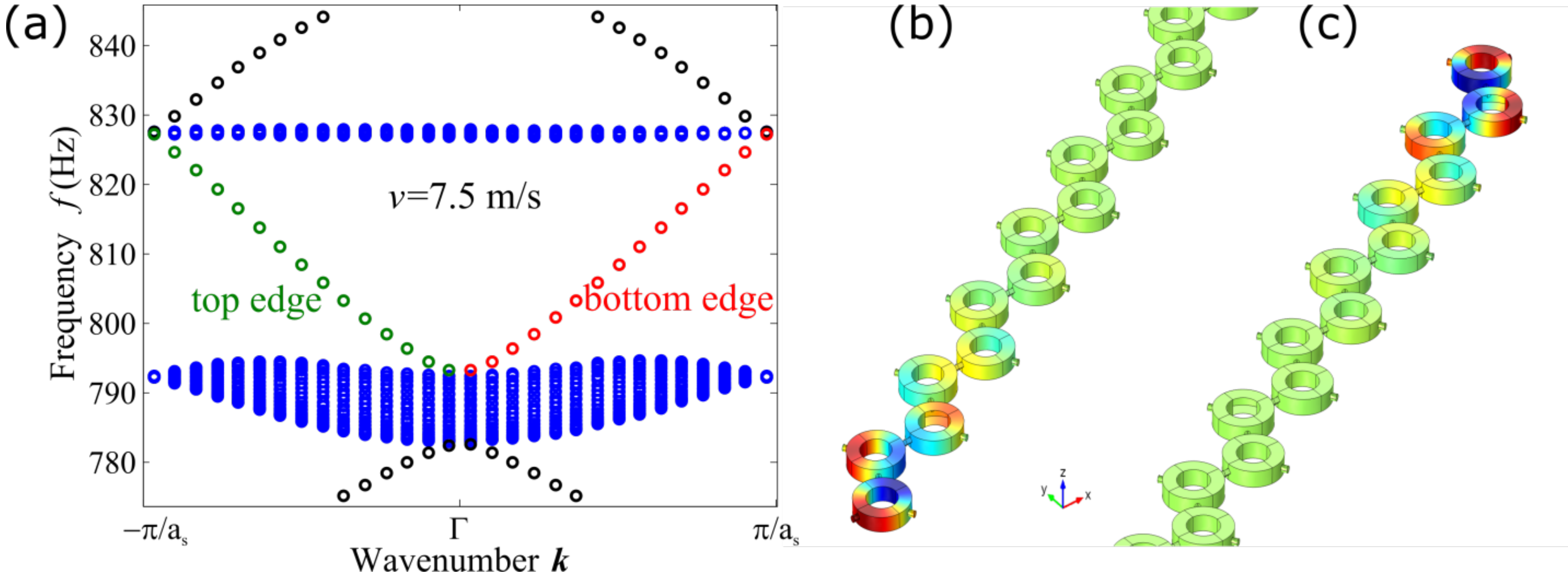


the Berry curvature of the top and bottom Dirac bands after gap opening



Acoustic analogue of QHE

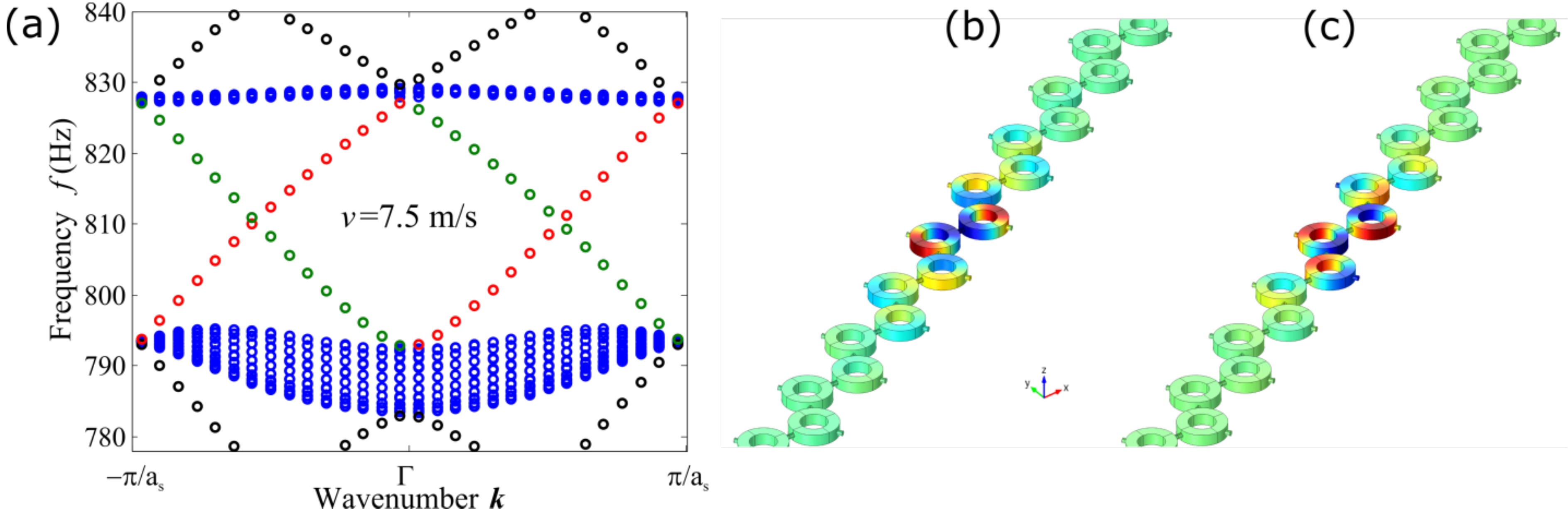
Topological edge modes in acoustic graphene.



(a) Acoustic band structure for a supercell of 20 unit cells and a uniform rotational bias velocity $v=7.5$ m/s. Bulk modes are shown by blue and edge modes by black, green and red colored markers. (b) and (c) Acoustic pressure profiles of the one-way edge mode localized at the bottom and top of the supercell, respectively, corresponding to the red and green bands in (a).

Acoustic analogue of QHE

Topological edge modes confined to the domain wall defined by the reversal of the air rotation inside the acoustic graphene



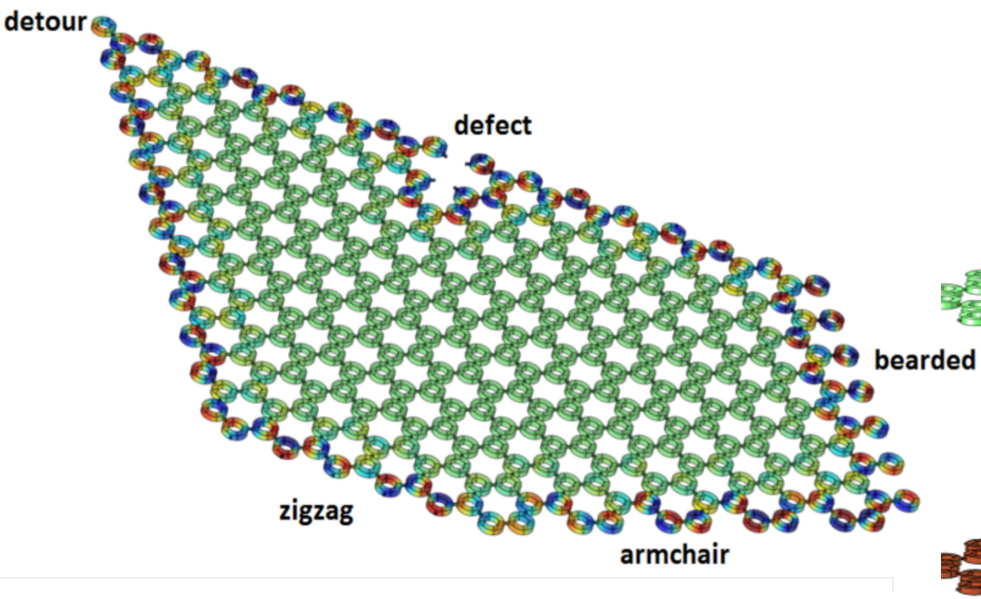
(a) Acoustic band structure for a supercell of 20 unit cells with domain wall at the center. The angular momentum bias is flipped within the lattice on one specific boundary along the domain wall from $v=7.5$ m/s to $v=-7.5$ m/s.

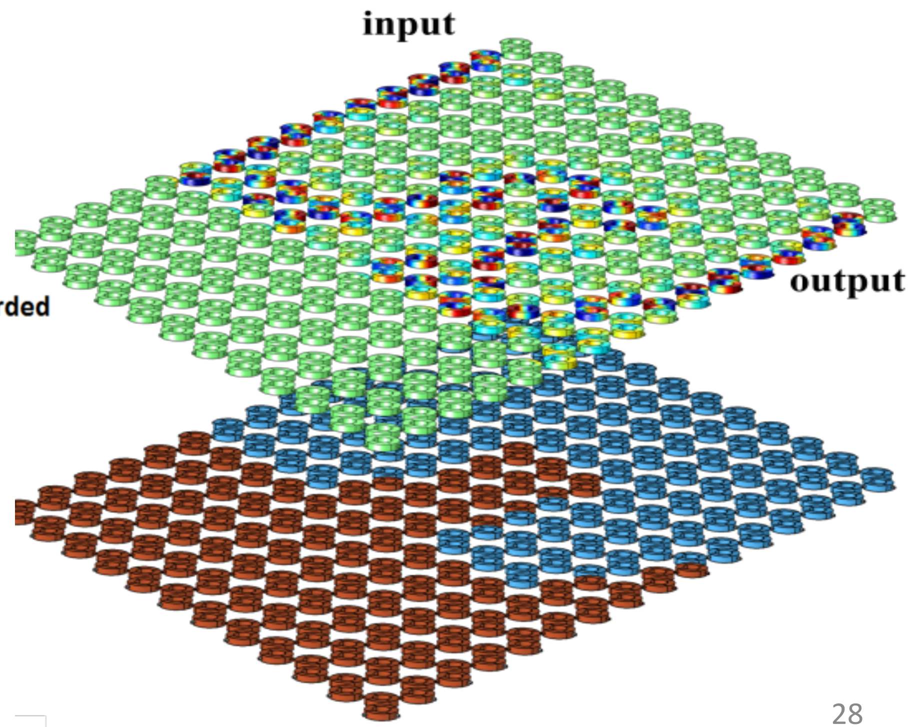
Acoustic analogue of QHE

Numerical demonstration of topological robustness of acoustic edge modes.

One-way (counterclockwise) edge mode propagates along different cuts of the acoustic graphene and around deliberately introduced defect.

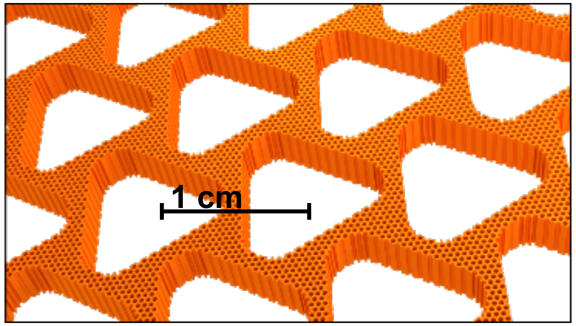
Excitation of the one-way (counterclockwise) edge mode and its propagation (top subplot) along the irregularly shaped domain wall created by the reversal of the Doppler bias.



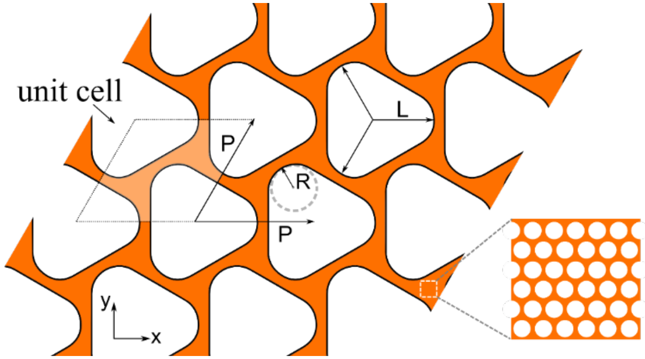


Phononic (elastic) analogue of the QSHE

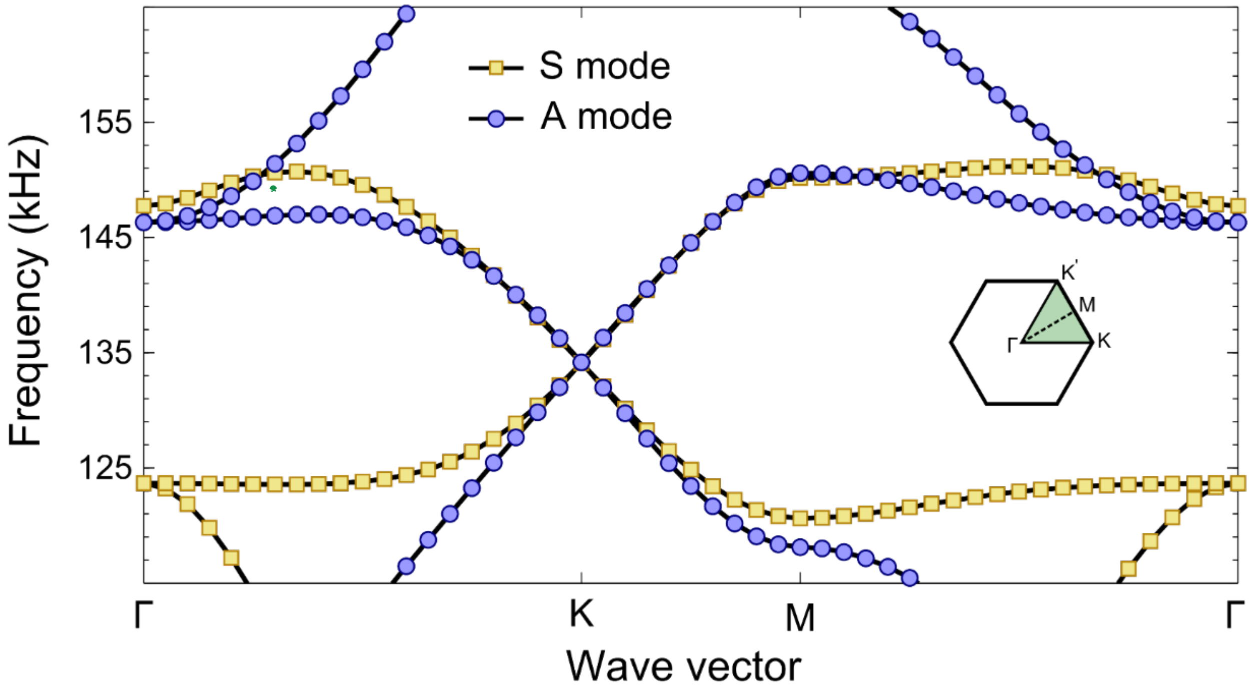
Concept: Metamaterial phononic crystal with doubly degenerate Dirac-like modes
Dual-scale structuring is necessary to match S and A dispersions



Slab of aluminum

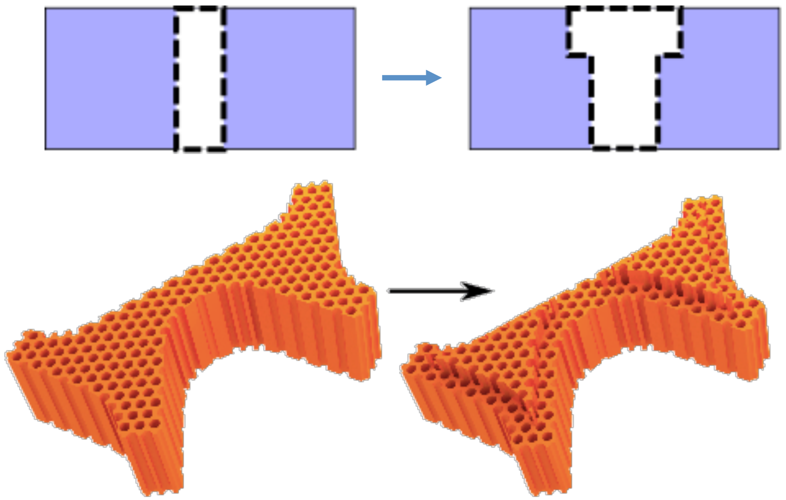


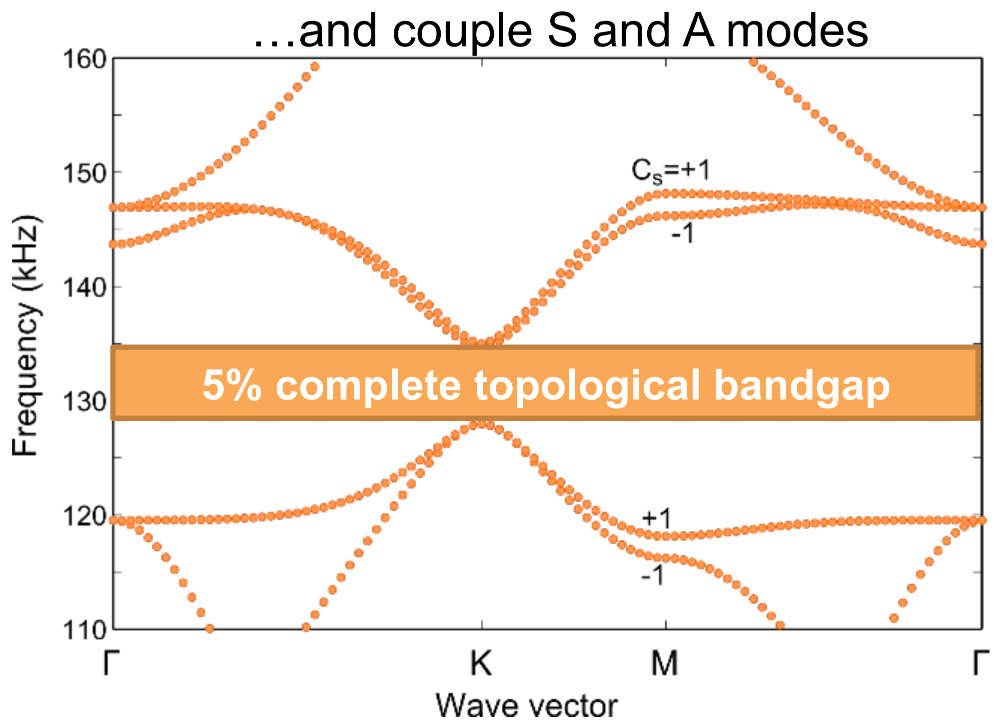
Phononic band structure



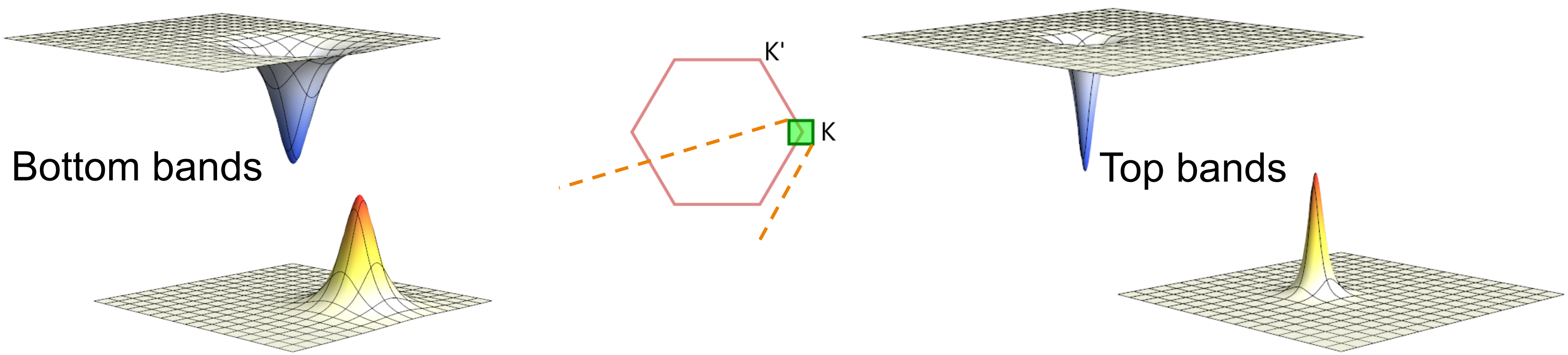
Emulating spin-orbit coupling and transition to phononic QSHE

Opening a counterbore breaks σ_z, while preserves in-plane symmetries.

