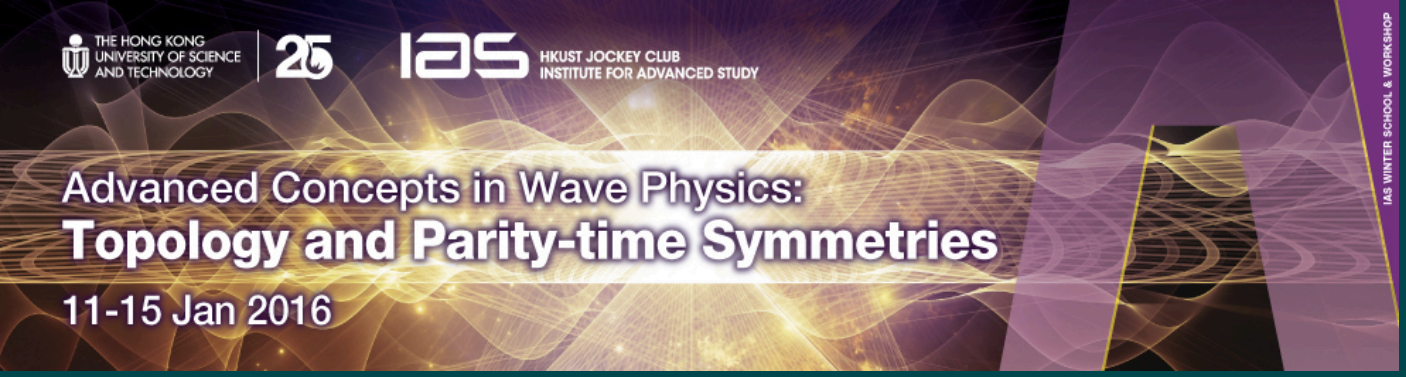


Tunable topological phononic crystals

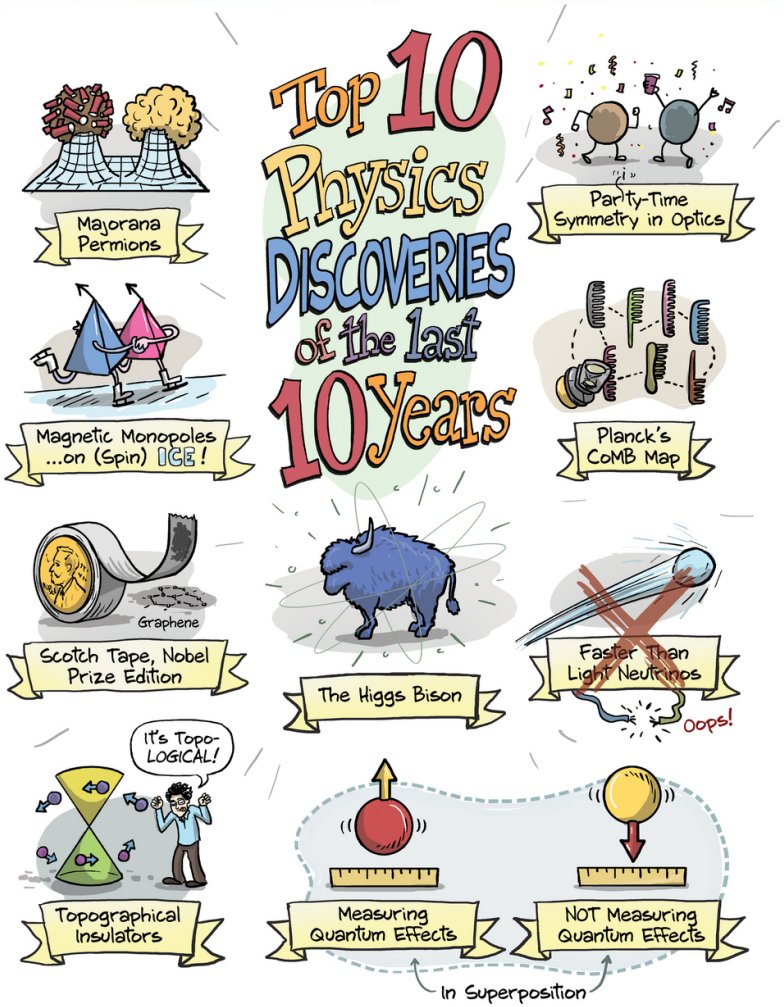
Zeguo Chen (陈泽国) and Ying Wu (吴莹)
King Abdullah University of Science and Technology

12 Jan 2016, Hong Kong

Outline

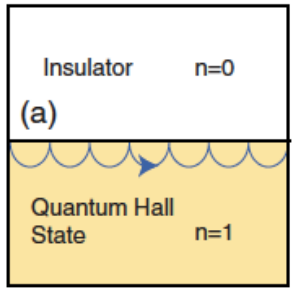
- Introduction
  - Background and motivation
- Tunable topological phononic crystals
  - Design
  - Physical model
  - Topological properties
  - Demonstration
- Summary

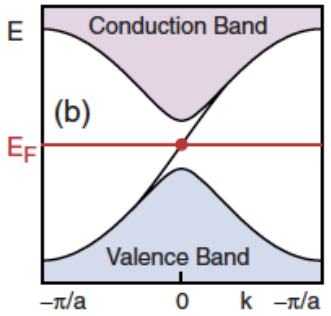
Introduction



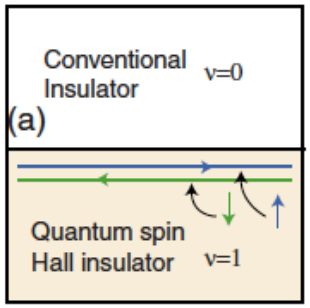
Nat. Phys. **11**, 799 (2015)

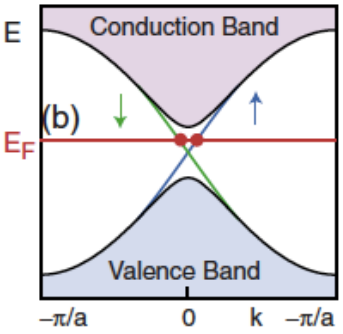
- QH state





- QSH states





One way propagation edge states.

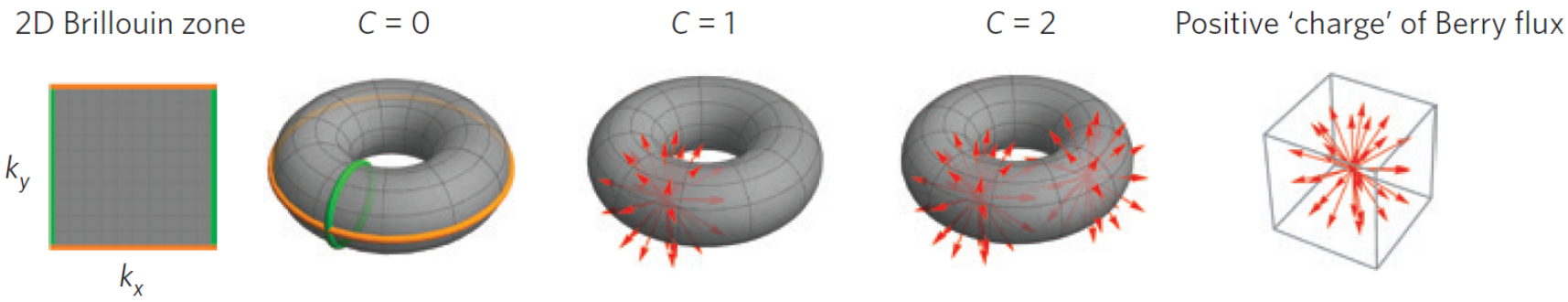
Rev. Mod. Phys. 82 3045 (2010)

TKNN invariant

- Chern number.
  - Arises from topology that differentiates QH (non-trivial) and an ordinary insulator (trivial).
  - Integration of Berry flux in the BZ.

