Topological nanophotonics based on semiconductor photonic crystals

Satoshi Iwamoto

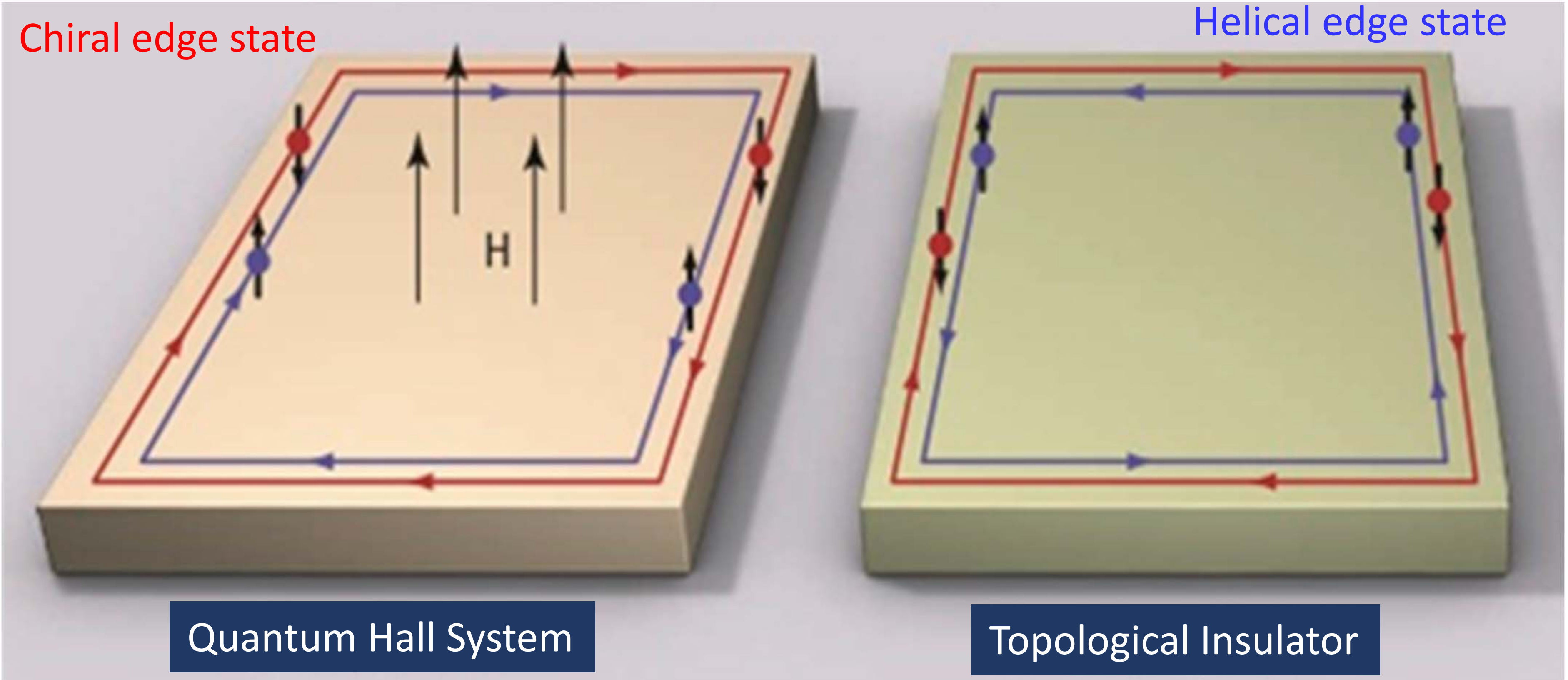
Research Center for Advance Science and Technology, the University of Tokyo
Institute of Industrial Science, the University of Tokyo

e-mail: iwamoto@iis.u-tokyo.ac.jp

Web: http://www.iwamoto.iis.u-tokyo.ac.jp/en/index.html

Contents

Topology: from condensed matter physics to photonics



S. Oh, Science **340**, 153 (2013).

Topological edge states of electrons

Electron transport without dissipation

- ✓ Immune to disorders
- ✓ Suppressed back scattering
- ✓ Strong unidirectionality

→ Novel devices in electronics and spintronics

In photonics? → Yes

Topological photonics

PRL **100,** 013904 (2008) PHYSICAL REVIEW LETTERS week ending 11 JANUARY 2008

Possible Realization of Directional Optical Waveguides in Photonic Crystals with Broken Time-Reversal Symmetry

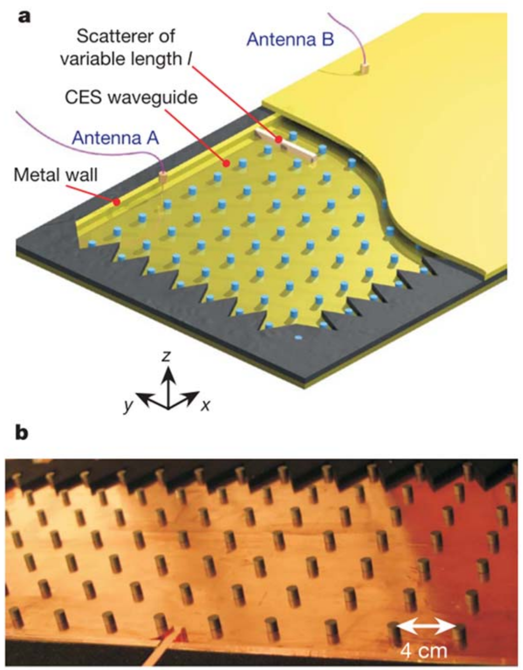
F. D. M. Haldane and S. Raghu*

Department of Physics, Princeton University, Princeton, New Jersey 08544-0708, USA

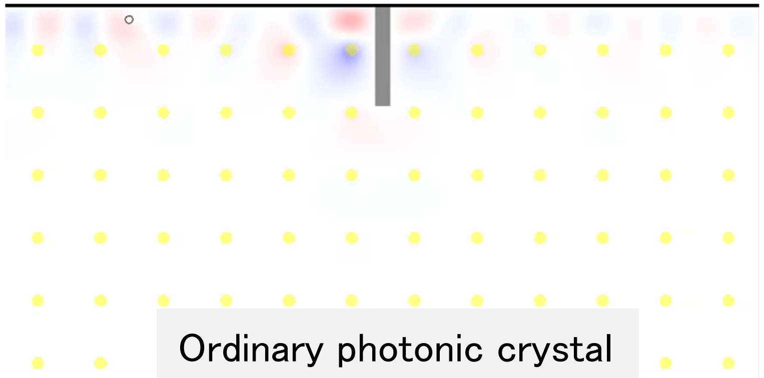
(Received 23 March 2005; revised manuscript received 30 May 2007; published 10 January 2008)

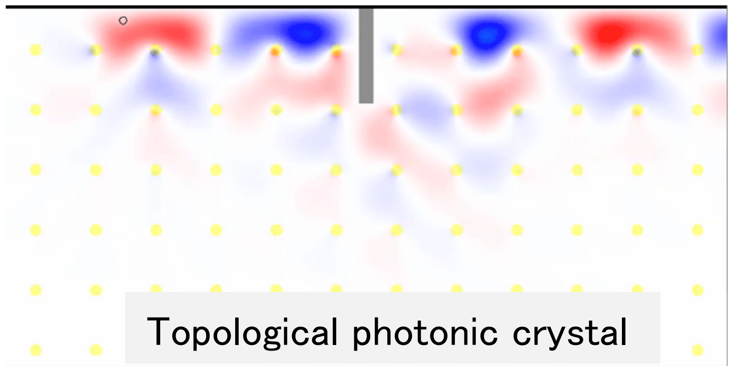
We show how, in principle, to construct analogs of quantum Hall edge states in "photonic crystals" made with nonreciprocal (Faraday-effect) media. These form "one-way waveguides" that allow electromagnetic energy to flow in one direction only.

First demonstration @microwave (2009)



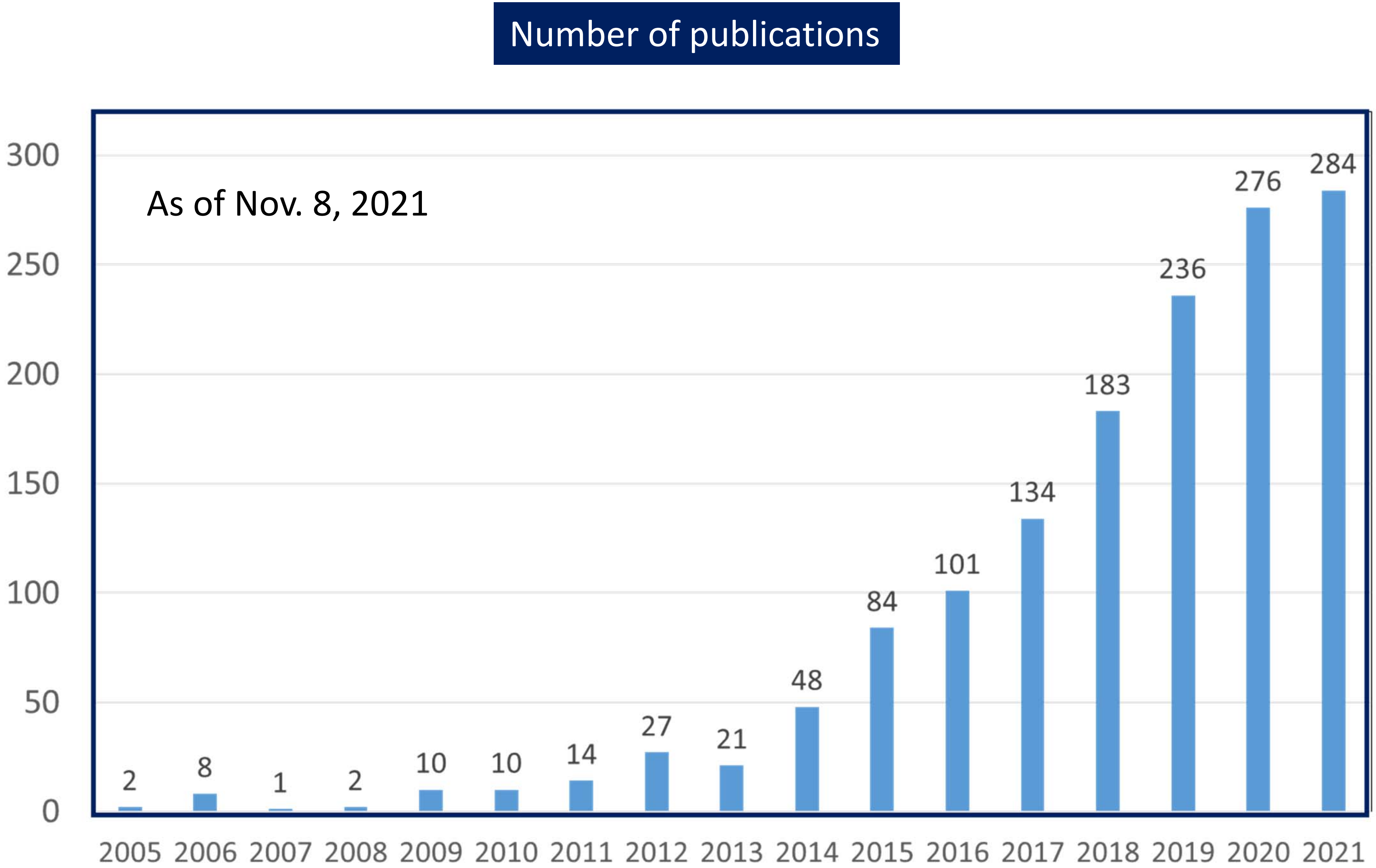
Z. Wang *et al.*, Nature **461**, 772 (2009).





Growing attention

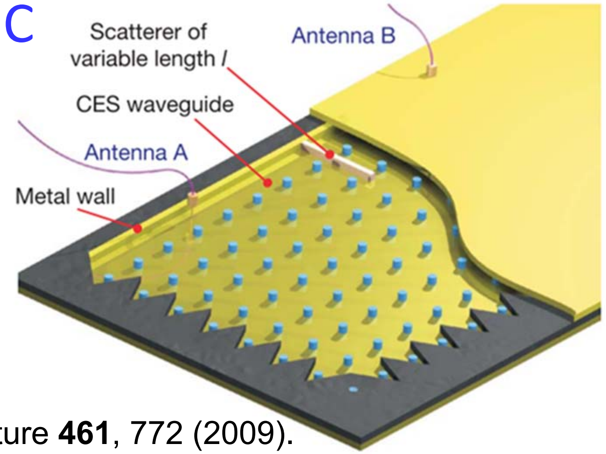
Source: Web of Science



Some of main platforms for topological photonics

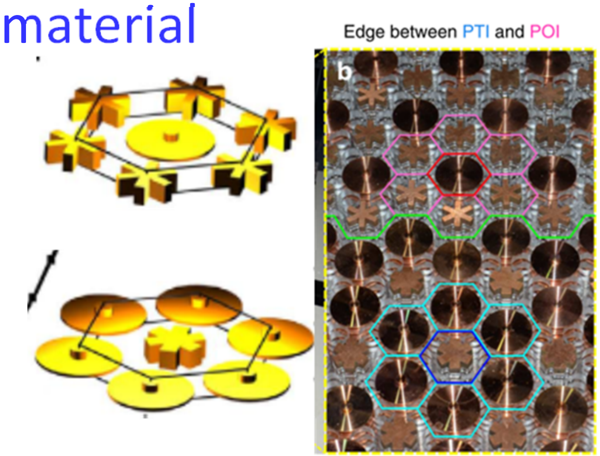
Microwave

MO-PhC



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

Metamaterial

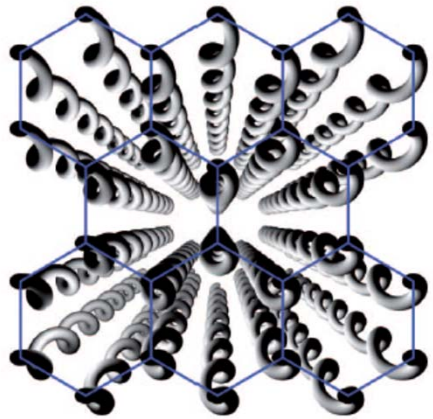


Trivial

Interface

Topological

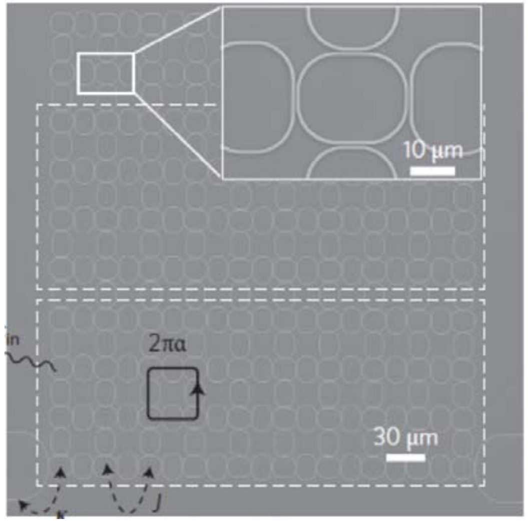
Visible to NIR



Waveguide array

> cm

M. C. Rechtsman *et al*., Nature **496**, 196 (2013).

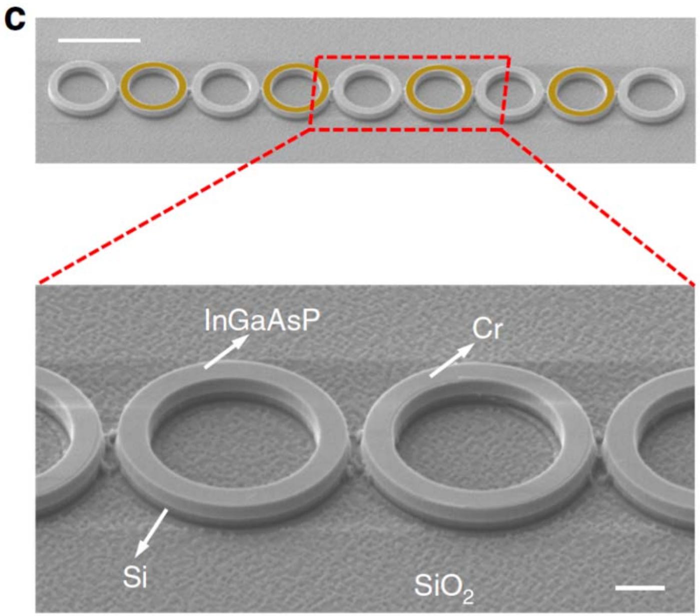


Ring cavities

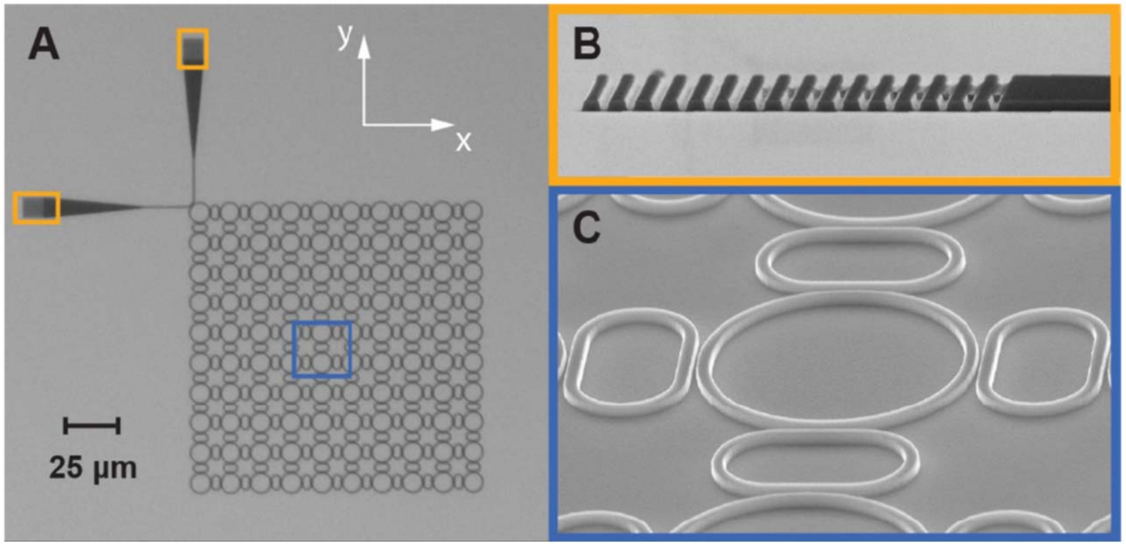
～mm

M. Hafezi *et al*., Nat. Phys. 7, 907 (2011). Nat. Photonics 7, 1001 (2013)

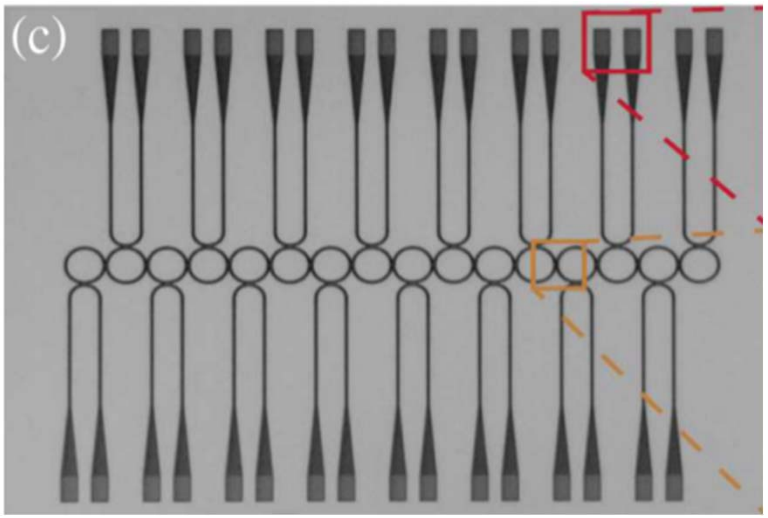
Topological lasers



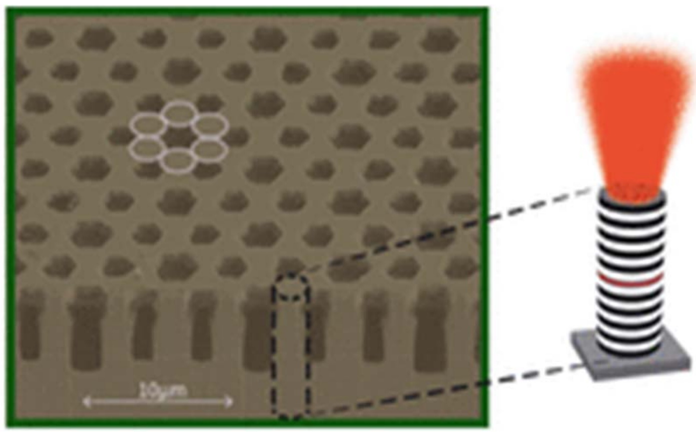
H. Zhao *et al.*, Nat. Commun. **9**, 981 (2018).