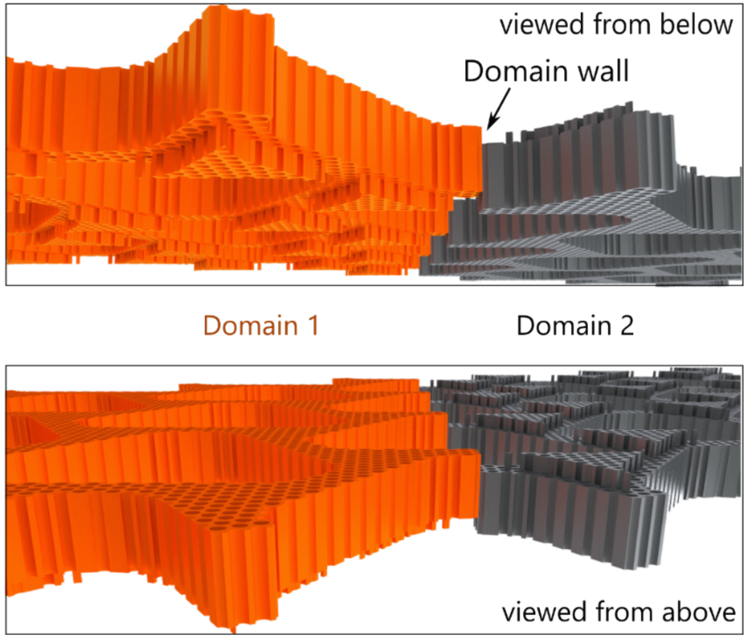


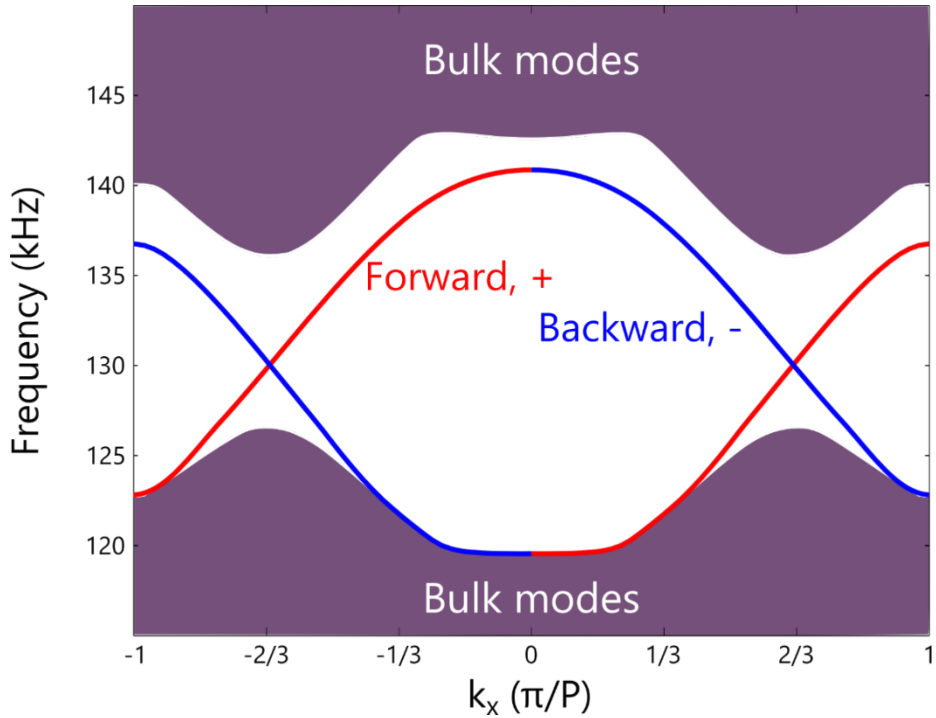


Berry curvature near K point:



Topologically robust edge modes in Quantum Spin Hall Effect crystal

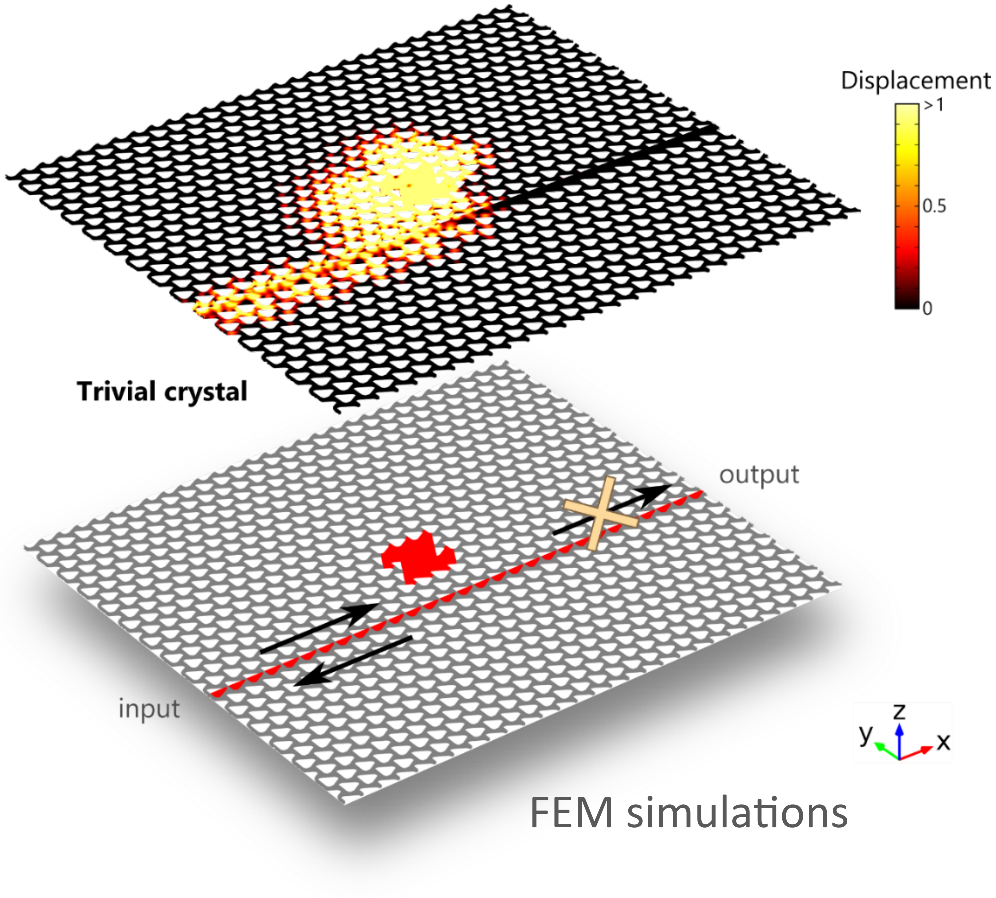




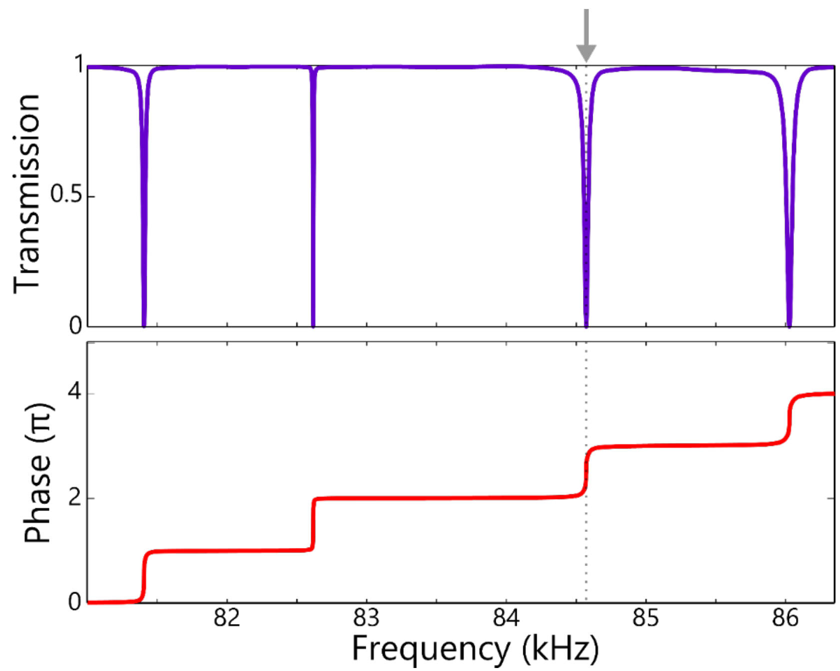
Massless helical edge states, spin locked to the propagation direction.

Time reversal operation changes the direction as well as the spin.

Trivial crystals are prone to defects and disorders

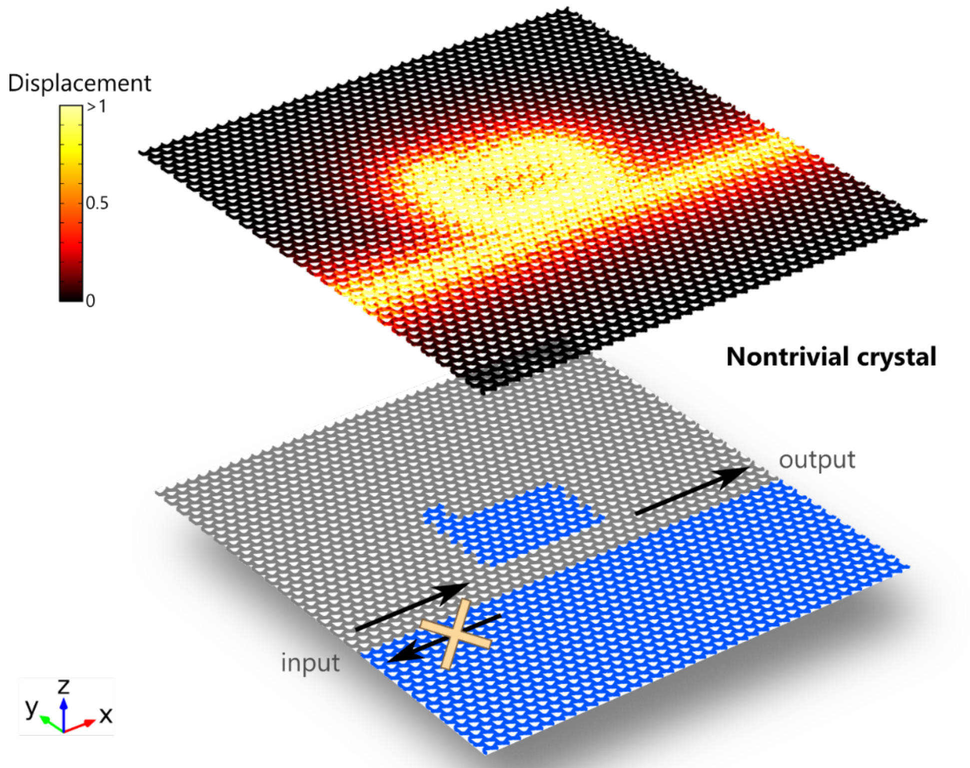


FEM simulations

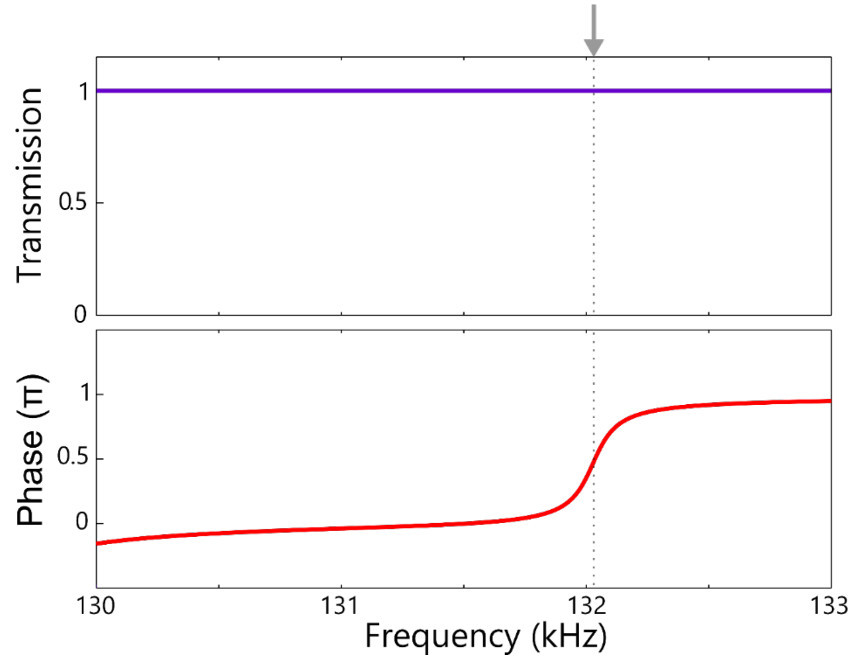


Each time a resonance occurs, phase changes by π and transmission drops to zero.