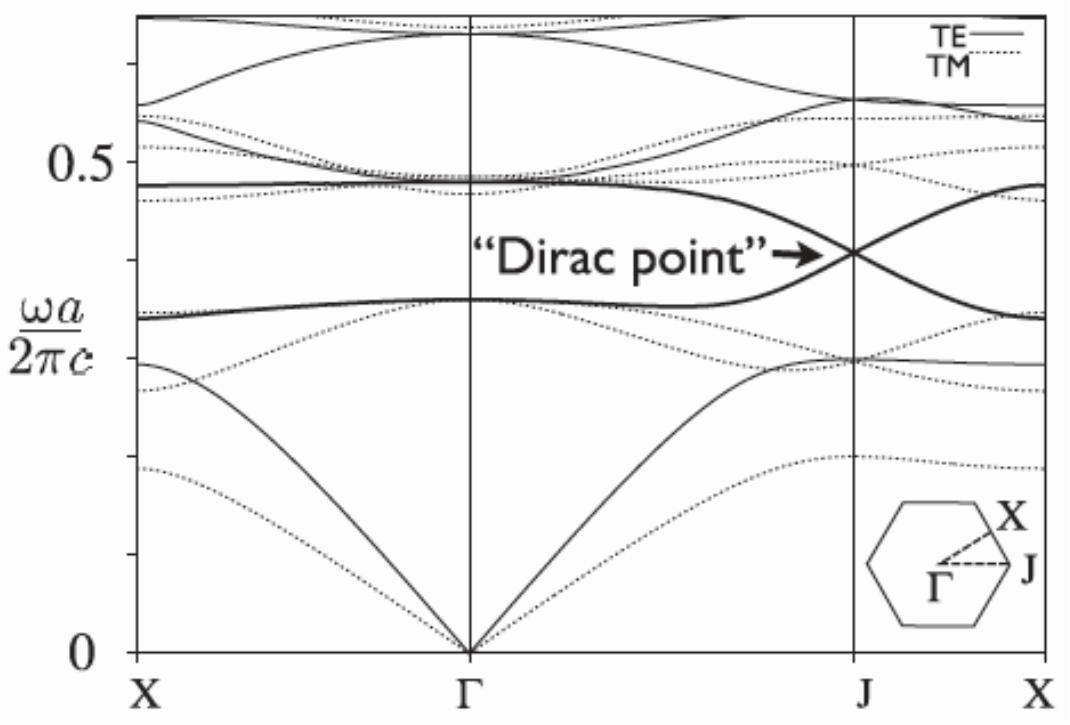
Berry connection

$$C_m = \frac{1}{2\pi}\int d^2\vec{k}\,\nabla \times \vec{A}_m \quad \Leftarrow \quad \vec{A}_m = i\left\langle u_m \middle| \nabla_k \middle| u_m \right\rangle$$

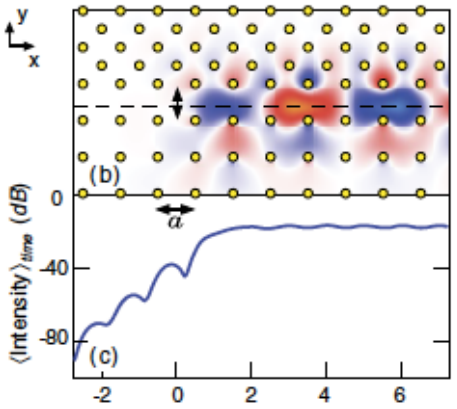


Nat. Photonics 8 821 (2014)

Classical analogues in photonic systems



Phys. Rev. Lett. **100**, 013904 (2008).



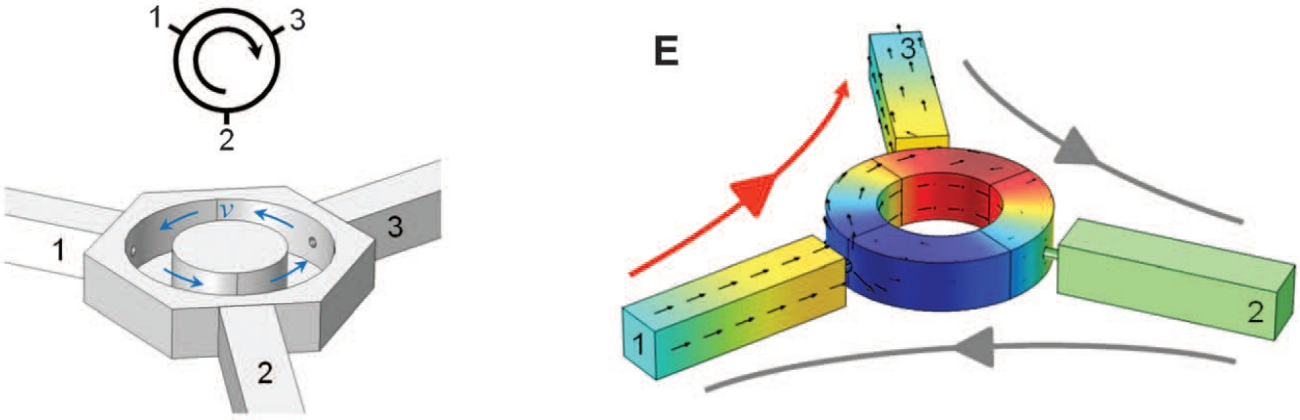
$$\boldsymbol{\mu} = \begin{bmatrix} \mu & i\kappa & 0 \\ -i\kappa & \mu & 0 \\ 0 & 0 & \mu_0 \end{bmatrix}.$$

YIG material

Phys. Rev. Lett. **100**, 013905 (2008)

About acoustics

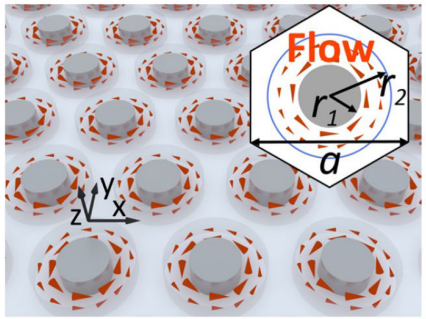
- Breaking Time-reversal symmetry in acoustics

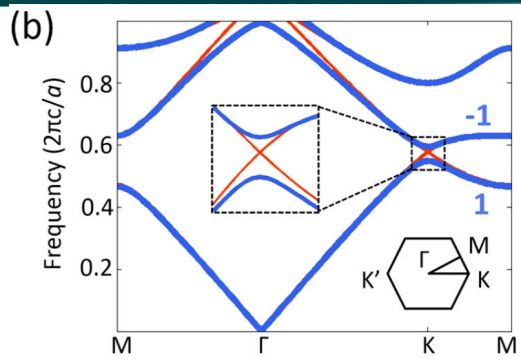


Nonreciprocal air-flow-contained acoustic circulator

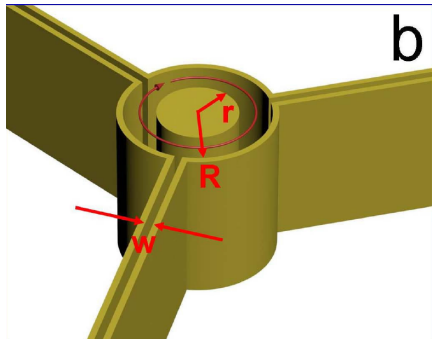
Science 343, 516 (2014)

