Sandia National Laboratories

SAND2019-9418C

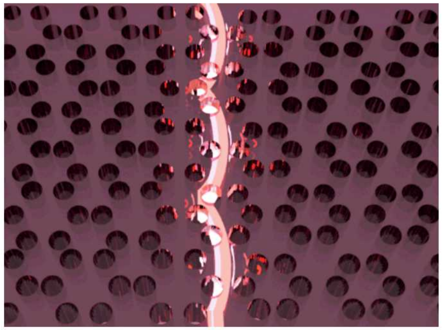
Optical Frequency Topological Photonic Structures

Ganapathi Subramania

Sandia National Laboratories, Albuquerque, NM

Collaborators: P. Duke Anderson(SNL), Jason Dominguez (SNL), and Anthony James (SNL),
and Stavroula Foteinopoulou (Univ. of NM)

Aug 11-15, 2019 ,SPIE Optics and Photonics
San Diego, CA, USA



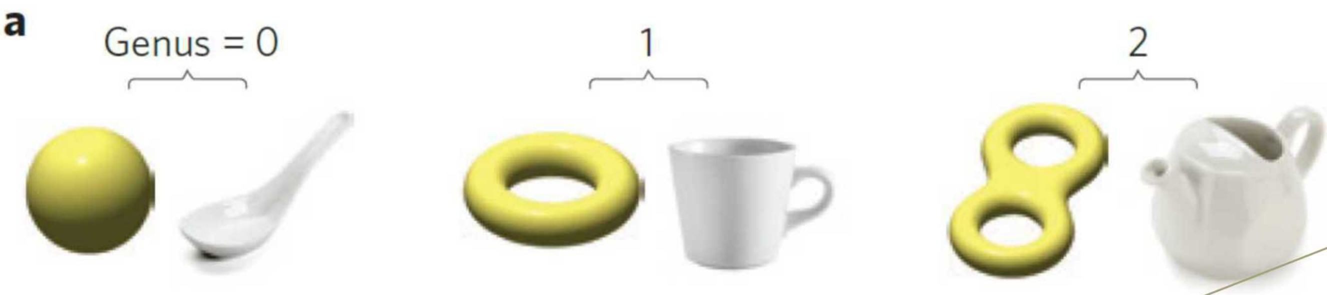
Supported by the Laboratory Directed Research and Development program at Sandia National Laboratories, a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525..

Outline

- Brief Introduction
- Pseudo spin based all dielectric topological structure
- Silicon-on-insulator (SOI) implementation
- III-nitride
- Summary

Topological Protection

Topological Protection: Approaches that exploit topological properties of the phase space of a system can offer stability and robustness to the system of interest from external disturbances such as scattering, decoherence etc.



Total Gaussian curvature

Topological invariant : genus = $$\frac{1}{2\pi}\int_{\text{surface}} \mathcal{K}\,dA = 2(1-g)$$

- Need to create a topological transition to affect the system.

➢ Non-trivial topological system can provide new ways of control in electronics and **photonics**. (Eg. Loss-less unidirectional, scatter-free transport)

L. Lu, J. D. Joannopoulos, and M. Soljacic, "Topological photonics," Nat Photon **8**, 821-829 (2014).

Topological Photonics Research Activities

Sandia National Laboratories

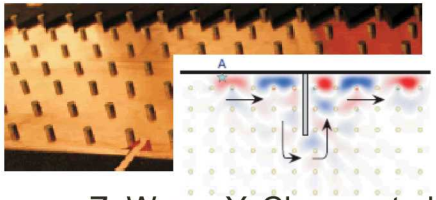
PHYSICAL REVIEW A **78**, 033834 (2008)

Analogs of quantum-Hall-effect edge states in photonic crystals

S. Raghu*
Department of Physics, Stanford University, Stanford, California 94305-4045, USA

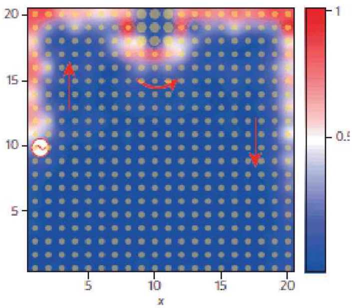
F. D. M. Haldane
Department of Physics, Princeton University, Princeton, New Jersey 08544-0708, USA

One- way transport at microwave frequency



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

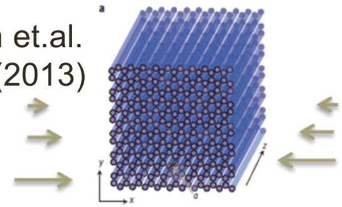
One-way edge transport



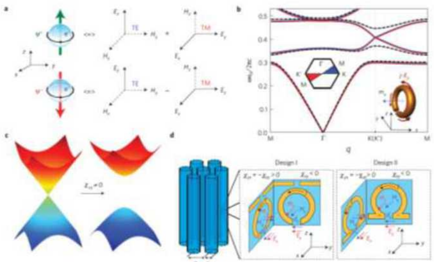
K.Fang, Z. Yu , S.H.Fan , **Nat. Phot. 6 ,** (2012)

Strain induced pseud mag. field in optical fiber arrays

M.Rechtsman et.al. **Nat. Phot. 7** (2013)

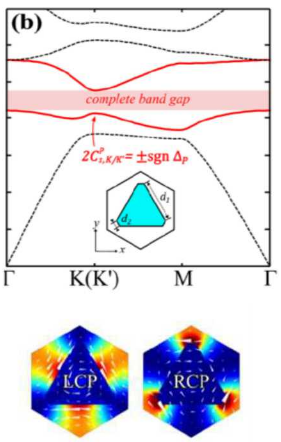


Metamaterial PTI



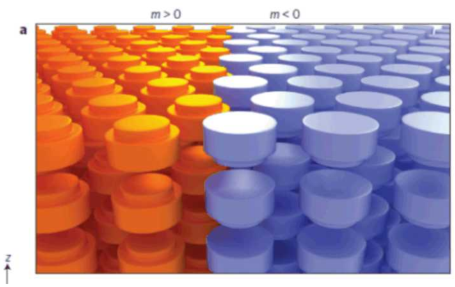
A. B. Khanikaev et.al. Nat Mater **12** (3), 233-239 (2013).

Valley hall PTI



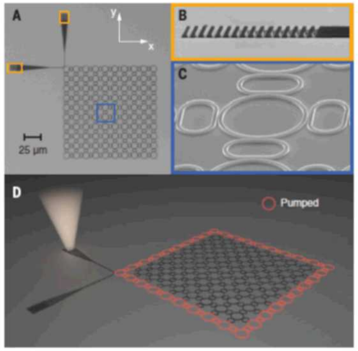
M. Tzuhsuan and S. Gennady, NJP.**18** (2), 025012 (2016).

3D All dielectric PTI



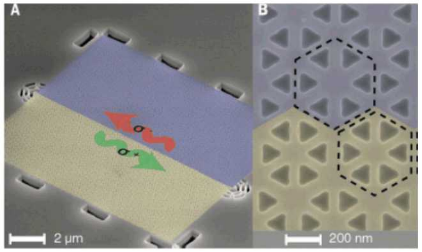
A. Slobozhanyuk, et.al. , Nat Photon **11** (2), 130-136 (2017).

PTI lasing



Bandres, M. A. *et al*. *Science* **359**, eaar1231 (2018).

Topological edge states in III-V



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

Topological Photonics Spin Hall in Dielectric PC

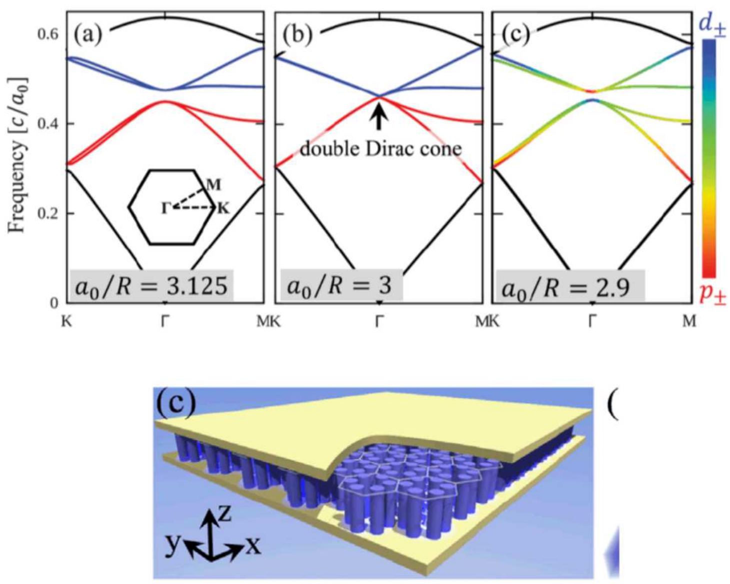
Sandia National Laboratories

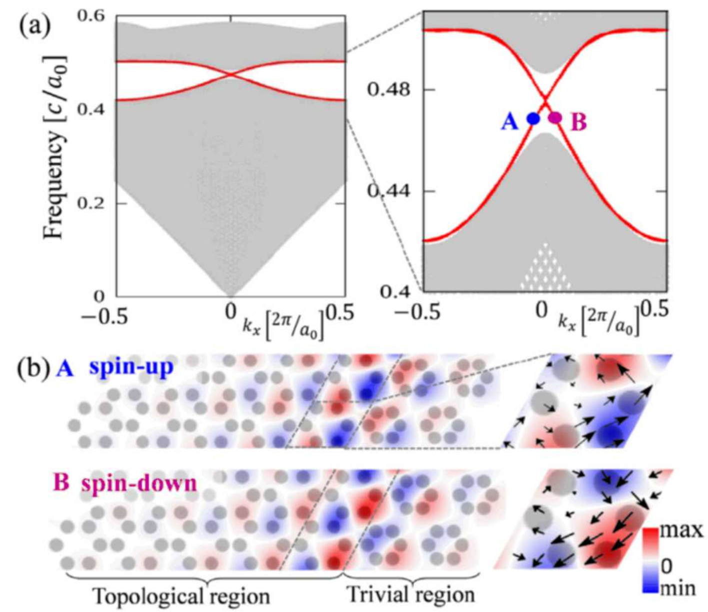
PRL 114, 223901 (2015) PHYSICAL REVIEW LETTERS week ending 5 JUNE 2015

Scheme for Achieving a Topological Photonic Crystal by Using Dielectric Material

Long-Hua Wu and Xiao Hu*
International Center for Materials Nanoarchitectonics (WPI-MANA), National Institute for Materials Science, Tsukuba 305-0044, Japan
Graduate School of Pure and Applied Sciences, University of Tsukuba, Tsukuba 305-8571, Japan