Robustness against defects and disorders in Quantum Spin Hall Effect crystal

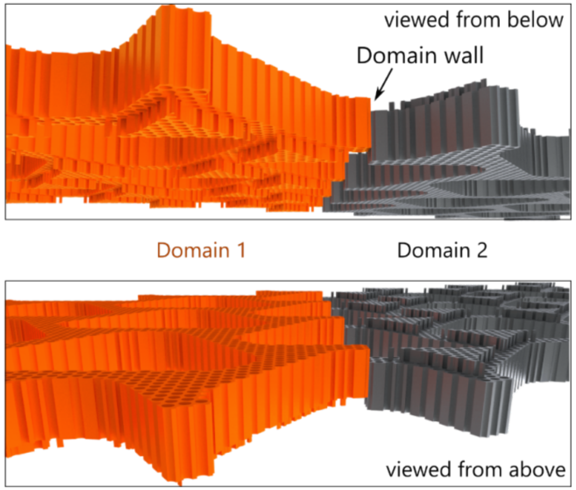


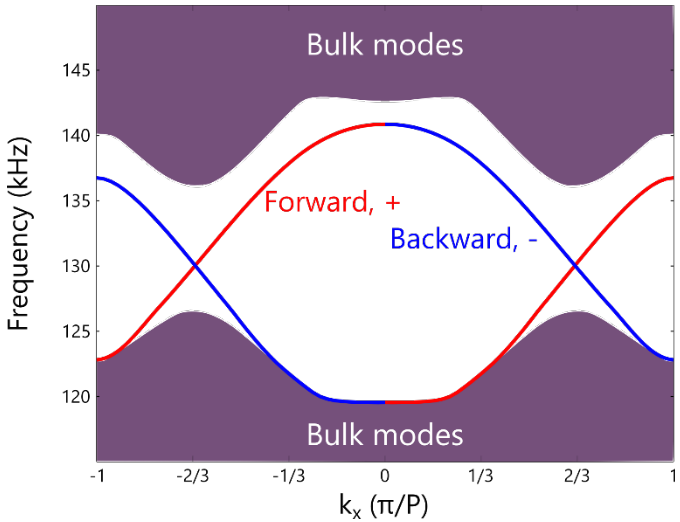
FEM simulations

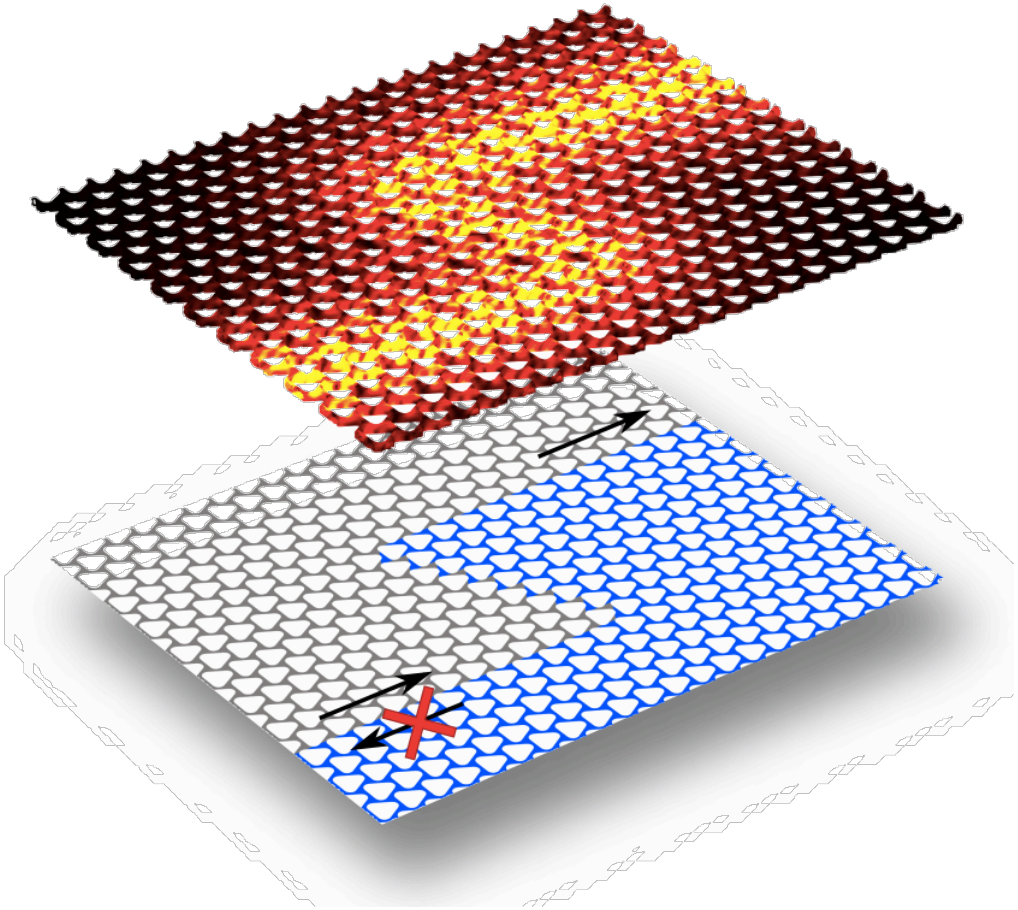


Resonance manifests itself only in the **phase!**

Robustness against sharp bends and rerouting in Quantum Spin Hall Effect crystal

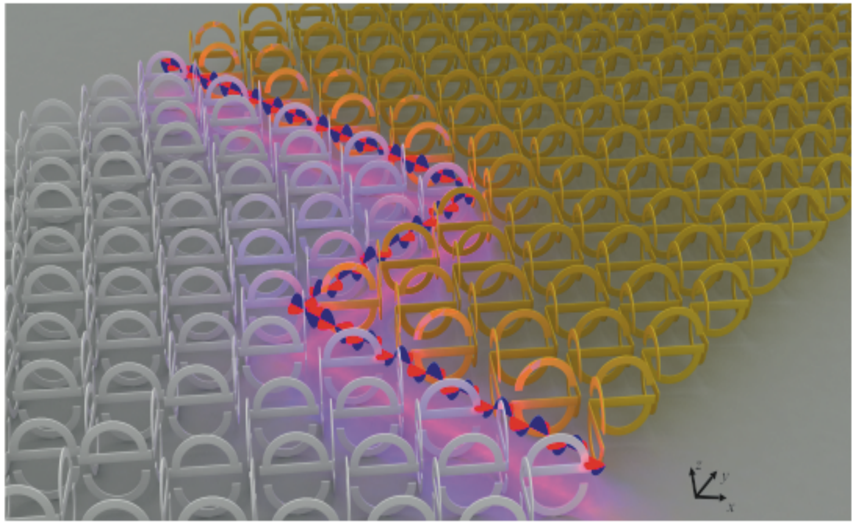


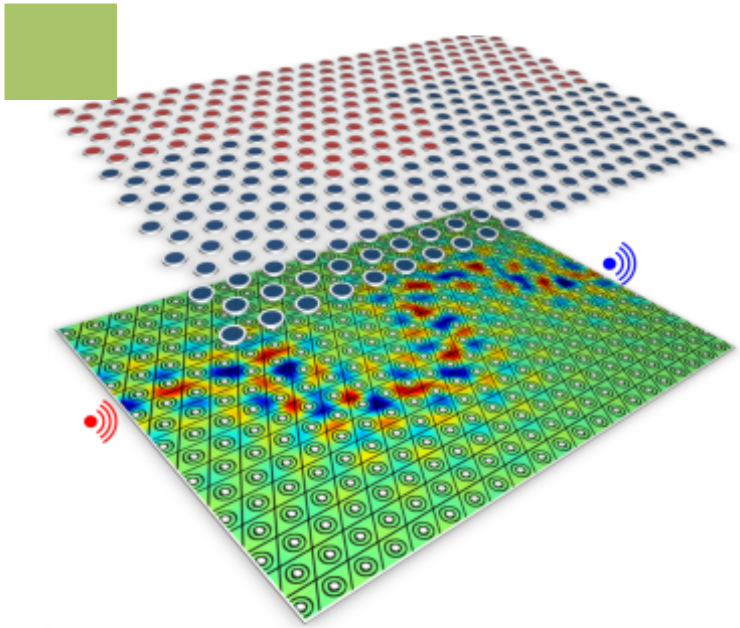




Summary and Outlook

- **Photonics and acoustic metamaterials offers an excellent platform for emulating topological states of condensed matter.**
- **Topologically protected edge states robust to structural imperfections with and without time reversal symmetry are possible for photons and phonons**
- **Topological edge states envision a broad range of applications such as reconfigurable waveguides with controllable routing along the domain walls, and integrated optical systems where interaction among optical elements has "one-way" character.**

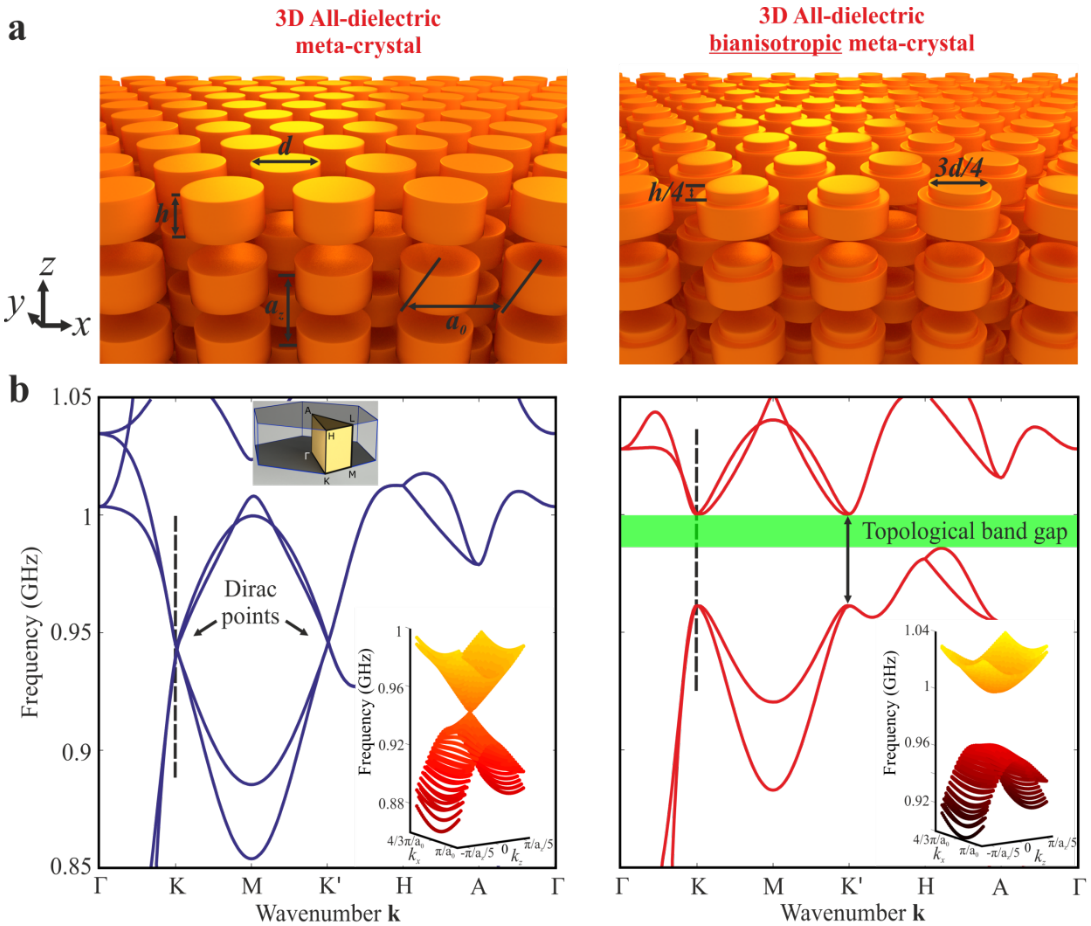




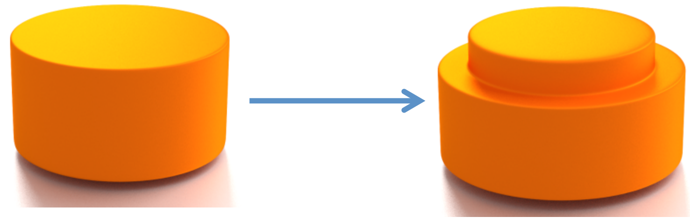
Three dimensional all-dielectric photonic topological insulators

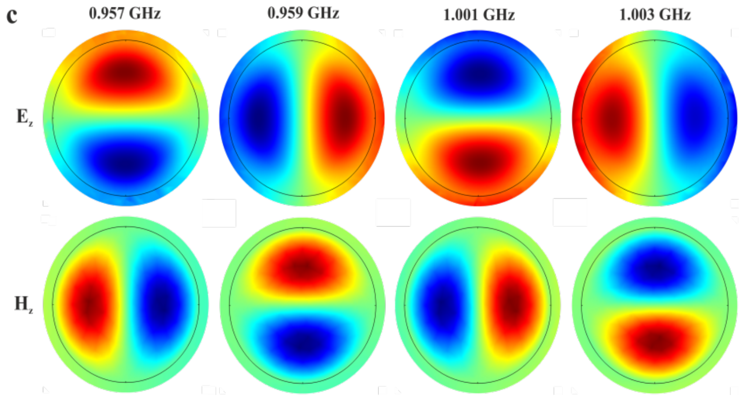
Under review in Nature Photonics since Feb 2016.

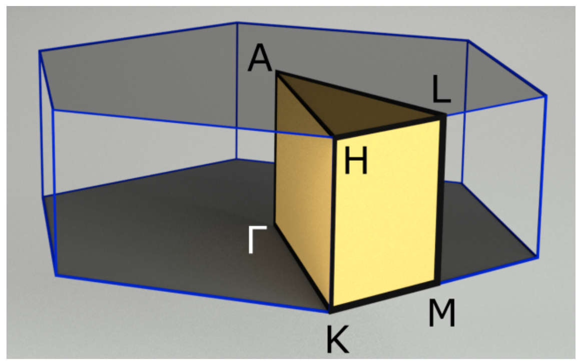
3D Photonic dual metacrystal



Degeneracy between magnetic and electric dipolar modes of the cylinders + all-dielectric bianisotropy



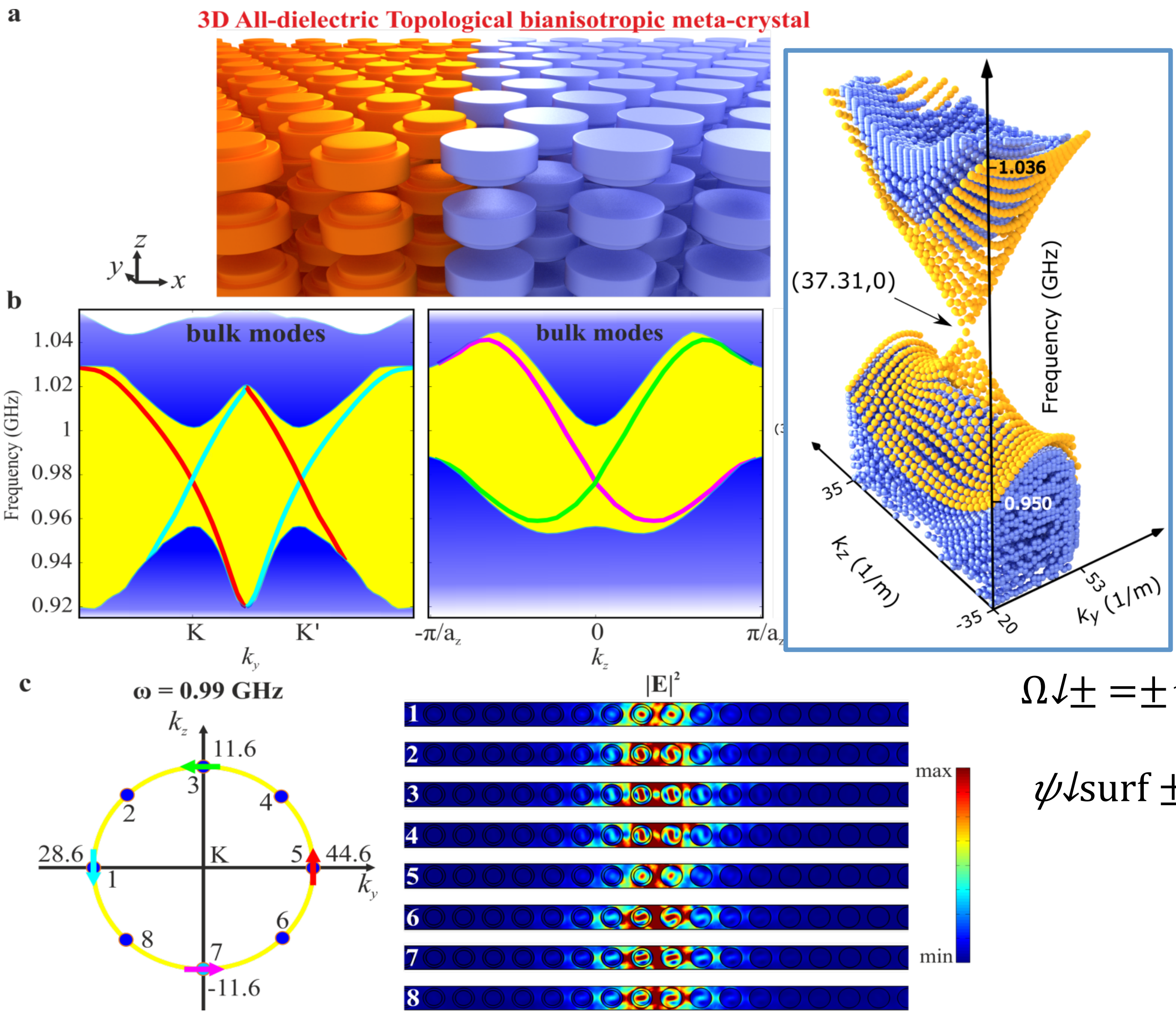




$= \omega_0 + v_{||} s_0 (\delta k_x \sigma_x + \delta k_y \sigma_y) + v_z s_y \sigma_z$

$k_z + m s_z \sigma_z$

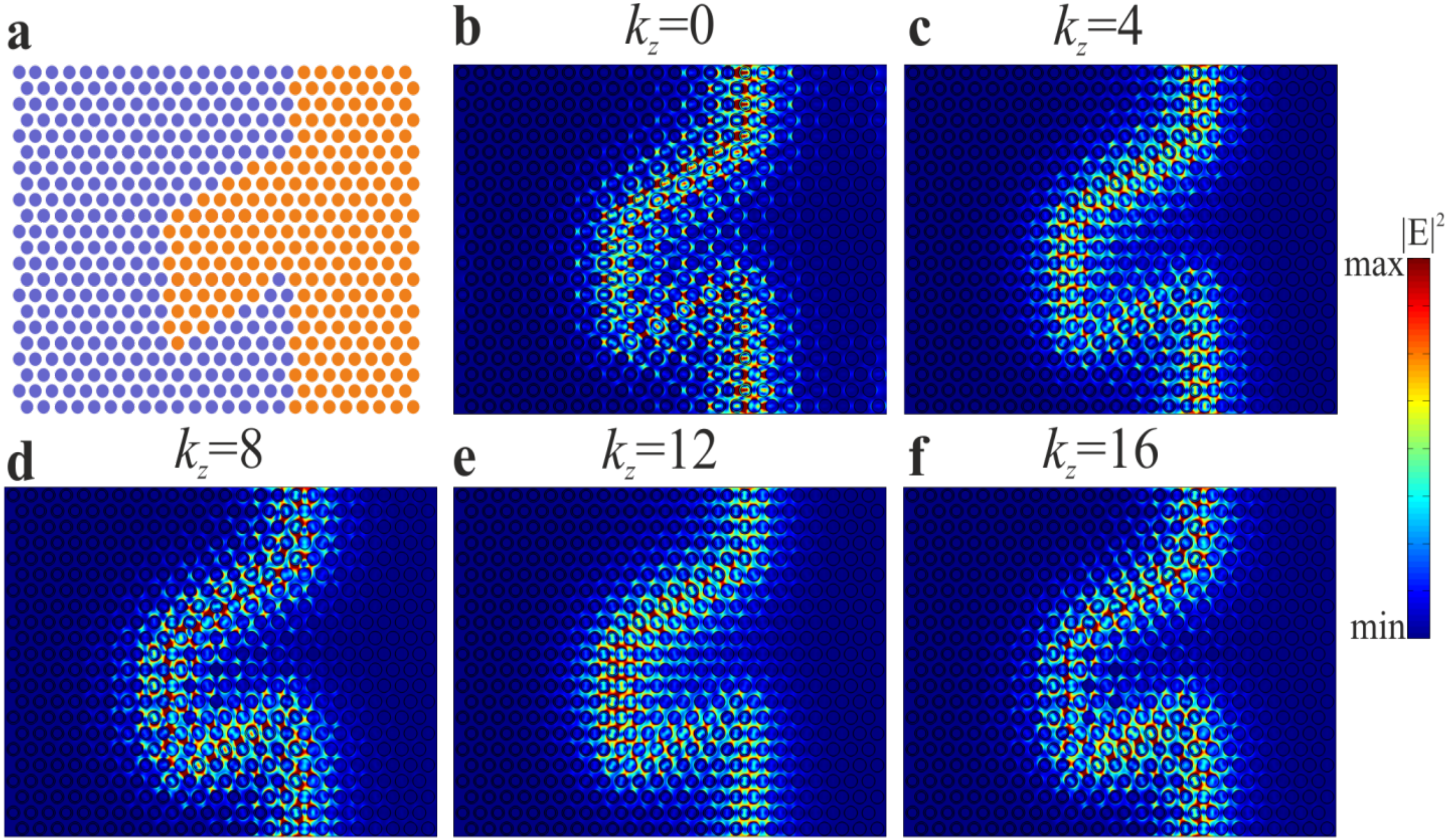
Topological edge states of 2D domain walls