M. A. Bandres *et al.*, Science **359** eaar4005 (2018).



M. Parto et al., Phys. Rev. Lett. **120**, 113901 (2018)

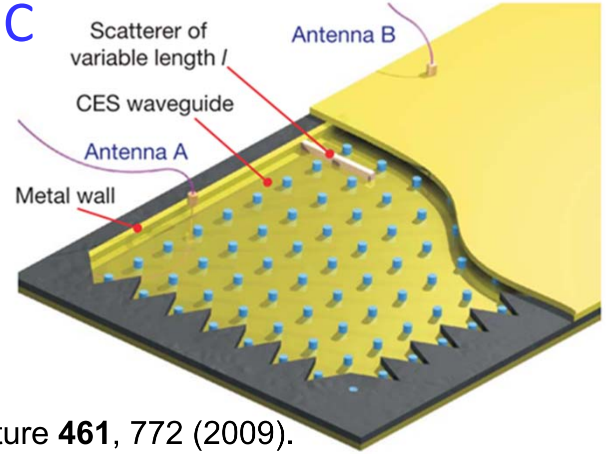


A. Dikopoltsev et al., Science **373** , 1514 (2021)

Some of main platforms for topological photonics

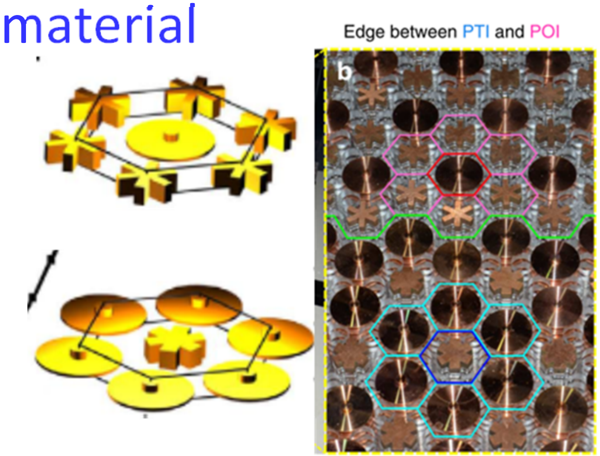
Microwave

MO-PhC



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

Metamaterial

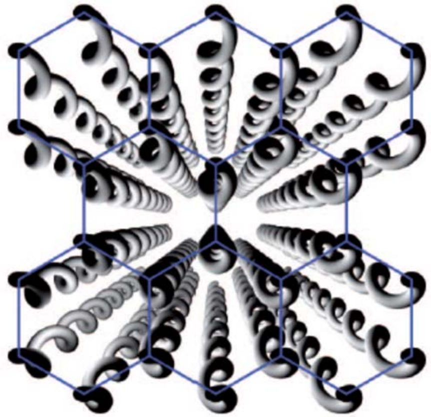


Trivial

Interface

Topological

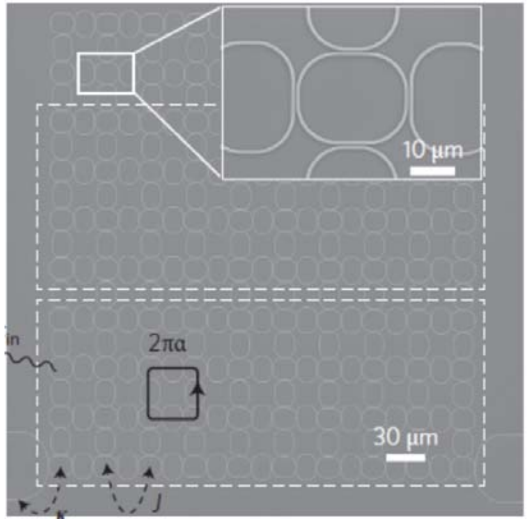
Visible to NIR



Waveguide array

> cm

M. C. Rechtsman *et al*., Nature **496**, 196 (2013).



Ring cavities

～mm

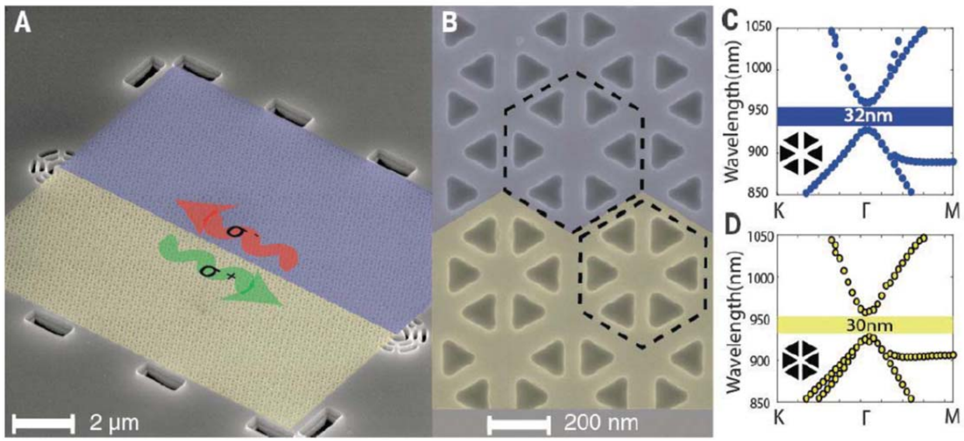
M. Hafezi *et al*., Nat. Phys. 7, 907 (2011). Nat. Photonics 7, 1001 (2013)

Photonic waveguide robust against defects and sharp turns → Useful in future highly-integrated photonic circuits
Novel optical devices

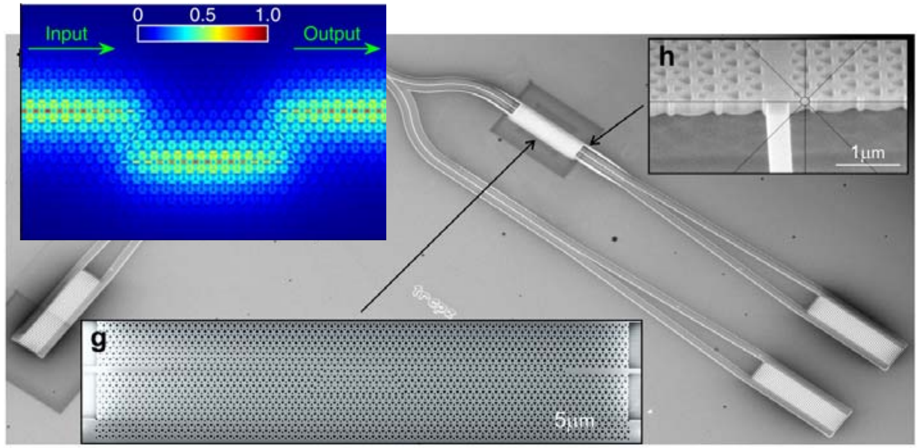
→ Topological photonics for integrated photonics

Topological photonics based on semiconductor PhCs

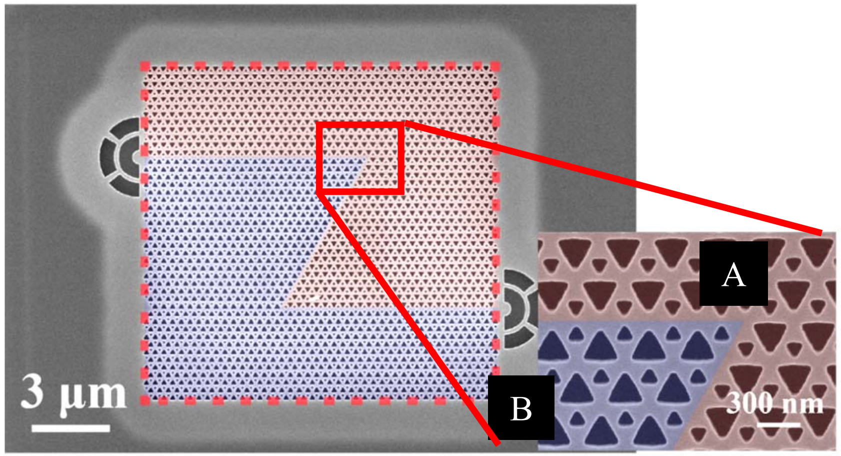
- ✓ Compatible with the present PIC technology
- ✓ Potential ability to miniaturize devices



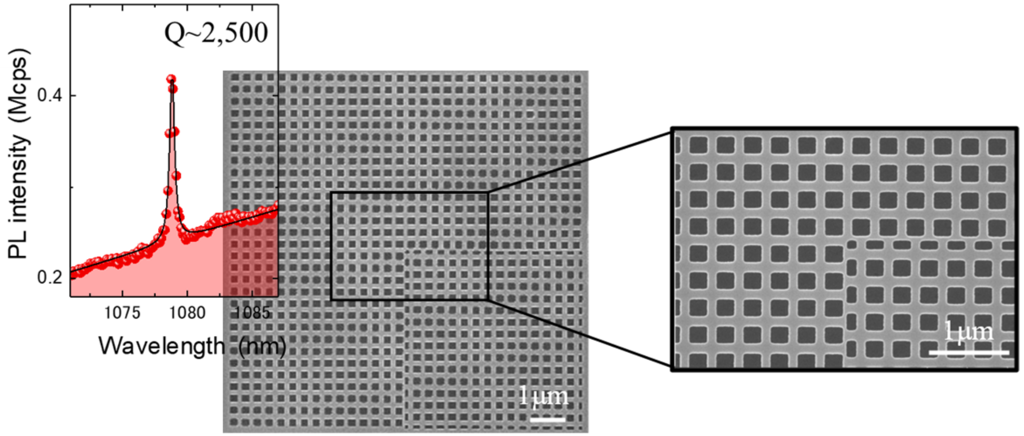
S. Barik *et al.*, Science **359**, 666 (2018)



M. I. Shalsev, *et al*. Nat, Nanotech. **14**, 31 (2019).



T. Yamaguchi, *et al*., APEX **12**, 62005 (2019)



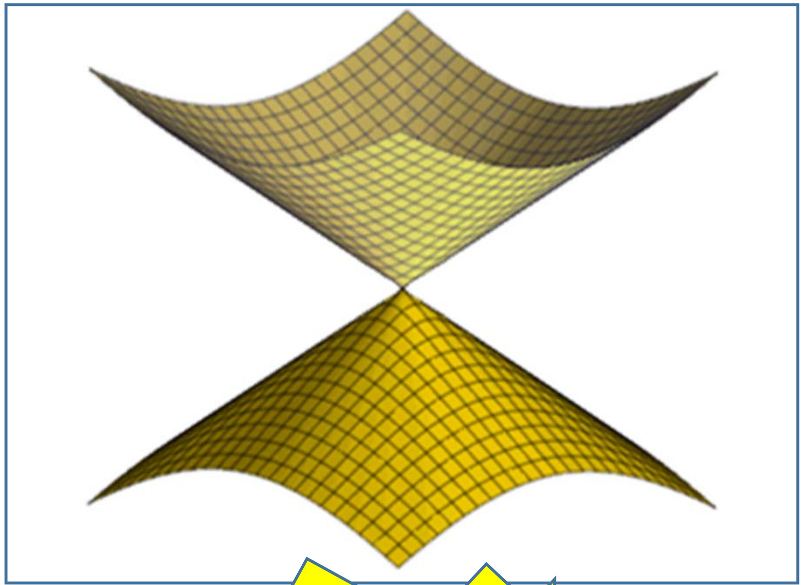
Y. Ota et al., Optica **6** 786 (2019).

Photonic waveguides and cavities exploiting topological edge states
Highly efficient lasers and other functional devices

Review paper: S. Iwamoto *et al*., Opt. Mater. Express **11**, 319 (2021)
Y. Ota et al., Nanophotonics **9**, 547 (2020).