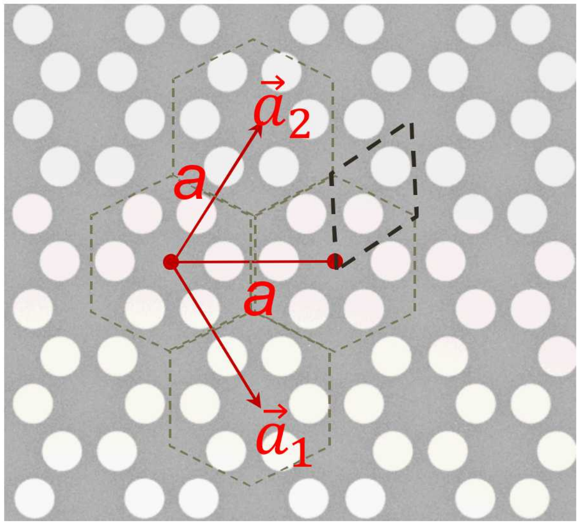
(Received 10 February 2015; published 3 June 2015)

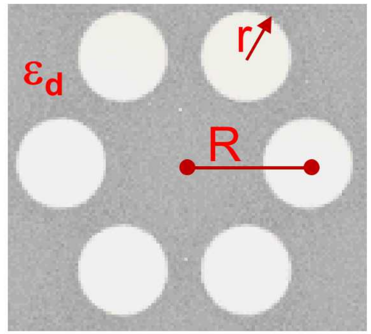


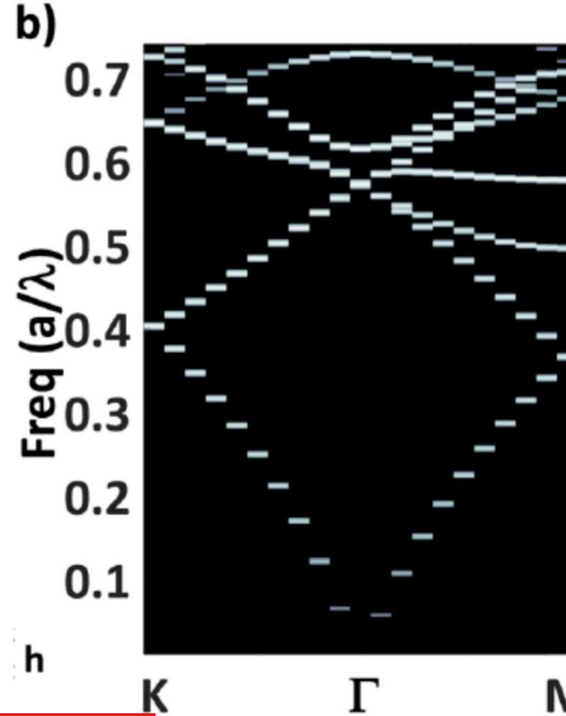


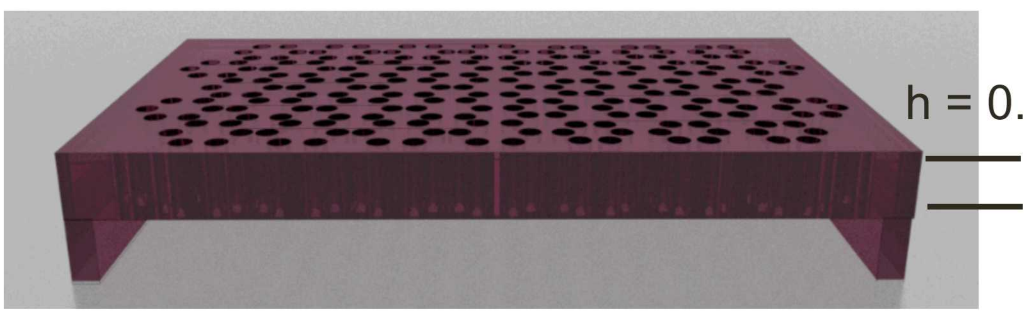
Modified honeycomb lattice of hexagonal cylindrical dielectric rods

Thin-slab Photonic Crystal Design









h = 0.25a

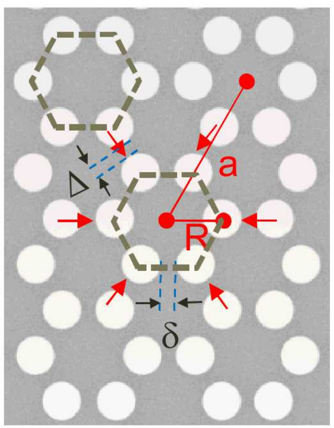
a/R = 3.0

r=0.13a

Calculated with FDTD (Lumerical ®)

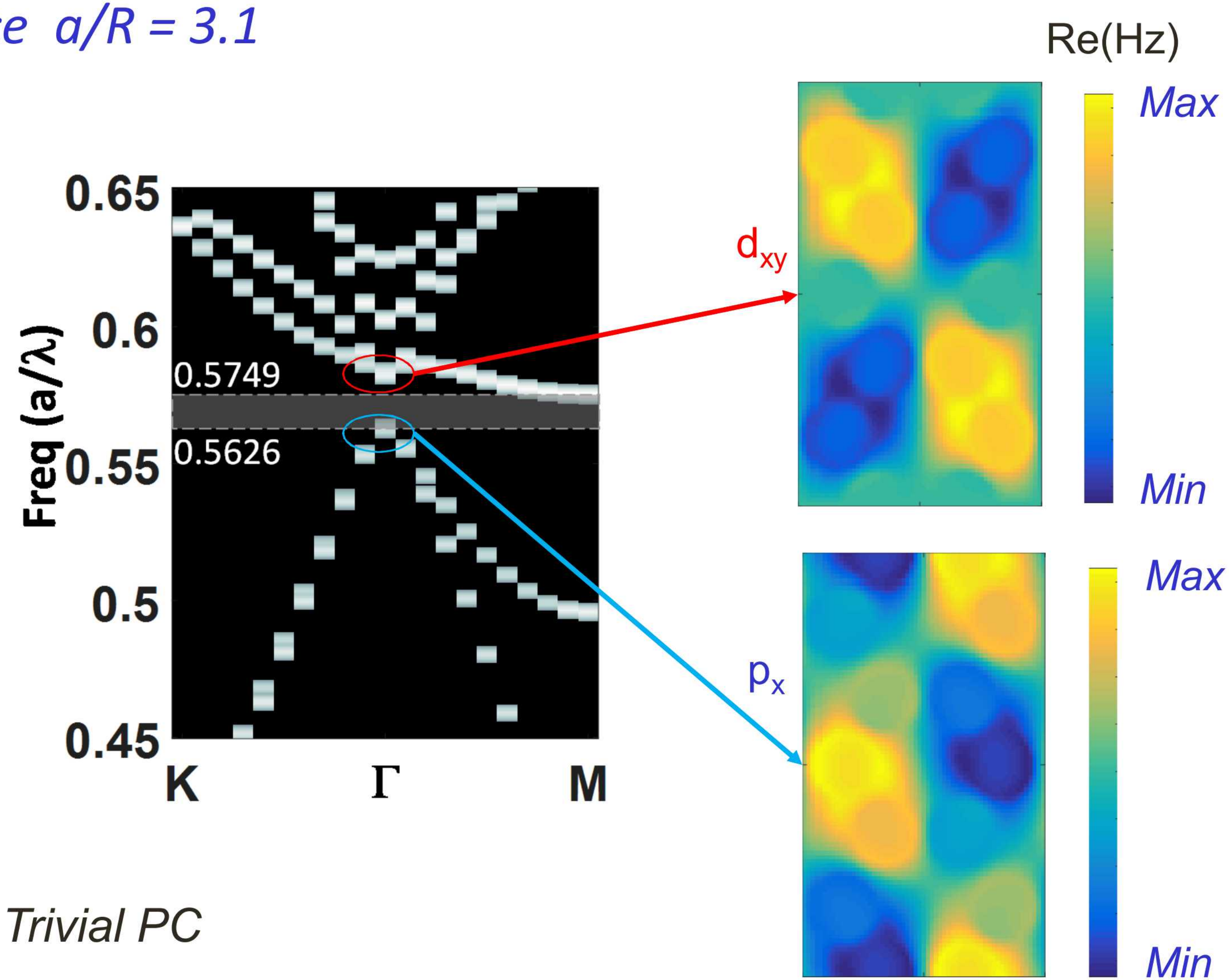
Circular Hole Array Honeycomb Lattice Photonic Crystal