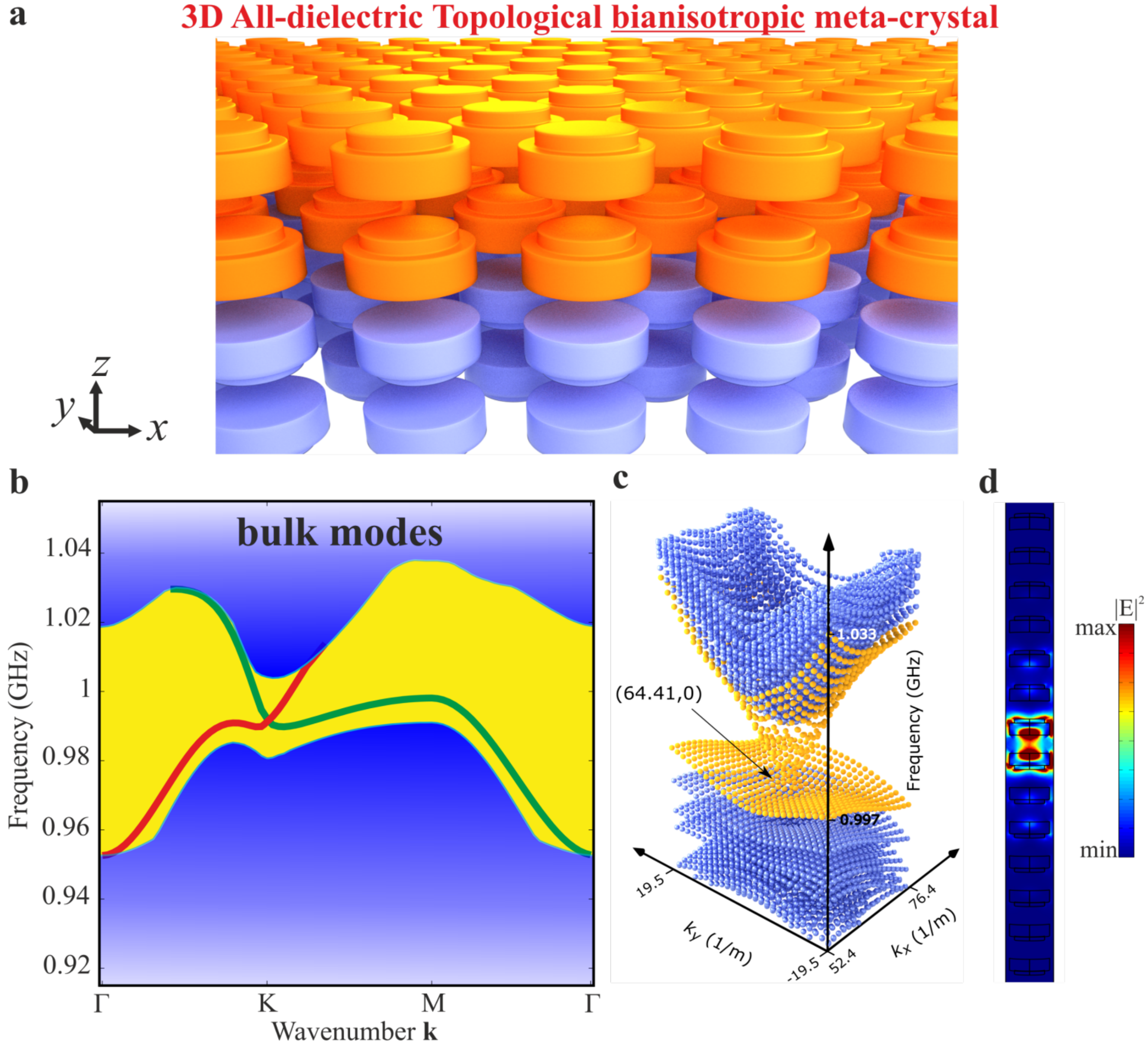
$\Omega_{\pm} = \pm\sqrt{\zeta^2 + v_F^2 (k_x^2$

$\psi_{surf}^{\pm} \sim ($■■$a^{sw} @(\zeta-$

Topological robustness in three-dimensions

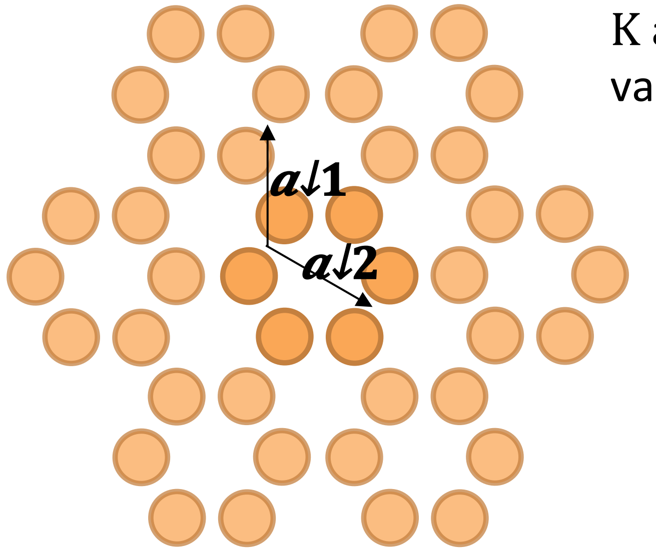


Vertical cut – non-topological interface

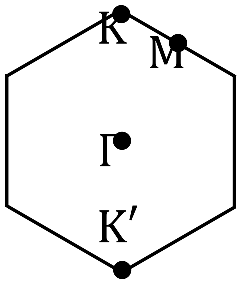


All-dielectric and plasmonic symmetry protected topological metasurfaces

Lattice symmetry protected photonic topological metasurface (PTM)

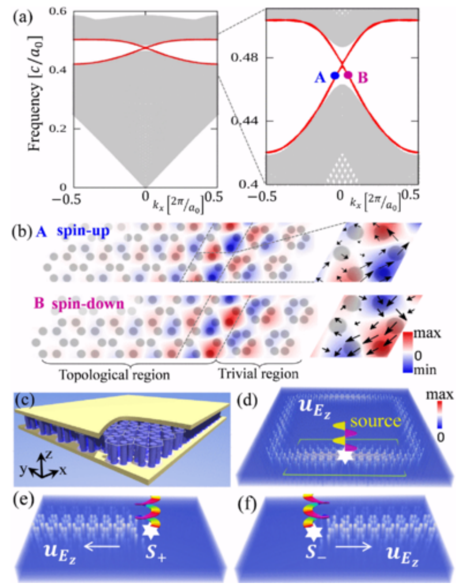


K and K′ valleys as pseudo-spin: valley Chern insulator

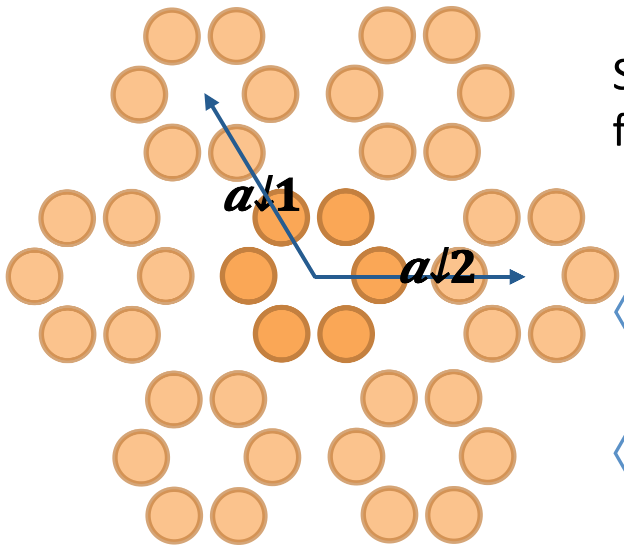


$K=(0, 4/3\ \pi/a_0)$

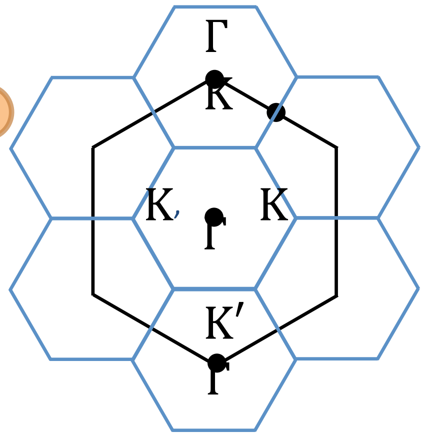
$K'=(0, -4/3\ \pi/a_0)$



Phys. Rev. Lett. **114**, 223901 (2015)



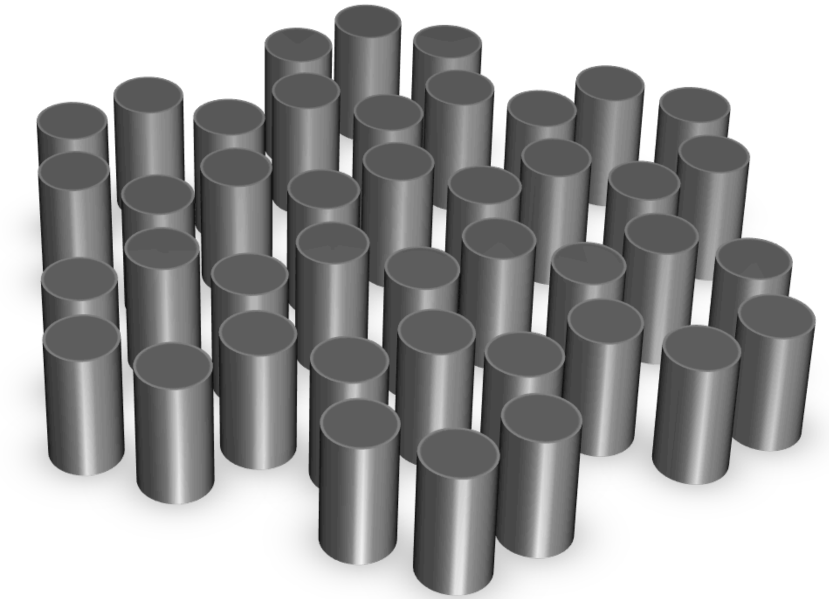
Shrinking/Expanding the "hexamer" leads to folding of K and K' points to Γ point of the new lattice.



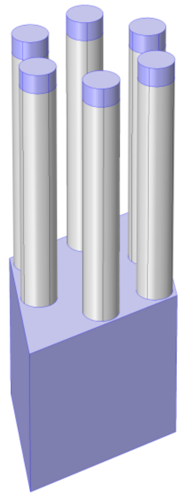
As a result of such symmetry reduction, valleys/pseudo-spins mix leading to the topological transition

Phys. Rev. Lett. **114**, 223901 (2015)

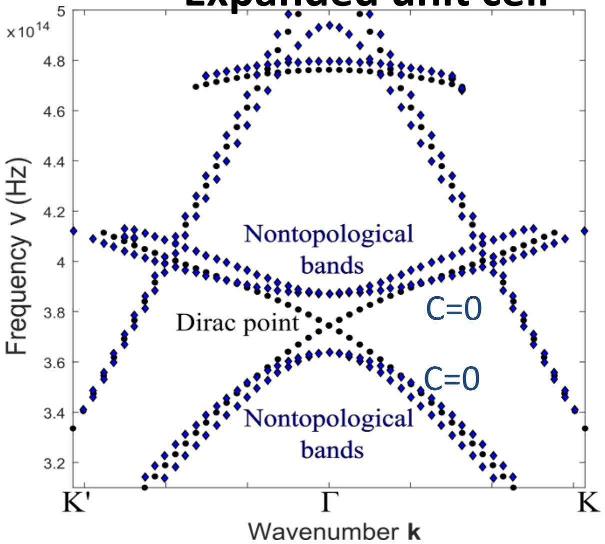
SOS (Silicon on Sapphire) implementation of all-dielectric PTM: modeling



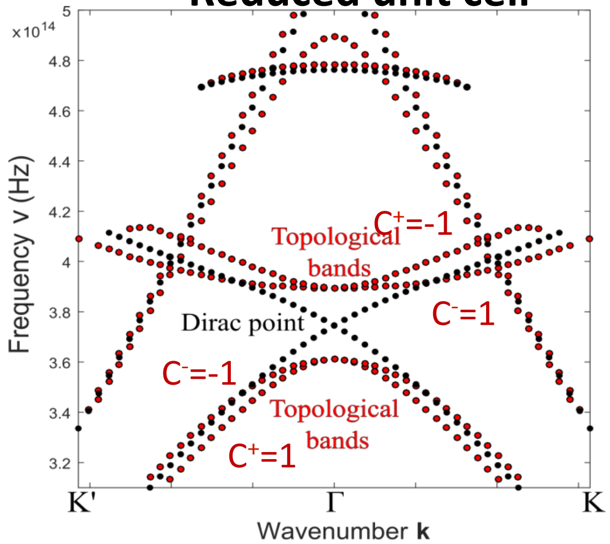
The unit cell modeled in COMSOL® Multiphysics