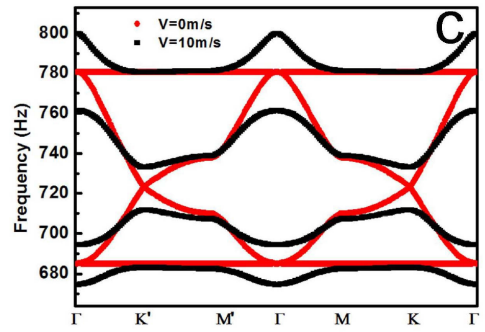
About acoustics



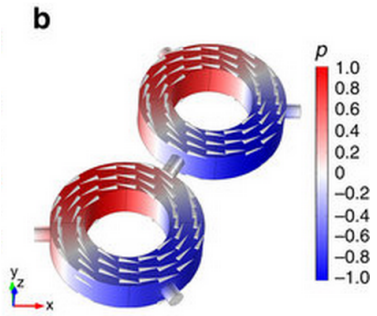


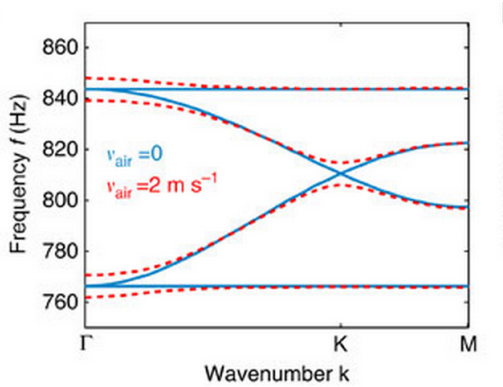
PRL 114, 114301 (2015)





NJP **17**, 053016 (2015).

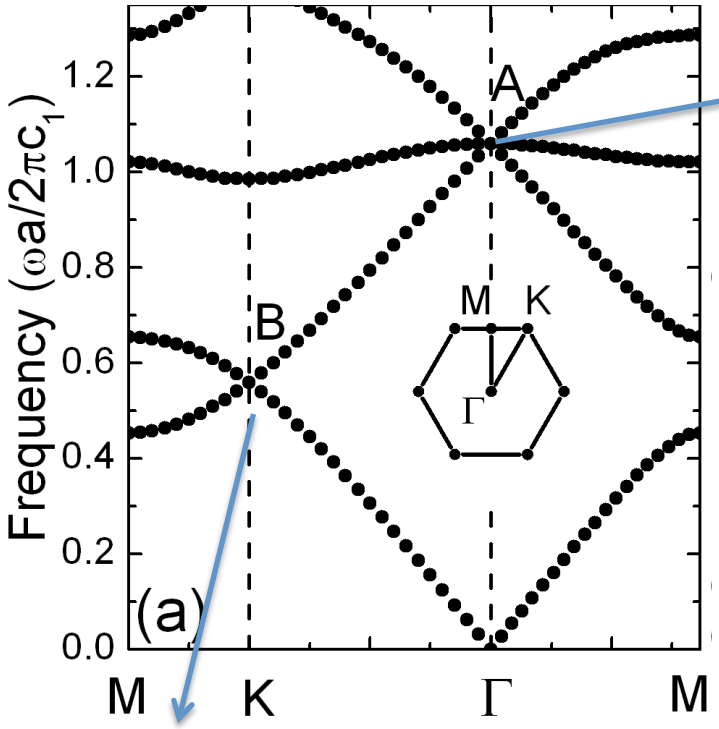




Nat. Commun. **6**, 8260 (2015).

Motivation

- From deterministic degeneracy at K point to accidental degeneracy at Γ point



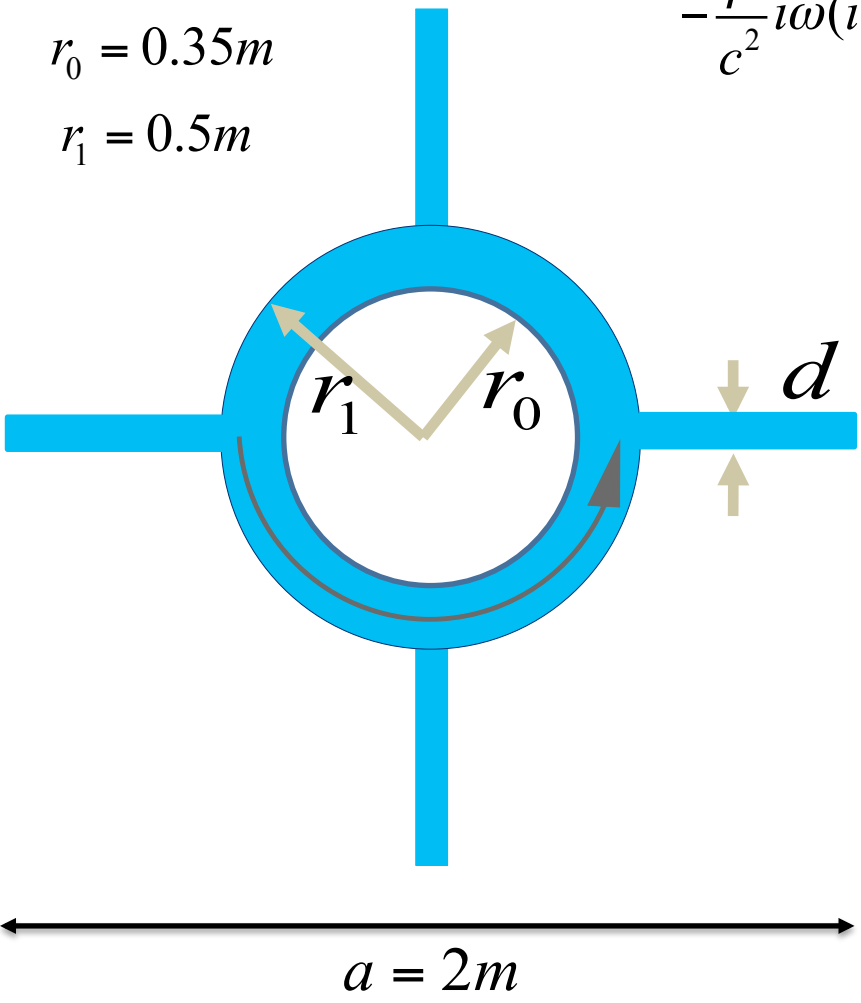
Accidental degeneracy

What happens if time-reversal symmetry is broken and ,at the same time, geometry changes as well?