Compressed lattice a/R = 3.1



$\Delta = a - 2\,(R + r)$

$\delta = R - 2r$

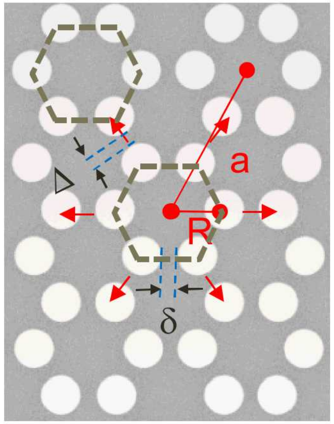


Topologically Trivial PC

P. D. Anderson and G.Subramania, Optics Express **25** (19), 23293 (2017).

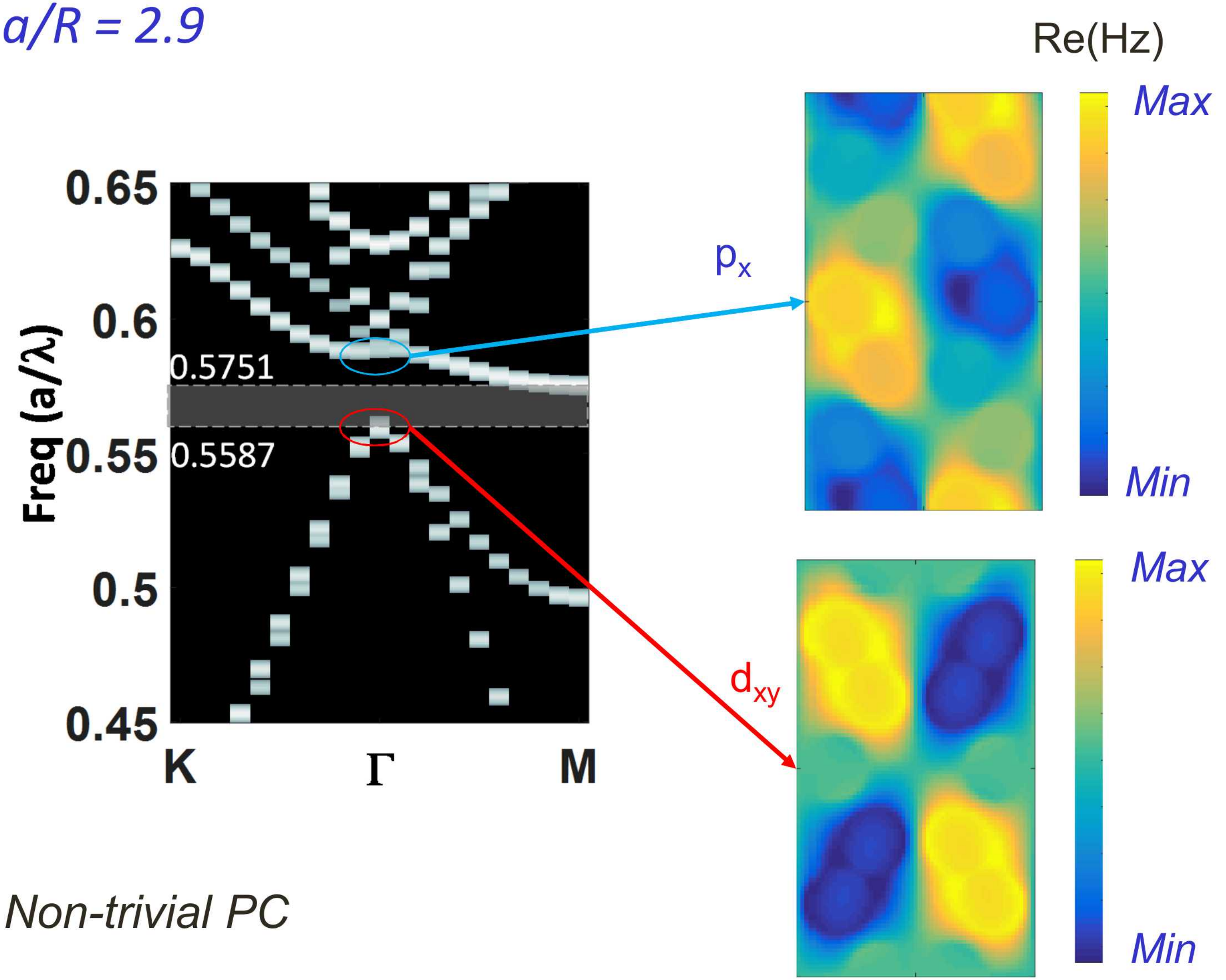
Circular Hole Array Honeycomb Lattice Photonic Crystal

Expanded lattice a/R = 2.9



Δ=a-2 (R+r)

δ=R -2r



Topologically Non-trivial PC

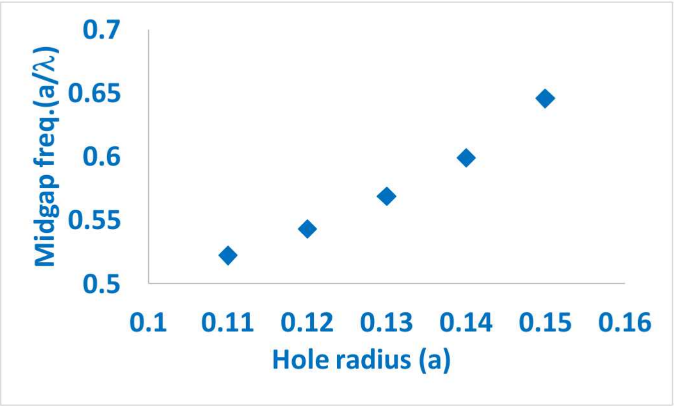
P. D. Anderson and G.Subramania, Optics Express **25** (19), 23293 (2017).

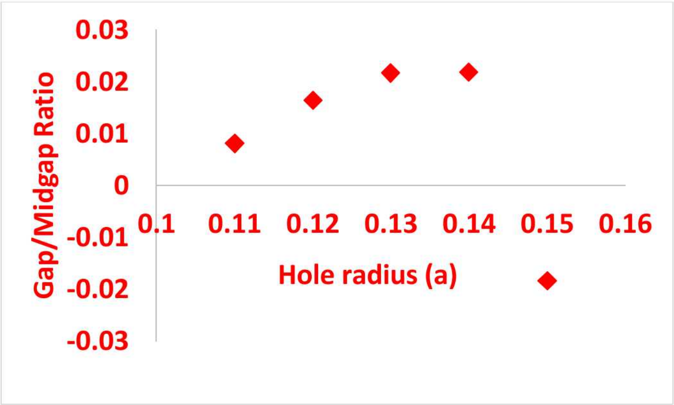
Circular Hole Array Honeycomb Lattice Photonic Crystal

Hole radius 'r' dependence

Membrane thickness 'h' = 0.25a

Compressed a/R = 3.1

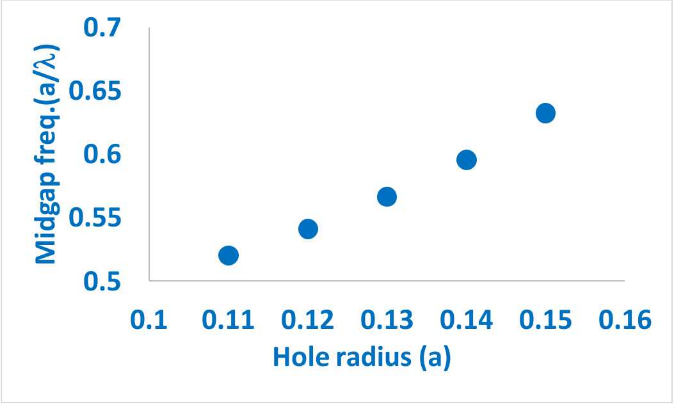


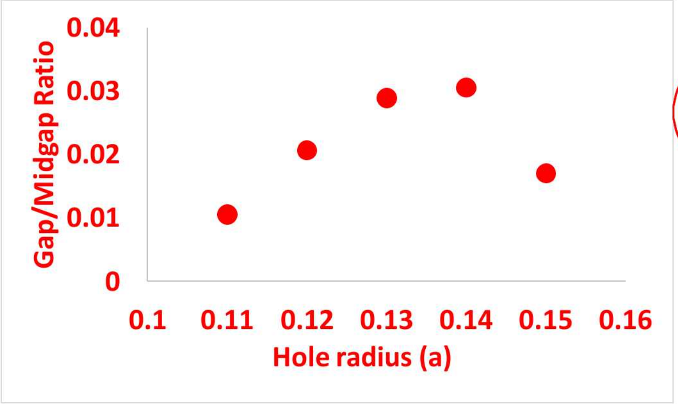


At λ ~ 1500nm

Δλ ~ 30nm

Expanded a/R = 2.9





At λ ~ 1500nm

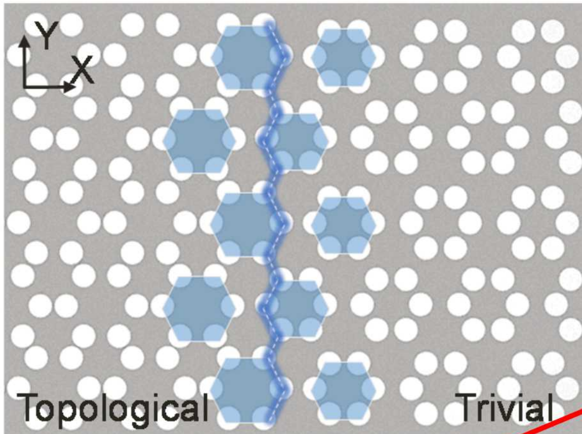
Δλ ~ 45nm

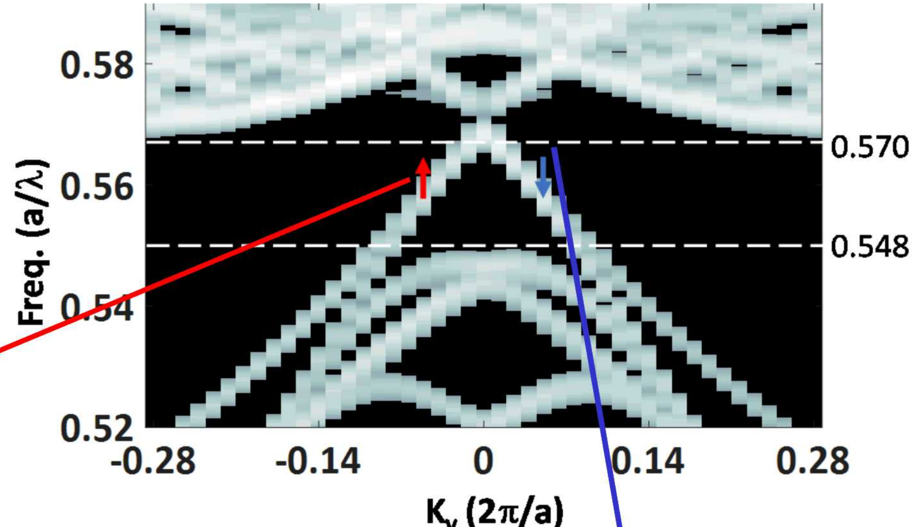
Reasonable operational bandwidth possible at the telecom frequencies

P. D. Anderson and G.Subramania, Optics Express **25** (19), 23293 (2017).

Unidirectional Edge State Propagation

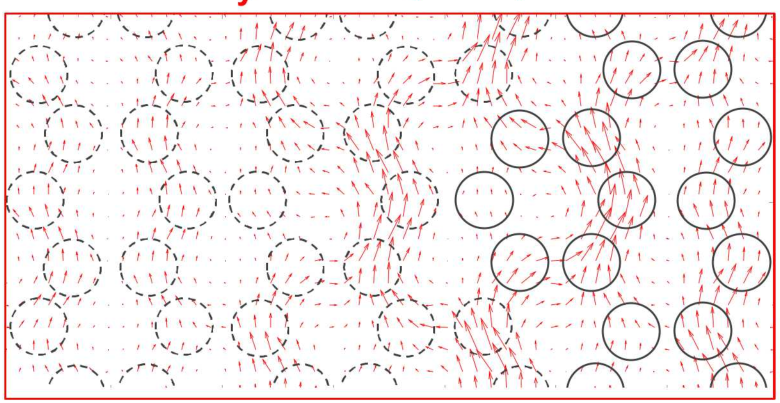
Zig-zag interface

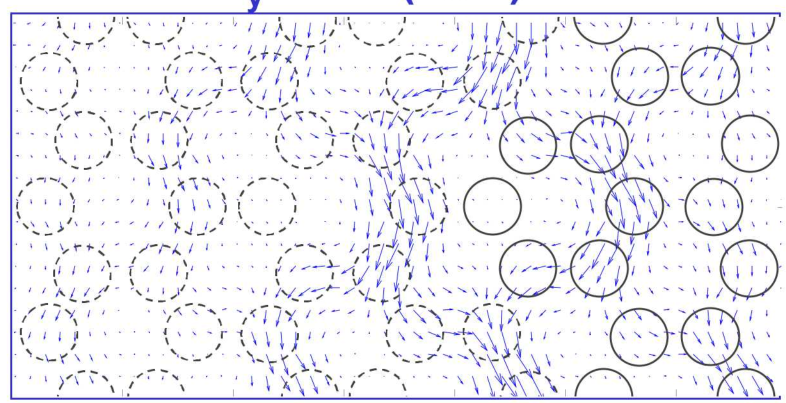




k_y= -0.05(2π/a)

k_y= 0.05(2π/a)