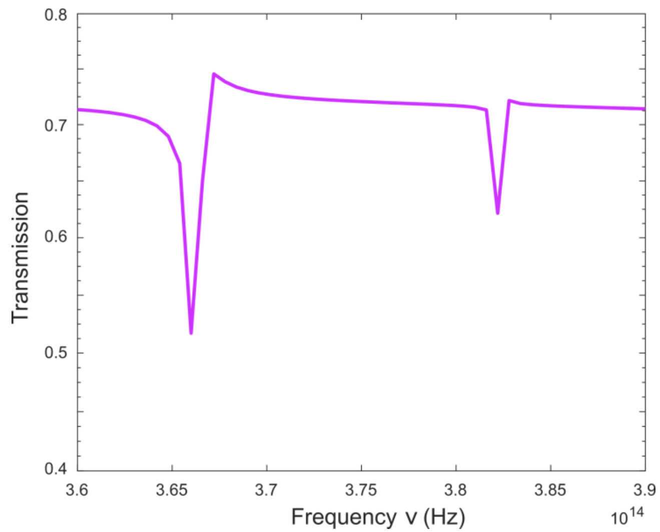


Expanded unit cell

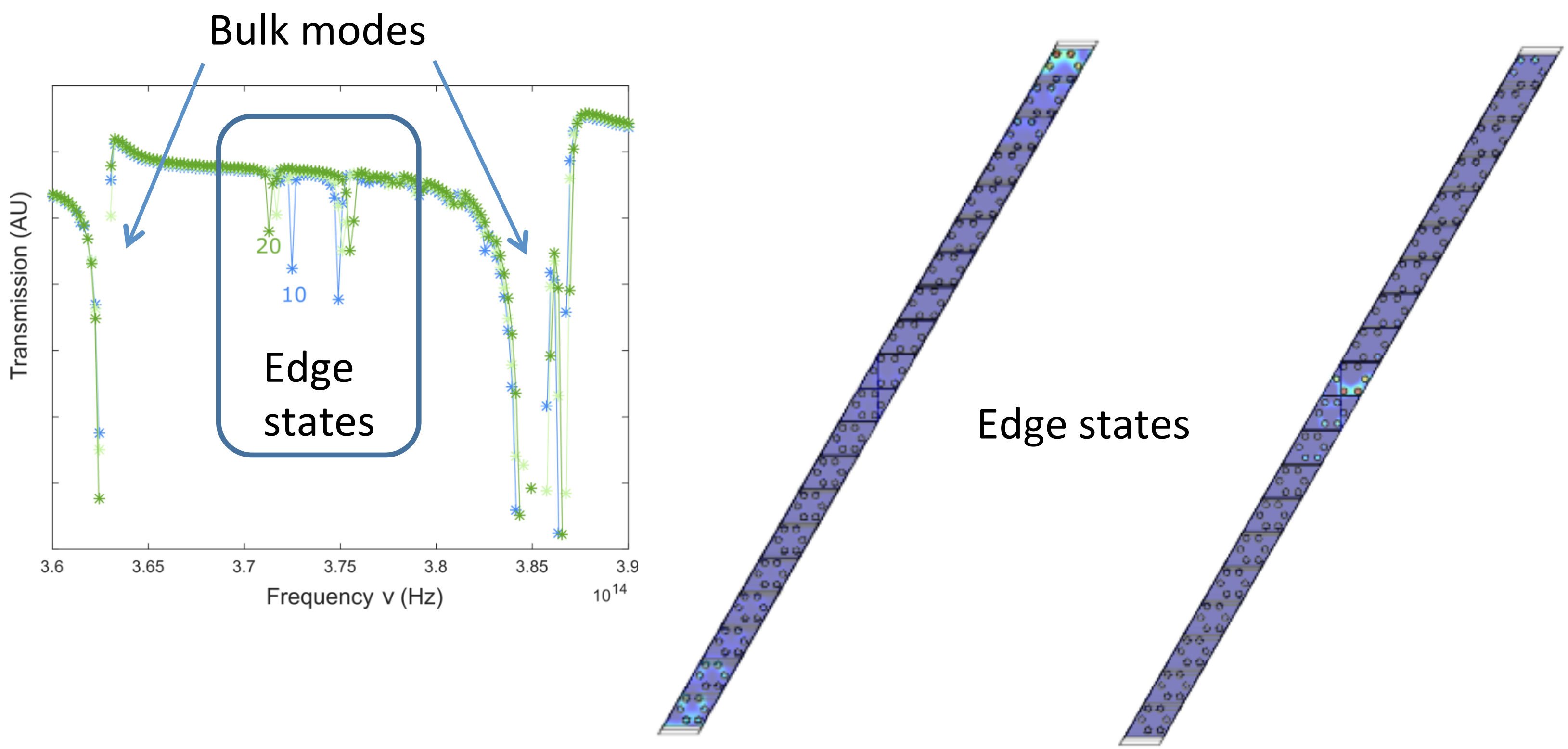


Reduced unit cell



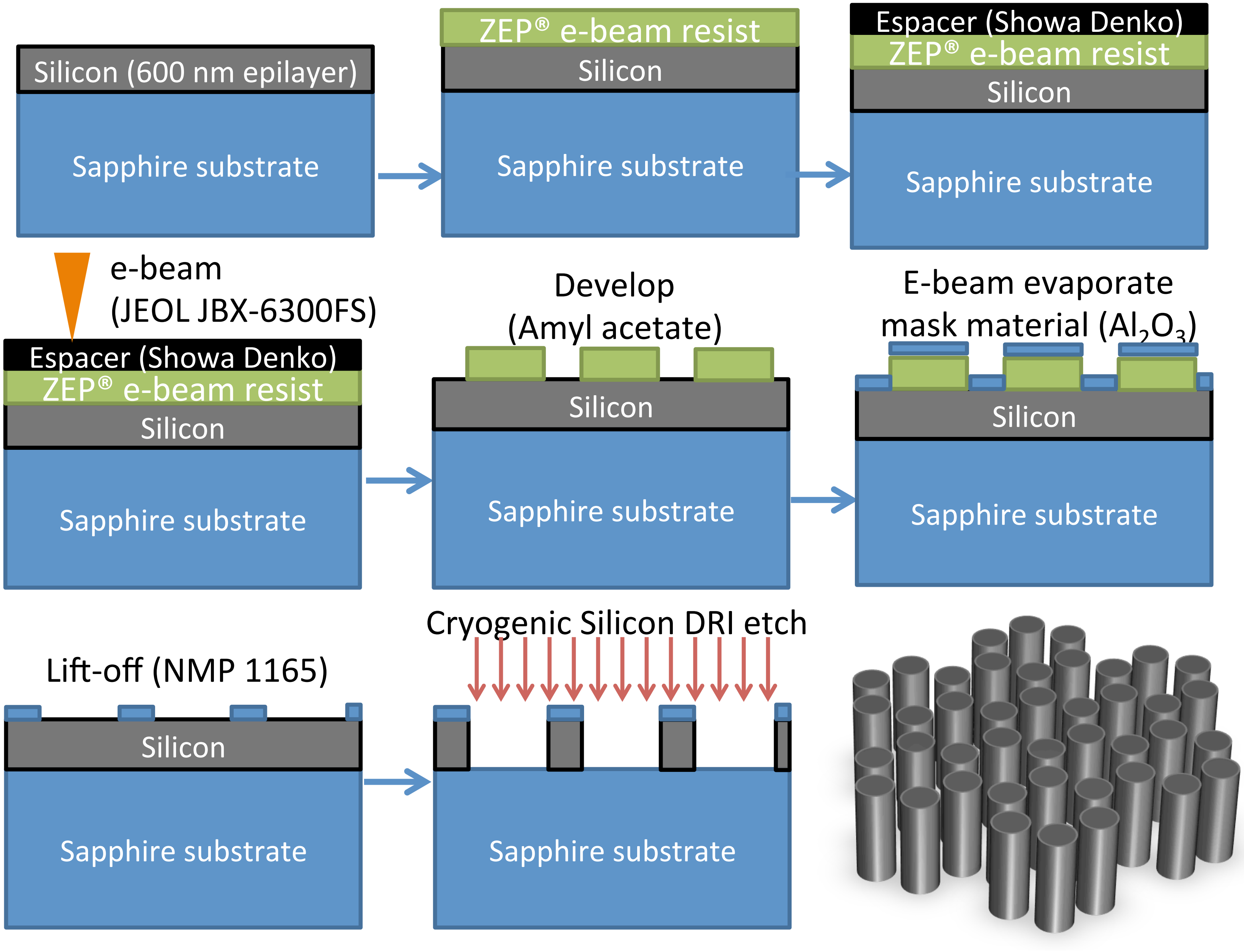


Direct excitation of topological edge states in all-dielectric topological metasurface: modeling

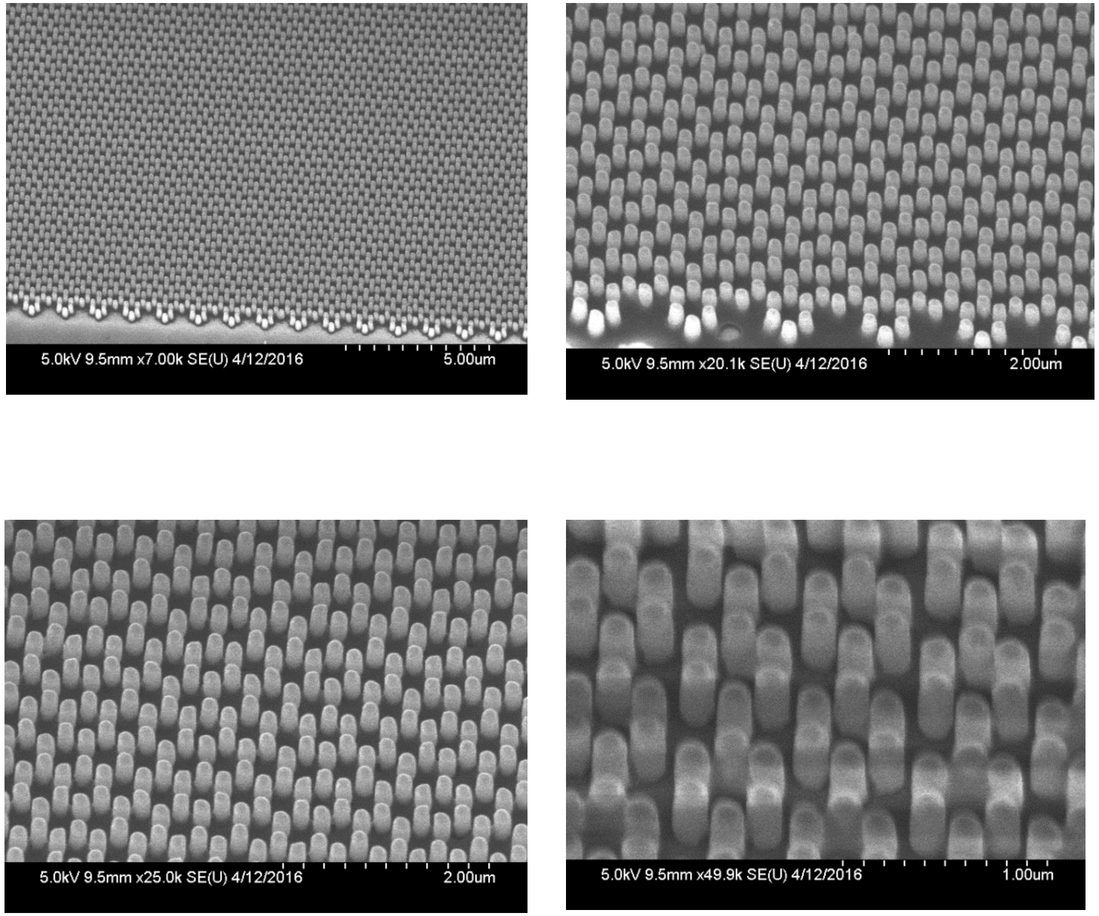


The large scale simulations of the supercell formed by 20 unit cells of 10 topologically trivial cells and 10 topologically nontrivial cells. The excitation of the edge states is evidenced by both the transmission spectra and field profiles under oblique incidence.

SOS (Silicon on Sapphire) implementation - recipe

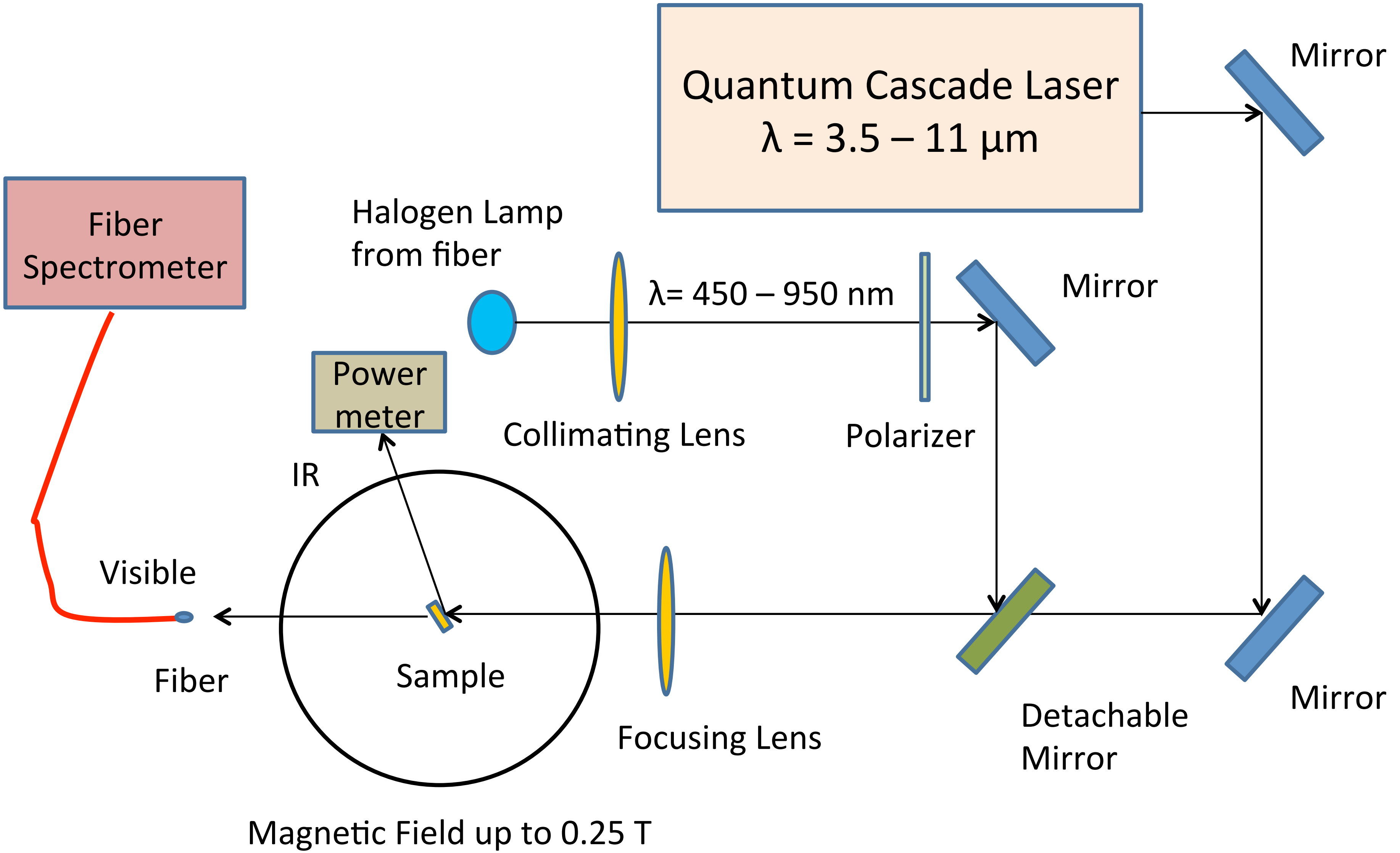


SOS (Silicon on Sapphire) implementation-result

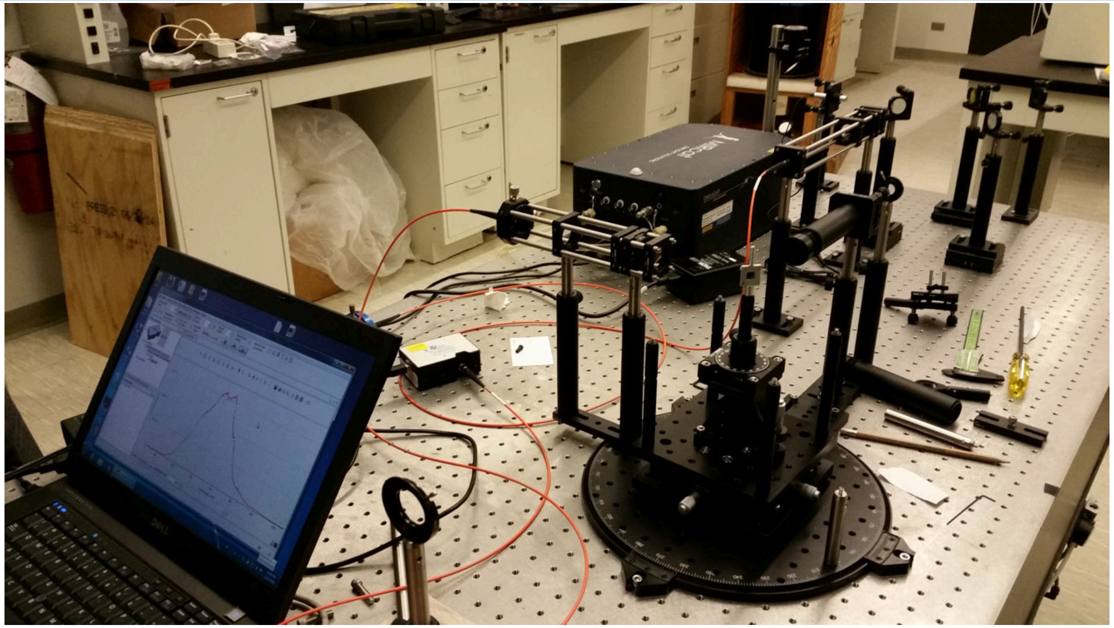


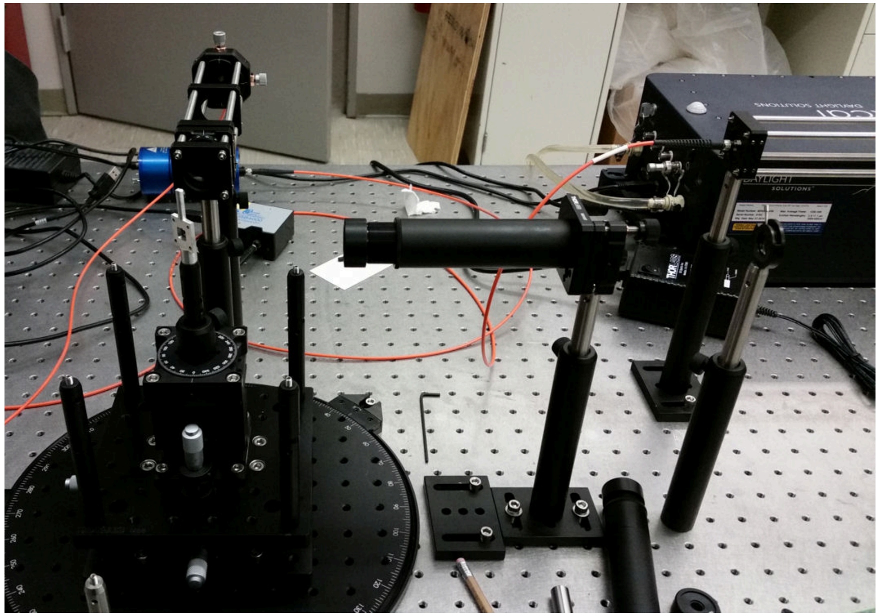
(Nano-fabrication and SEM imaging was performed in the Center for Functional Nanomaterials of Brookhaven National Laboratory)

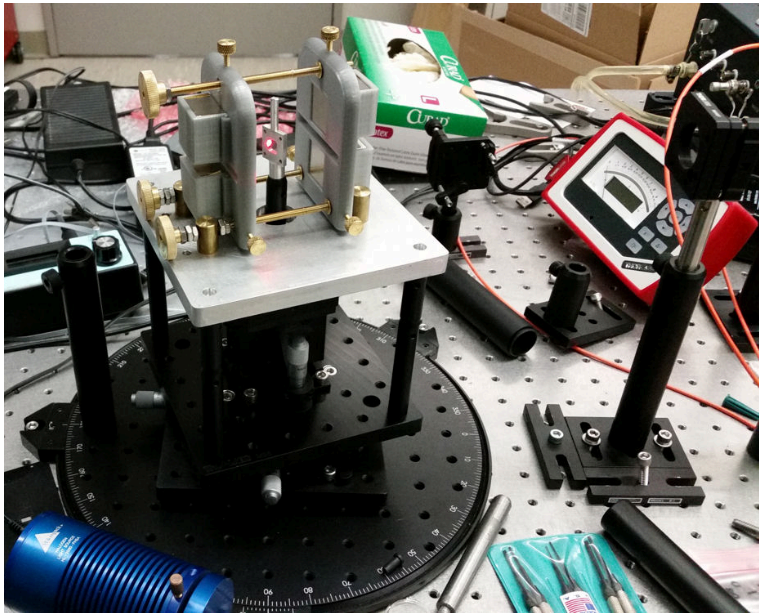
Experimental Set-up of the IR and Visible Spectroscopy



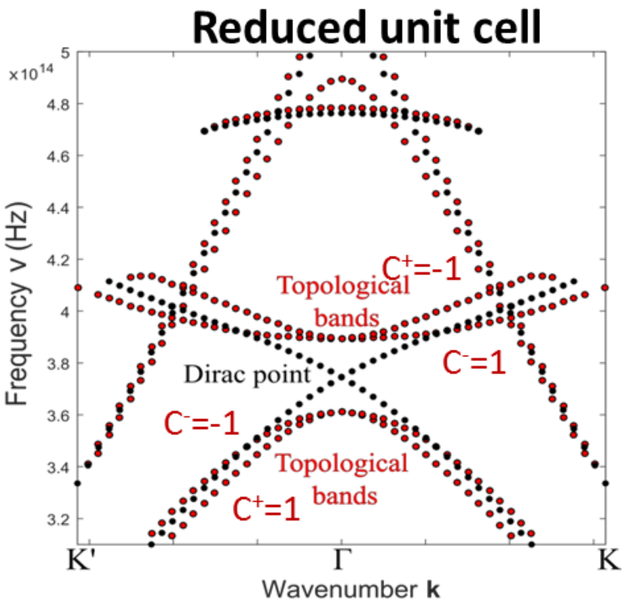
Experimental Set-up for IR and Visible Spectroscopy