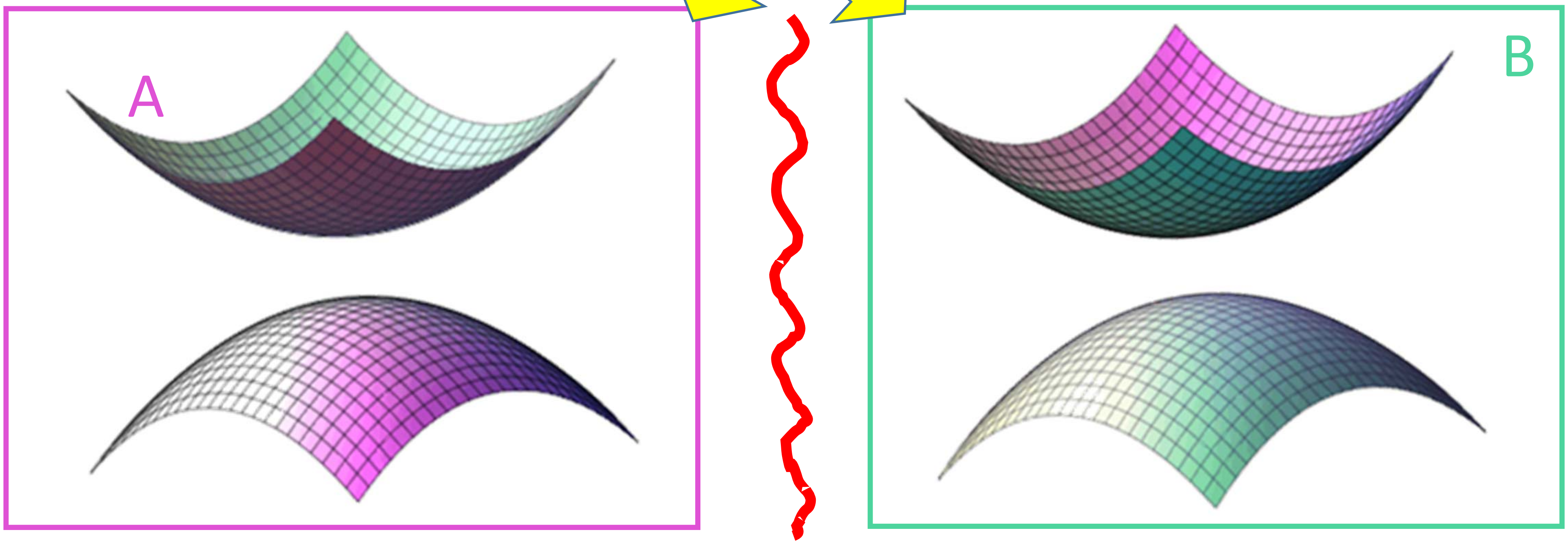
How to get topological edge states

1. Prepare a photonic Dirac point

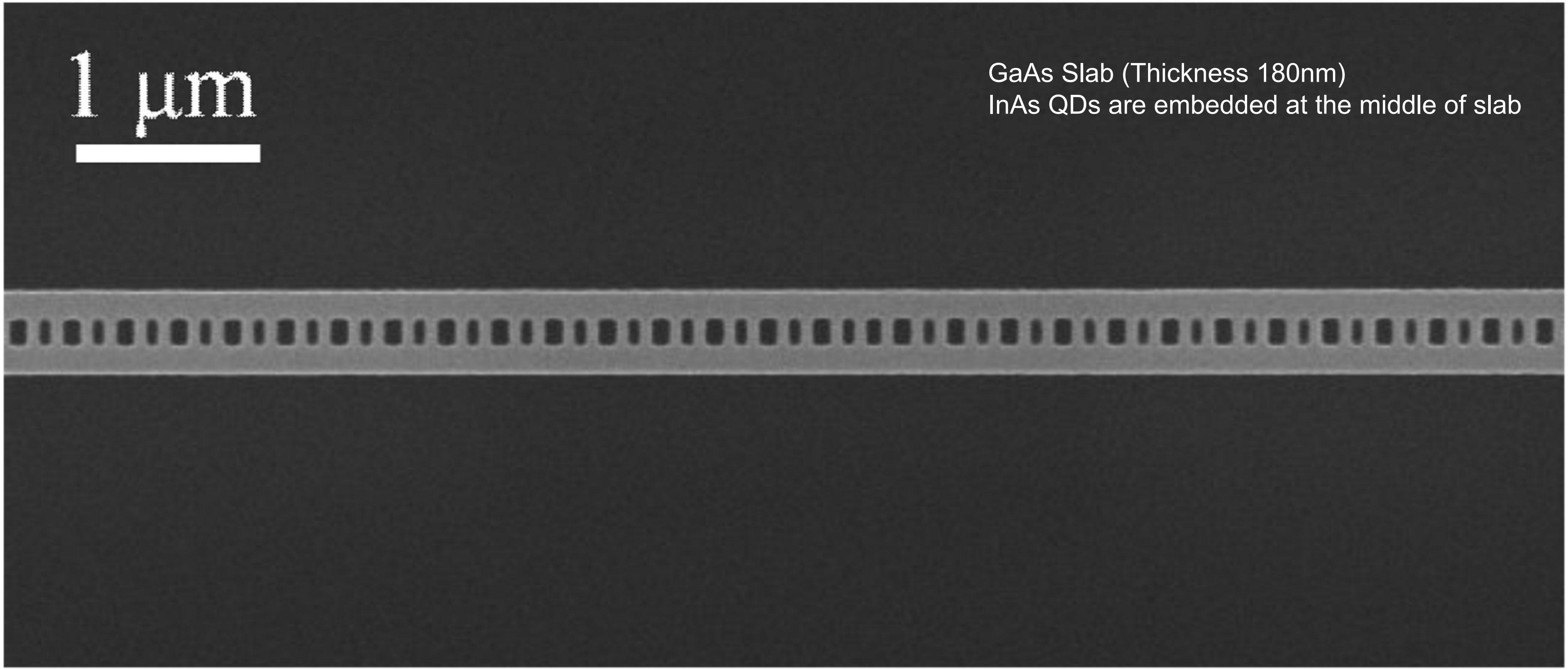


2. Open the gap by tuning system parameter(s)

3. Make an interface

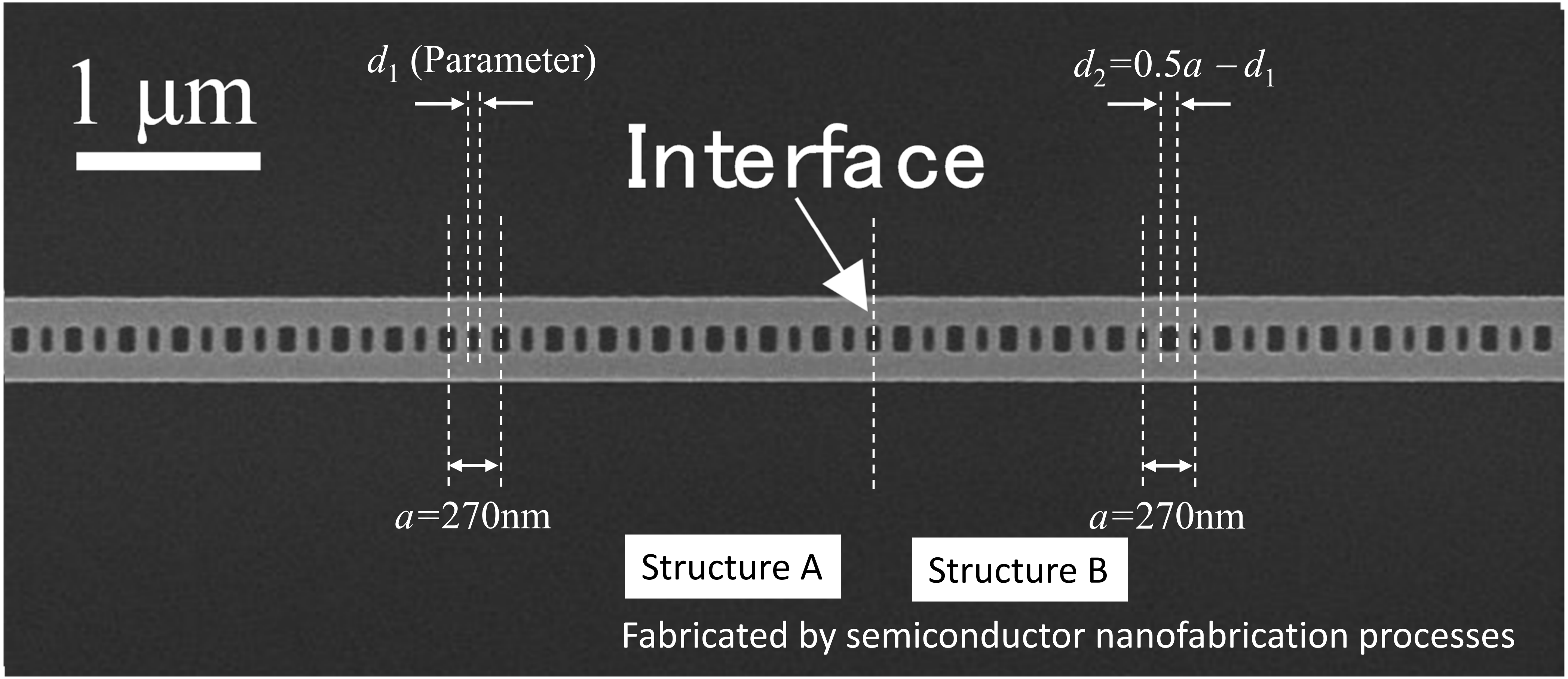


Topological PhC nanobeam cavity



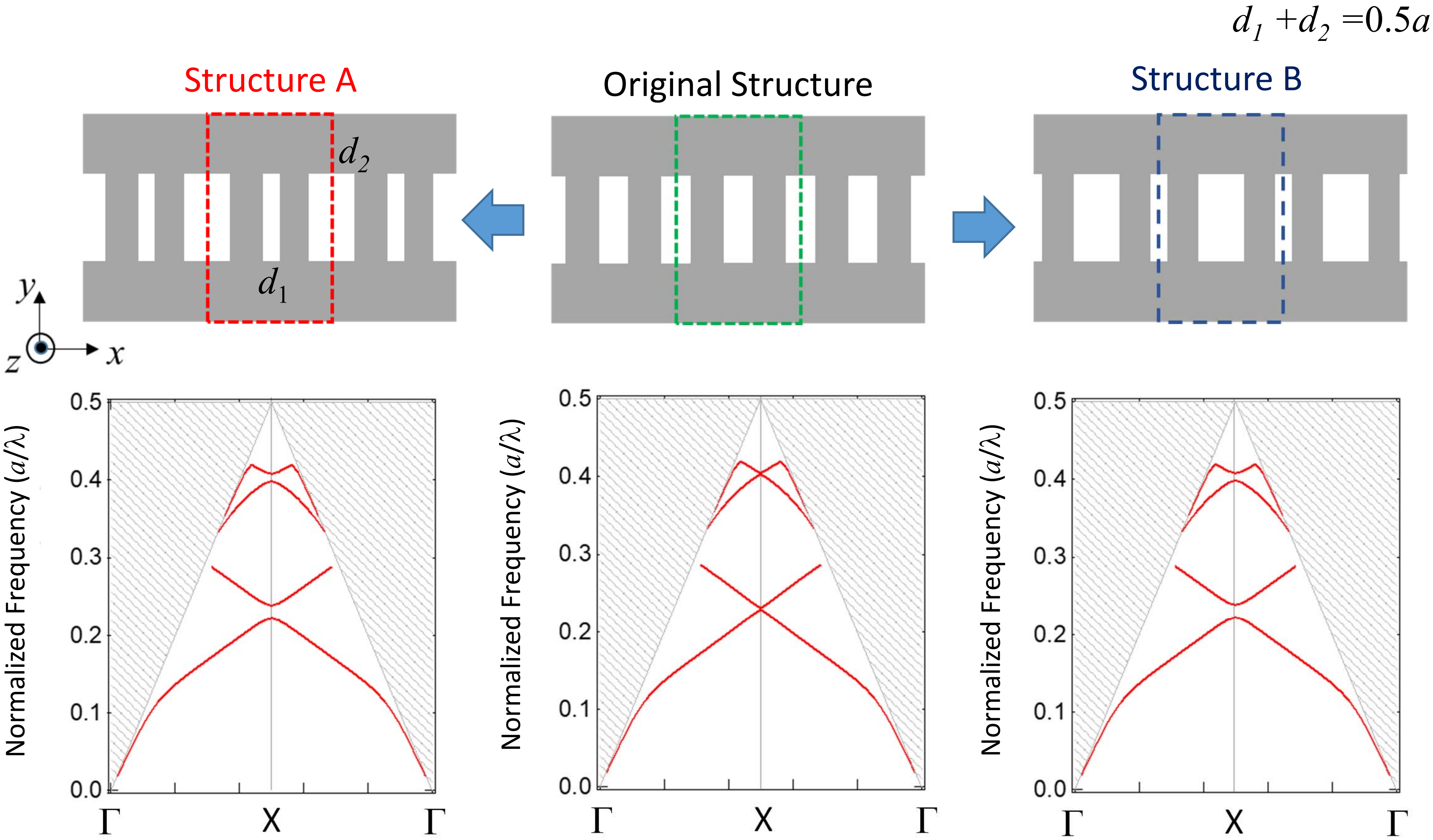
Y. Ota, S. Iwamoto *et al*., Communications Physics 1, 86 (2018).

Topological PhC nanobeam cavity



Y. Ota, S. Iwamoto *et al*., Communications Physics 1, 86 (2018).

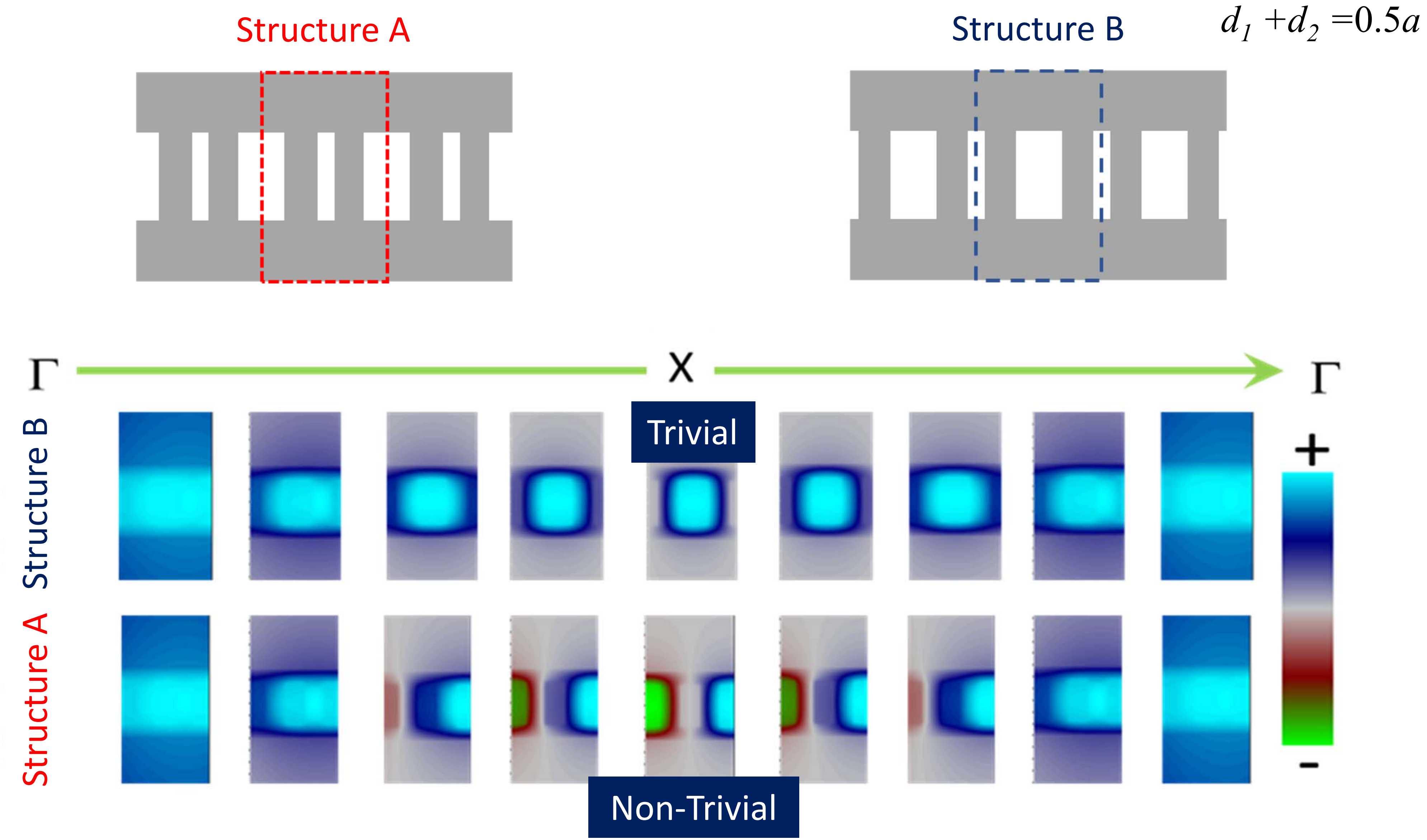
PhC nanobeam with 2 holes in unit cell: band diagram



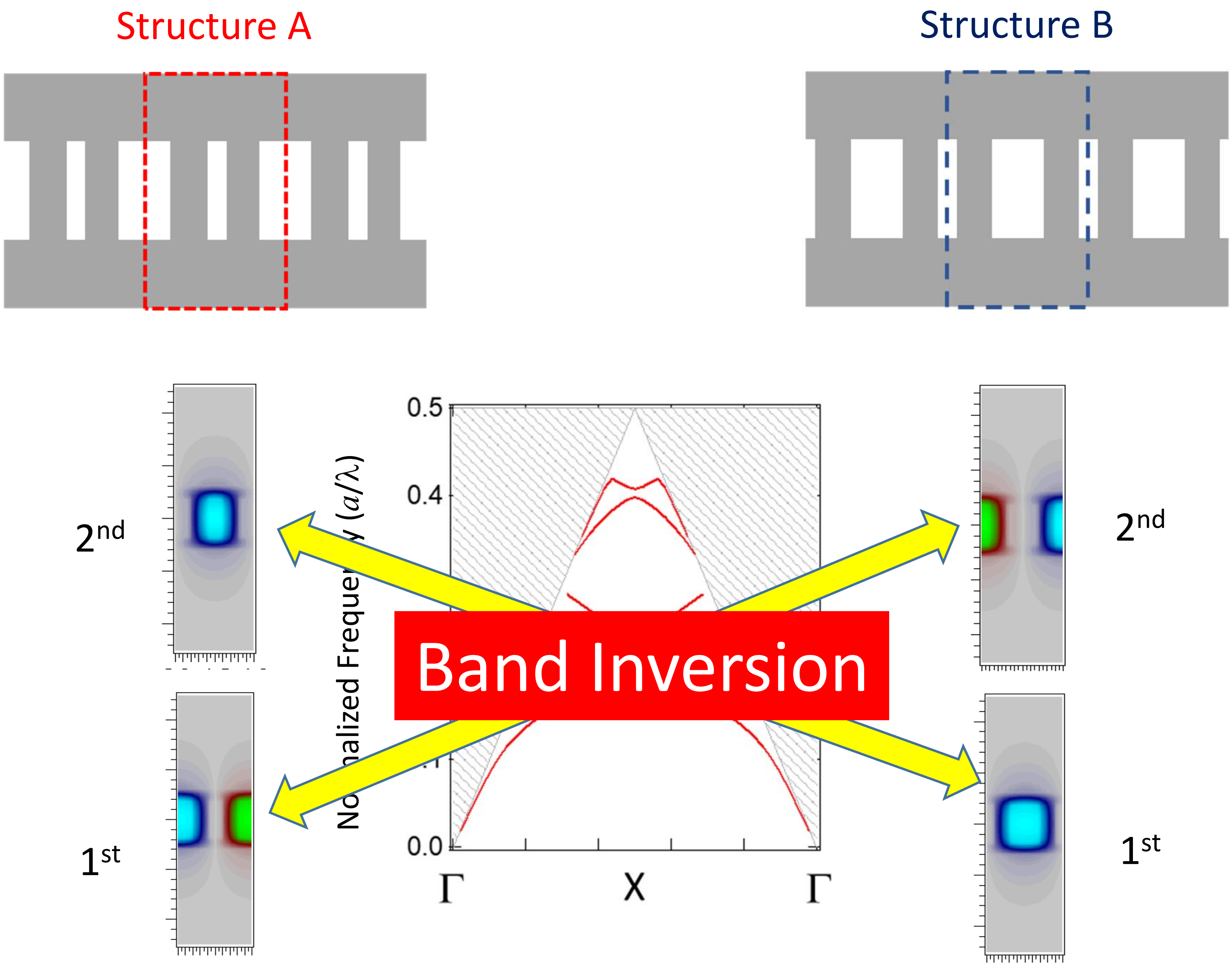
No difference in photonic band diagram

→Need to investigate field distributions

PhC nanobeam with 2 holes in unit cell: mode distributions



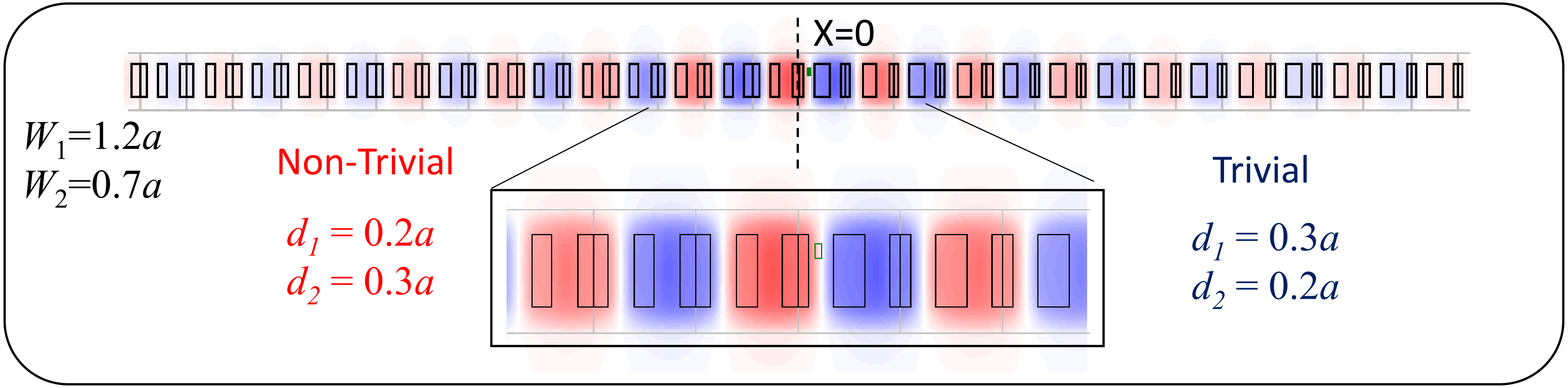
PhC nanobeam with 2 holes in unit cell: band inversion



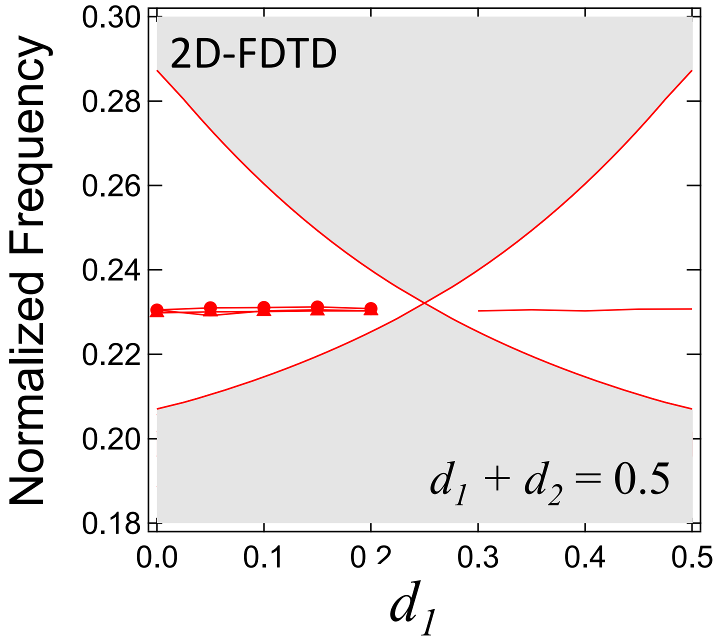
Topologically Distinct

Topological edge state: localized cavity mode

Bulk-edge correspondence→ Single 0D edge mode at the interface

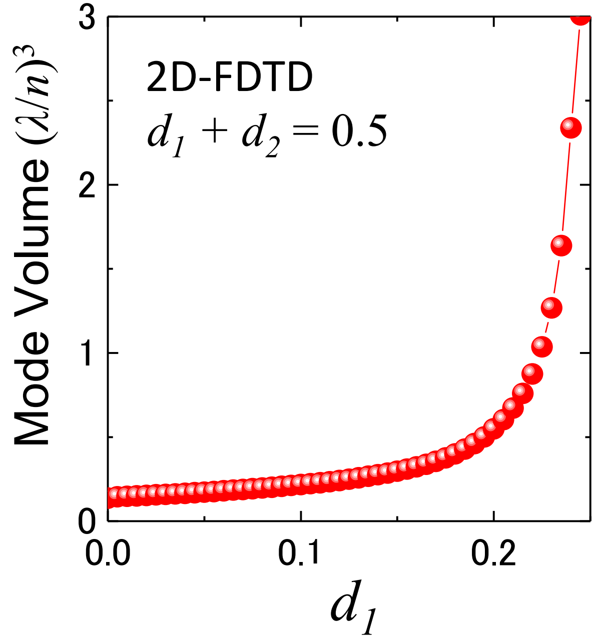


Mode Frequency



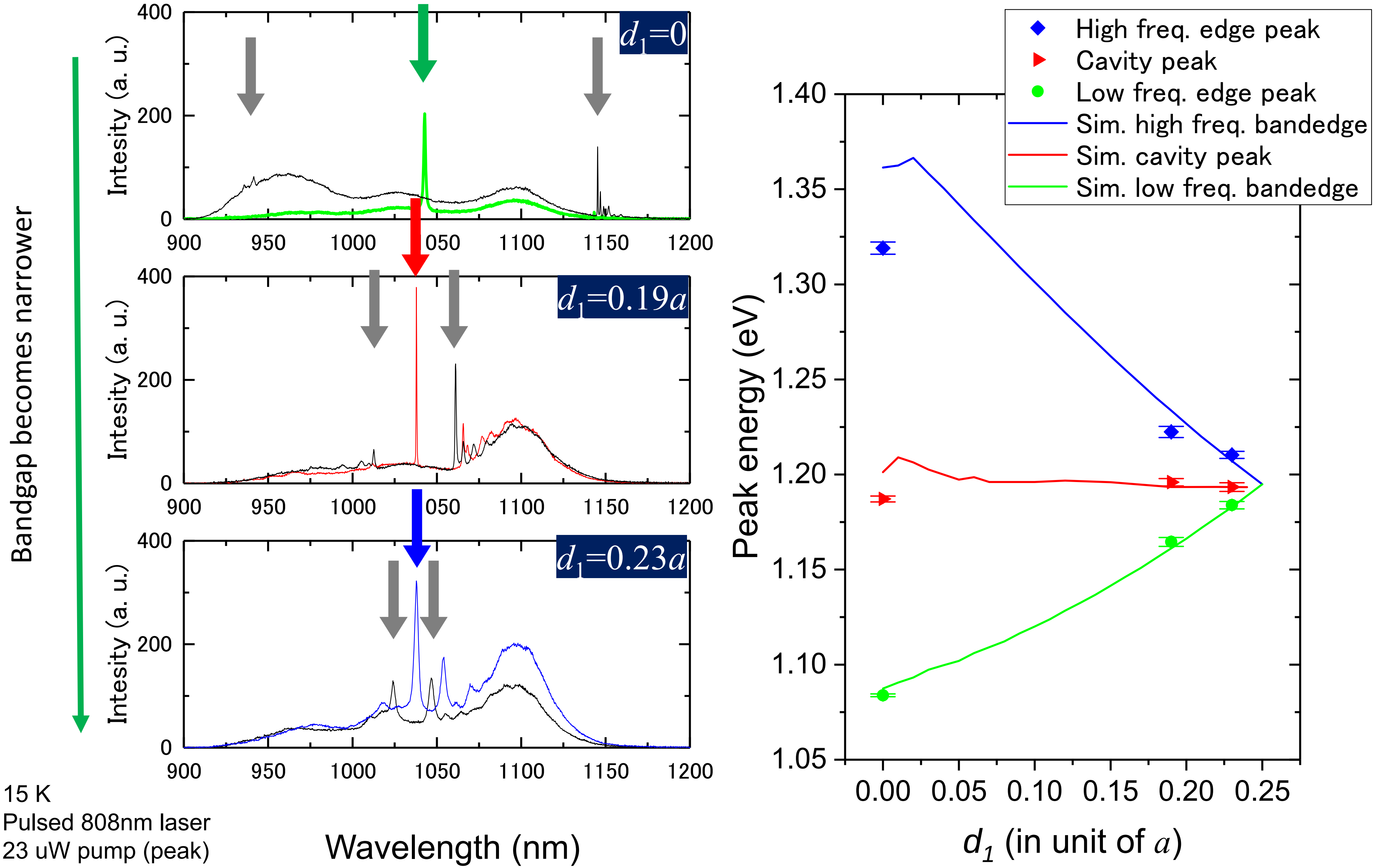
No shift in resonant freq. as d_1 changes