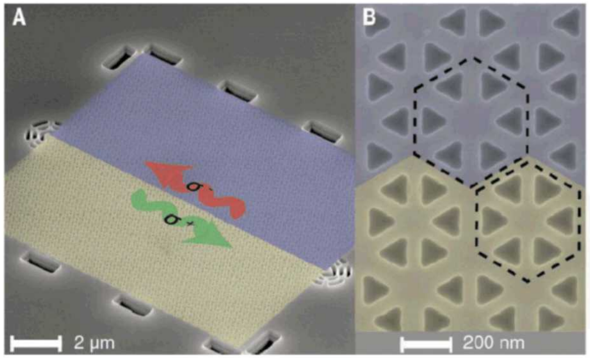


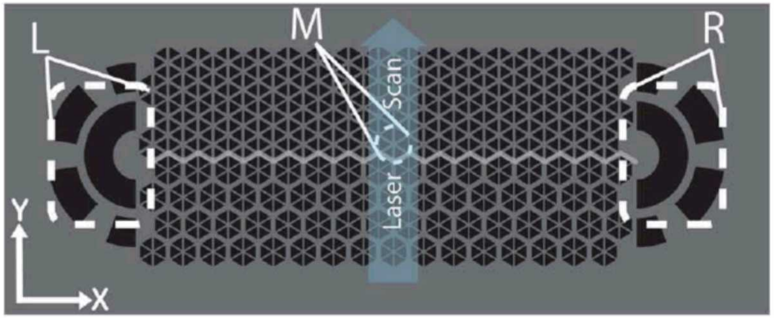
P. D. Anderson and G.Subramania, Optics Express **25** (19), 23293 (2017).

How to launch a helical source?

Quantum Dot based Helical Sources

Barik, S., et al. (2018). "A topological quantum optics interface." Science **359**(6376): 666.

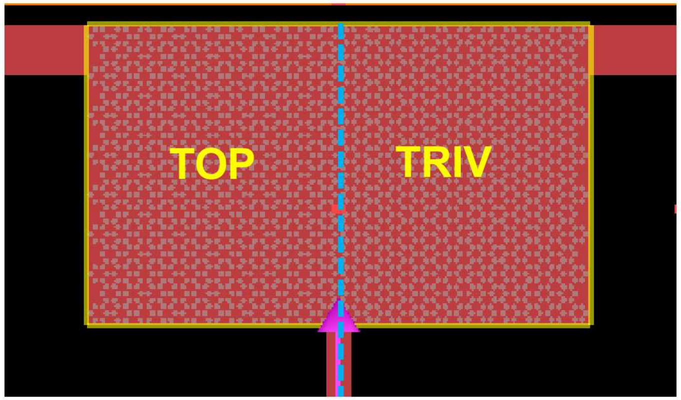


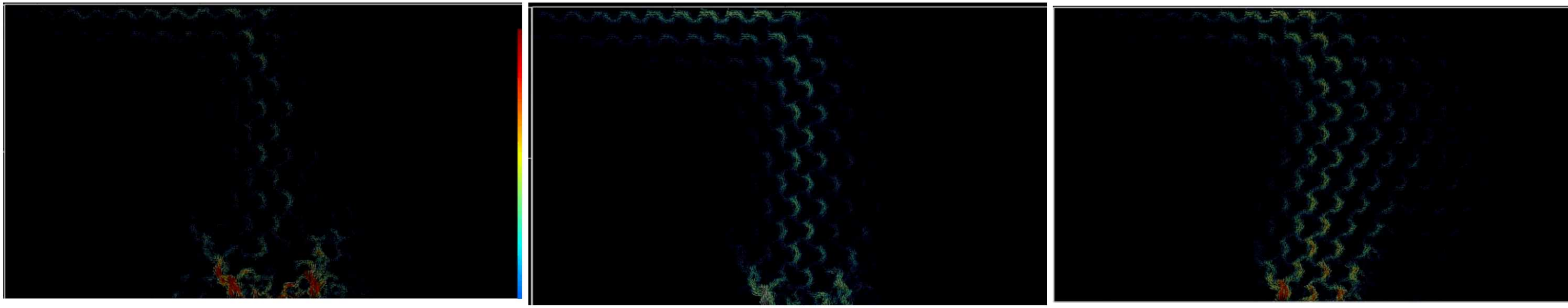


- Create a quantum dot inside the structure
- Apply high B field to split energy level as well as helicity
- Unidirectional propagation of single photon source
- Bandwidth difficult to demonstrate

What about a passive structure to manipulate light incident from elsewhere?

Demonstrating Topological Behavior in a Waveguide System

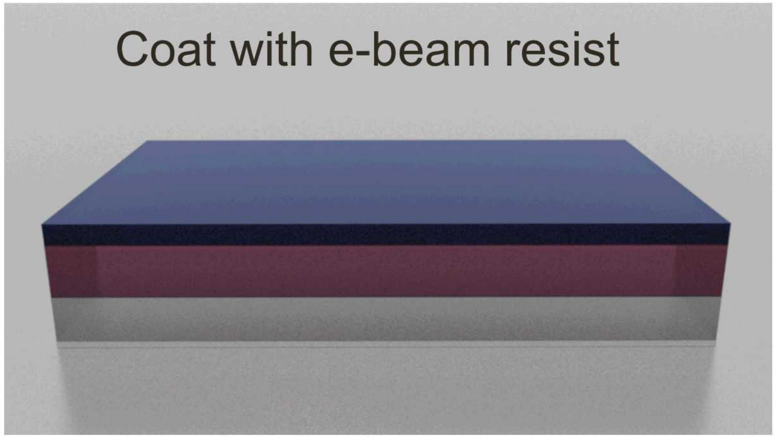


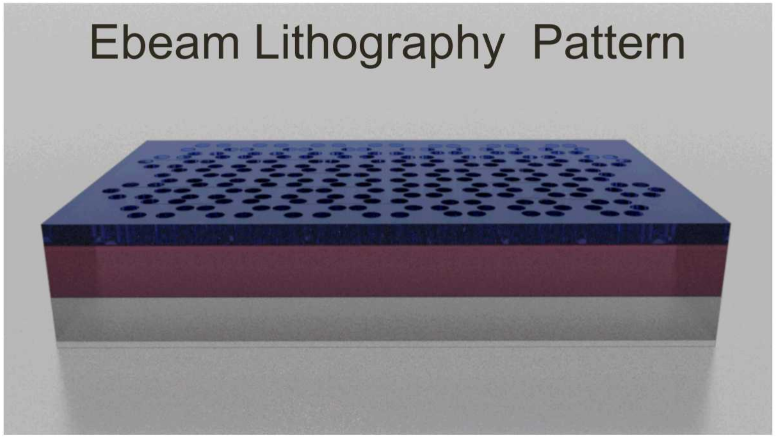


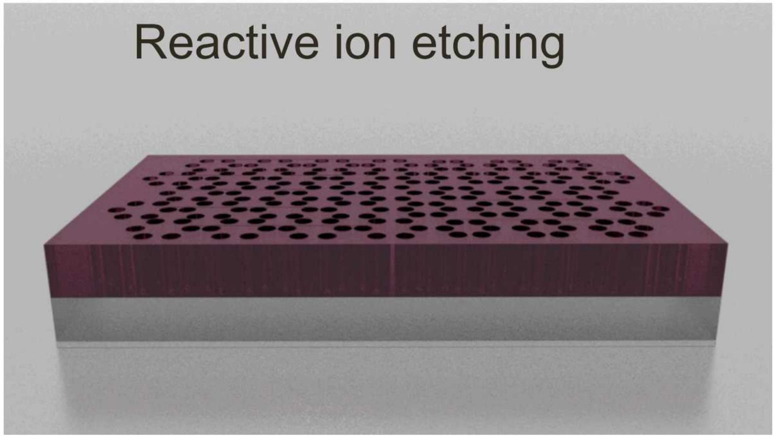
$a/\lambda \sim 0.557$ $a/\lambda \sim 0.552$ $a/\lambda \sim 0.543$

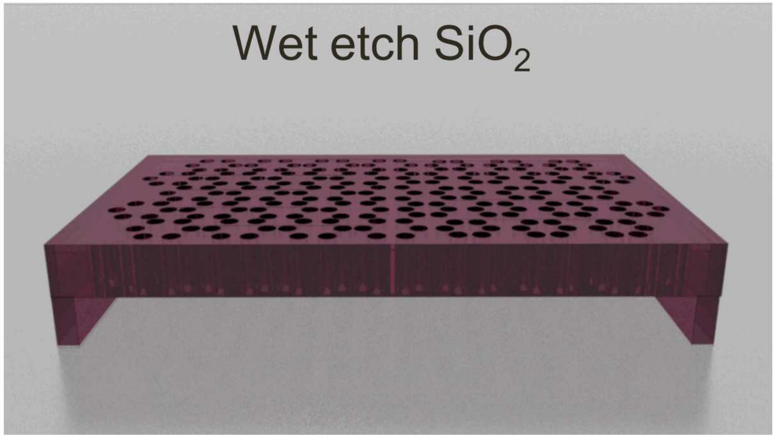
- This is can be implemented experimentally
- Can observe the bandwidth of top. behavior