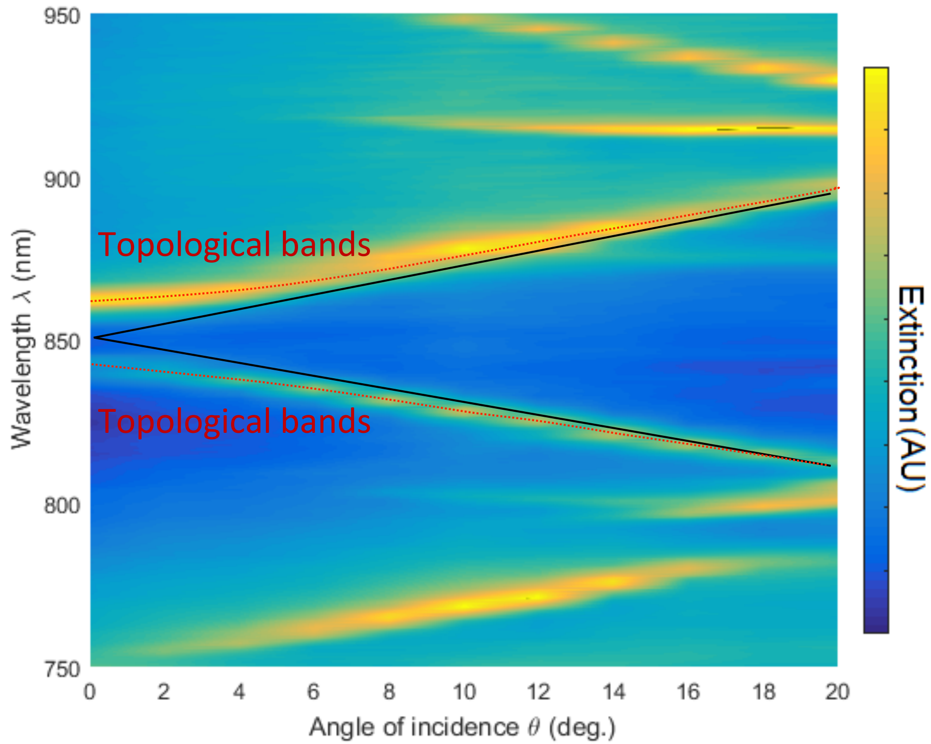






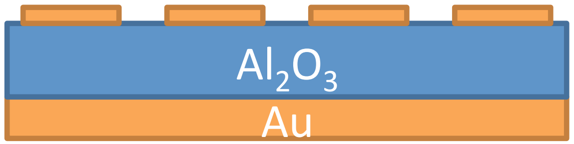
Optical characterization of the all-dielectric topological metasurface

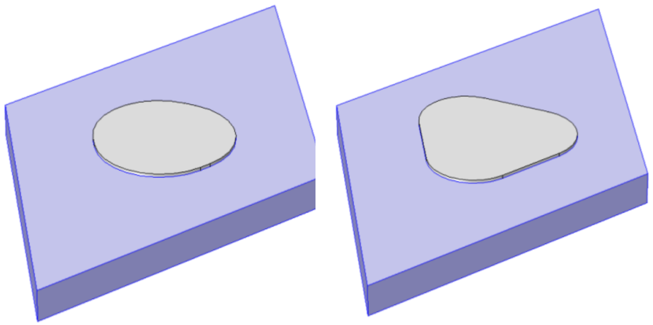


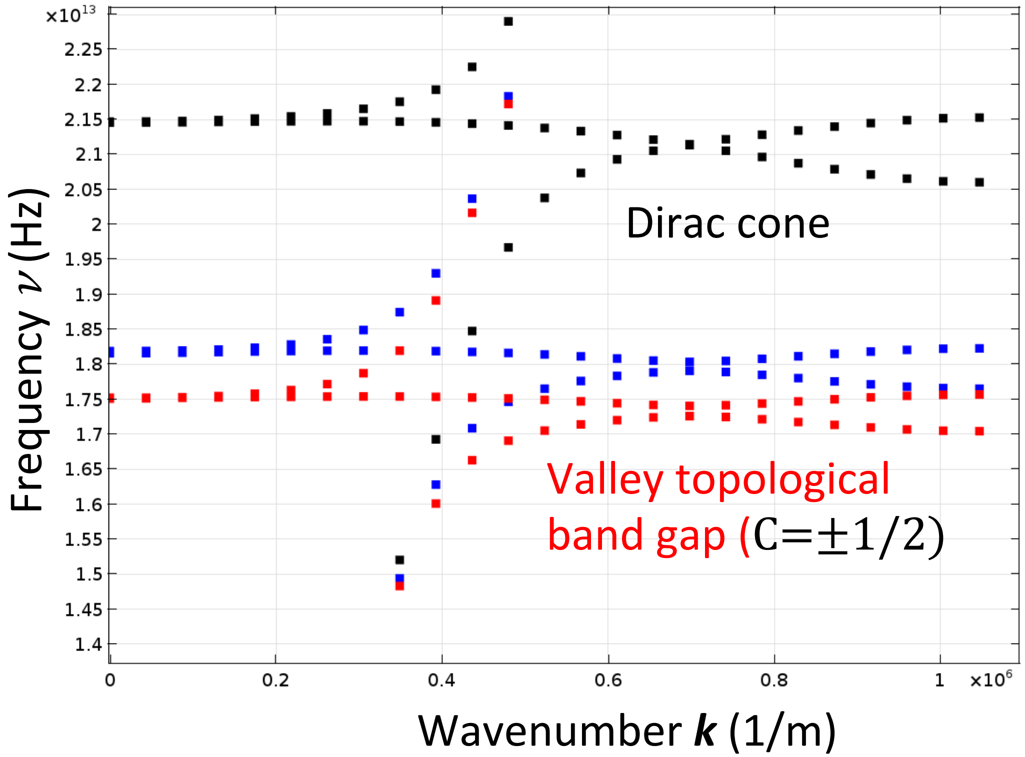


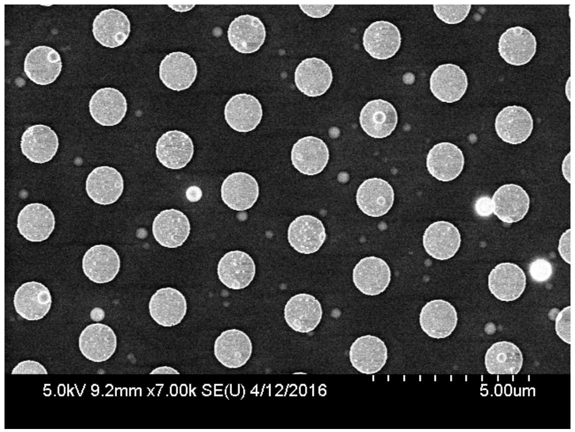
Next step – fabrication of samples with domain walls and observation of the edge states!

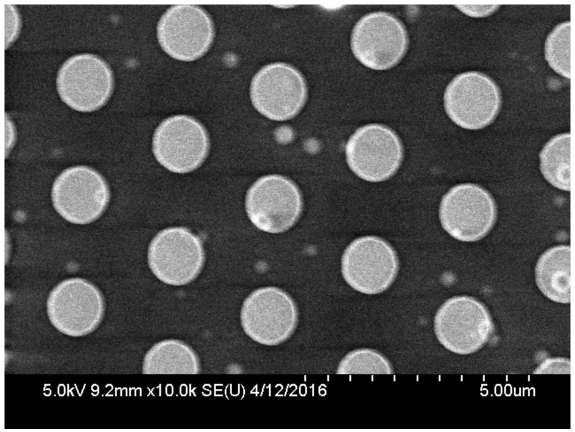
Topological plasmonics in mid-IR (work in progress)







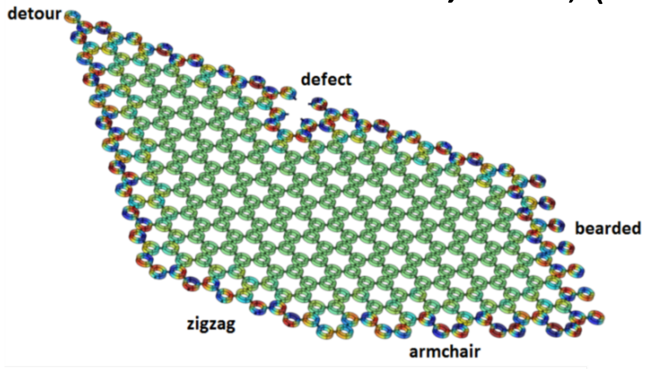




Acoustic and elastic topological states

1) Acoustic analogue of Quantum Hall effect

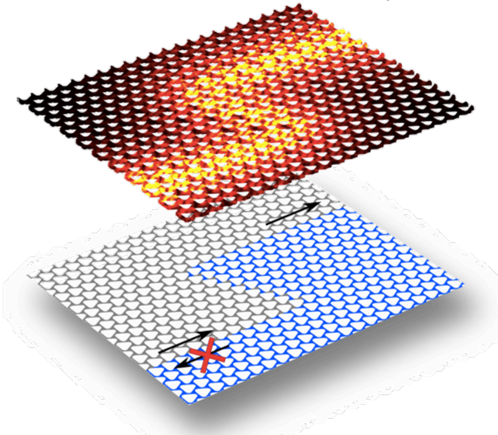
Nature Communications **6,** 8260, (2015).



In collaboration with Andrea Alu (UT Austin)

2) Acoustic analogue of Quantum Spin Hall Effect

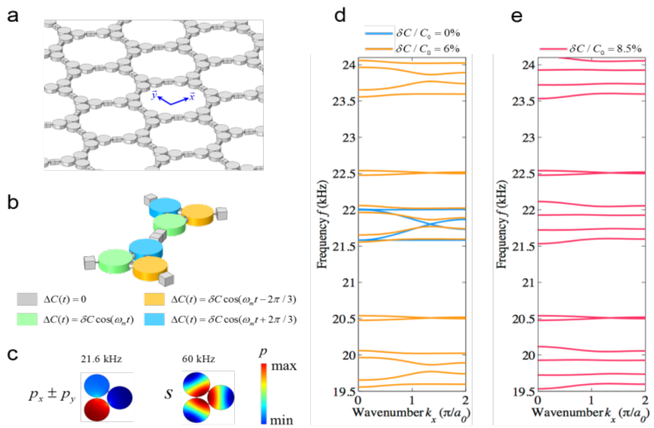
Nature Communications **6**, 8682 (2015).



In collaboration with Zheng Wang and Hossein Mousavi (UT Austin)

3) Floquet Topological Insulators for Sound

Nature Communications (2016).



Acoustic analogue of QHE

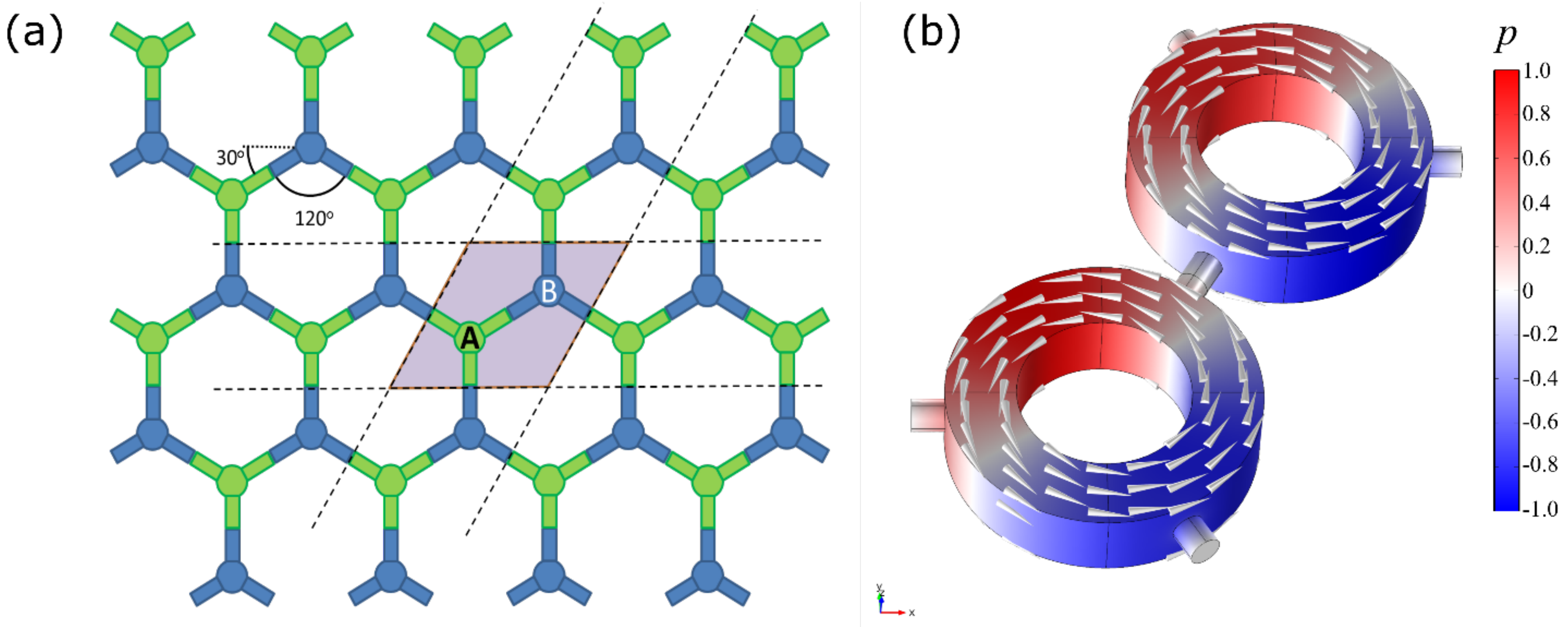
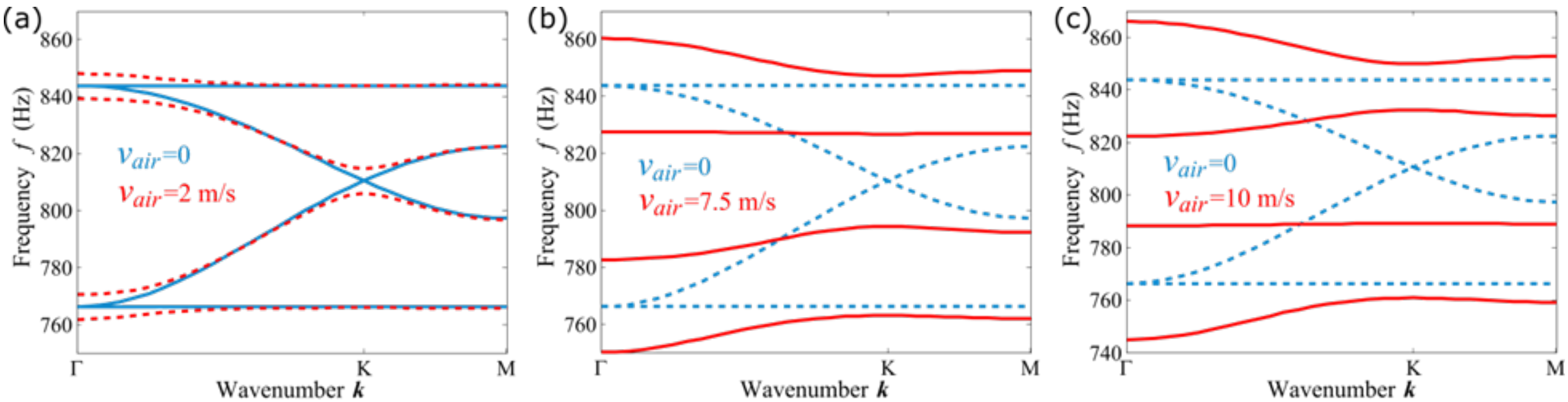


Figure 1| A diatomic hexagonal array to form the acoustic analogue of a graphene layer. (a) Lattice with two rotated Y-junctions/atoms (A and B, respectively) per unit cell (shaded region). (b) One unit cell of the lattice modelled in COMSOL Multiphysics, with acoustic pressure distribution shown in color for one of the Dirac modes of interest. The gray arrows indicate the direction of air flow in the resonators.

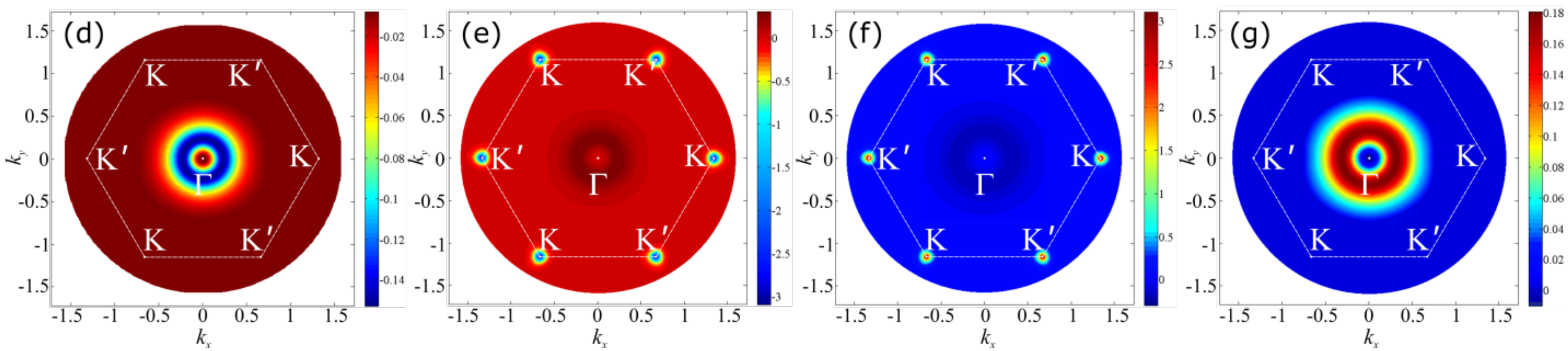
Acoustic analogue of QHE

Band structure of acoustic graphene with increasing air velocity inside the resonators.

Band diagrams obtained using first-principle numerical calculations.