Protected by TRS

PRB **86** 035141 (2012)

Sample

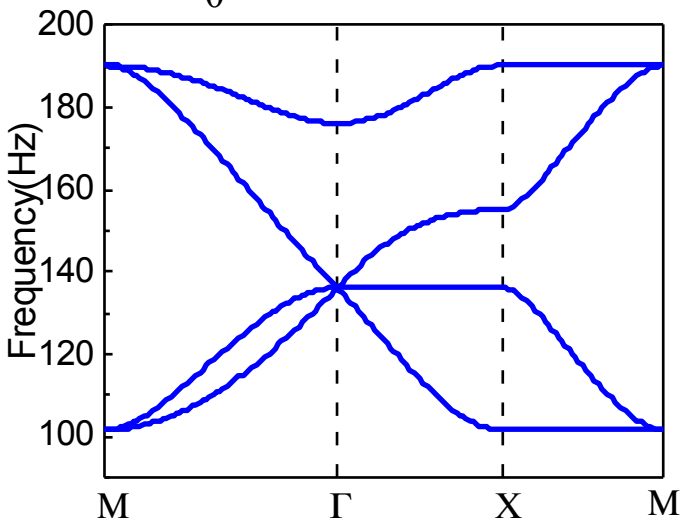


$$-\frac{\rho}{c^2} i\omega(i\omega\phi + \vec{v}\cdot\nabla\phi) + \nabla\cdot(\rho\nabla\phi - \frac{\rho}{c^2}(i\omega\phi + \vec{v}\cdot\nabla\phi)\vec{v}) = 0$$

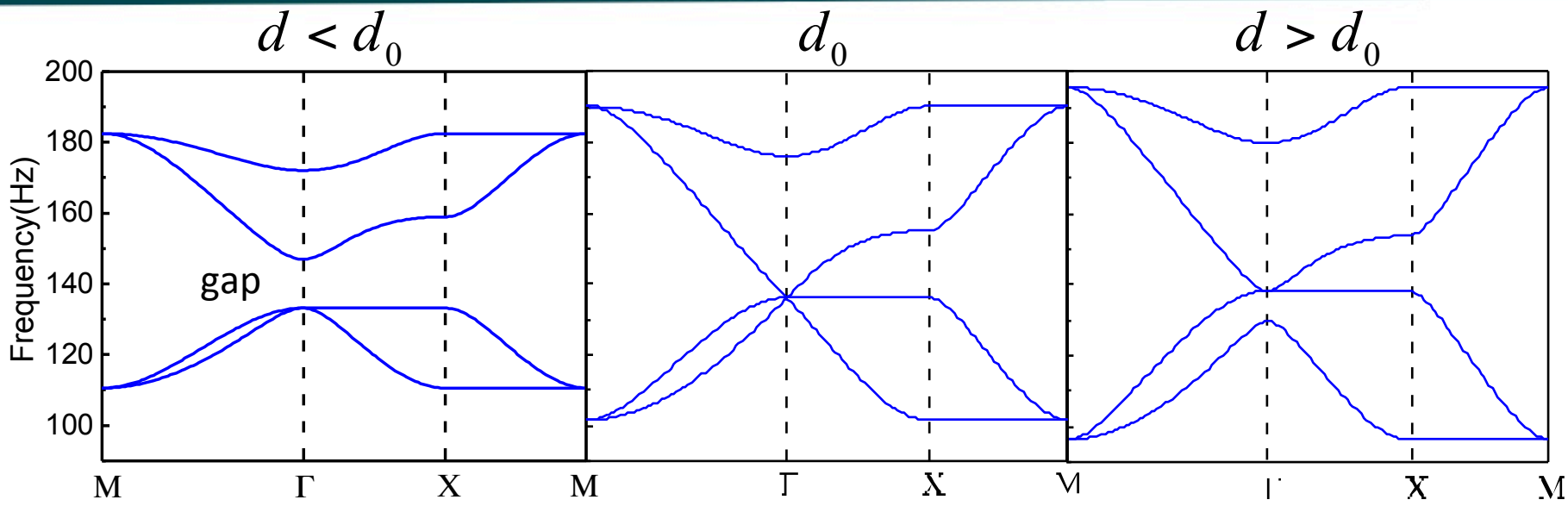
No air flow $\vec{v} = 0$

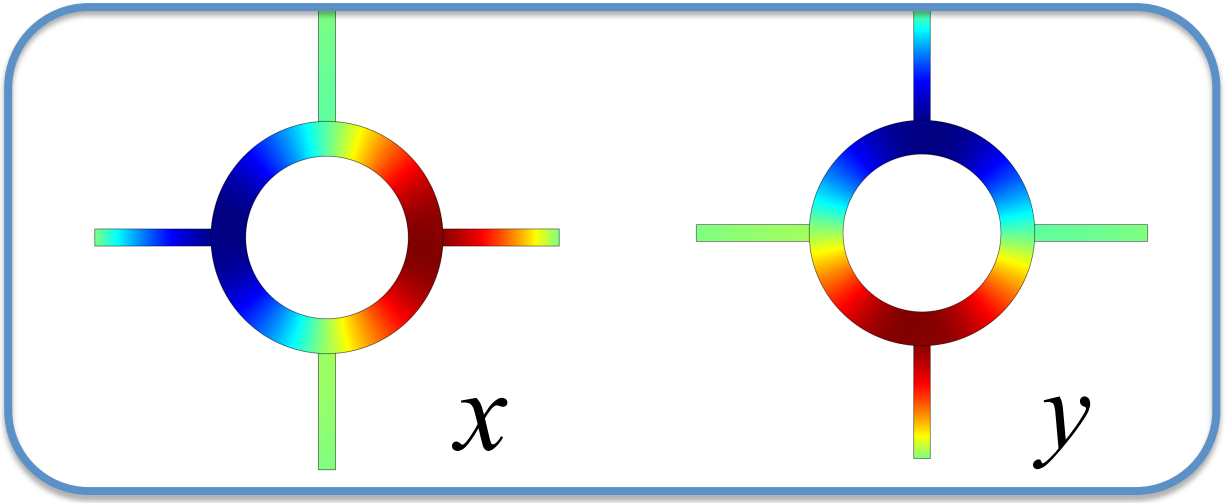
$$\frac{\rho}{c^2}\omega^2\phi + \nabla\cdot(\rho\nabla\phi) = 0$$