Fabrication on Silicon on Insulator (SOI) - Membrane





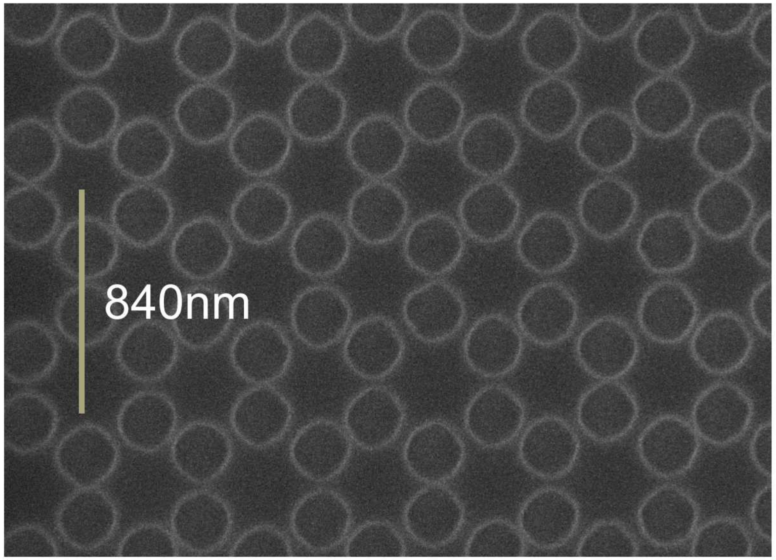




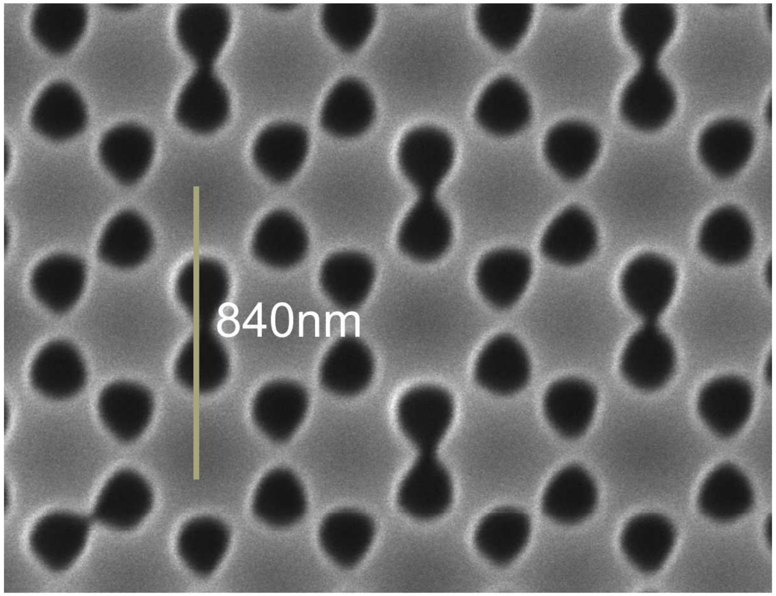
Fabrication on Silicon on Insulator (SOI) - Membrane

- For λ ~ 1500 operation a ~ 840nm
- Hole radius 'r'= 0.13*840= 110nm or 'd' ~ 220nm
  - Typical feature sizes at the necks ~ 30-50nm

After pattern write in resist



After pattern transfer

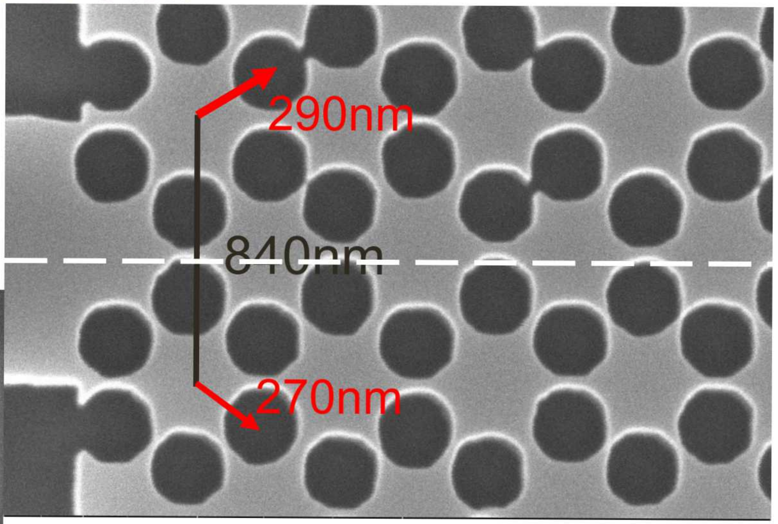


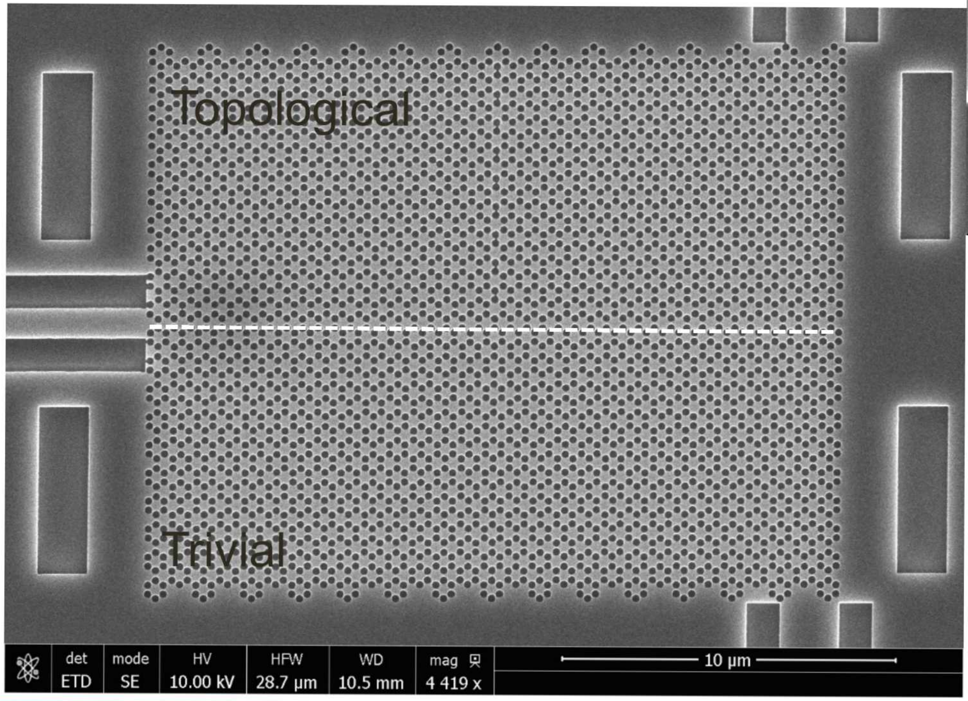
Issues with 'necking' of adjacent holes - addressed with SiO2 hard mask

Fabrication on Silicon on Insulator (SOI) - Membrane

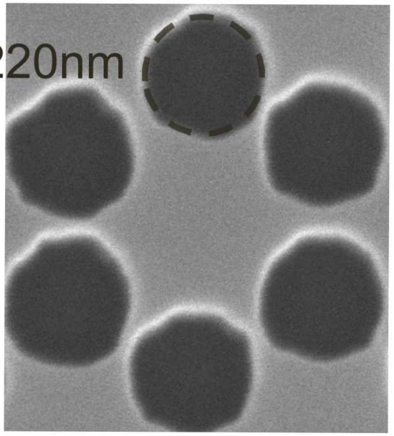
Pattern transfer to Si

- ~ 50 nm SiO2 is used as hardmask for pattern transfer
- Highly selective HBr based RIE for Si etch





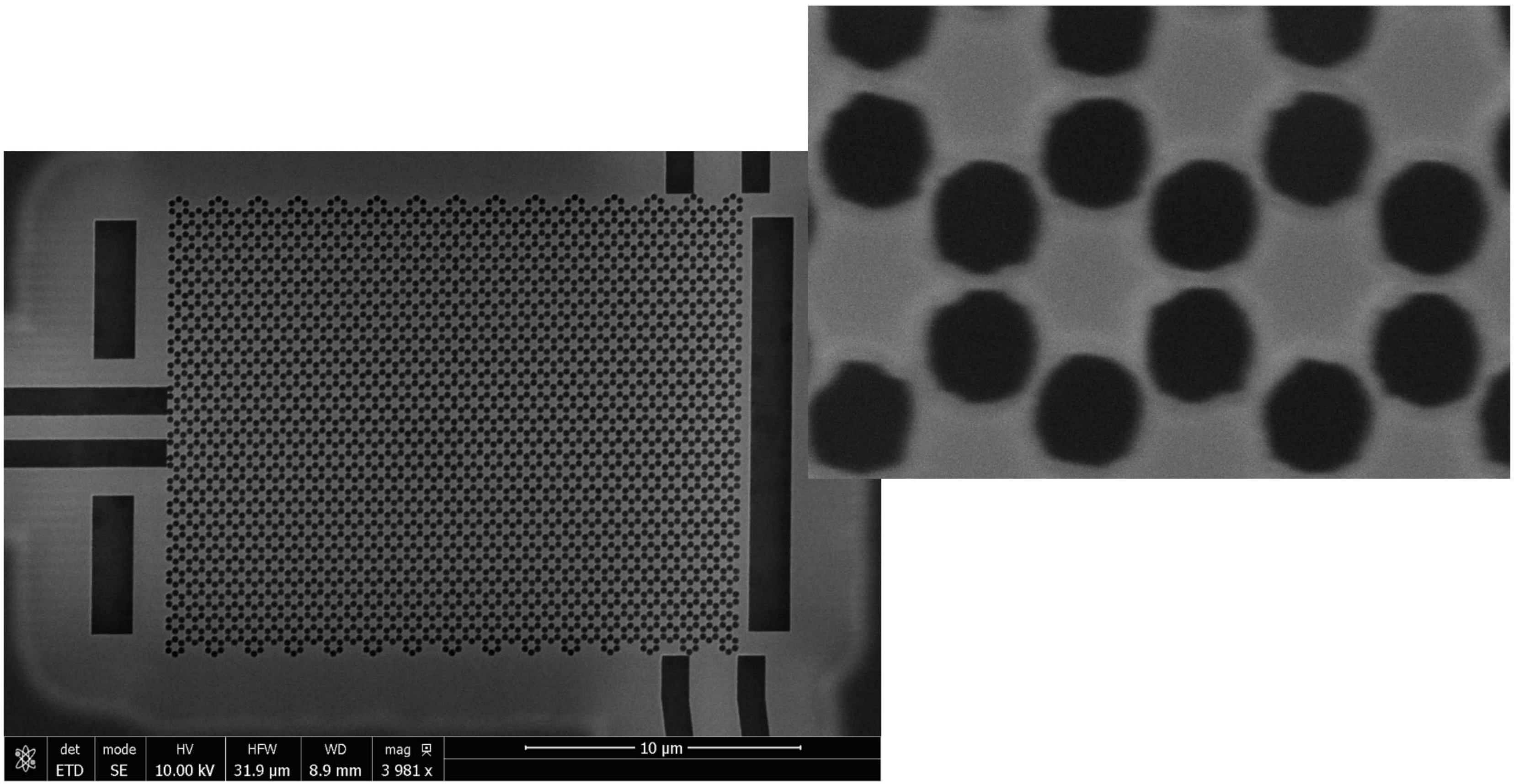
d = 220nm



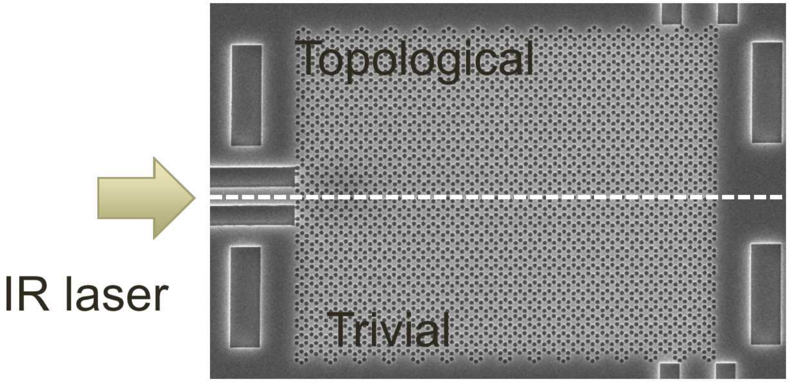
Fabrication on Silicon on Insulator (SOI) - Membrane