Cavity mode volume



Single mode even with large mode volume

Topological PhC nanocavity: μ−PL



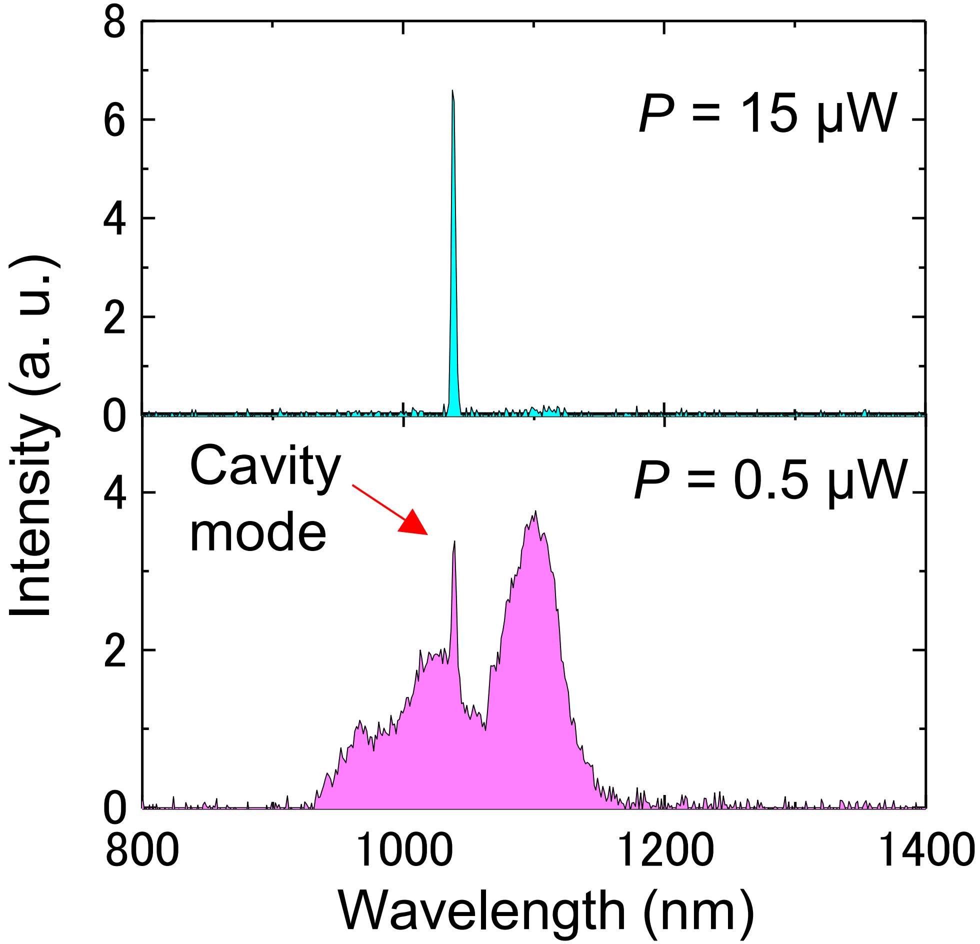
15 K
Pulsed 808nm laser
23 uW pump (peak)
5 MHz, 20 ns

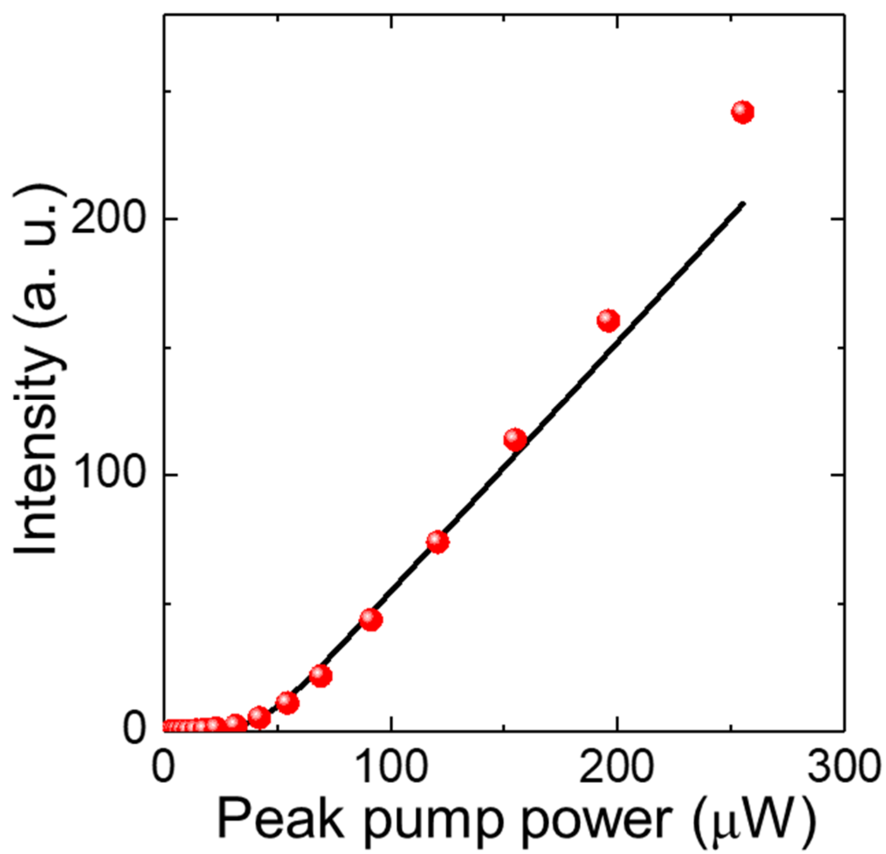
Cavity mode wavelengths are almost same for different d_1

Lasing oscillation in Zak-phase controlled 1D PhC nanobeam cavity

μ-PL characterization at 15K

Excitation: intensity-modulated LD (808nm, 0.5 MHz repetition, 20 ns pulse duration)

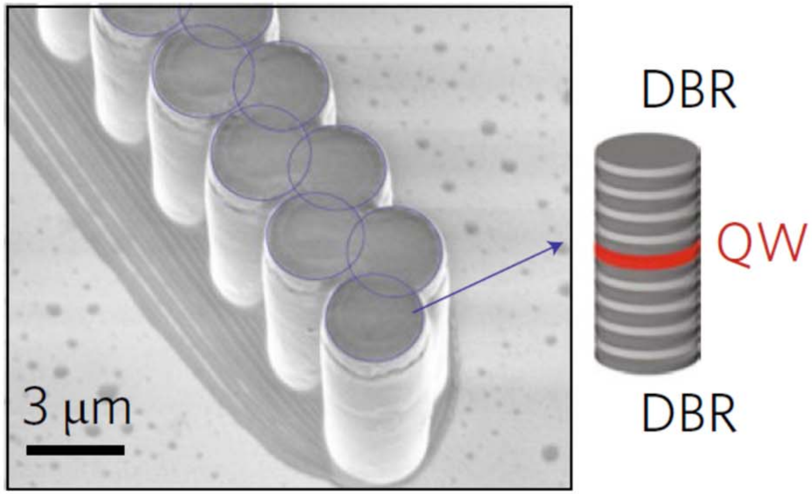


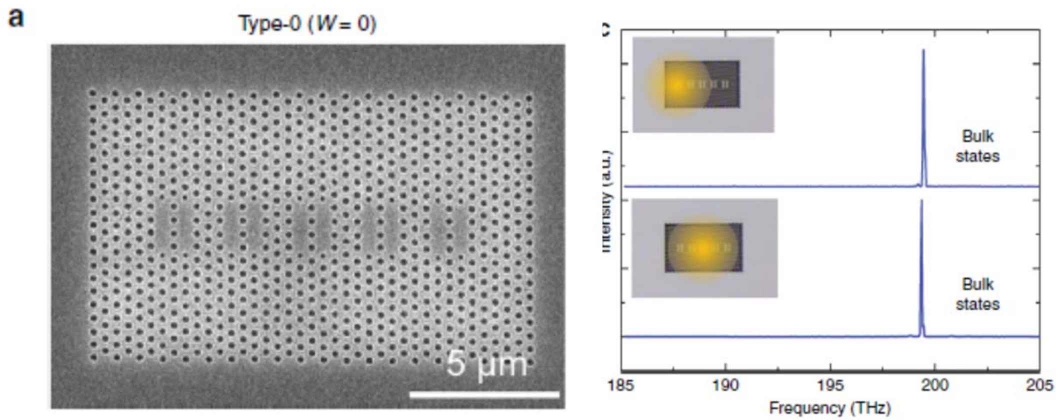


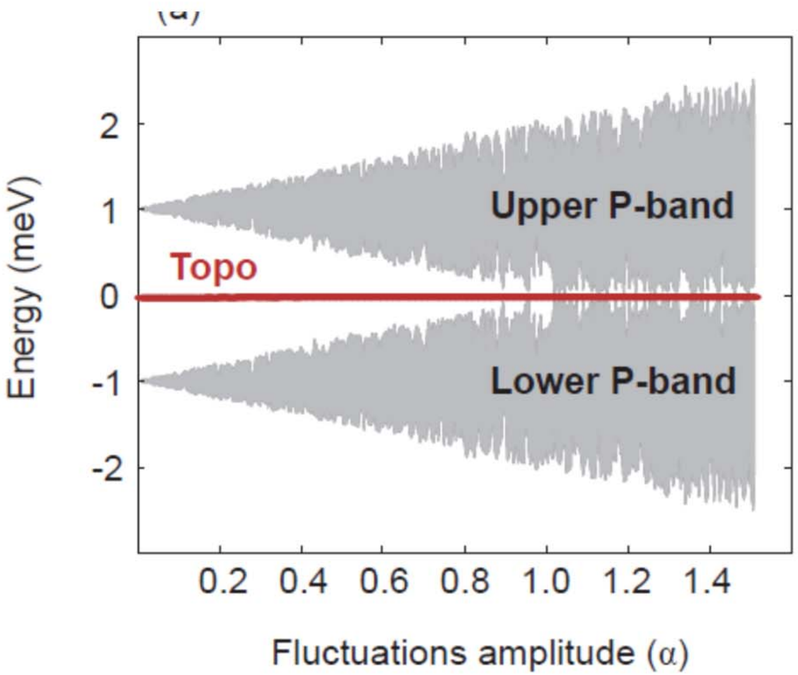
First realization of topological nanocavity laser with a mode volume close to the diffraction limit

Y. Ota, S. Iwamoto *et al.*, Communications Physics **1**, 86 (2018).

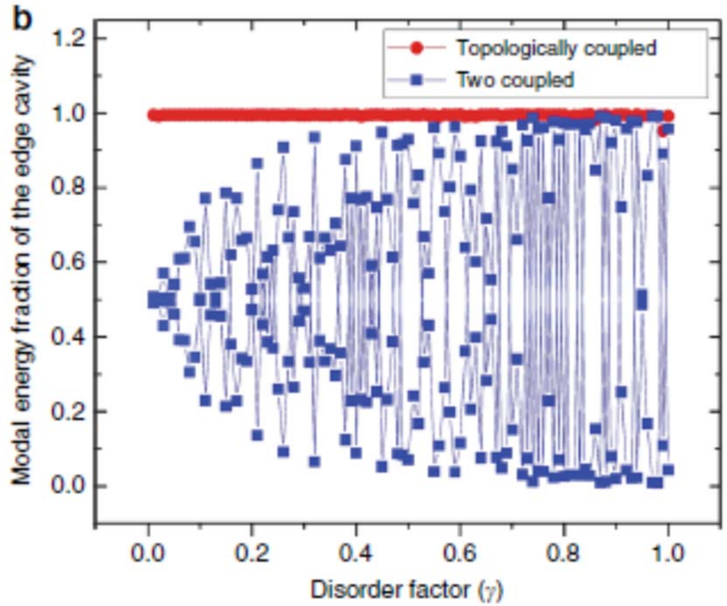
1D topological lasers: robustness







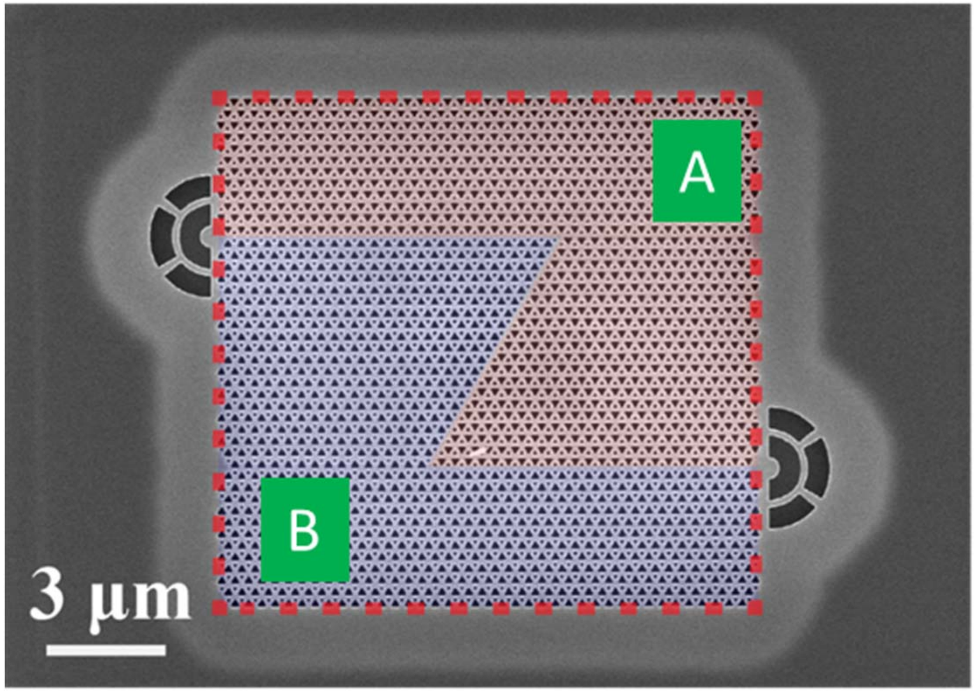
P. St-Jean *et al.*, Nat. Phton. **11**, 651 (2017).

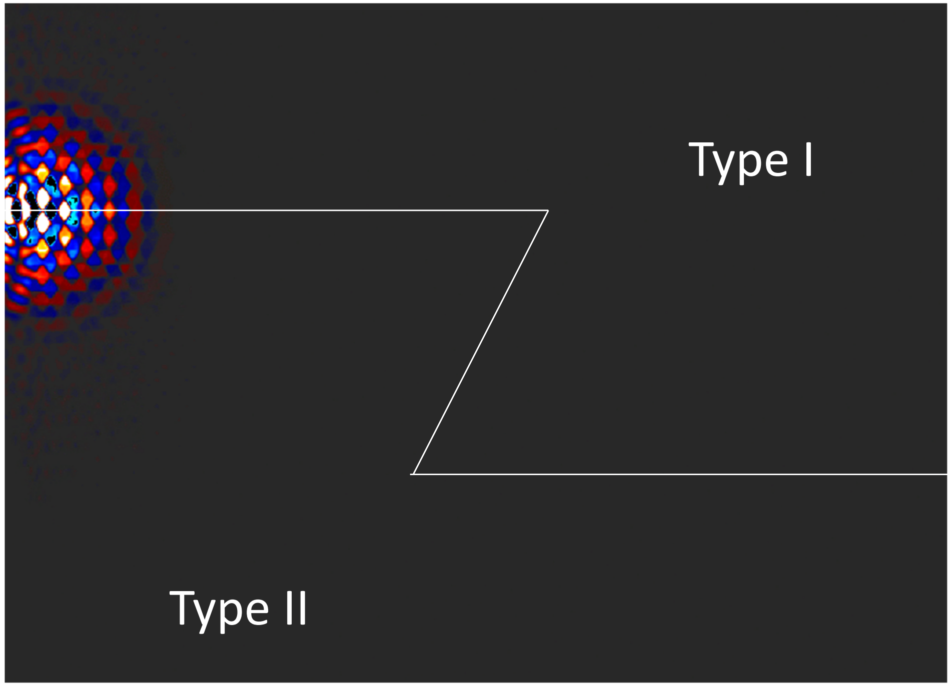


C. Han et al., Light: Science & Applications **8**, 40 (2019).

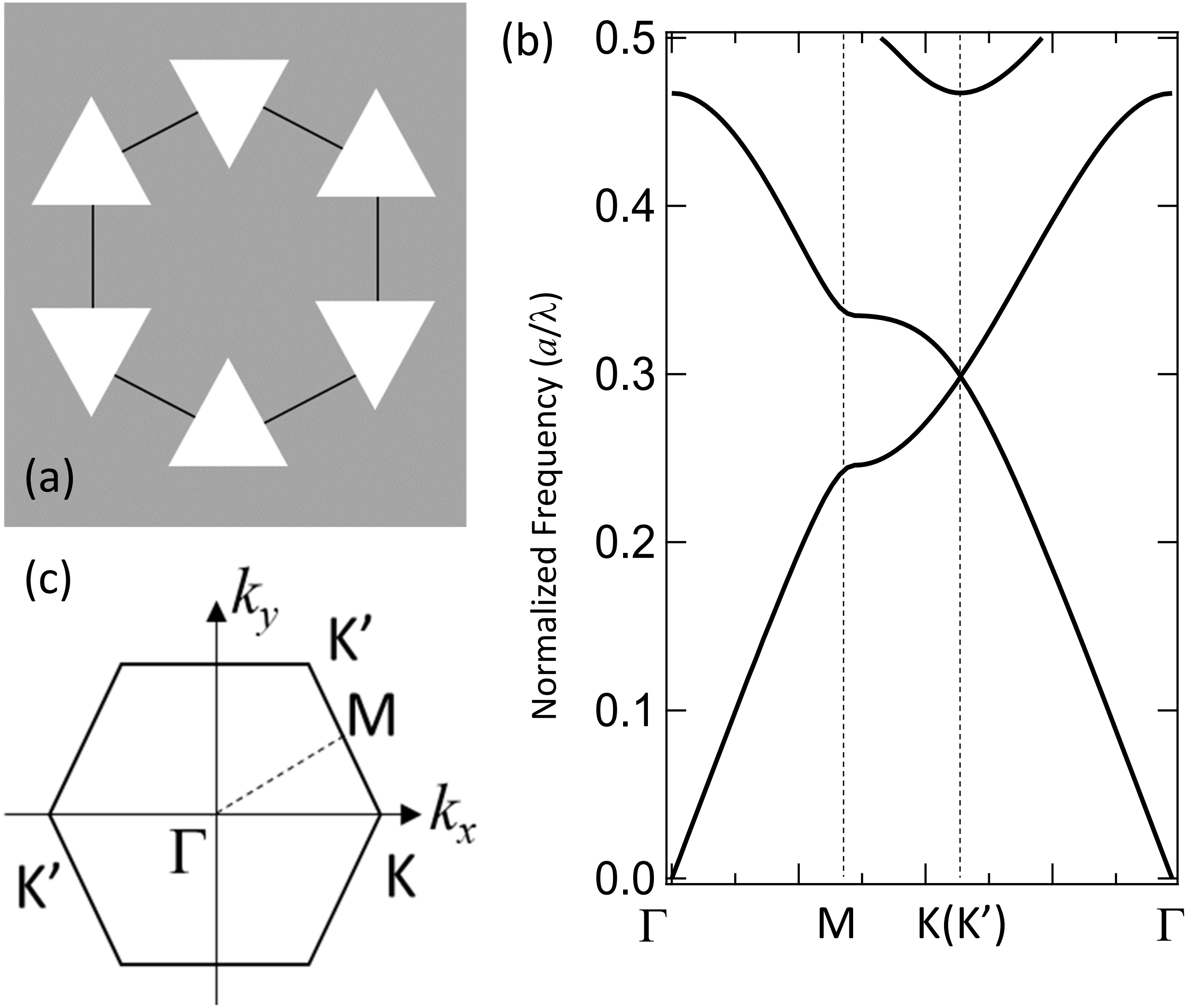
✓ Robust single mode operation is expected