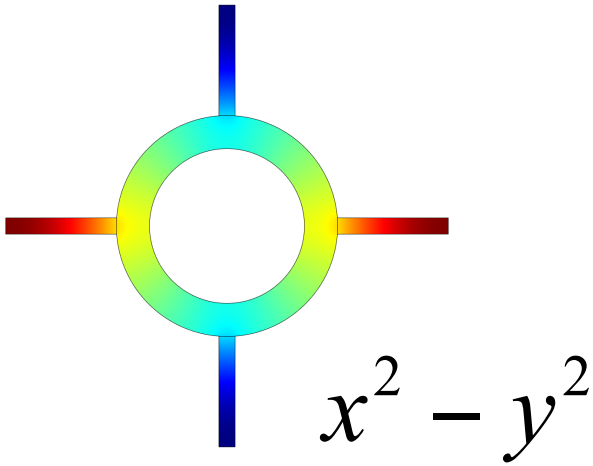
$$d_0 = 0.07336m$$



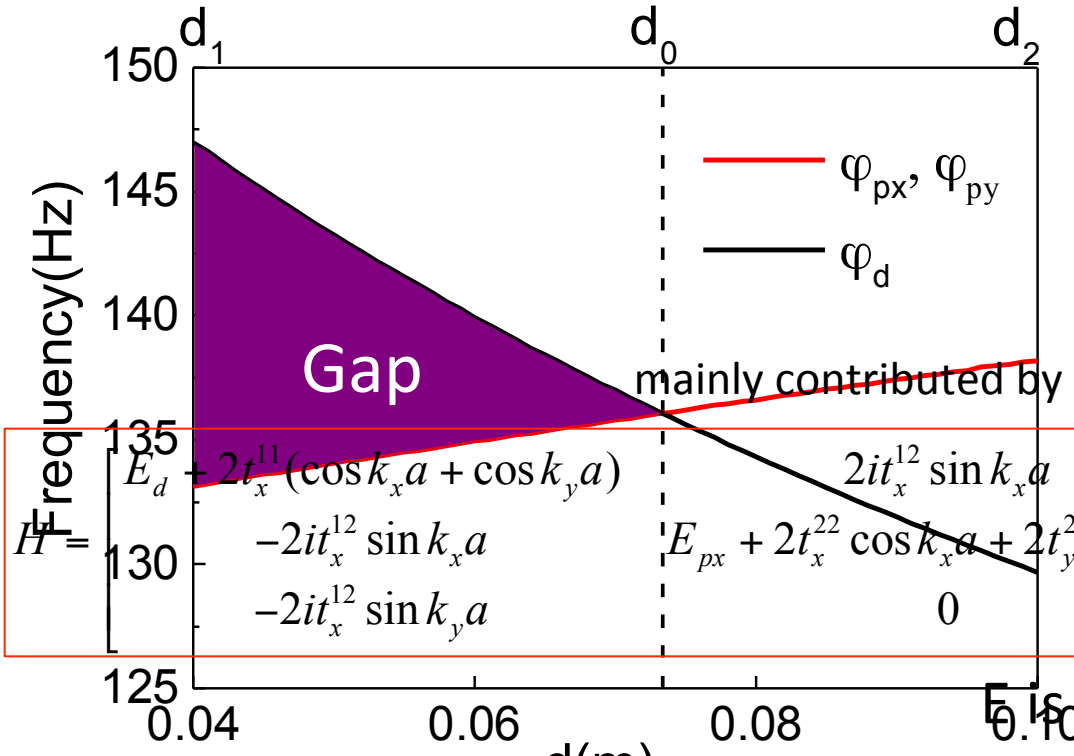
Without air flow

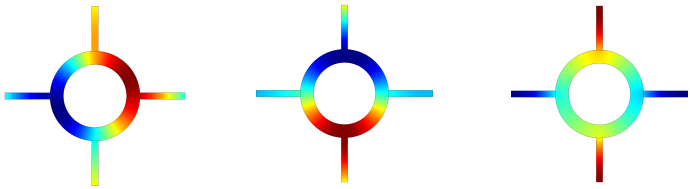






A tight-binding model





$$t_m^{ij} = \left\langle \Phi_i(\vec{r}) \middle| H \middle| \Phi_j(\vec{r} + \vec{r}_m) \right\rangle$$

mainly contributed by the wave functions inside the waveguide

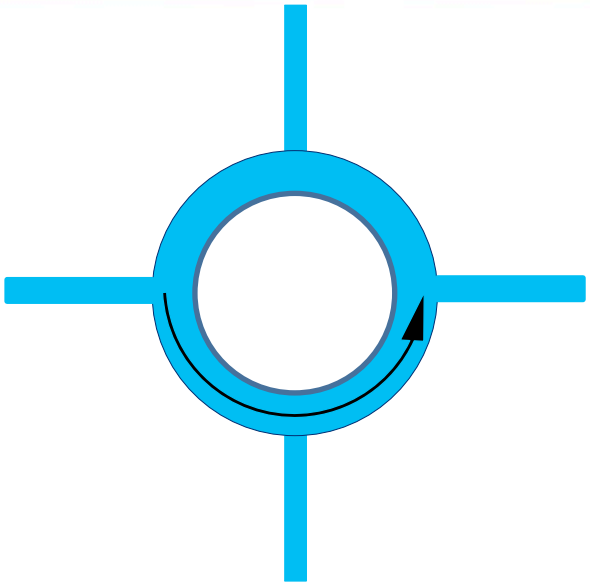
$$H = \begin{bmatrix} E_d + 2t_x^{11}(\cos k_x a + \cos k_y a) & 2it_x^{12} \sin k_x a & 2it_x^{12} \sin k_y a \\ -2it_x^{12} \sin k_x a & E_{px} + 2t_x^{22} \cos k_x a + 2t_y^{22} \cos k_y a & 0 \\ -2it_x^{12} \sin k_y a & 0 & E_{py} + 2t_y^{22} \cos k_x a + 2t_x^{22} \cos k_y a \end{bmatrix}$$

E is the on-site energy of the rings

$$\vec{k} = 0 \Rightarrow H = \begin{bmatrix} E_d + 2t_x^{11} & 0 & 0 \\ 0 & E_{px} + 2t_x^{22} + 2t_y^{22} & 0 \\ 0 & 0 & E_{py} + 2t_y^{22} + 2t_x^{22} \end{bmatrix}$$

Eigenvalue depends on the width of the waveguide.

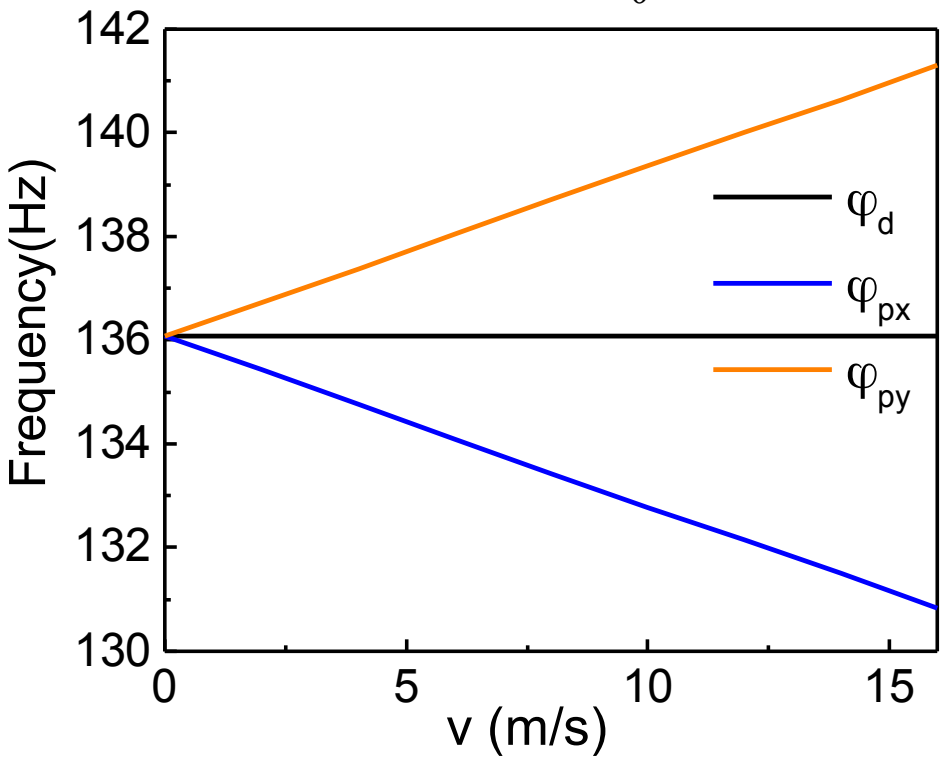
Breaking $\mathscr{T}$ Symmetry: with air flow



$$\vec{v}(x,y) = \left(\frac{-vy}{\sqrt{x^2+y^2}}, \frac{vx}{\sqrt{x^2+y^2}}\right) = v\vec{e}_\theta$$