Release etch for membrane

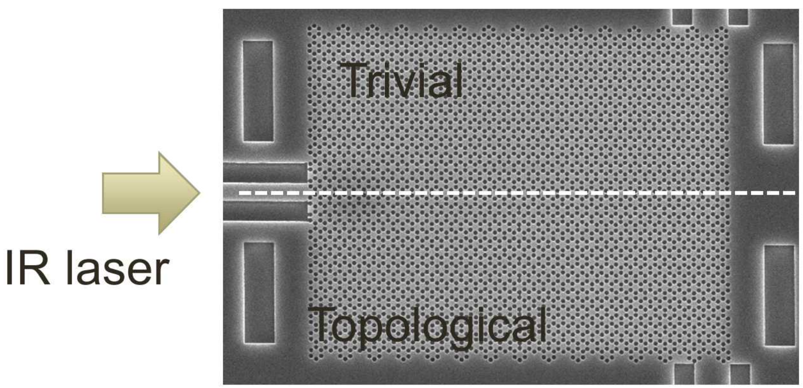
- Reduced etch depth to ~ 1.0 μm shows improvements

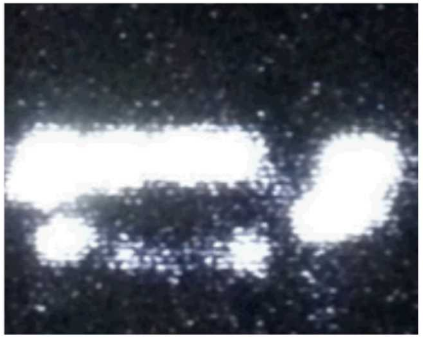


Optical Spectroscopy



λ ~ 1536nm





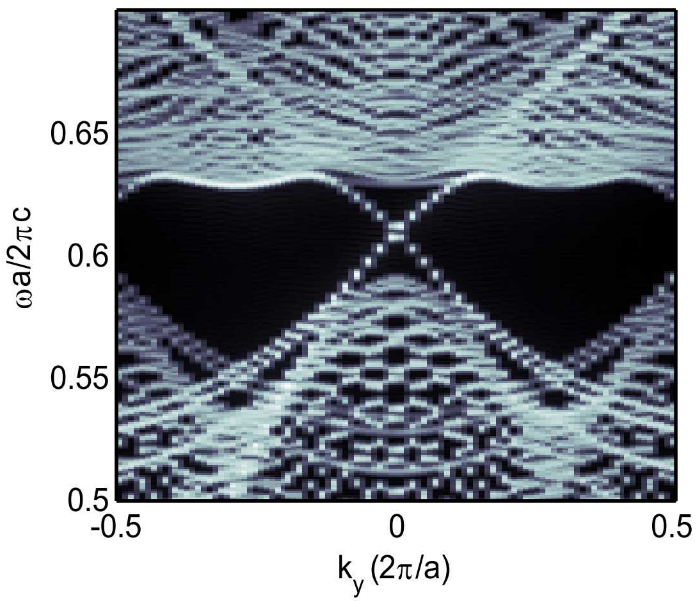
Light propagation shows clear distinction based on orientation of the Topological PhC relative to the Trivial PhC

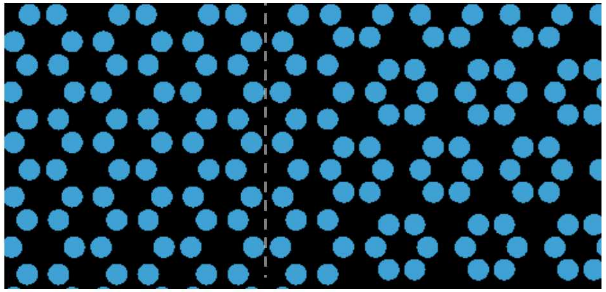
III –nitride based structures for Active Topological PhCs