Valley photonic crystal and topological slow-light waveguide





Photonic graphene

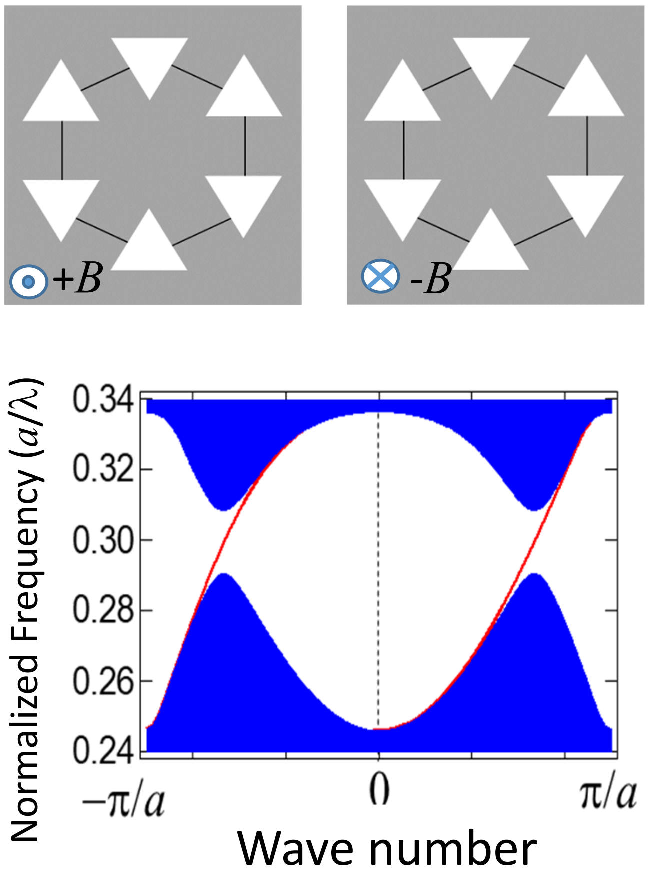


Photonic Dirac point at K(K')

Photonic topological phases and edge states in 2D PhCs

Photonic Quantum Hall system

Broken time reversal symmetry

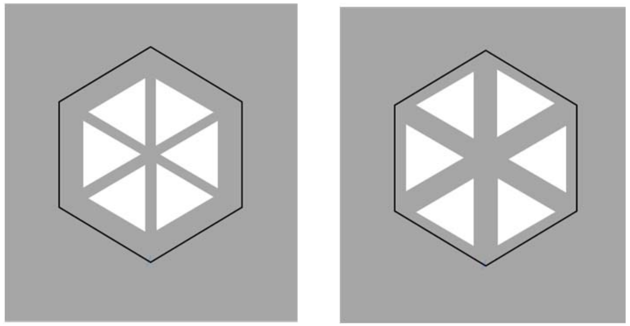


Chiral edge state

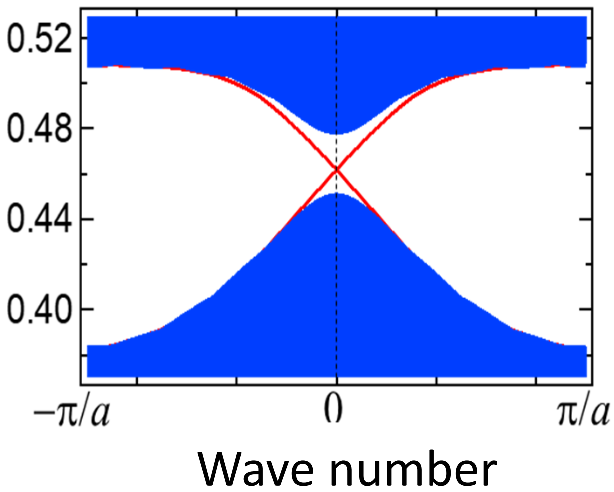
Photonic Quantum Spin Hall System

Photonic Quantum valley Hall System

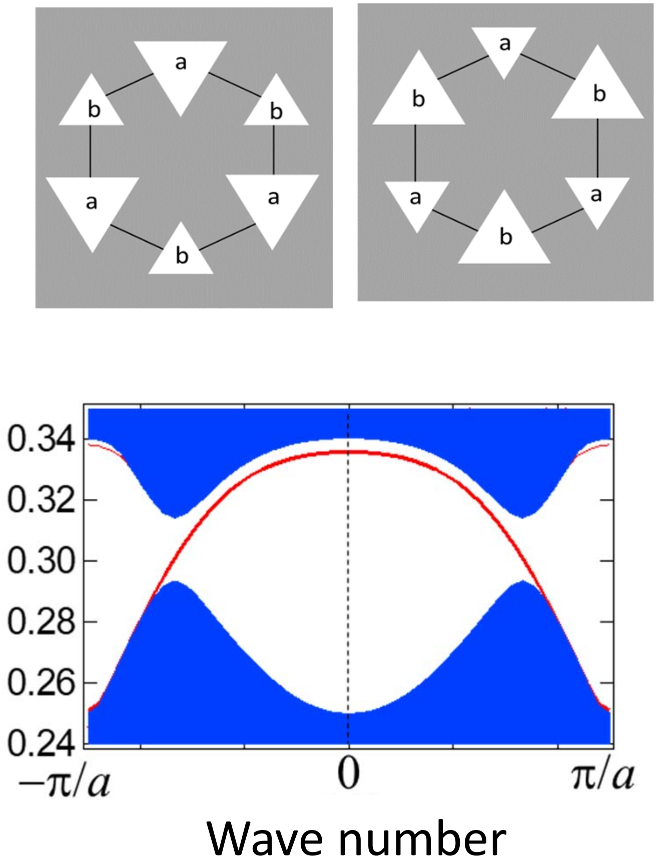
Time reversal symmetry preserved



Wu and Hu, PRL **114**, 223901 (2015).



Helical edge state



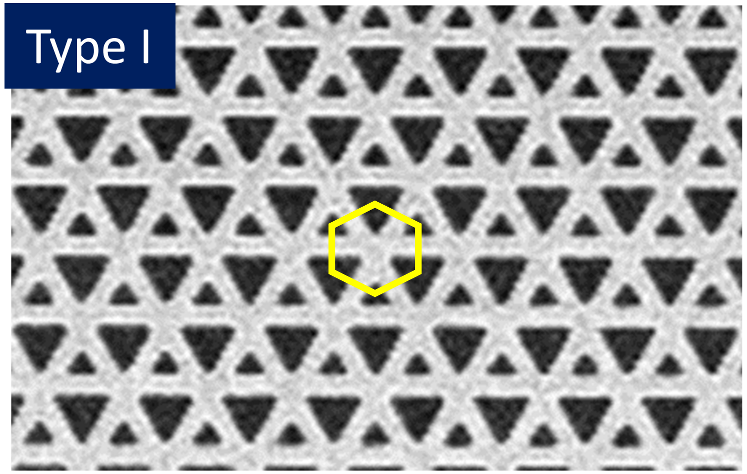
Valley kink state

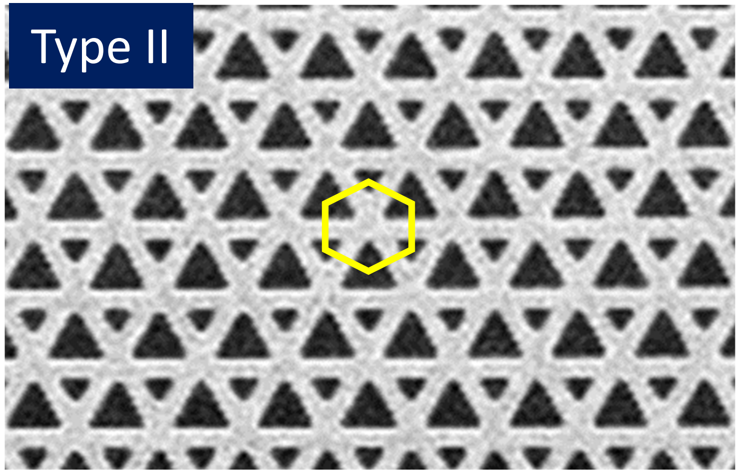
Strong — Robustness — Weak

Difficult — Realization — Easy

Valley Photonic Crystals

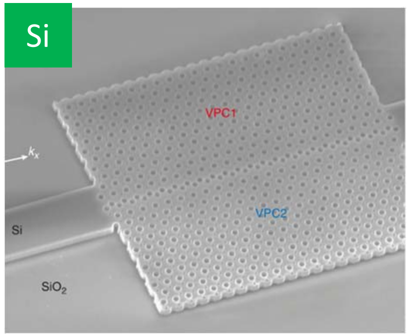
Originally proposed by T. Ma and G. Shvets, New J. Phys. **18**, 025012 (2016).



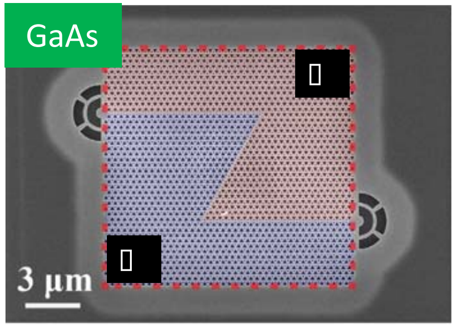


Topological edge states (valley kink states) appear at the interface

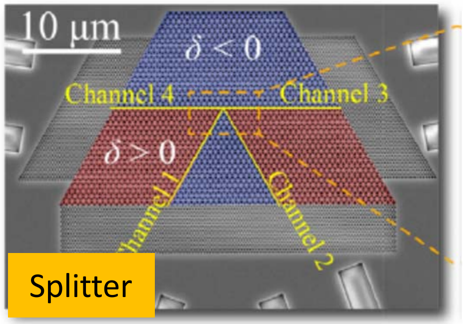
Semiconductor-based Integrated VPhC Waveguides



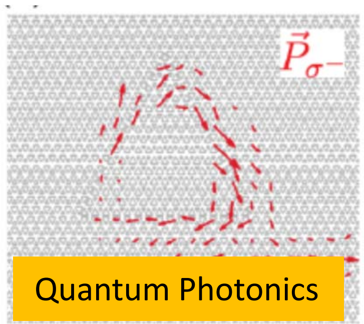
M. I. Shalaev *et al*.,
Nat. Nanotechnol. **14**, 31 (2019).
X. –T. He *et al*.,
Nat. Commun. **10**, 872 (2019).



T. Yamaguchi *et al*,
Appl. Phys. Express
12, 062005 (2019).



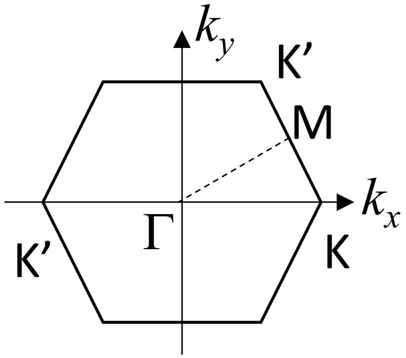
J. Ma *et al*.,
Laser Photonics Rev. **13**,
1900087 (2019)

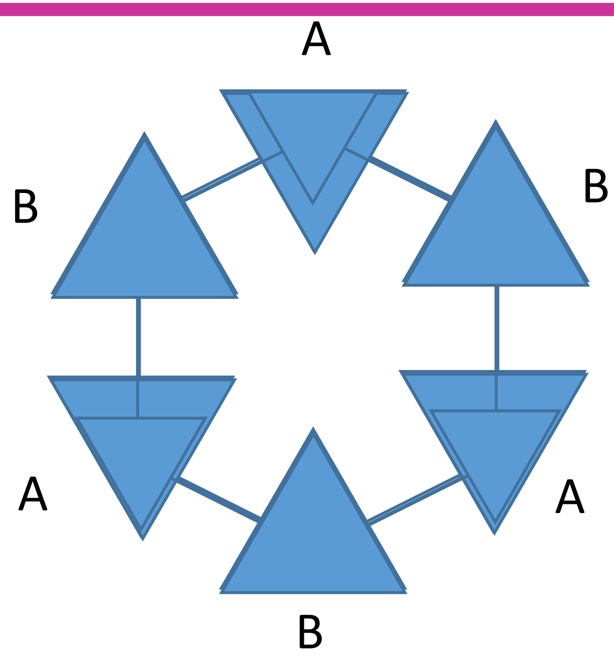


S. Barik *et al*.,
Phys. Rev. B **101**, 205303 (2020)

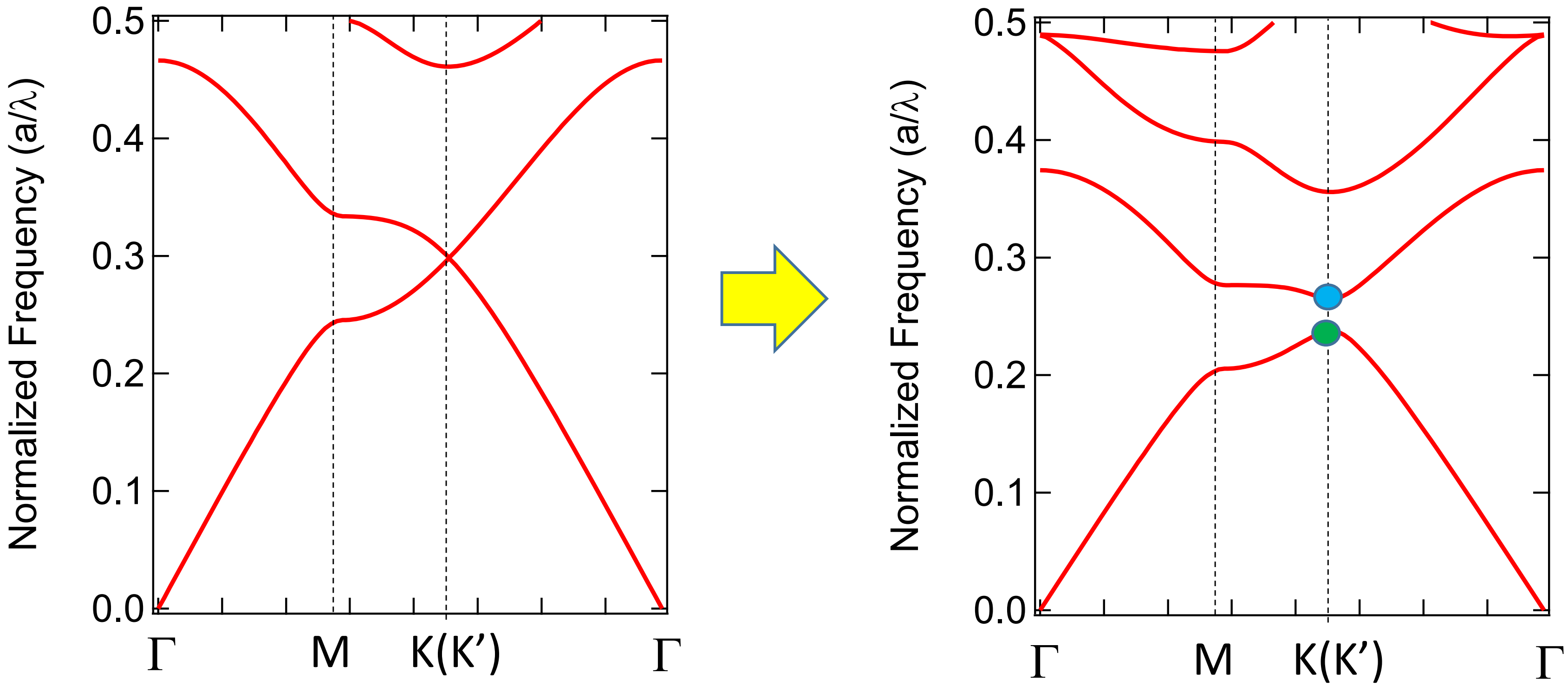
VPhC waveguide enables efficient light propagation through sharp bends
Potential applications in densely-integrated low-loss photonic circuits