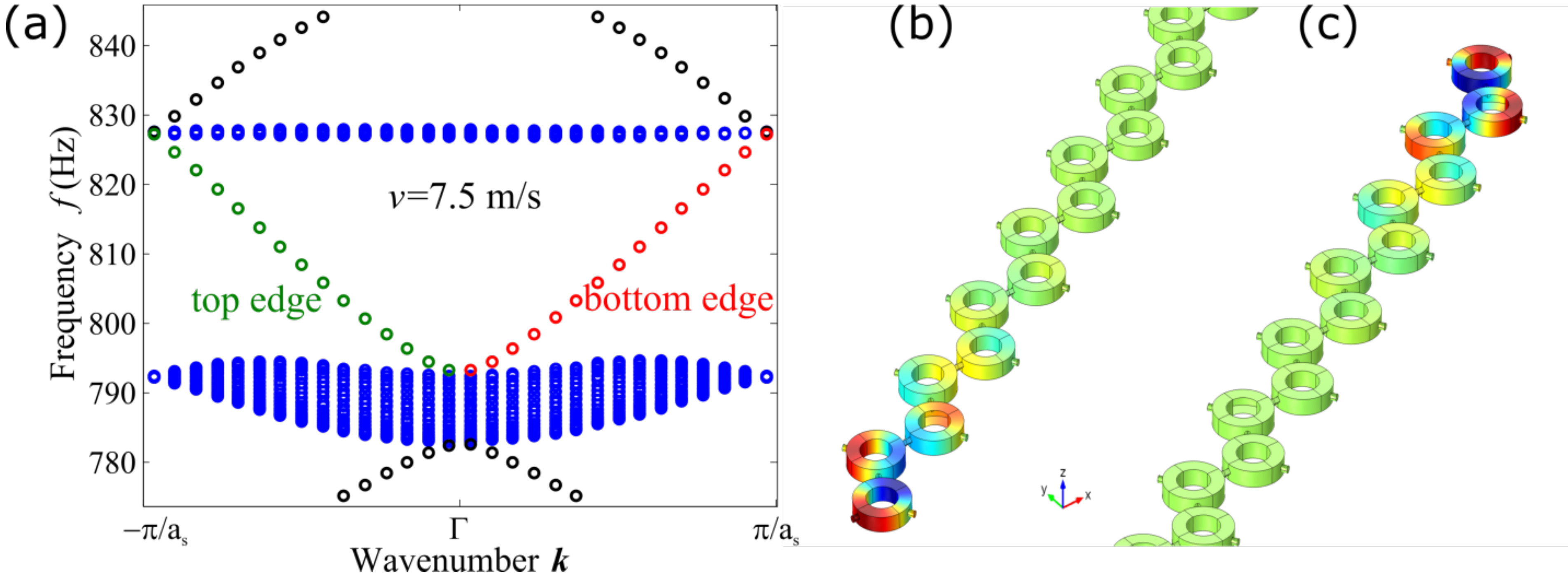


the Berry curvature of the top and bottom Dirac bands after gap opening



Acoustic analogue of QHE

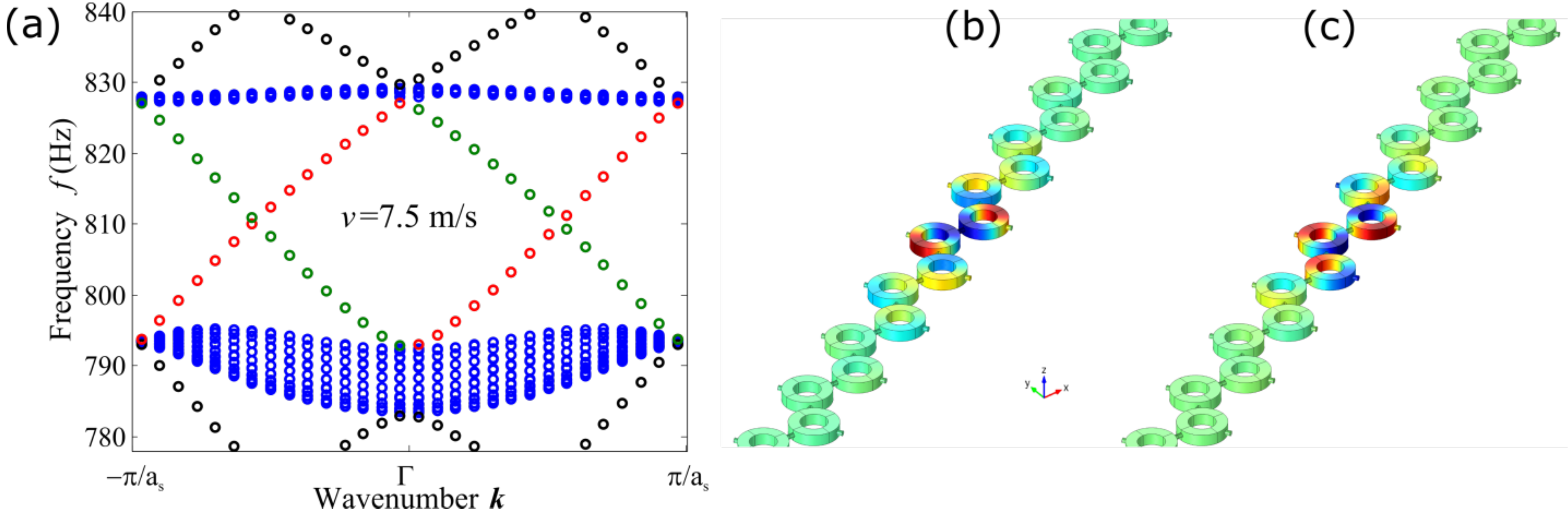
Topological edge modes in acoustic graphene.



(a) Acoustic band structure for a supercell of 20 unit cells and a uniform rotational bias velocity $v=7.5$ m/s. Bulk modes are shown by blue and edge modes by black, green and red colored markers. (b) and (c) Acoustic pressure profiles of the one-way edge mode localized at the bottom and top of the supercell, respectively, corresponding to the red and green bands in (a).

Acoustic analogue of QHE

Topological edge modes confined to the domain wall defined by the reversal of the air rotation inside the acoustic graphene



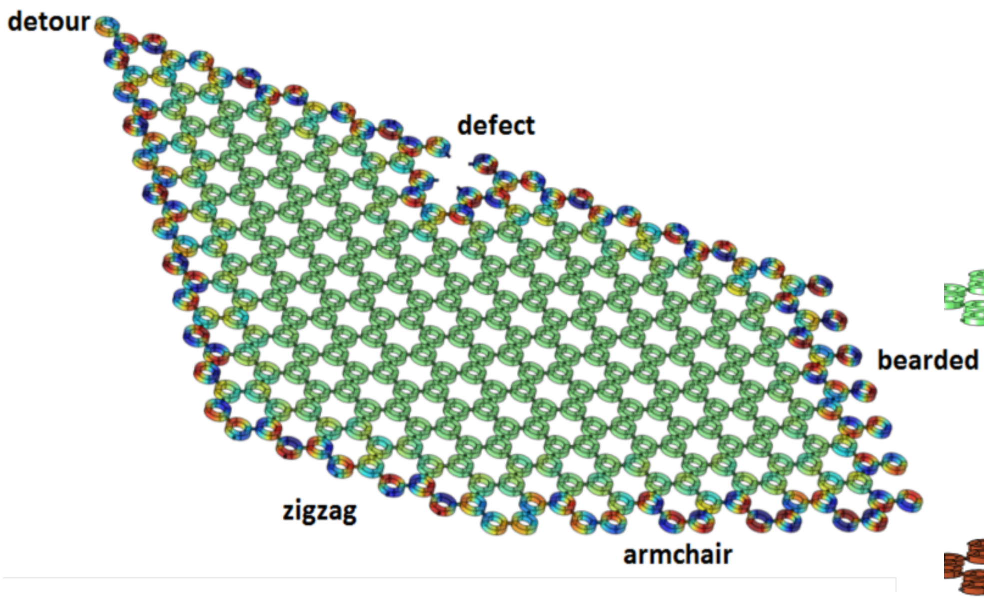
(a) Acoustic band structure for a supercell of 20 unit cells with domain wall at the center. The angular momentum bias is flipped within the lattice on one specific boundary along the domain wall from $v=7.5$ m/s to $v=-7.5$ m/s.

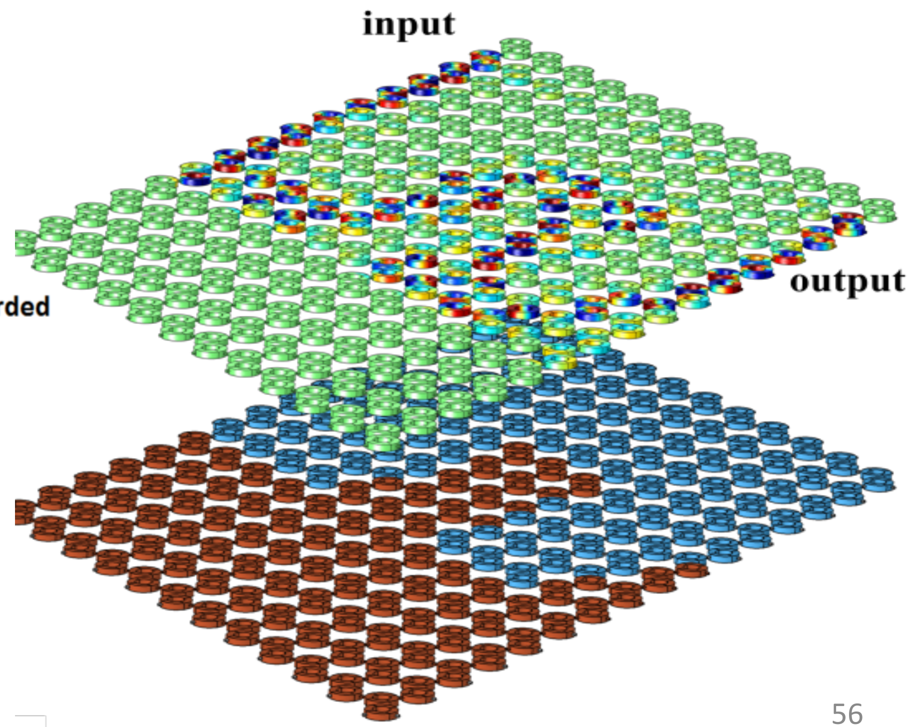
Acoustic analogue of QHE

Numerical demonstration of topological robustness of acoustic edge modes.

One-way (counterclockwise) edge mode propagates along different cuts of the acoustic graphene and around deliberately introduced defect.

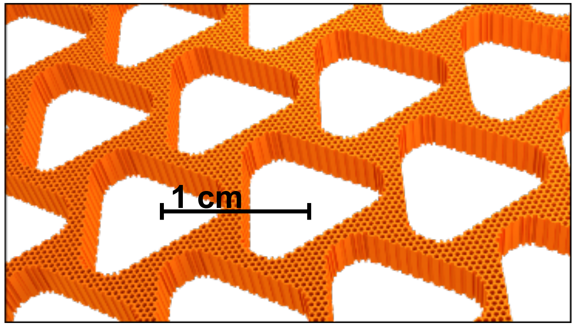
Excitation of the one-way (counterclockwise) edge mode and its propagation (top subplot) along the irregularly shaped domain wall created by the reversal of the Doppler bias.



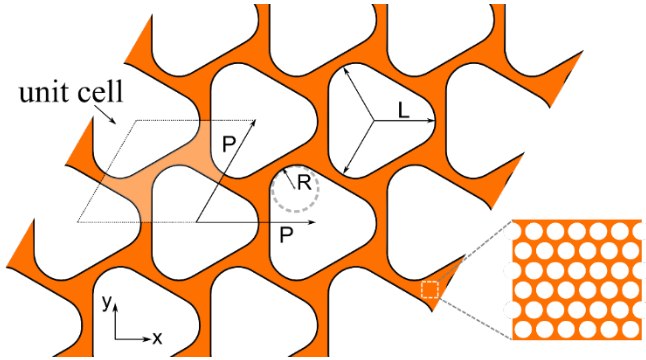


Phononic (elastic) analogue of the QSHE

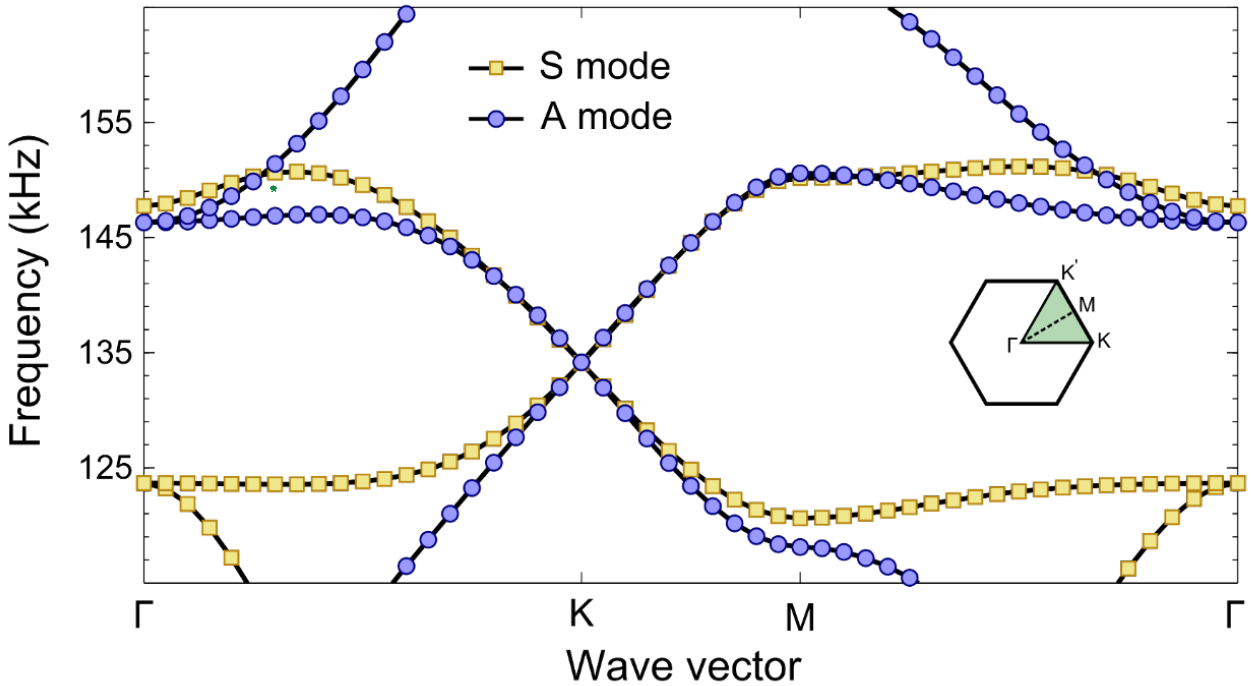
Concept: Metamaterial phononic crystal with doubly degenerate Dirac-like modes
Dual-scale structuring is necessary to match S and A dispersions



Slab of aluminum

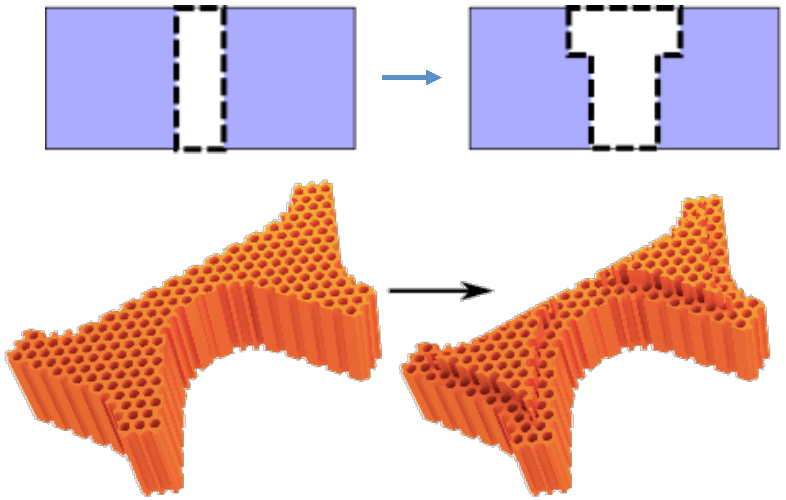


Phononic band structure

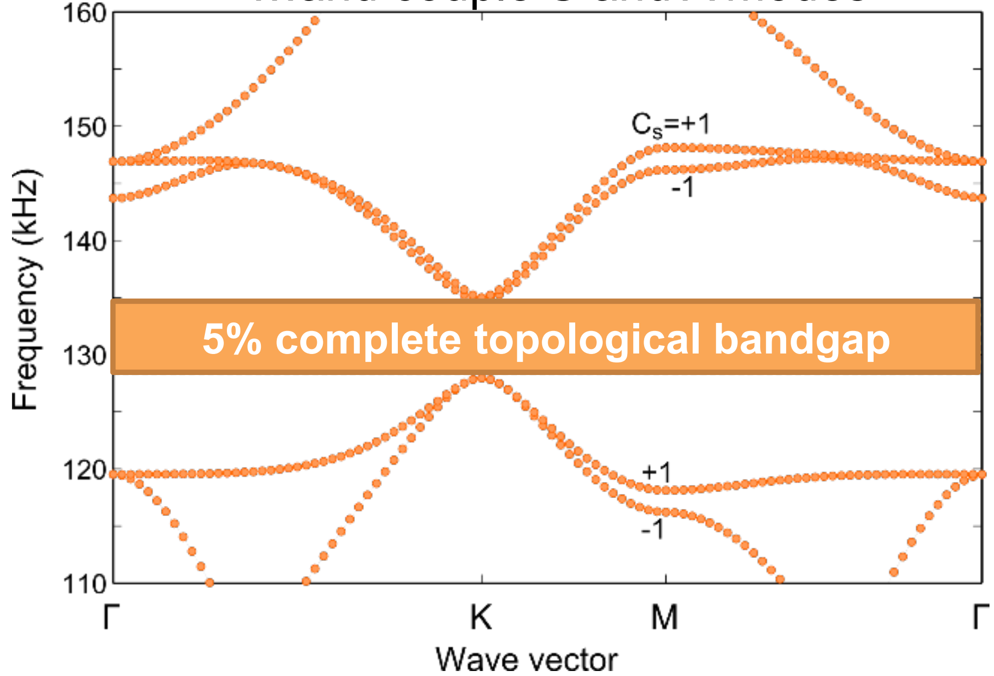


Emulating spin-orbit coupling and transition to phononic QSHE

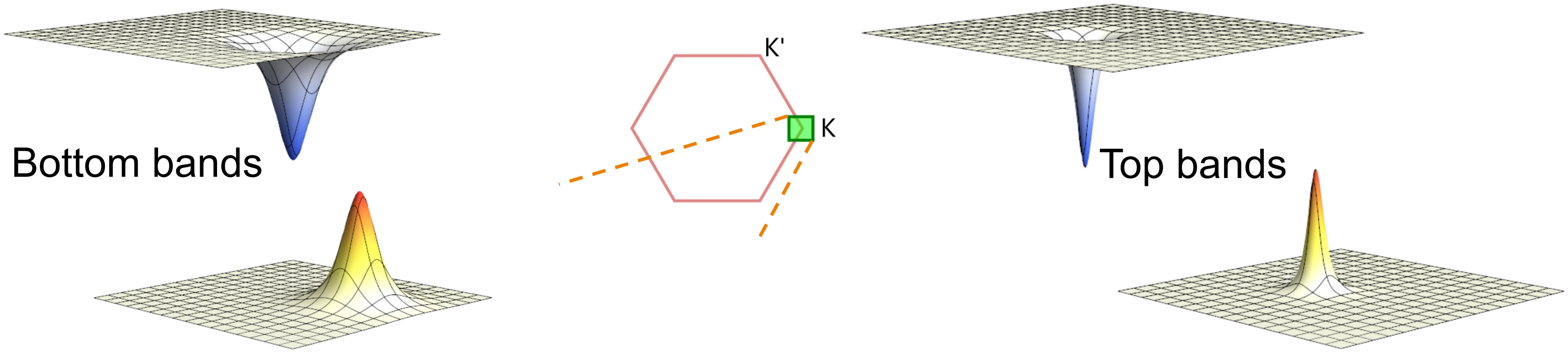
Opening a counterbore breaks σ_z ,
while preserves in-plane symmetries.