$$\omega_{\pm} = (c \pm v)/R_{av} \qquad R_{av} = (r_0 + r_1)/2$$

$$d = d_0$$

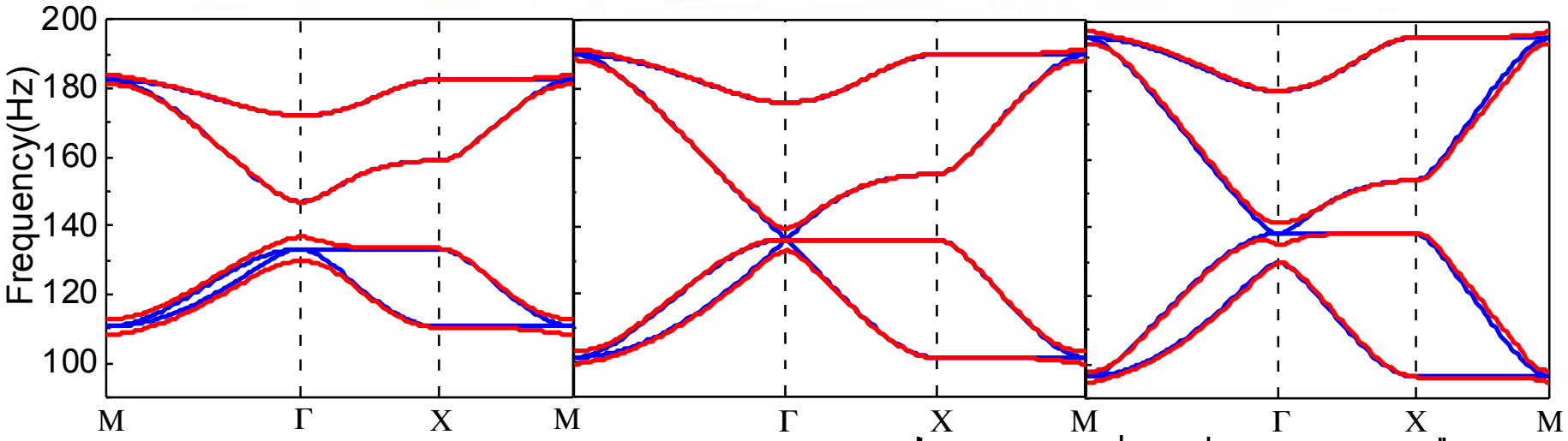


From C_{4v} to C_4.

φ_d almost does not change

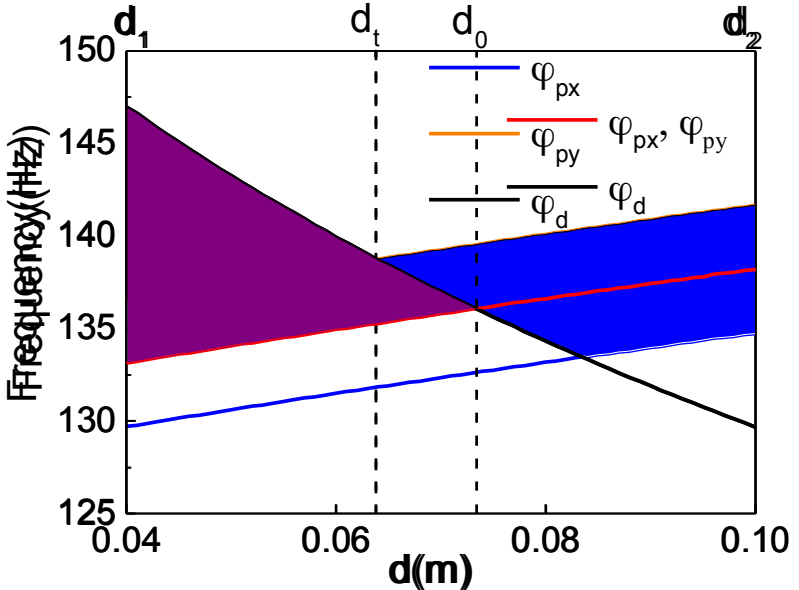
Degeneracy is lifted.

Band structures



- Degeneracy associated with φ_{px} and φ_{py} lifts.
- Branch associated with φ_d almost does not change.

Consistent with the Tight-Binding.



Topological property: Chern number

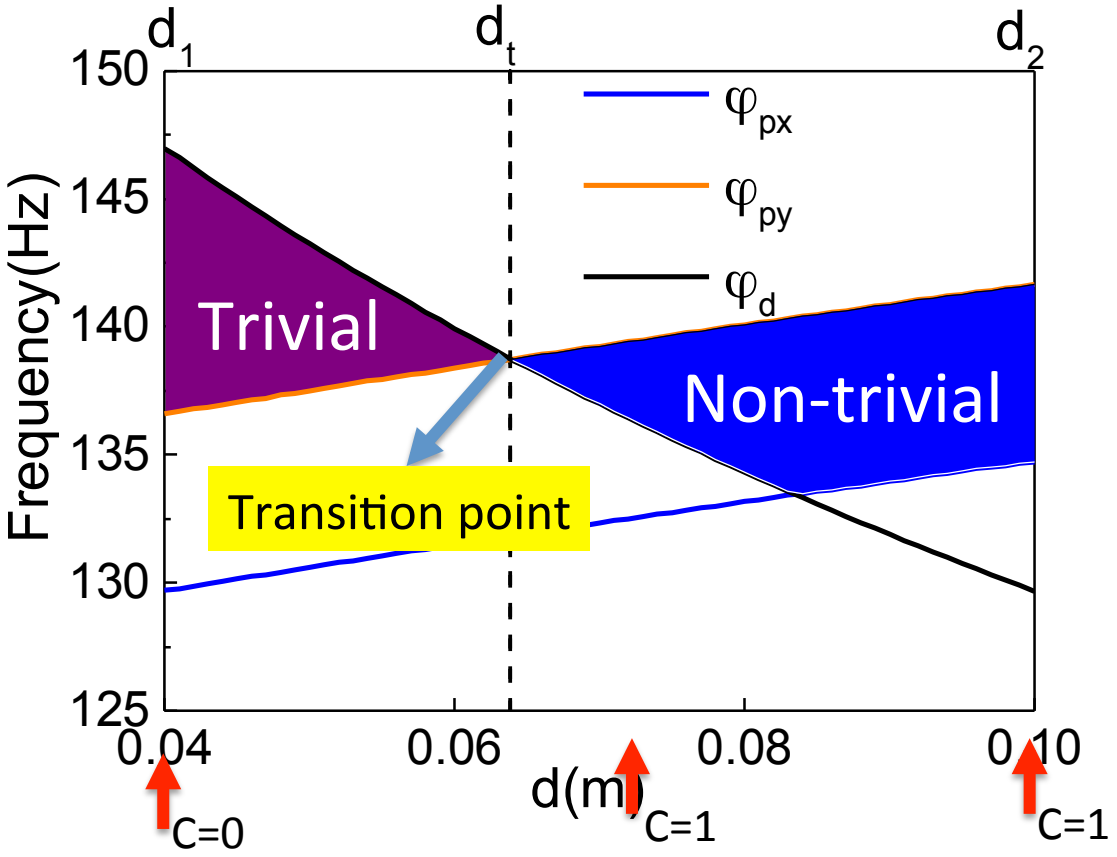
$$C = \frac{i}{2\pi}\sum_n \int_{BZ} \nabla_{\vec{k}} \times \left\langle u_n(\vec{k}) \middle| \nabla_{\vec{k}} \middle| u_n(\vec{k}) \right\rangle d^2\vec{k}$$