Valley Photonic Crystal

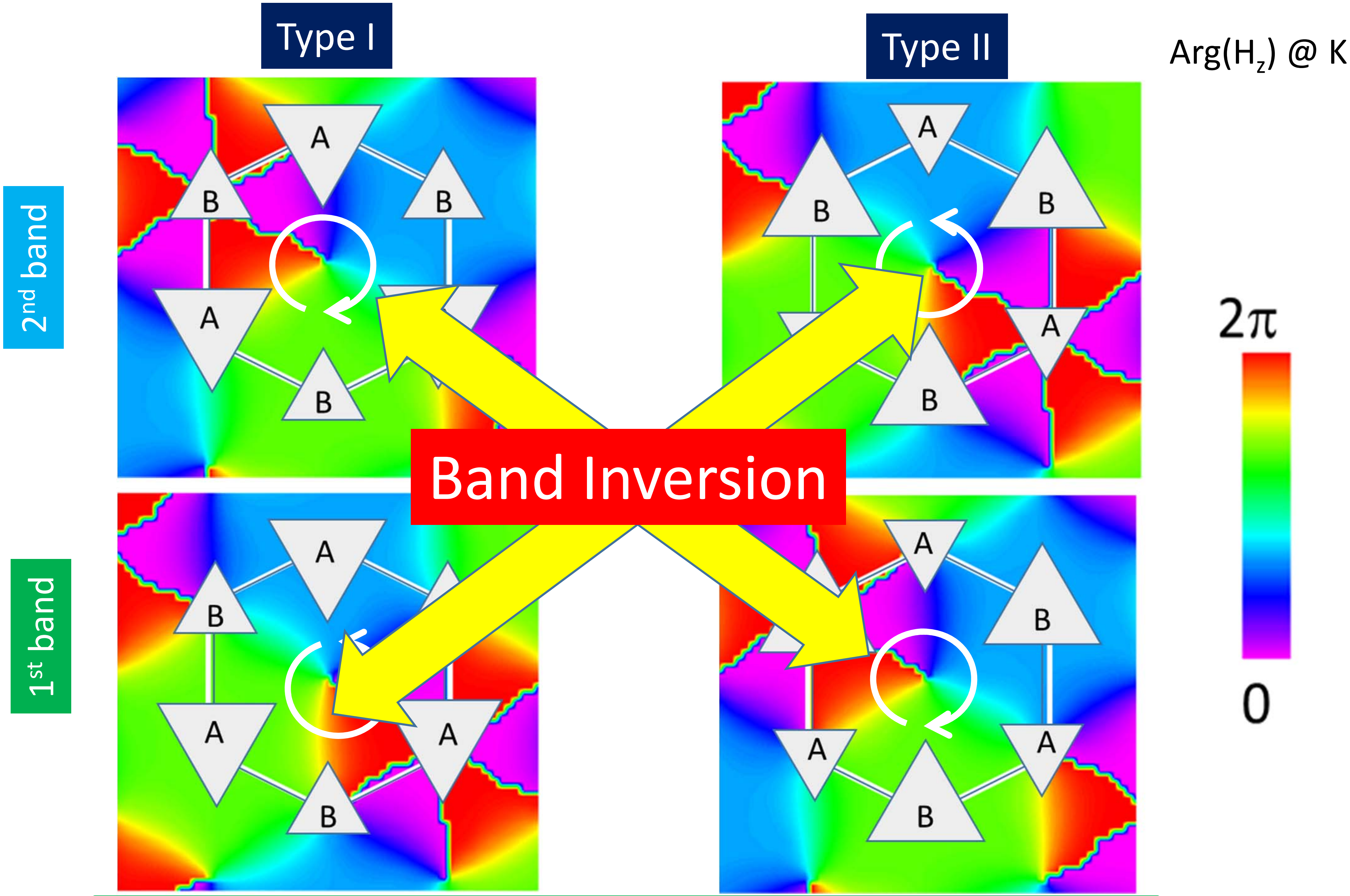




cf. graphene and 2D materials like transition metal dichalcogenide



Valley Photonic Crystal

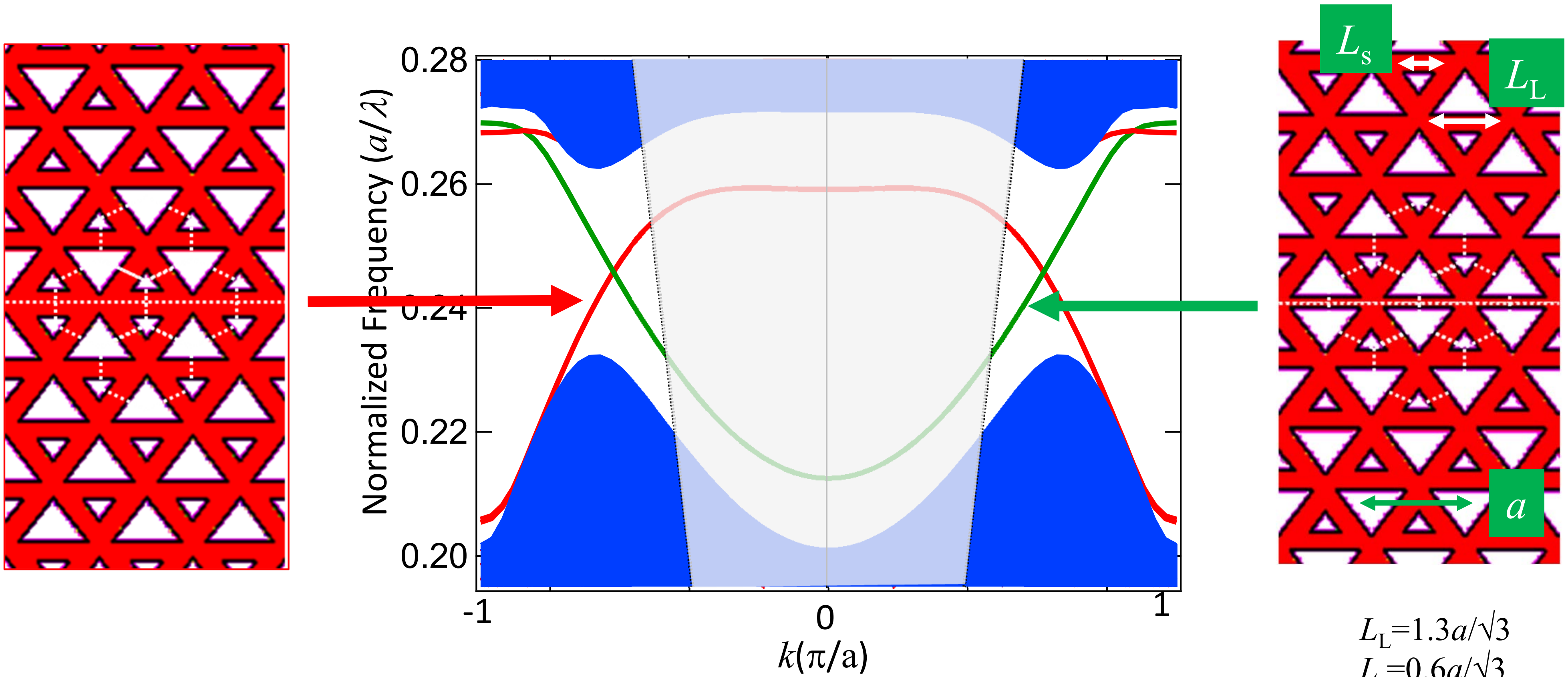


Same band structure but different field distributions

→Topologically-distinct structures

→Edge state exists due to the Bulk-Edge correspondence

Edge State at Zigzag Interface of VPhCs



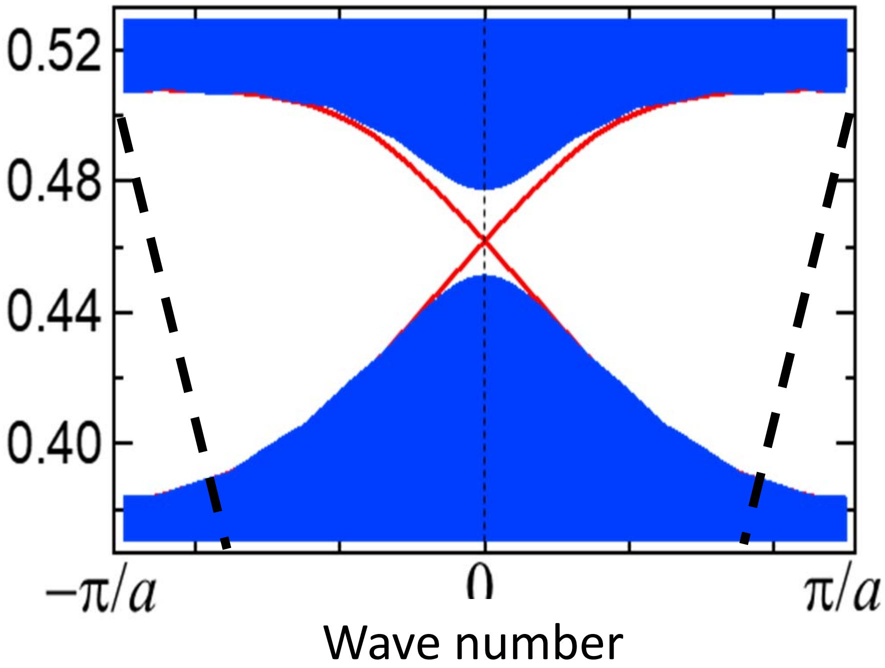
$L_L = 1.3a/\sqrt{3}$
$L_s = 0.6a/\sqrt{3}$
$n = 3.4$

- ✓ An edge state at each interface
- ✓ Edge states locate below light line

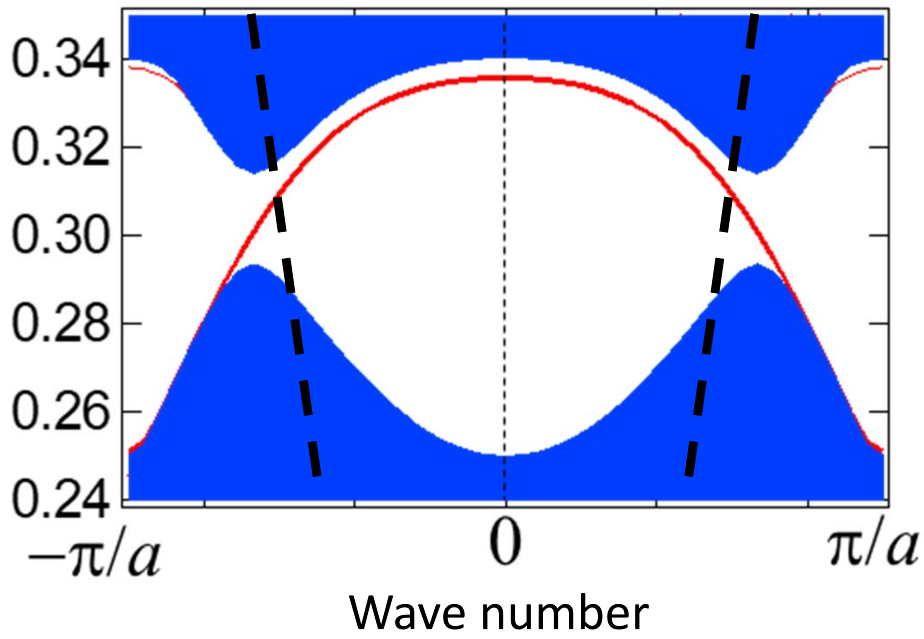
Light line problem

Photonic QSH system

based on band holding scheme
proposed by Wu and Hu, PRL **114**, 223901 (2015).



Photonic QVH system



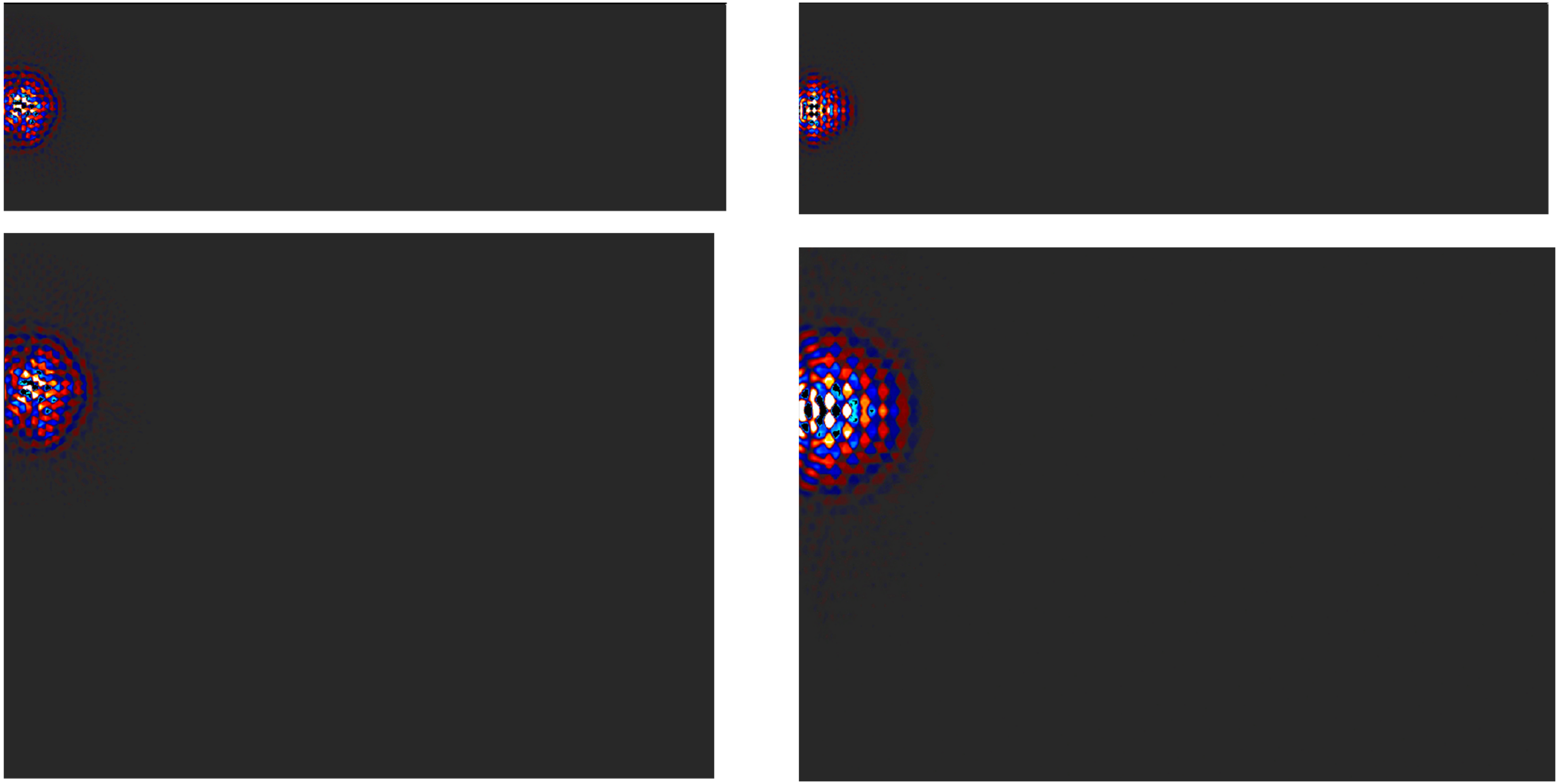
Edge states above light line
→radiation loss
→limit the propagation length

Edge states below light line
→no radiation loss
→suitable for waveguide applications

Impact of radiation loss

CW @ 1.1 μm, **3D-FDTD**

QSH-like WG Hy component **VPhC WG**

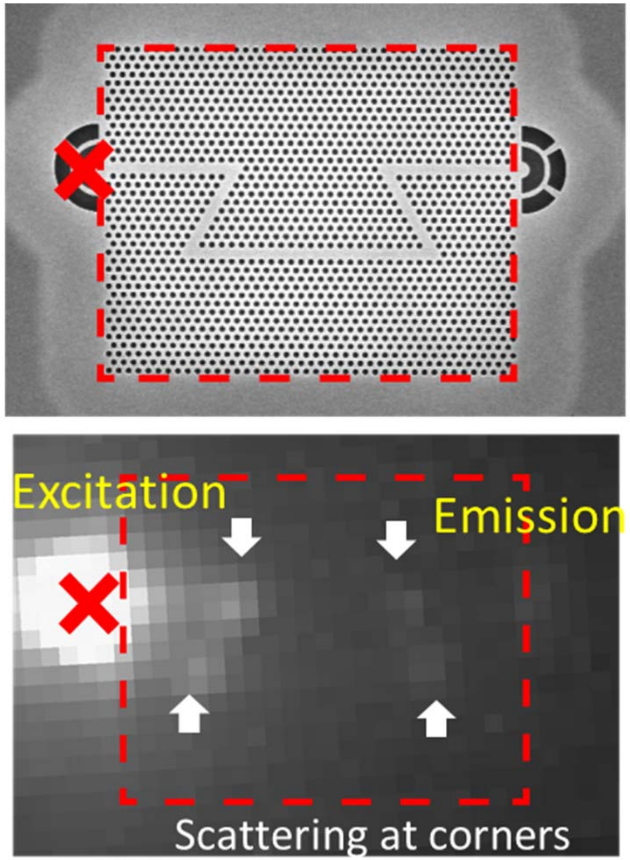


VPhC is beneficial for waveguide application

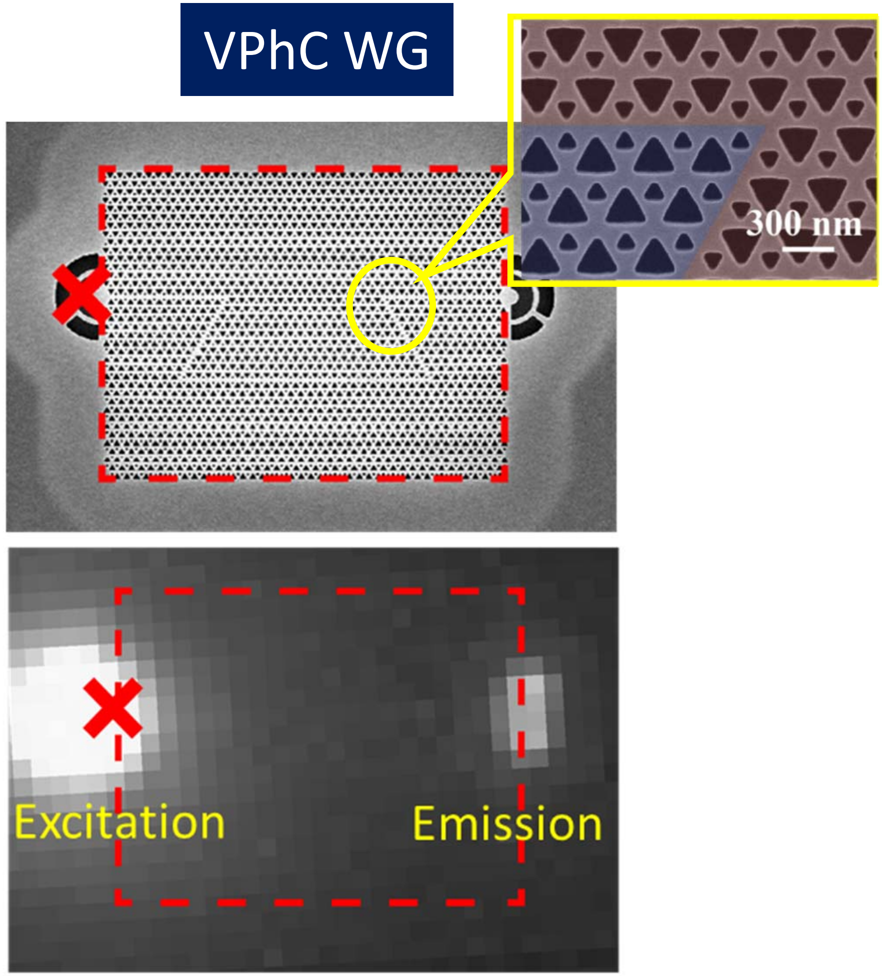
T. Yamaguchi *et al*, *unpublished*

Conventional PhC waveguide vs valley PhC waveguide

W1-type PhC WG



VPhC WG



VPhC：suppressed scattering at corners, high transmittance

Quantitative analysis

Direct quantification of topological protection in symmetry-protected photonic edge states at telecom wavelengths

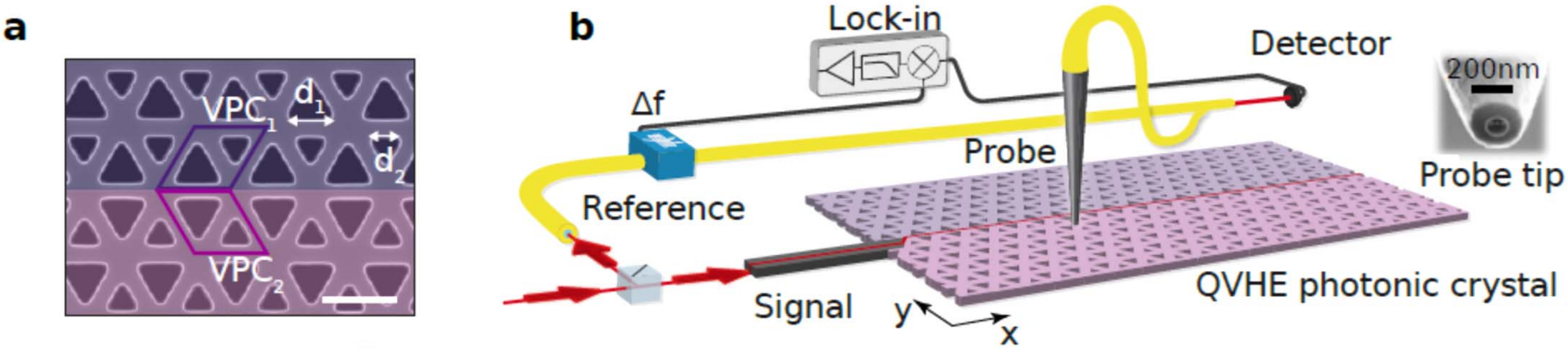
Light: Sci. Appl. **10**, 9 (2021).

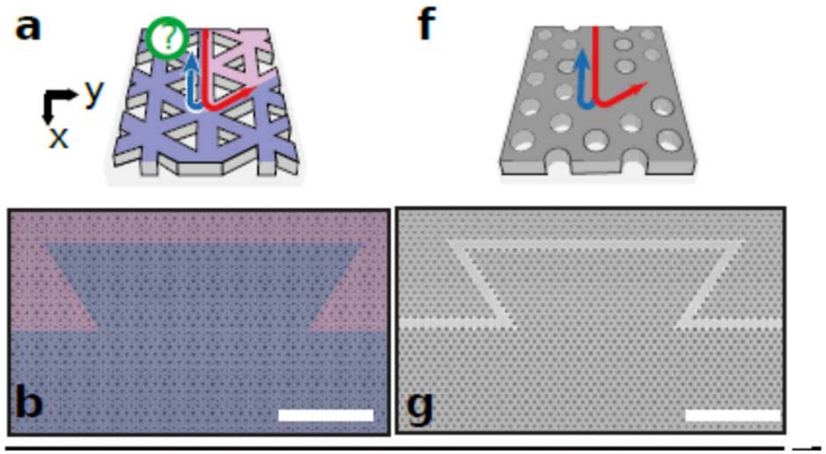
S. Arora,[1,*] T. Bauer,[1,*] R. Barczyk,[2,*] E. Verhagen,[2] and L. Kuipers[1,†]

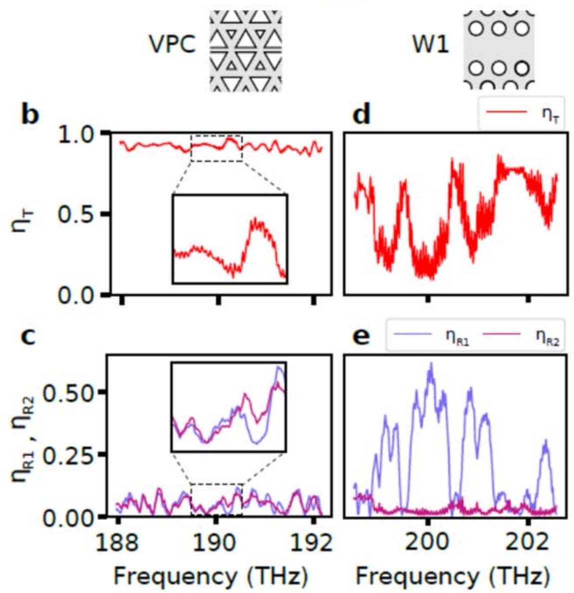
[1]*Kavli Institute of Nanoscience, Delft University of Technology, 2600 GA, Delft, The Netherlands*

[2]*Center for Nanophotonics, AMOLF, Science Park 104, 1098 XG Amsterdam, The Netherlands*

(Dated: August 17, 2020)