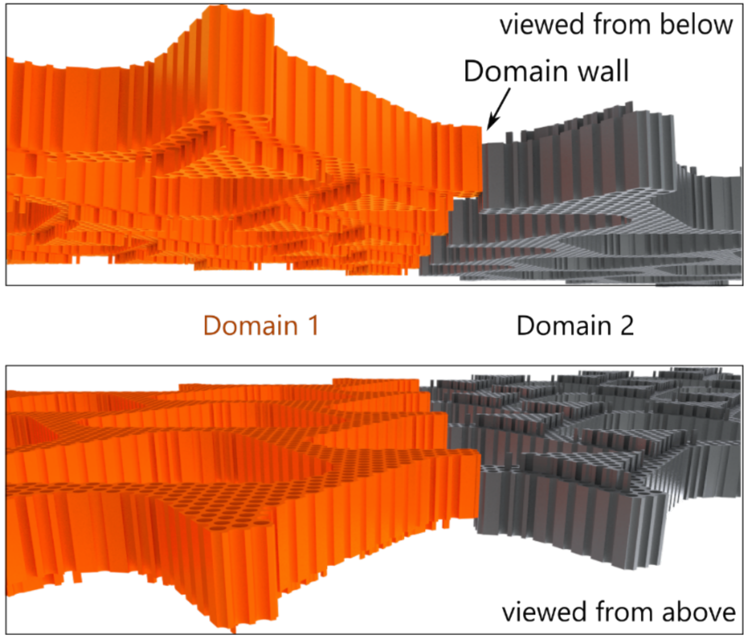
…and couple S and A modes

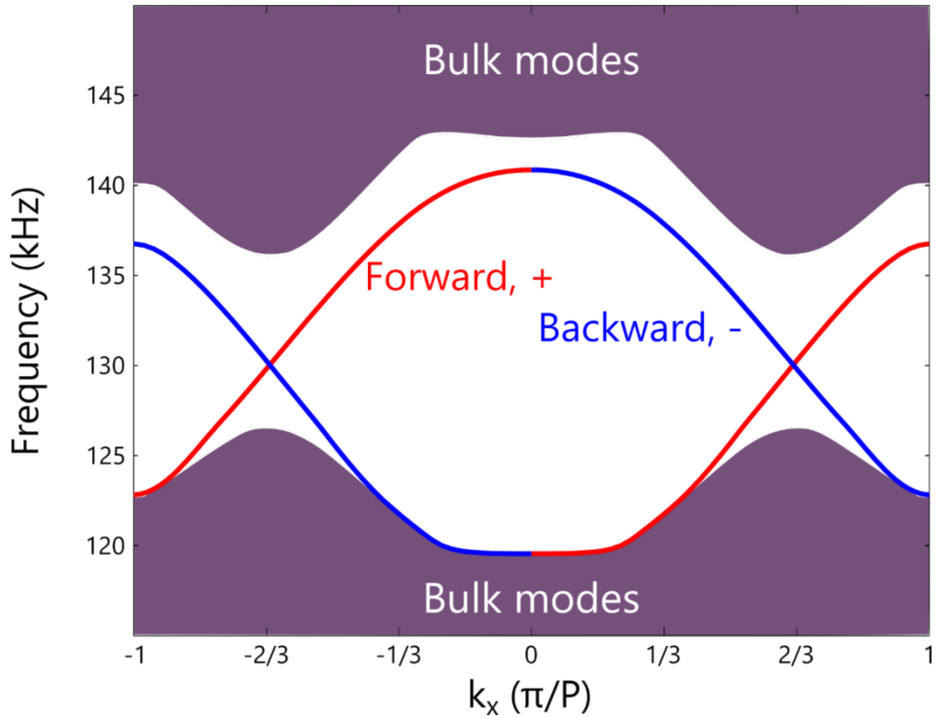


Berry curvature near K point:



Topologically robust edge modes

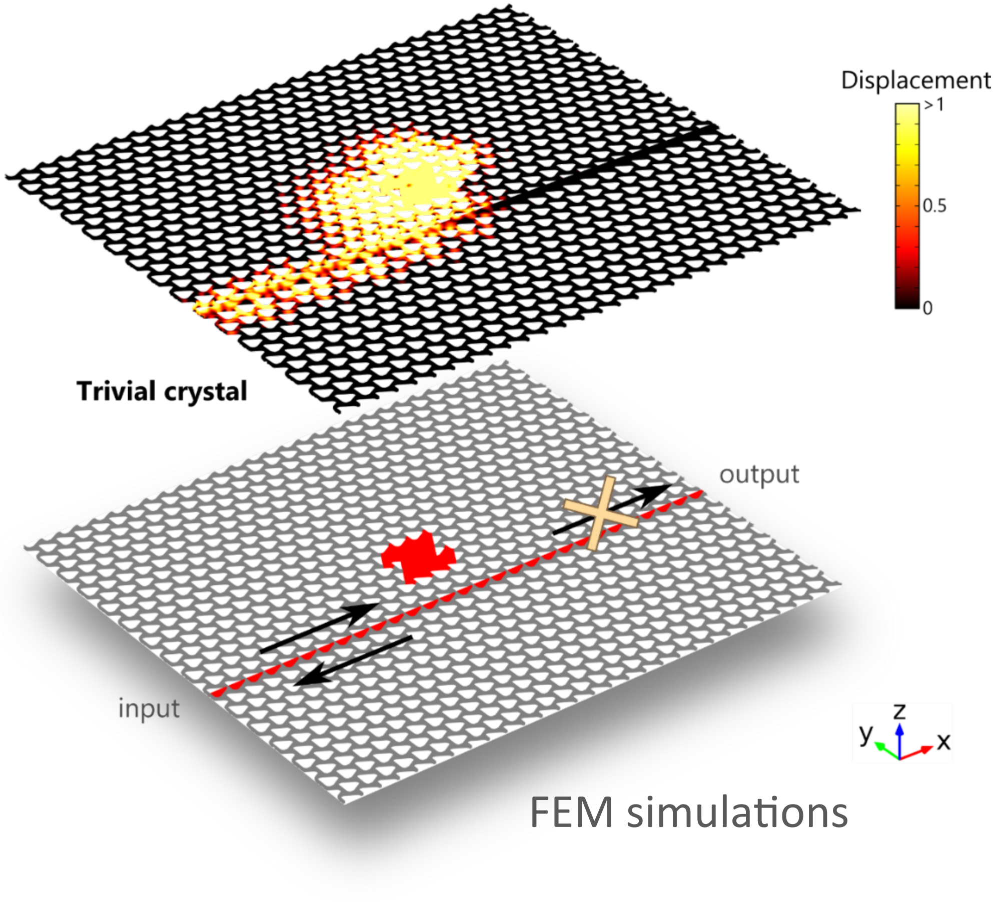




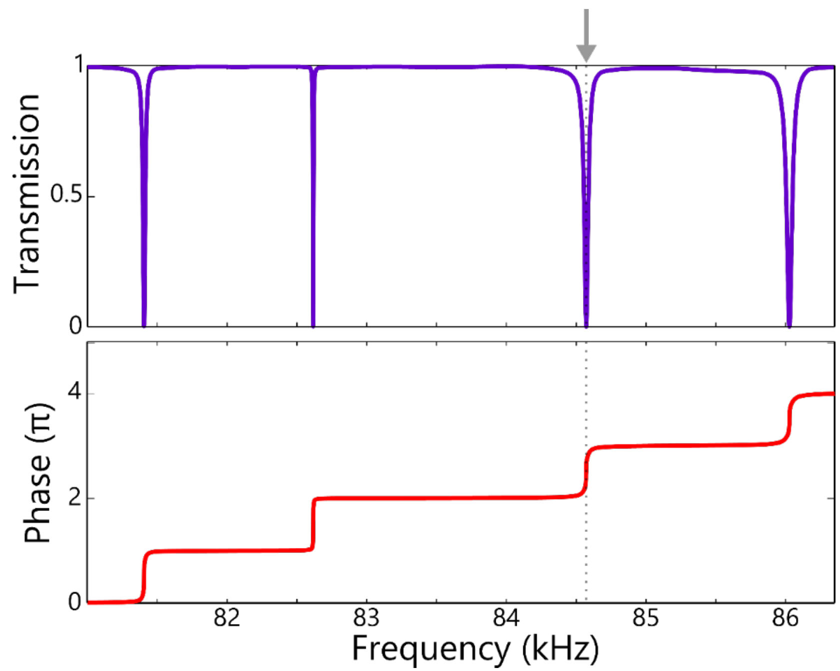
Massless helical edge states, spin locked to the propagation direction.

Time reversal operation changes the direction as well as the spin.

Trivial crystals are prone to defects and disorders

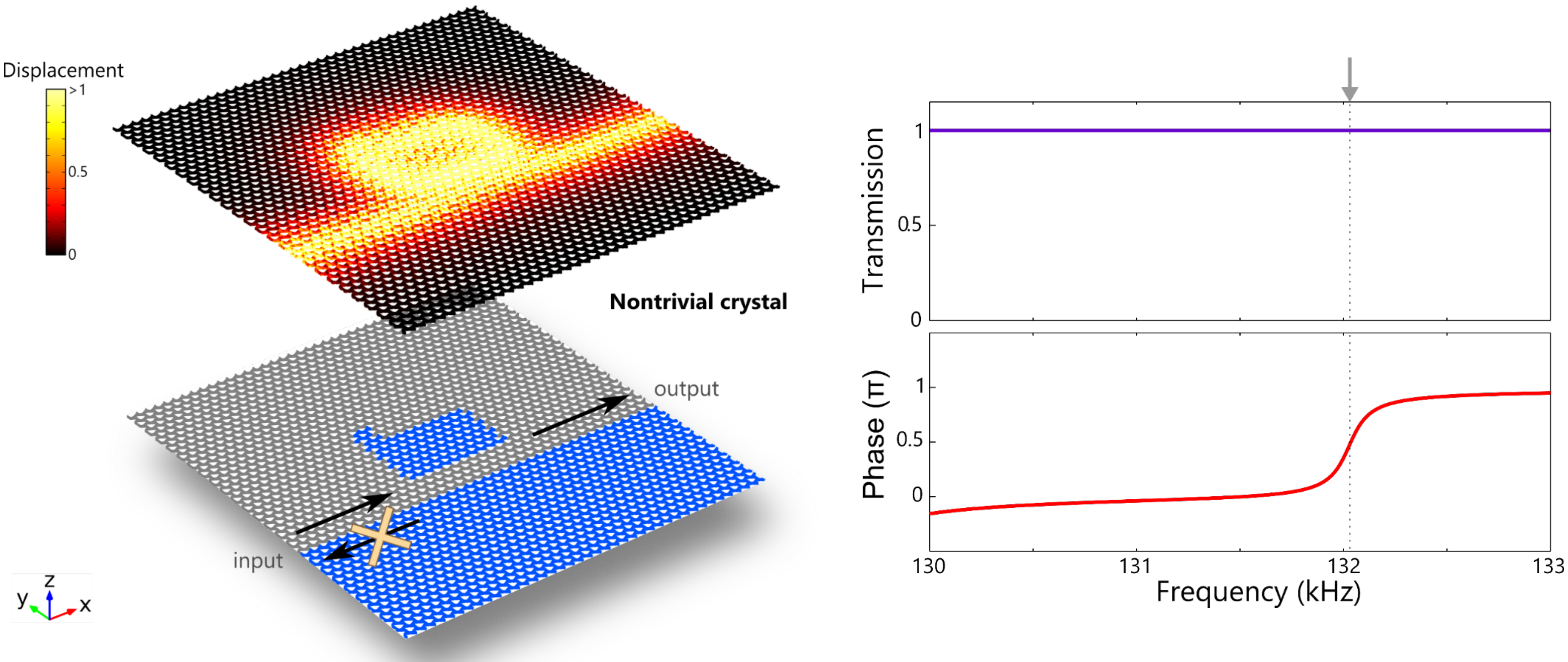


FEM simulations



Each time a resonance occurs, phase changes by π and transmission drops to zero.

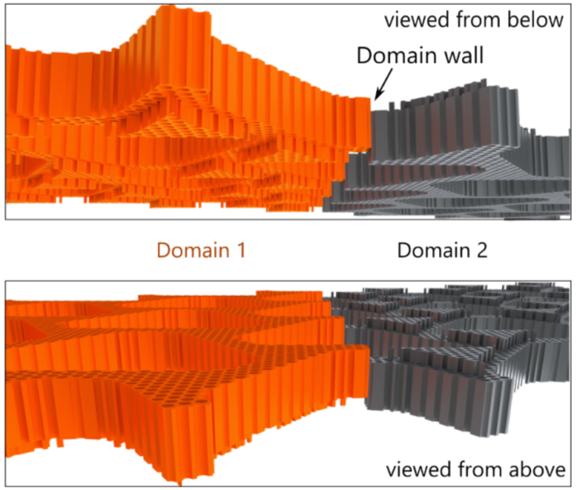
Robustness against defects and disorders in Quantum Spin Hall Effect crystal

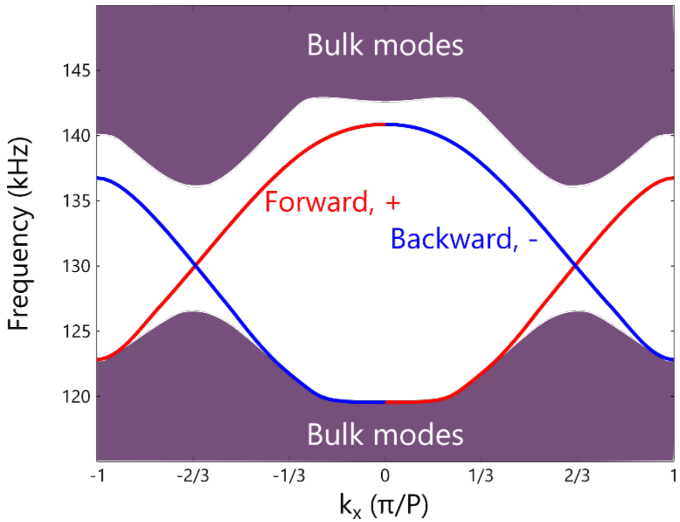


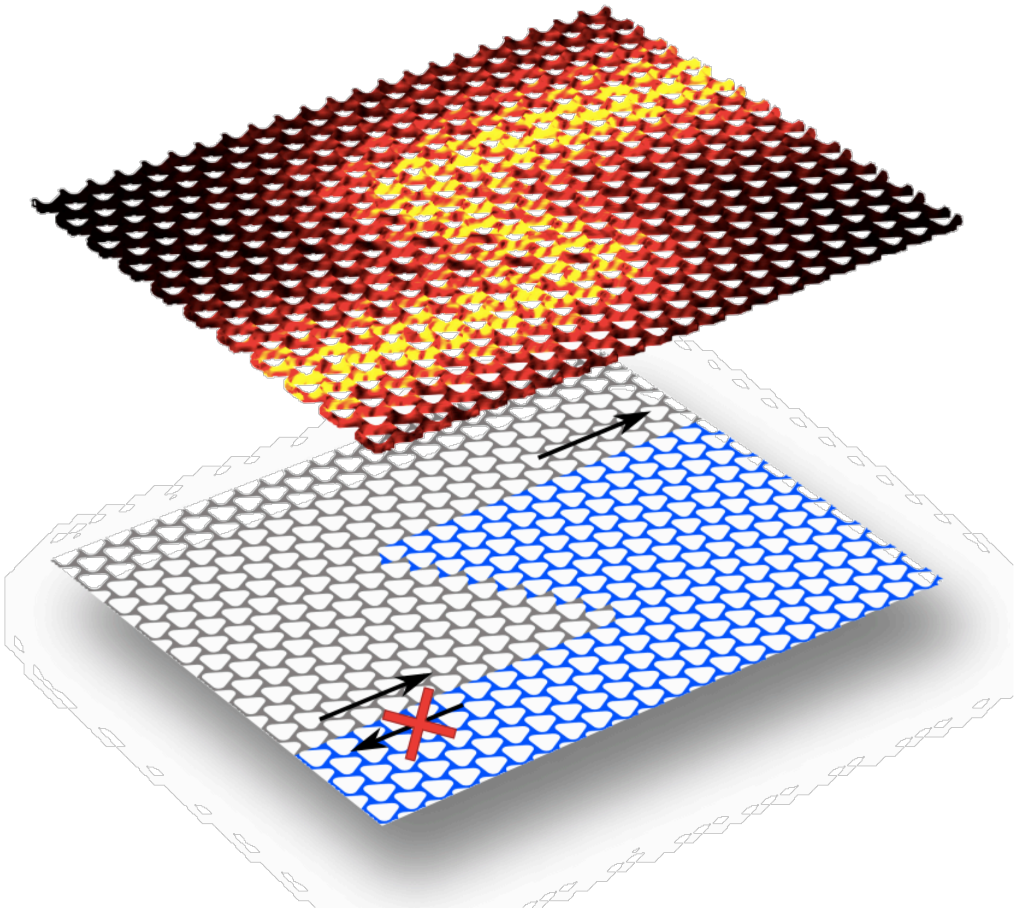
FEM simulations

Resonance manifests itself only in the **phase!**

Robustness against sharp bends and rerouting in Quantum Spin Hall Effect crystal







Summary and Outlook

- Photonic and acoustic systems offers an exceptional platform for emulating topological states of condensed matter and quantum relativistic phases.
- Topologically protected edge states robust to structural imperfections with and without time reversal symmetry are possible for photons and phonons
- Topological edge states envision a broad range of applications such as reconfigurable waveguides with controllable routing along the domain walls, and integrated optical systems where interaction among optical elements has “one-way” character.