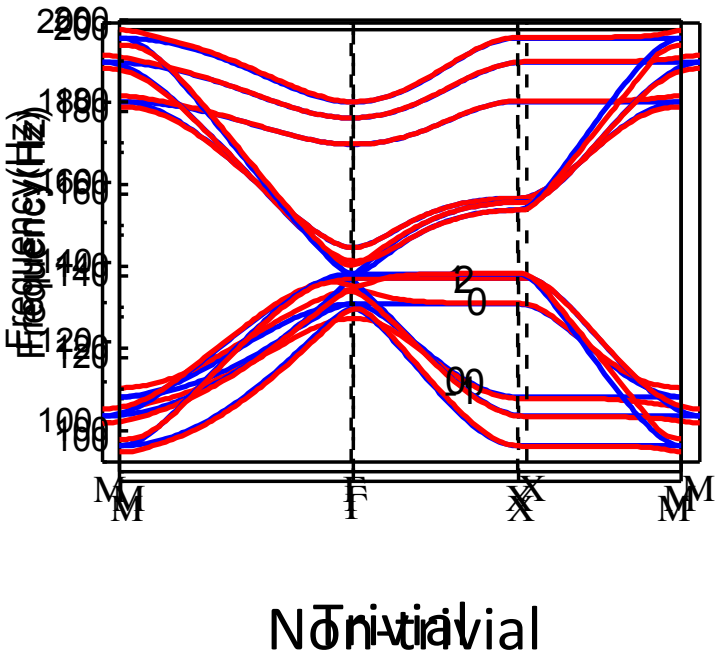
$$i^C = \prod_j \xi_j(\Gamma)\xi_j(\mathrm{M})\zeta_j(\mathrm{Y})$$

	d_1	d_0	d_2
$\hat{C}_4\Gamma_1$	$-i$	$-i$	-1
$\hat{C}_4 M_1$	$-i$	$-i$	$-i$
$\hat{C}_2 Y_1$	-1	-1	-1
$\hat{C}_4\Gamma_2$	i	-1	$-i$
$\hat{C}_4 M_2$	i	i	i
$\hat{C}_2 Y_2$	-1	-1	-1
C_{gap}	0	1	1

Phys. Rev. B **86**, 115112 (2012)

Topological properties



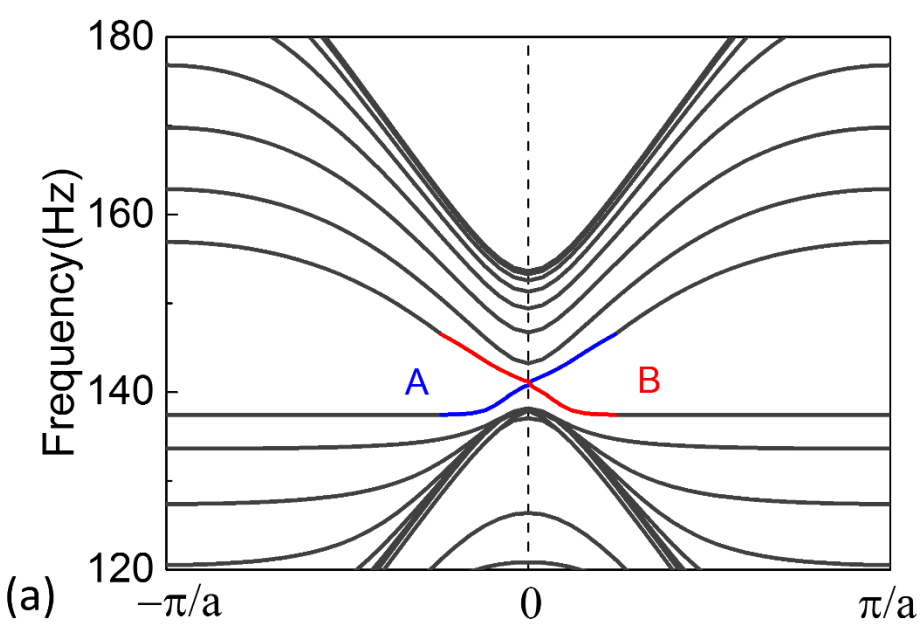


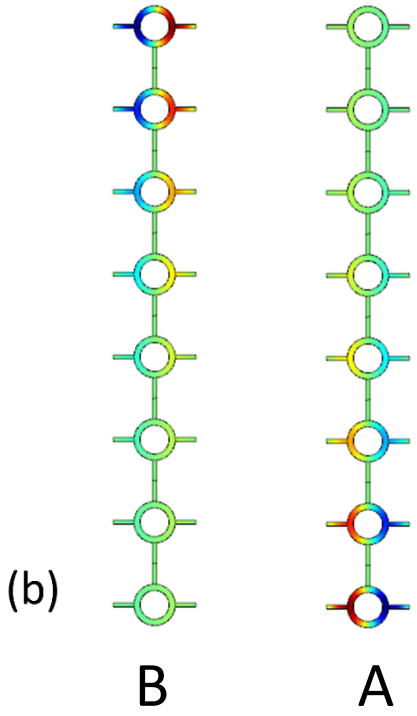
Transition point depends on:
geometry & intensity of the flow

Tunable!