VPhC WG is robust more than 100 times than conventional PhC WG

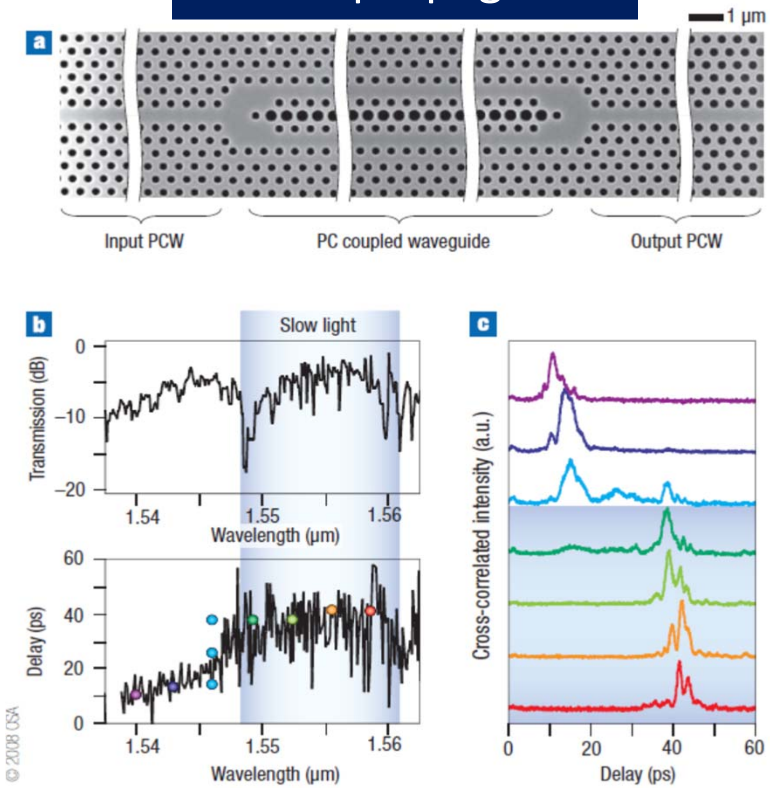
Slow light devices

Slow light: light with small group velocity

Group velocity $v_g = \frac{\partial \omega}{\partial k} \equiv c/n_g$ n_g: Group index

Photonic devices with smaller footprint

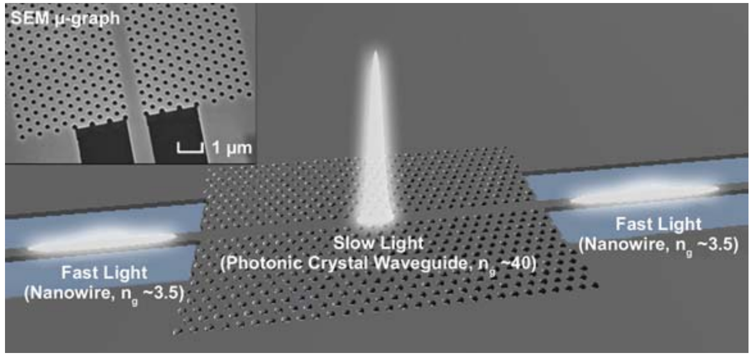
Slower propagation



Optical delay line, Buffer

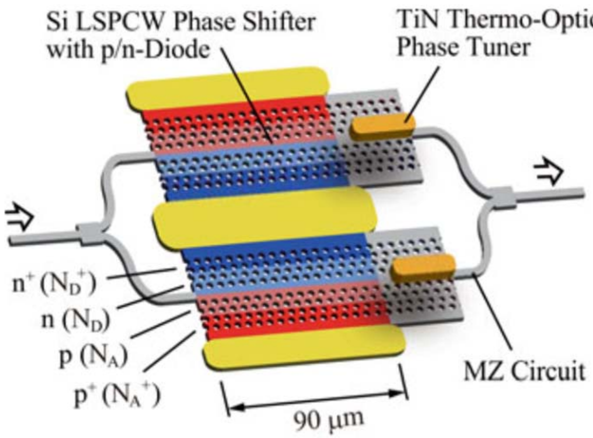
T. Baba, Nat. Photon. **2**, 465 (2008).
T. Baba et al., Opt. Express **16**, 9245 (2008).

Enhance light-matter interaction



Nonlinear Optical device

B. Corcoran et al., Opt. Express **18**, 7770 (2010)
https://www.photonics.com/a45914/The_Slow-Light_Race_Is_On



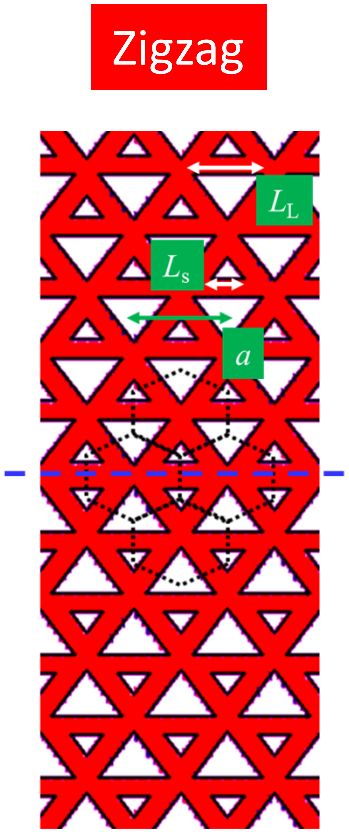
Optica modulator

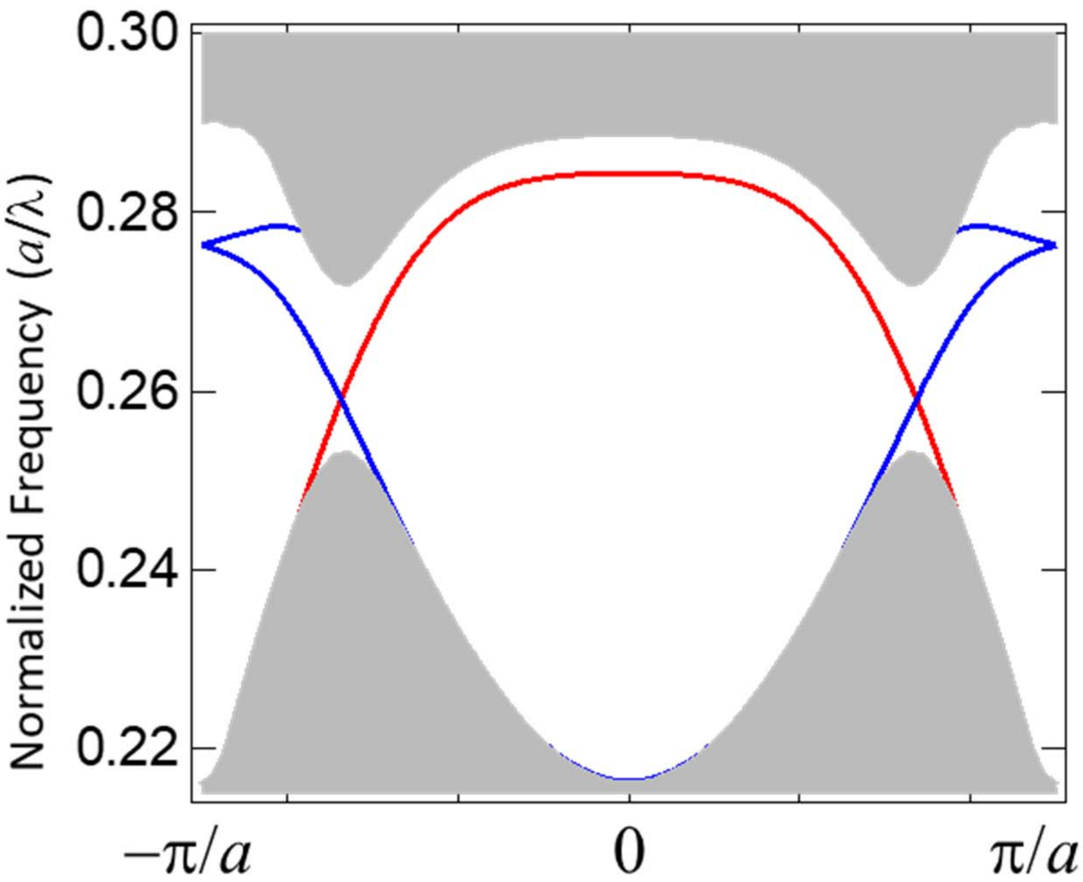
T. Tamura *et al.*,
J. Lightwave Technol.
33, 3034 (2015).

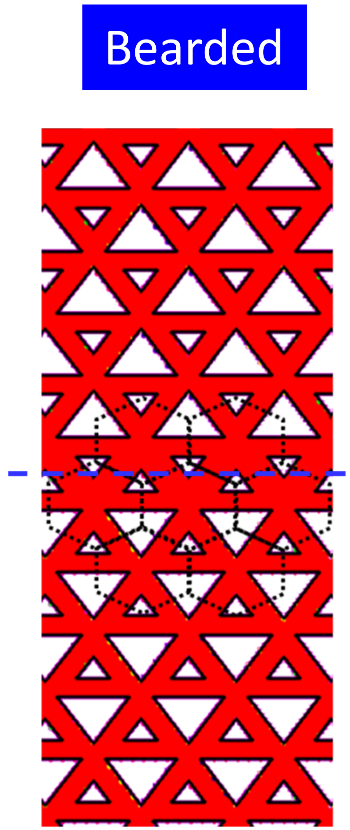
- ✓ More sensitive to disorder
- ✓ Difficult to bend slow light efficiently

Topological slow light has potential

Zigzag interface and bearded interface







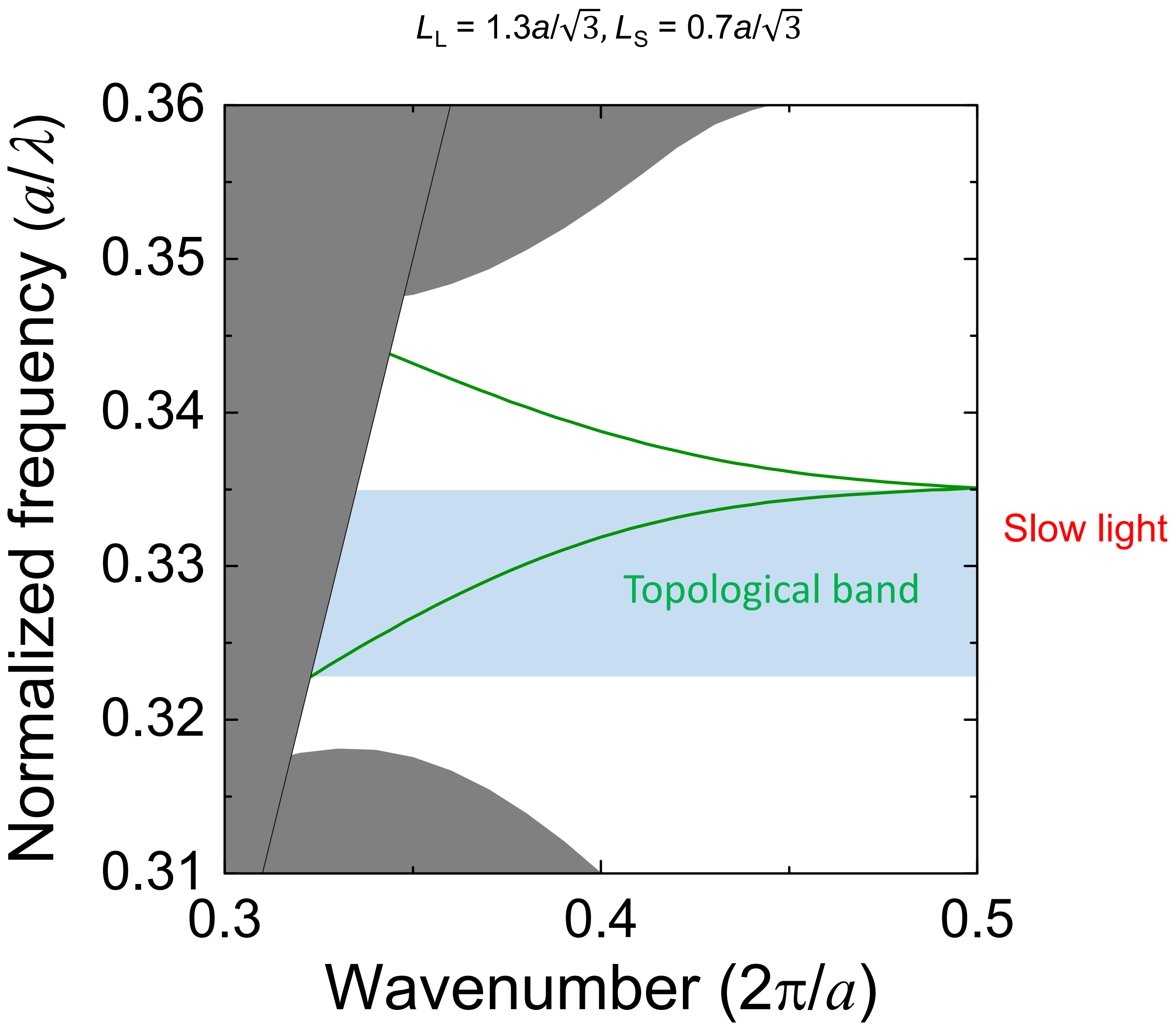
Waveguide modes at bearded interface

Band degeneracy at the Brillouin edge ← due to glide plane symmetry

Bands tend to flat at the Brillouin edge

→slow-light topological mode !?

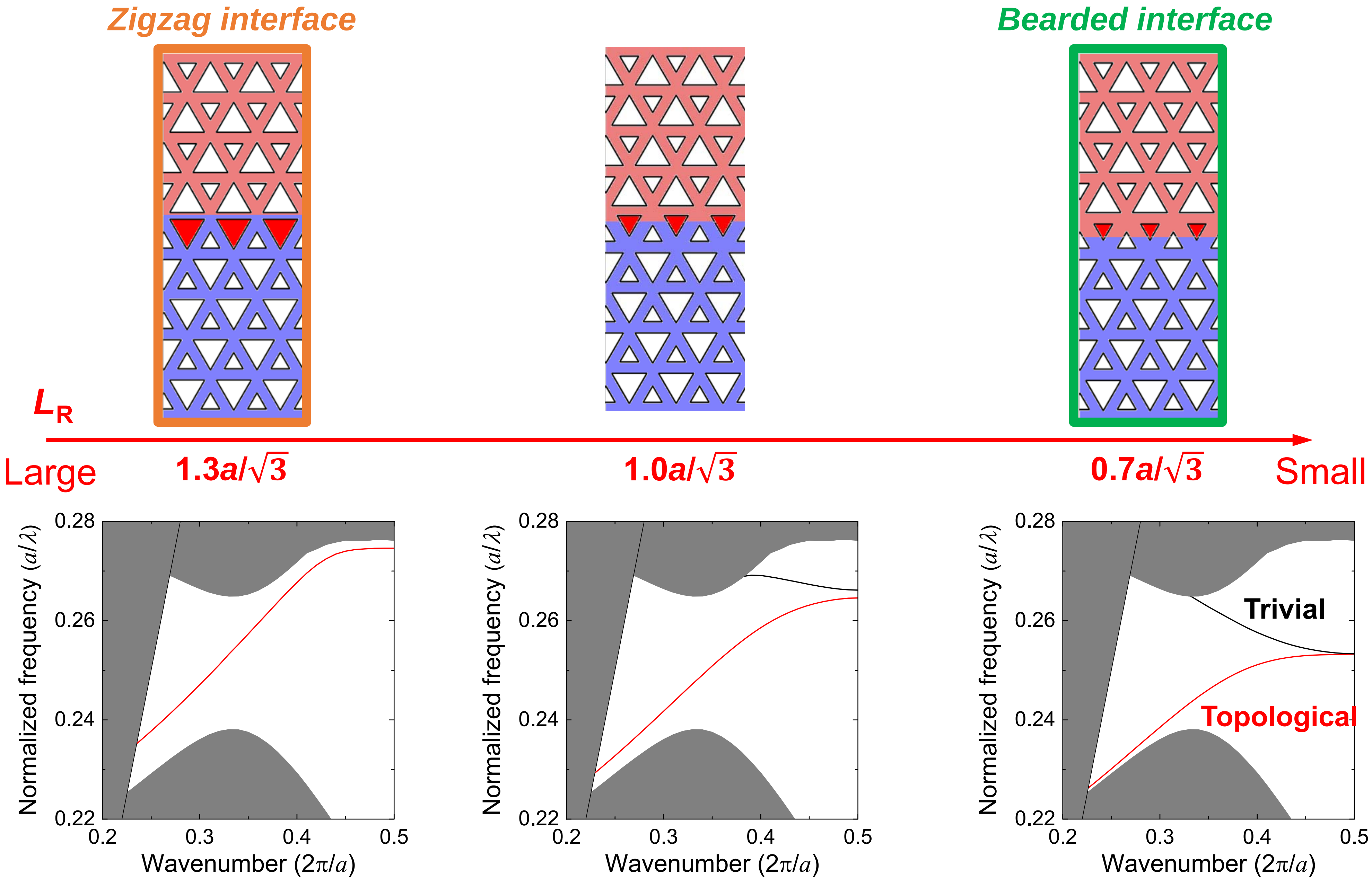
Slow light topological edge state in VPhC



Topological slow light at a bearded interface

H. Yoshimi *et al*., Opt. Lett. **45**, 2648 (2020).

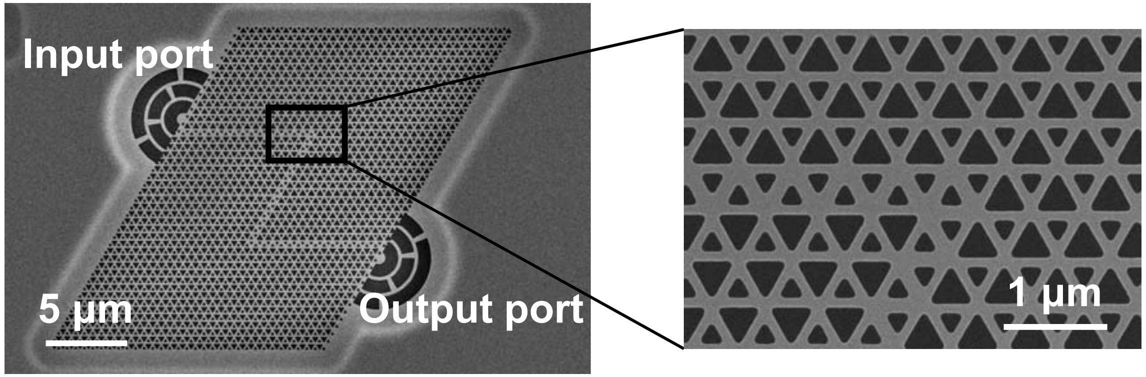
Which band is topological?