Topological edge state in honeycomb lattice structure in III-Nitride

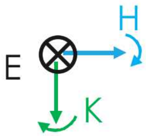
Modeling

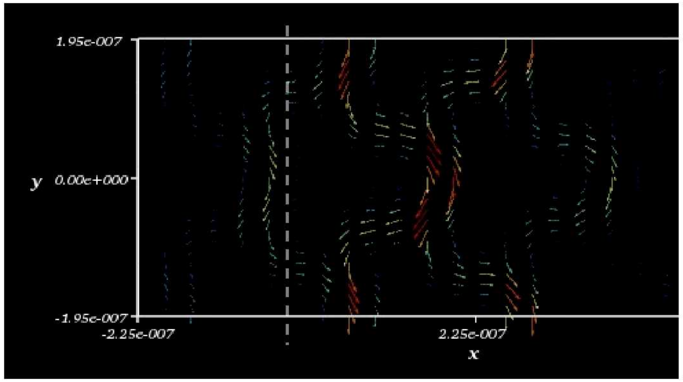
Band Structure



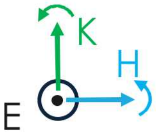


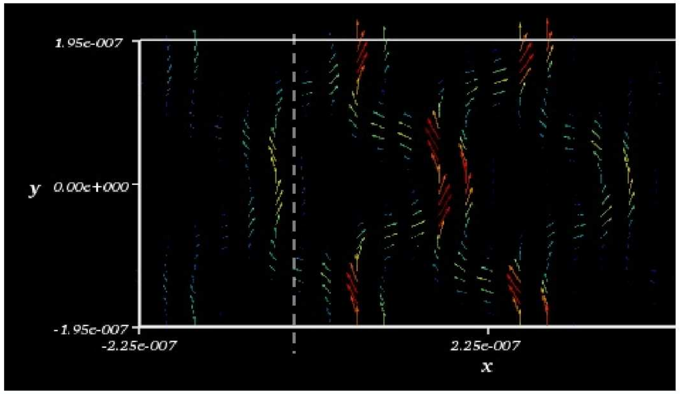
Spin-down state
a/λ = 0.618





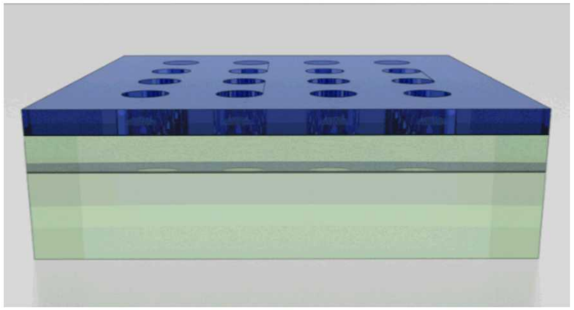
Spin-up state
a/λ = 0.60



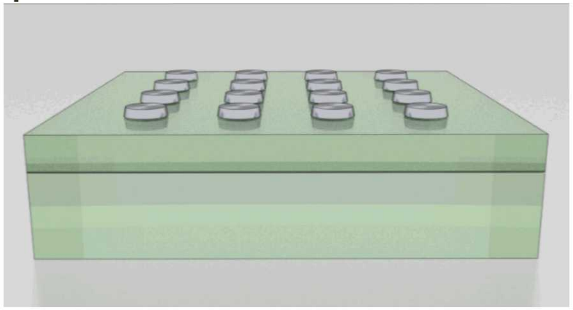


Fabrication procedure in GaN

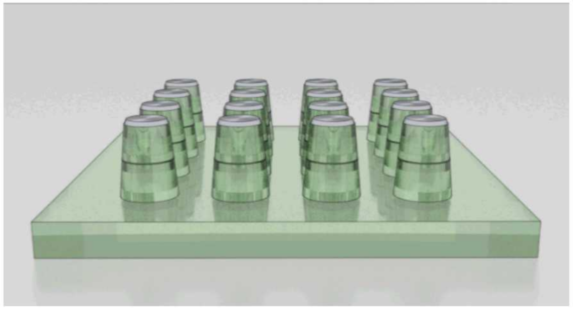
EBL pattern in PMMA



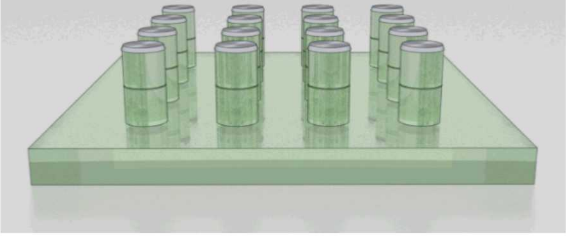
Ni evaporation and lift-off



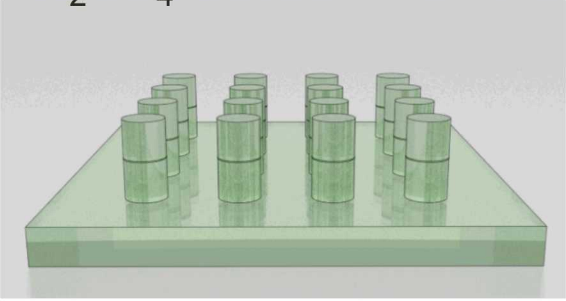
Cl2 based dry etch



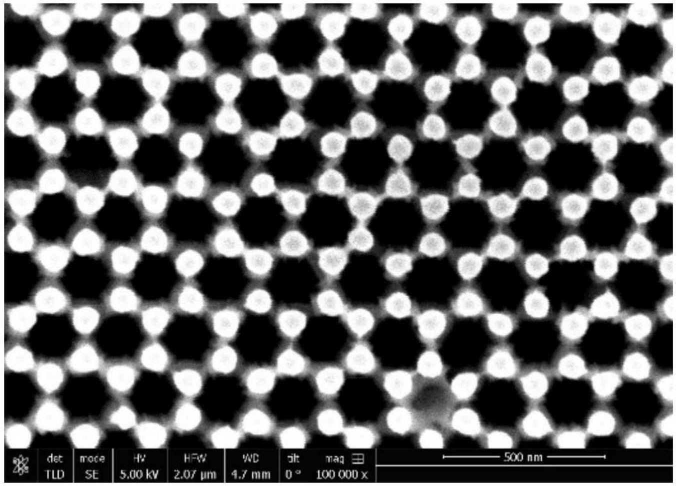
KOH based wet etch

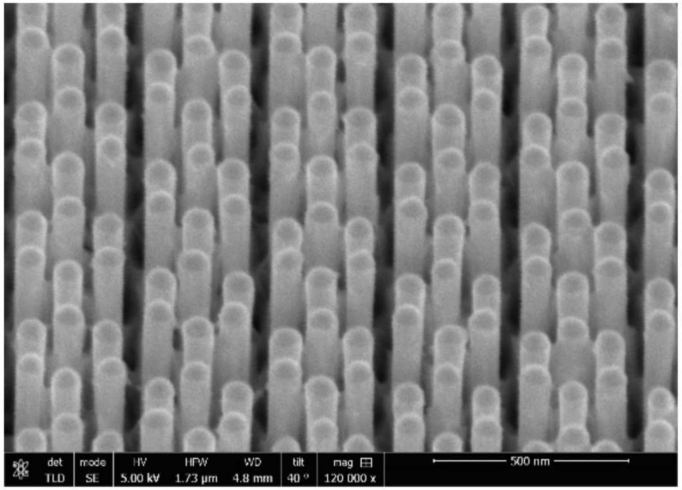


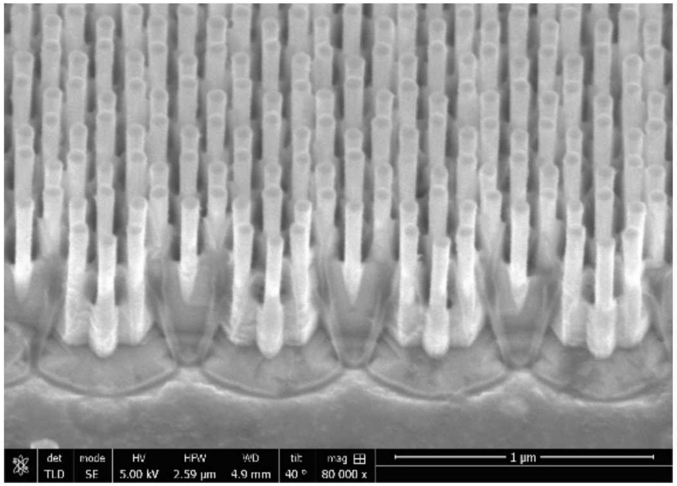
H_2SO_4–based Ni removal



Topological/Trivial lattice interface structure in III-Nitride







Ongoing …

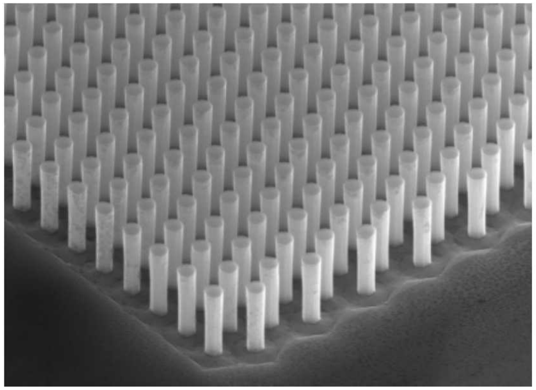
- ❑ Main challenges
  - ❑ Deeper etching

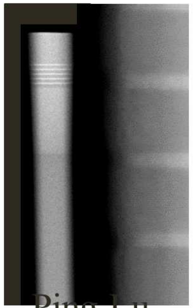
Topological structure in active material systems

PhC nanrod array have shown excellent light emission behavior

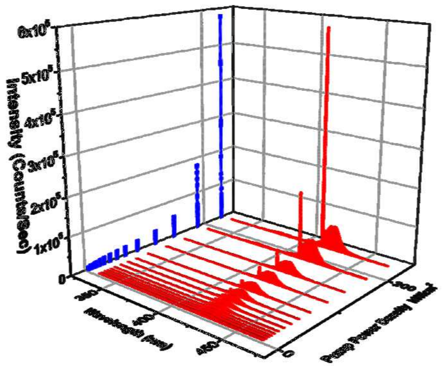
Photonic Crystal Laser Pixels

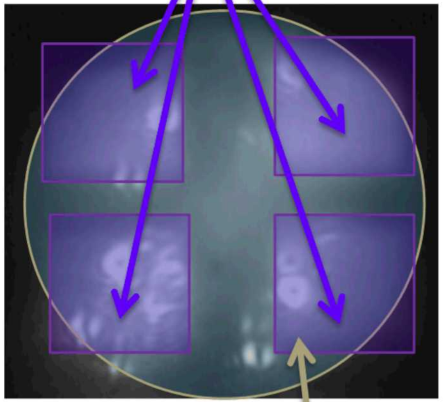
Demonstration of Lasing from PhC Array





Ping Lu,
Sandia

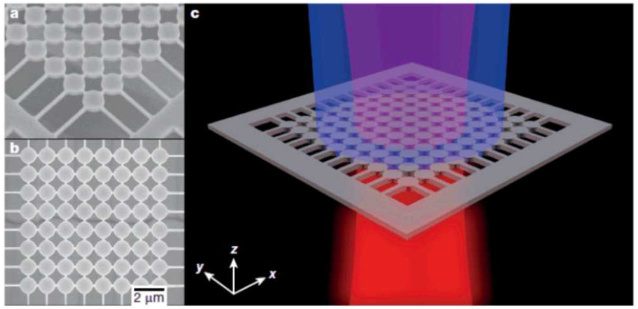




Pump Spot

J. B. Wright et,al., Sci. Rep. **3**, 2982 (2013).

Fabricated by using a top down approach from a planar GaN with InGaN Multiple quantum wells

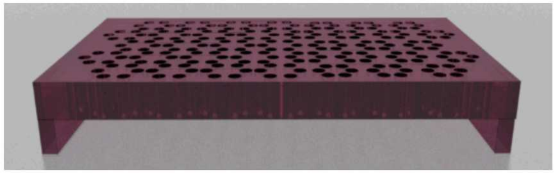


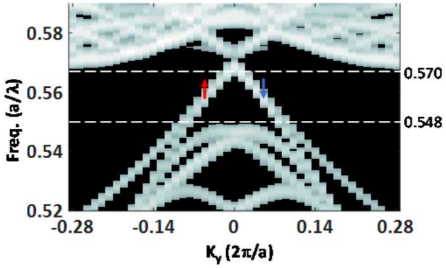
Light sources with topological charges?

A. Kodigala, et.al," Nature **541**, 196-199 (2017).

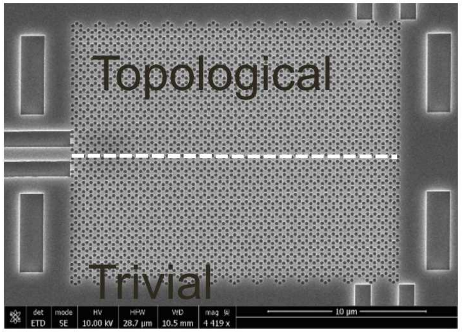
Summary

- Hole array honey comb lattice structure for photonic pseudo spin





- Fabrication in Silicon/SOI



- Fabrication in III-N

Thank you for your attention!