Edge states

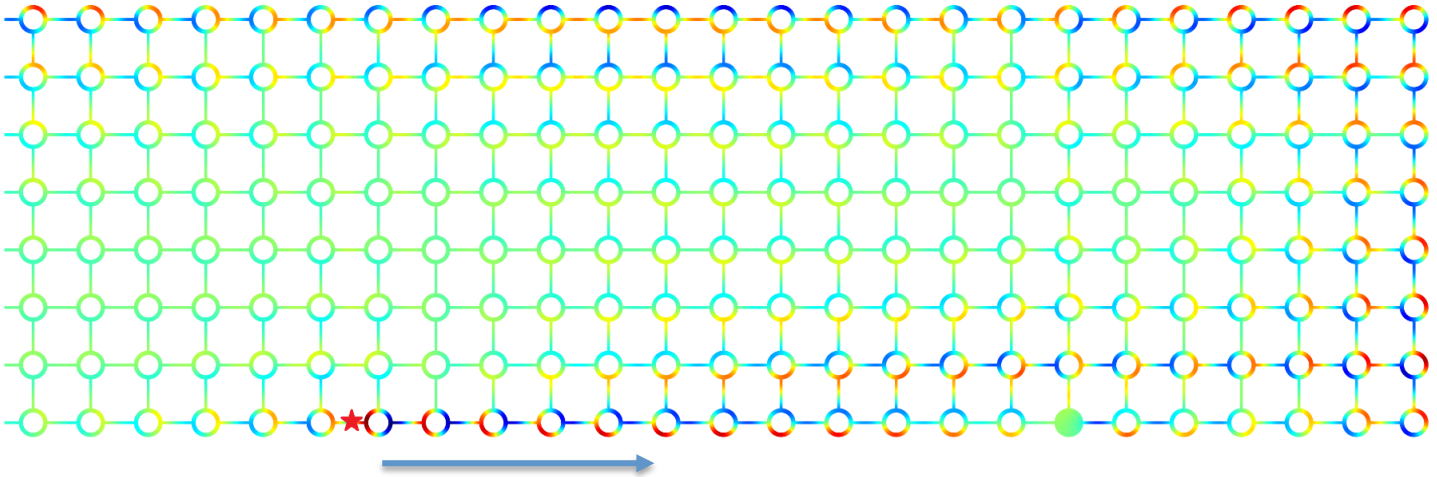
d = 0.1m





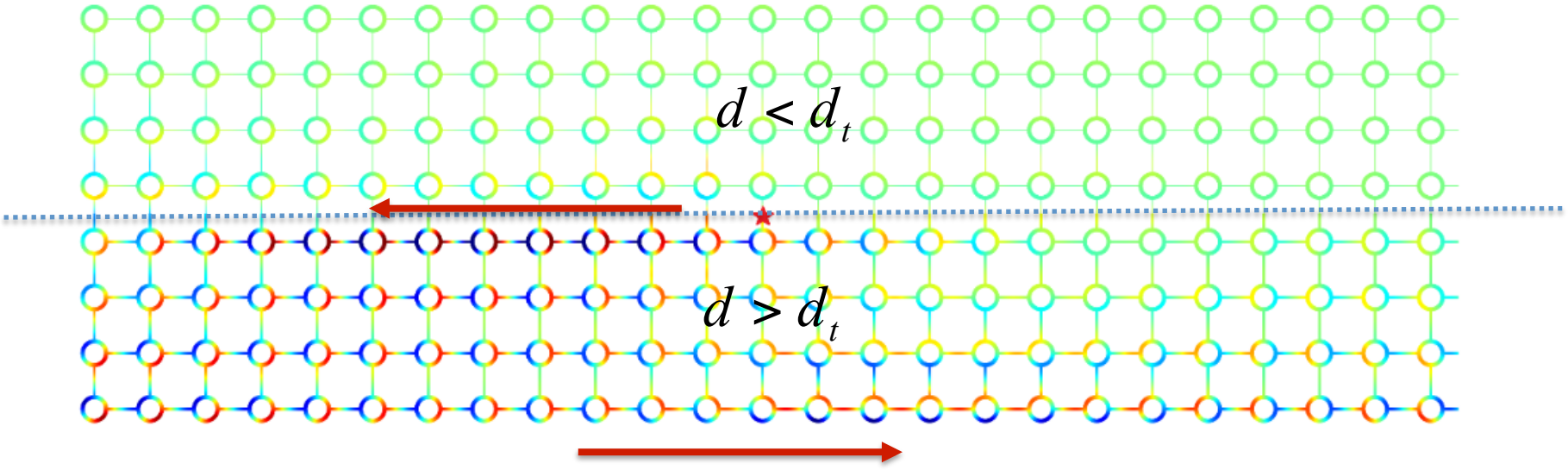
Demonstration I: fixed air flow

One-way propagation (defect immune)

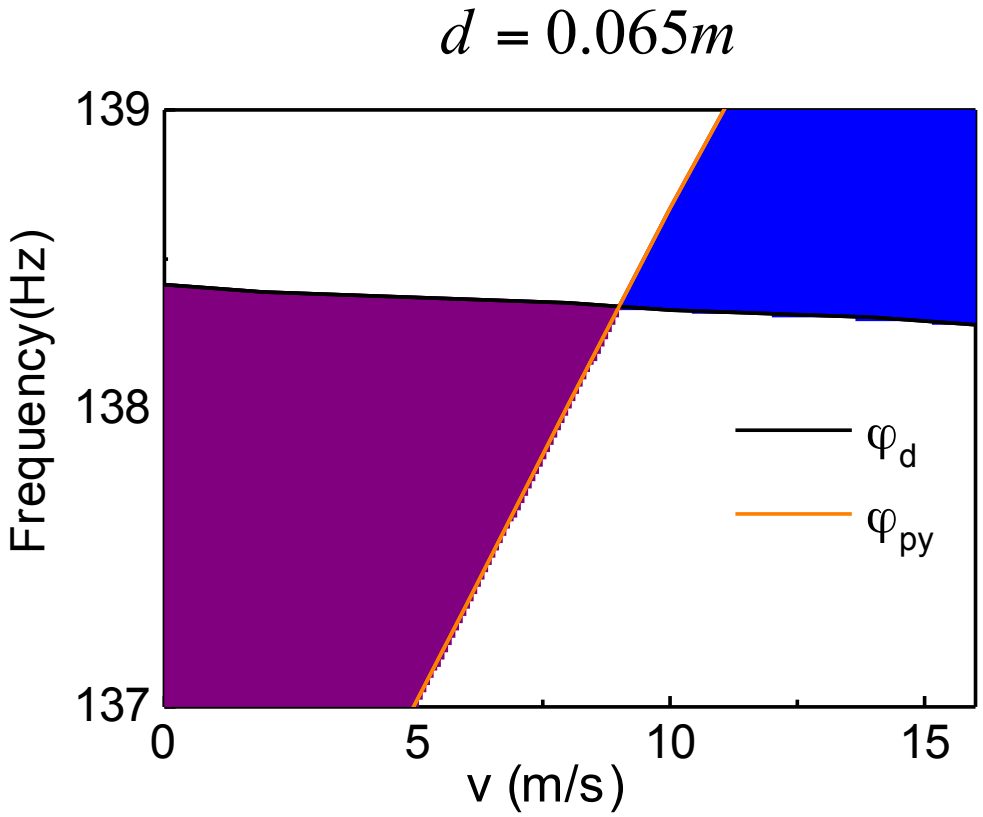


Demonstration I: fixed air flow

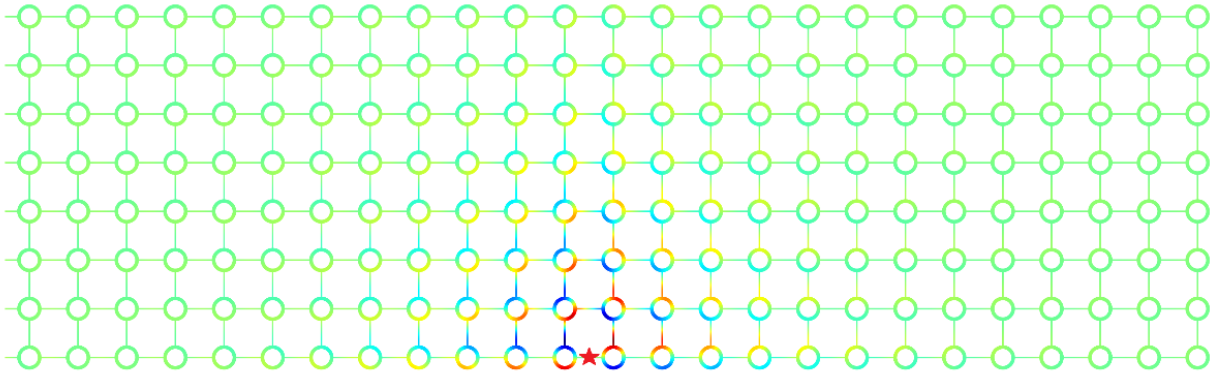
Interface state



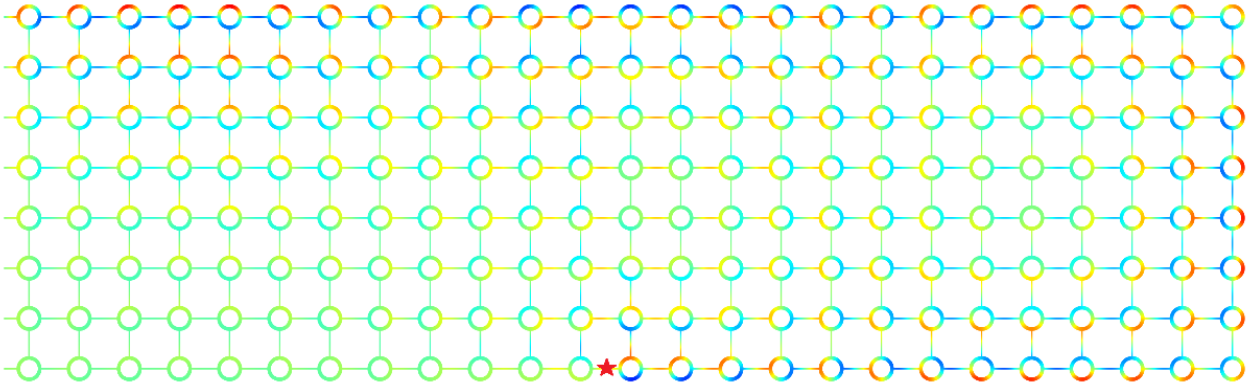
Demonstration II: fixed geometry



Demonstration II: fixed geometry



$v = 5m/s$



$v = 15m/s$

Summary

- Designed a topological phononic crystal
- Topological property depends on both the geometry and time-reversal symmetry
- One-way propagation edge state is observed.
- Tunable property is demonstrated.

Acknowledgement:

- KAUST baseline research fund.

Through Inspiration, Discovery

Thank you.

More information:
http://arxiv.org/abs/1512.00814
ying.wu@kaust.edu.sa
chen.zeguo@kaust.edu.sa