Topological edge state corresponds to the lower frequency band

Experimental demonstration

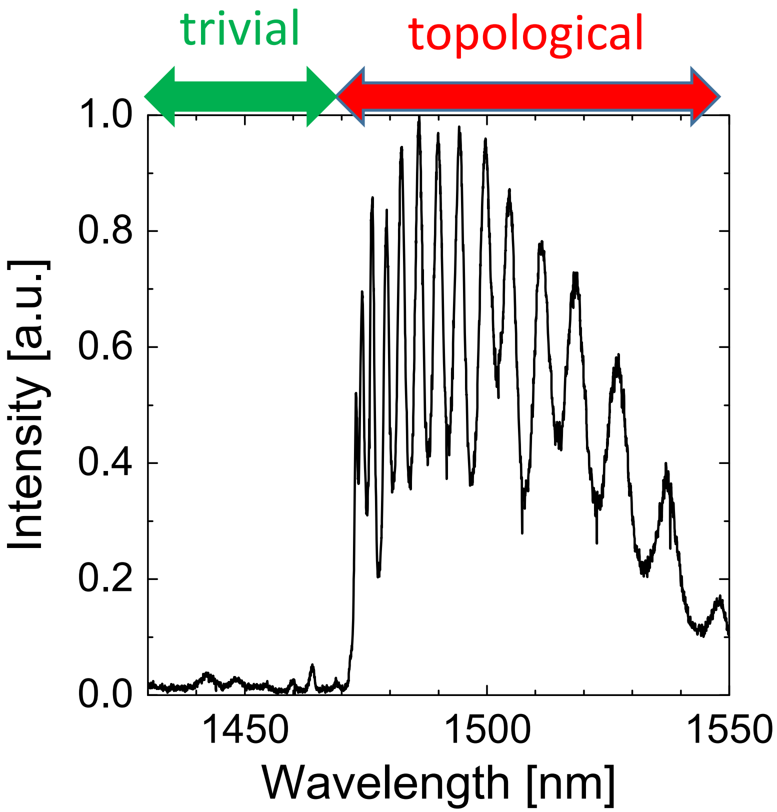
Patterned in
a SOI substrate



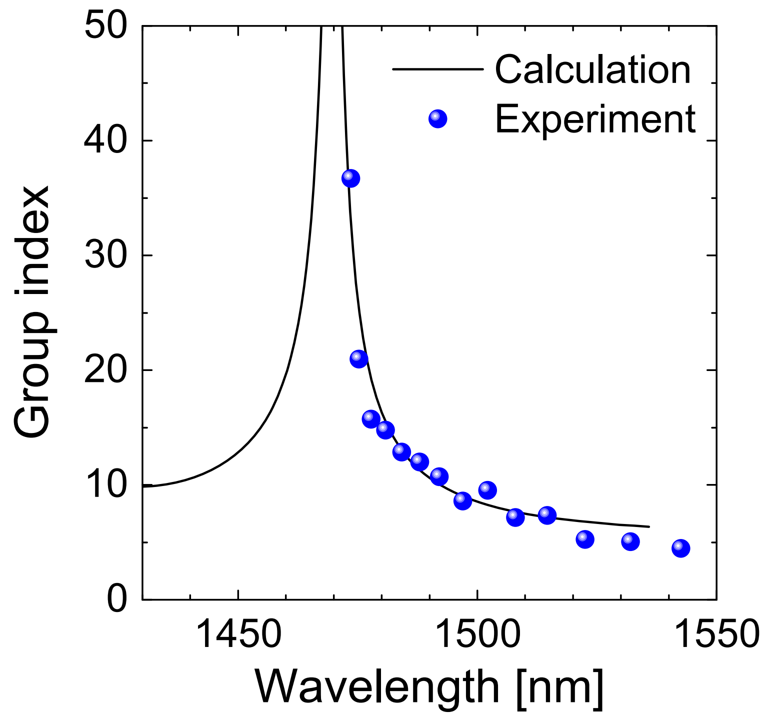
H. Yoshimi et al.,
Opt. Express **29**, 13441 (2021).

a = 530 nm,
L=45a=23.85 um

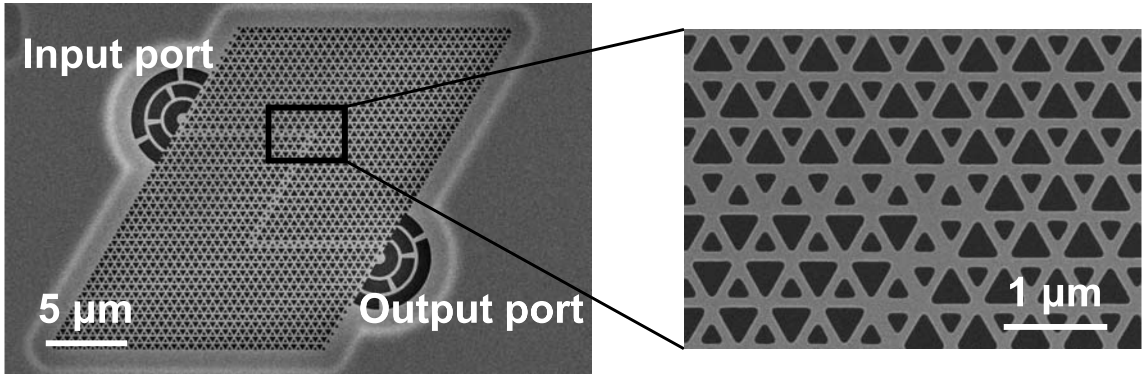
Transmission Spectrum



Group Index

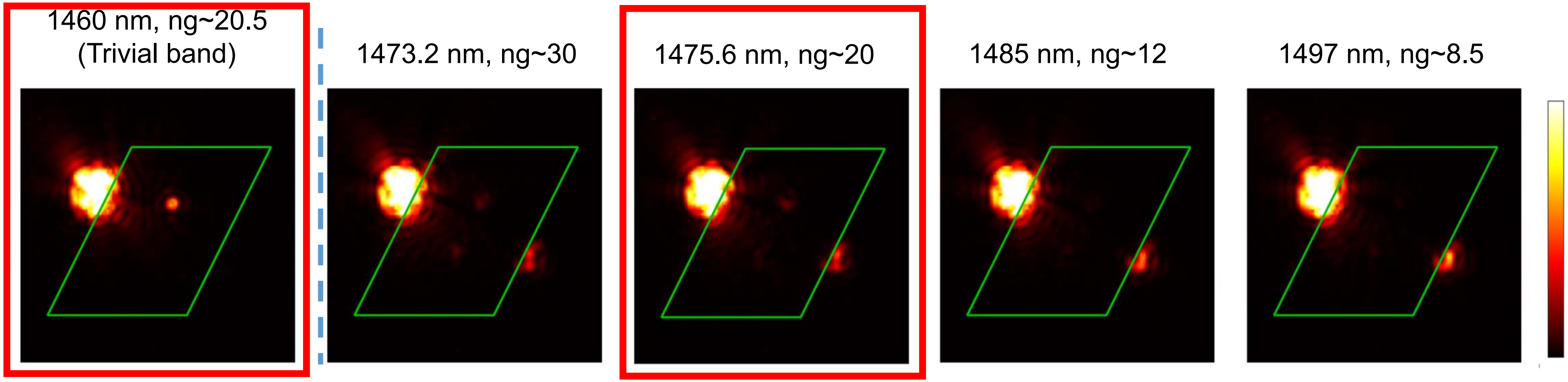


NIR Images



H. Yoshimi et al.,
Opt. Express **29**, 13441 (2021).

a = 530 nm,
L=45a=23.85 um



Efficient guiding of slow light under the presence of sharp bends

Applications

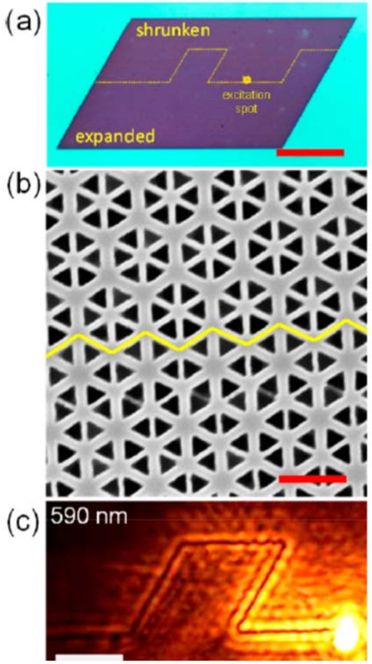
- ✓ Topologically-protected single photon source with Purcell enhancement
  K. Kuruma *et al*., CLEO2021 FW4I.2 (2021)
- ✓ Ring-cavity laser with topological slow light mode
  R. Miyazaki *et al*., SSDM 2021 E-5-04 (2021)

Other related topics

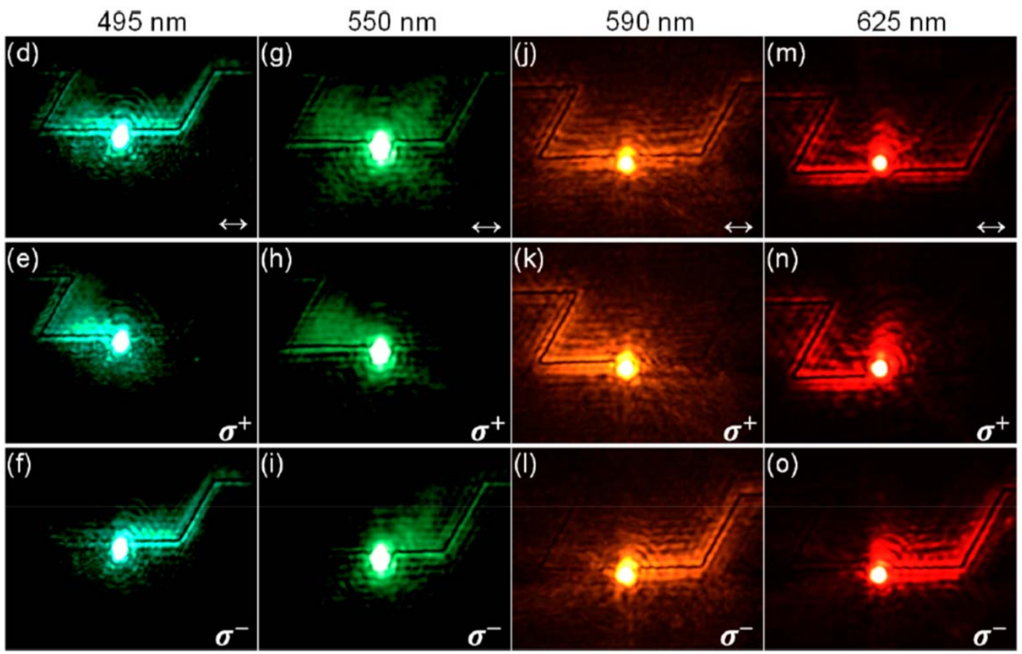
- ✓ Visible and THz
- ✓ Topological lasers

Visible and THz

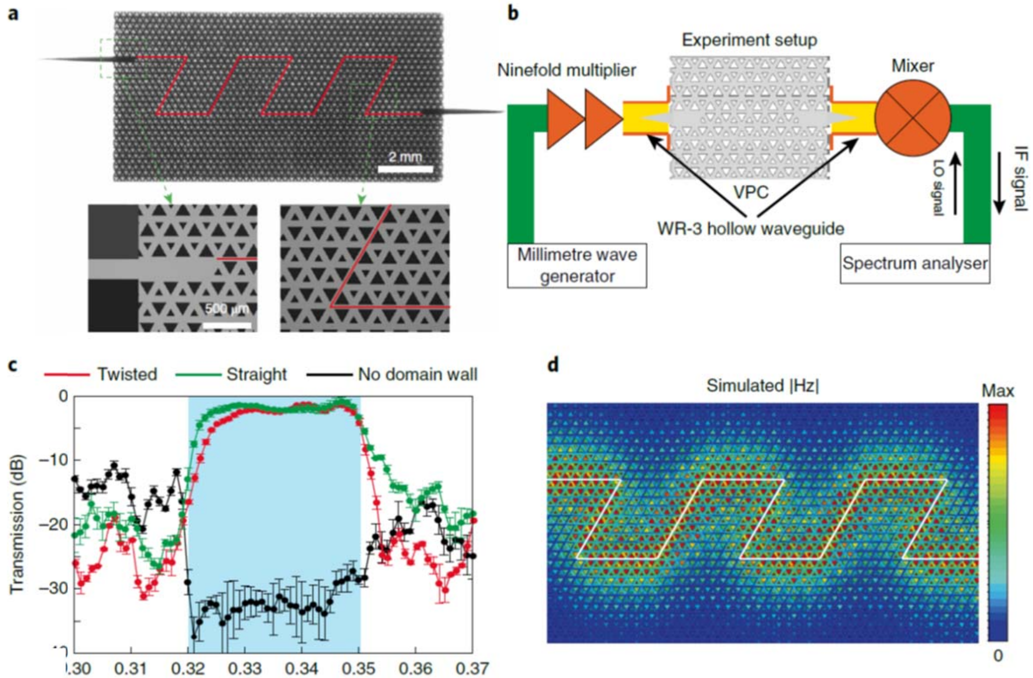
SiN topological PhC waveguide



W. Liu *et al*., Nnno Lett. **20**, 1329 (2020).

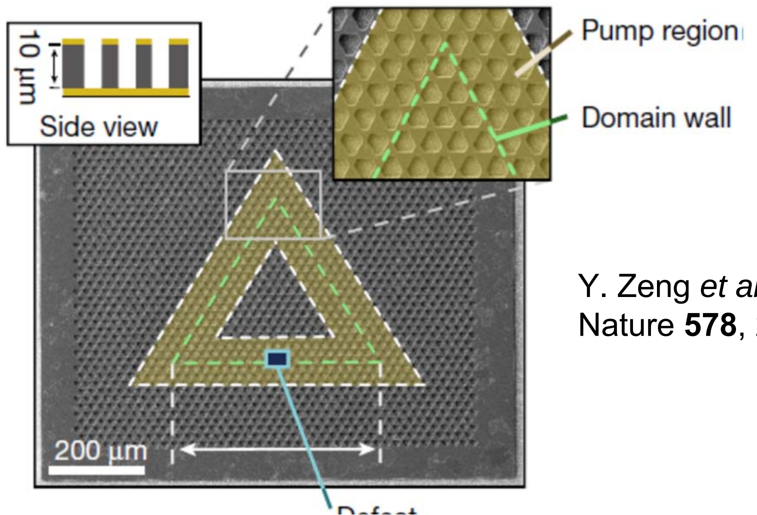


Topological THz chip



Y. Yang *et al*., Nat. Photon. **14,** 446 (2020)

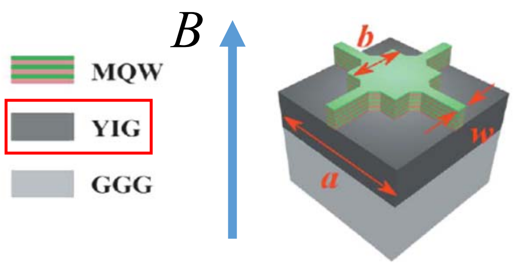
THz cascade laser

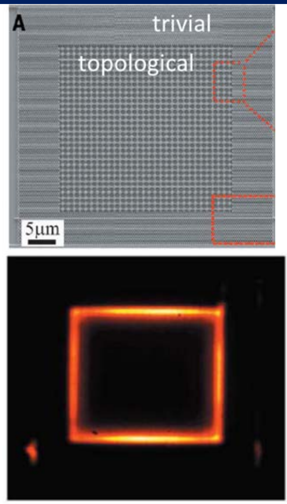


Y. Zeng *et al*., Nature **578**, 246 (2020).

Topological lasers in 2D PhCs

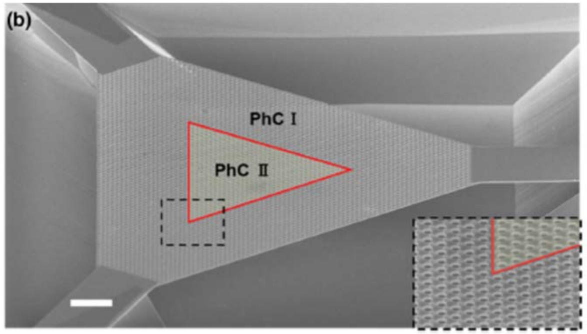
Chiral edge state in Photonic QH

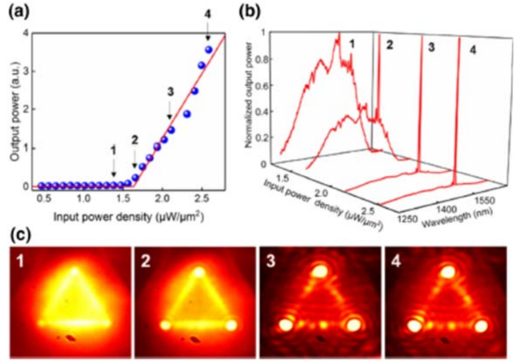




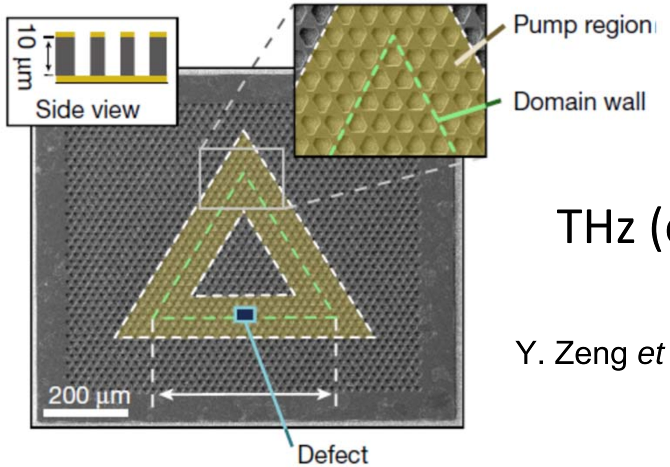
B. Bahari *et al.*,
Science **358**, 636 (2017).

Valley king state in Photonic QVH





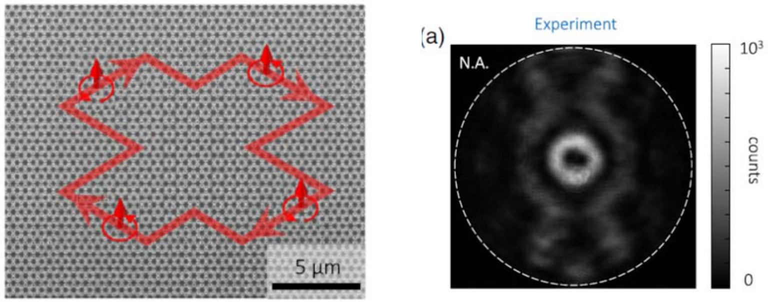
W. Noh *et al.*, Opt. Lett. **45**, 4108 (2020).



THz (cascade laser)

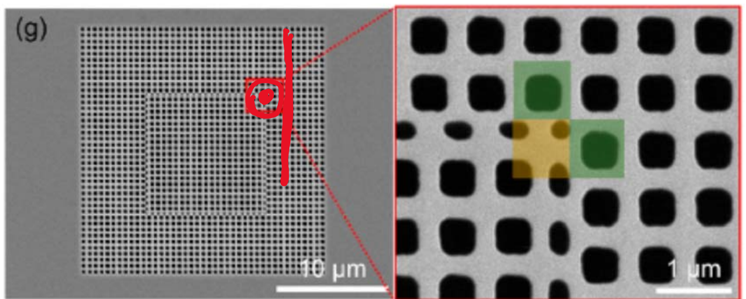
Y. Zeng *et al.*, Nature **578**, 246 (2020).

Helical edge state in Photonic QSH



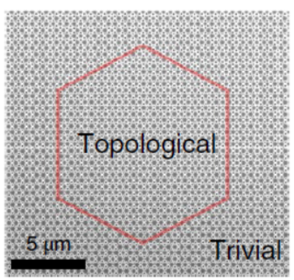
Z. –Q. Yang *et al.*, Phys. Rev. Lett. **125**, 013903 (2020).

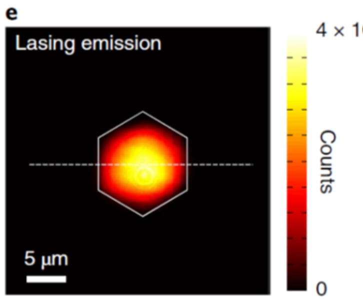
Corner state



C. Han *et al.*, ACS Photonics **7** 2027 (2020).

Bulk state of Photonic QSH





Z. –K. Shao *et al.*,
Nat. Nanotech. **15**, 67 (2020).

Other related topics

- ✓ Visible and THz
- ✓ Topological lasers
- ✓ Nonlinear optics
- ✓ Quantum Optics
- ✓ Topological localized states in 2D PhCs
  Corner state, Dirac vortex, Topological defect
- ✓ Synthetic dimension
- ✓ 3D topological photonics
- ✓ Non-Hermitian photonics

and many

See also our related papers:

- ✓ Topological lasers: N. Ishida, S. Iwamoto et al., arXiv:2108.11901 (2021).
- ✓ Corner state: Y. Ota, S. Iwamoto *et al*., Optica **6** 786 (2019).
- ✓ Synthetic dimension: A. Balčytis, T. Baba, S. Iwamoto *et al*., arXiv:2105.13742 (2021)
- ✓ 3D topological photonics: S. Takahashi, S. Iwamoto *et al*., Opt. Express **29**, 27127 (2019).
- ✓ Non-Hermitian PhC: C. F. Fong, S. Iwamoto *et al*., Phys. Rev. Research **3**, 043096 (2021).

Summary

- ✓ Semiconductor-based topological PhCs for future integrated photonic circuit technology

- ✓ Topological nanocavity in 1D nanobeam PhC
  - Simple example
  - Deterministic design of single cavity mode

- ✓ Valley photonic crystal
  - All dielectric structure
  - Valley kink state enabling robust light propagation

- ✓ Topological slow-light waveguide using a valley kink state

- ✓ Topology + nanophotonics can lead breakthroughs in future integrated photonics

Acknowledgements

Collaborators

Yasutomo Ota (Keio Univ.)
Takuto Yamaguchi (valley)
Hironobu Yoshimi (valley)

Wenbo Lin (Poincare and related)
Natsuko Ishida (SSH laser)
(Univ. of Tokyo)

Shun Takahashi (Kyoto Inst. Technol.) (Weyl, 3D)
Toshihiko Baba (Yokohama Nat. Univ.)
(Synthetic dimension)
Yasuhiro Hatsugai (Tsukuba Univ.) (Theory)
Katsunori Wakabayashi
(Kwansei Gakuin Univ.)(Theory)
Tomoki Ozawa (Tohoku Univ.) (Theory)
Katsuyuki Watanabe and Yasuhiko Arakawa
(Univ. of Tokyo) (QD growth)
Nobukiyo Kobayashi (DENJIKEN) (MO material)

Group Photo (June, 2020)

Funding

MEXT KAKENHI (15H05700, 15H05868, 17H02796, 17H06138, and 19K21959)
JST CREST(JPMJCR19T1), NEDO FS, Asahi Glass Foundation, Nippon Sheet Glass Foundation