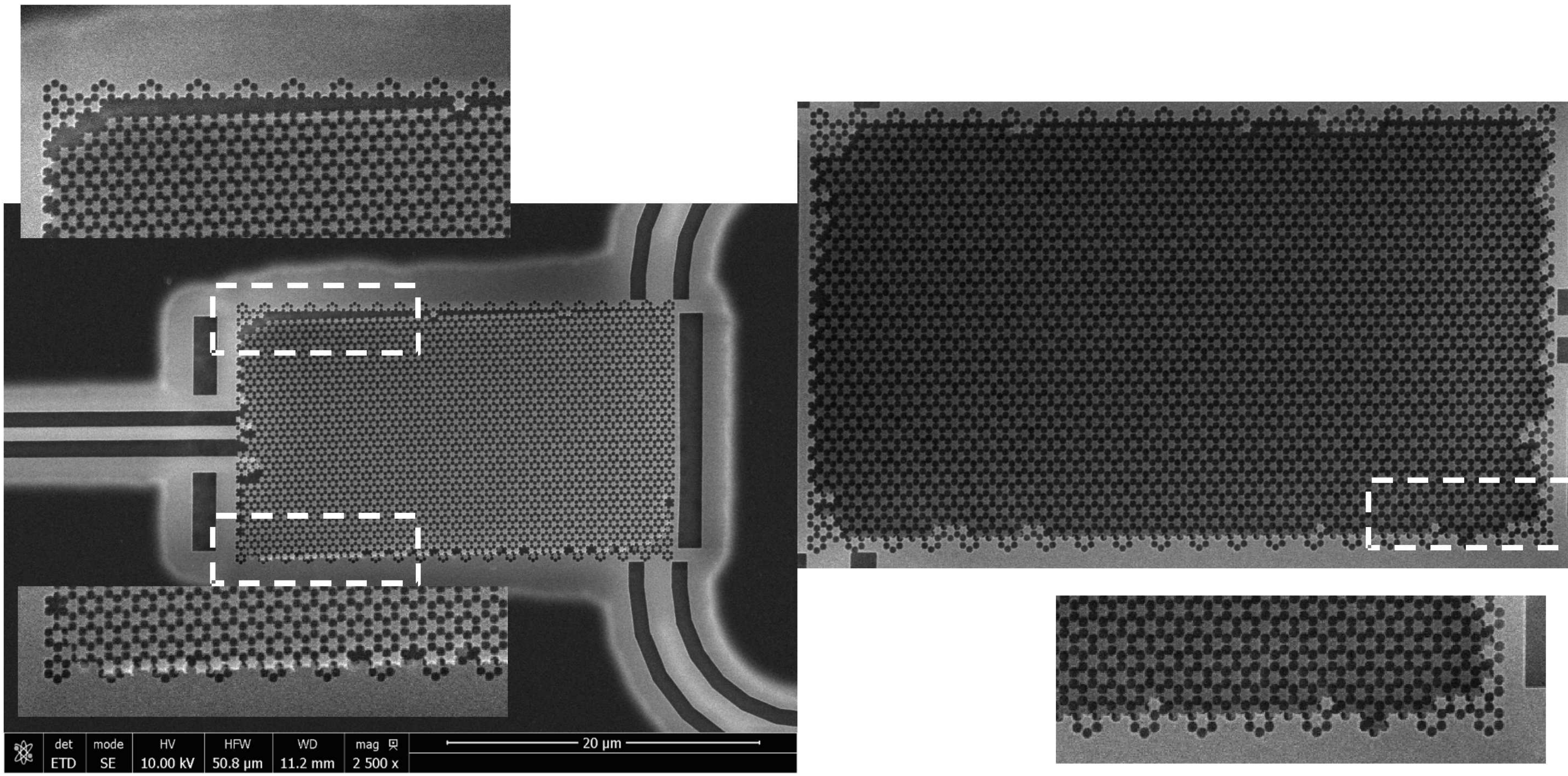
Sandia National Laboratories

Extras …

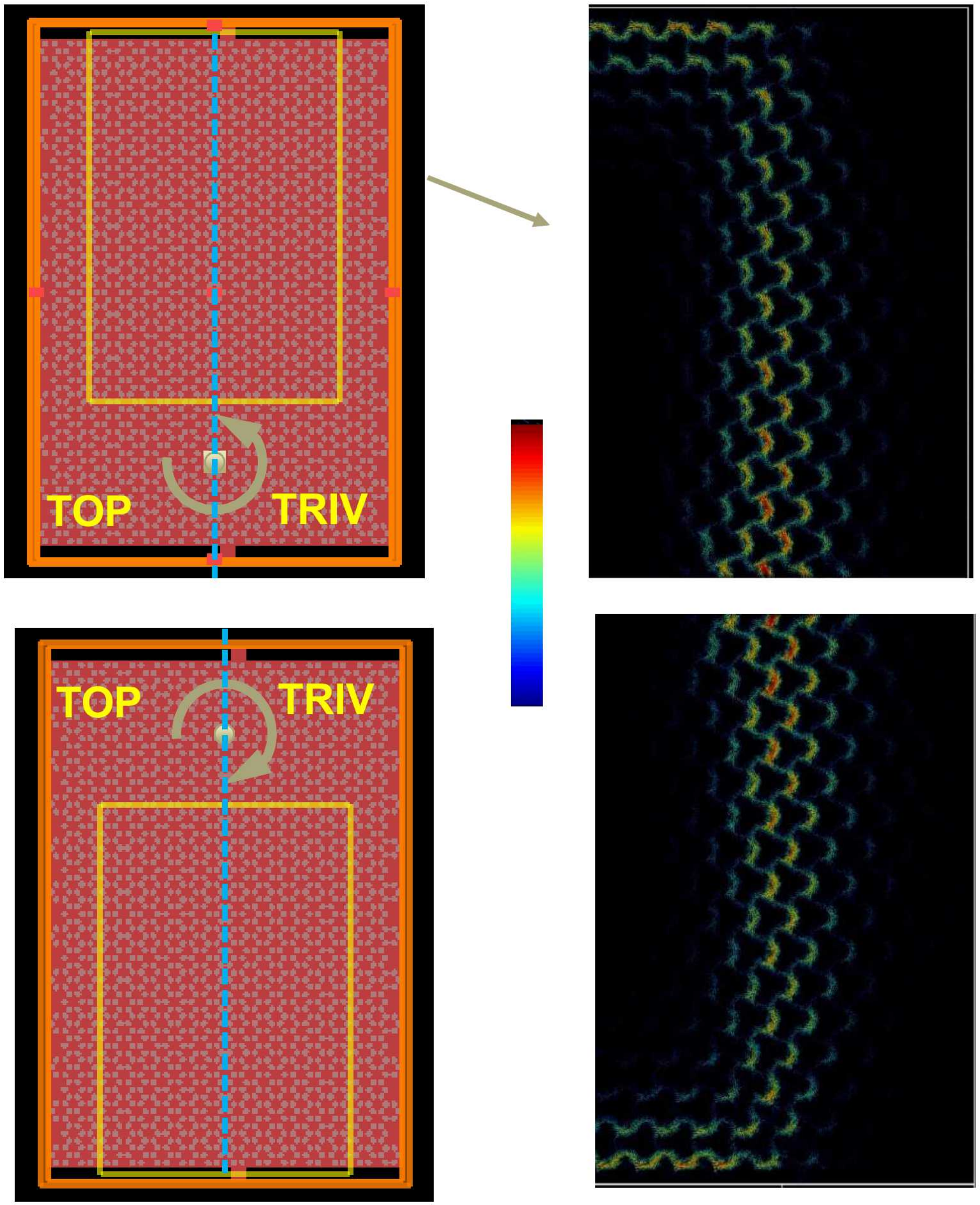
Fabrication on Silicon on Insulator (SOI) - Membrane

Release etch for membrane

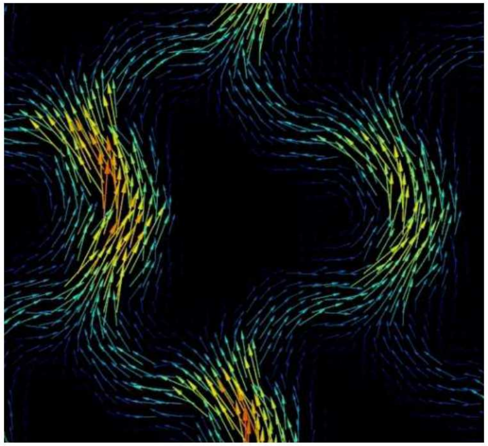
- Wet etch in buffered oxide etchant for 15-20min : 1.6 to 1.8 μm deep
- Narrow bridge necks + Si epi stress causes some challenges



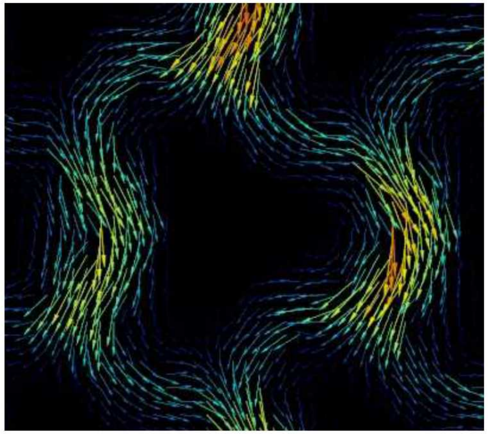
Unidirectional Propagation with Helical Sources



a/λ ~ 0.567

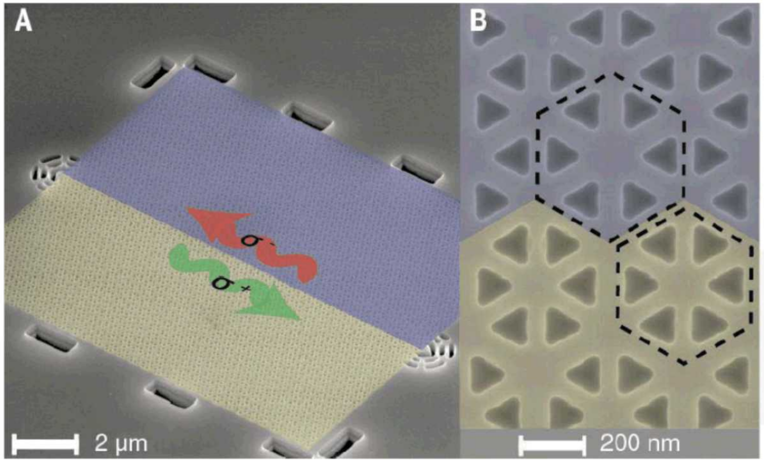


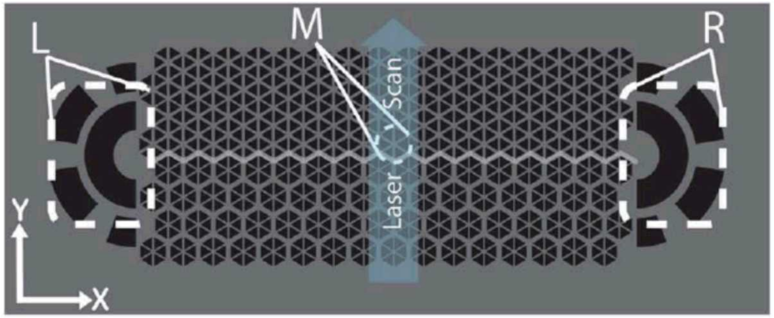
up



down

Quantum Dot based Helical Sources

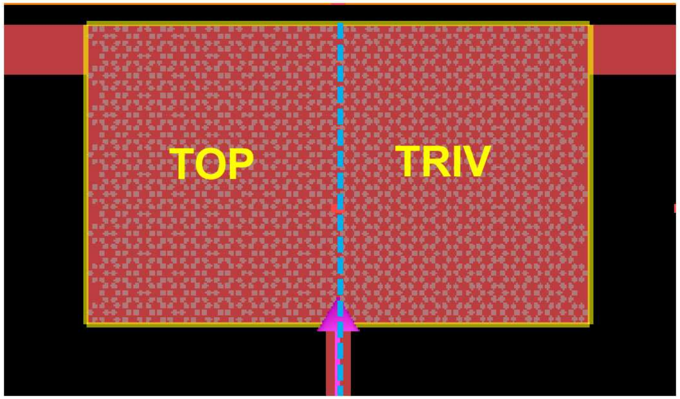


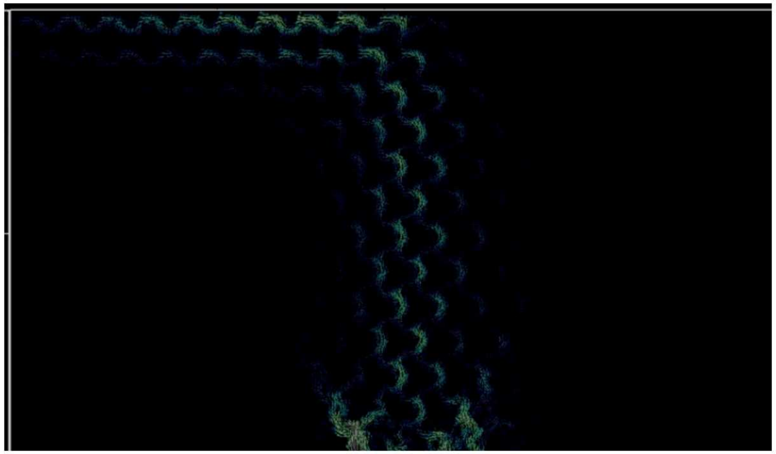


Barik, S., et al. (2018). "A topological quantum optics interface." Science **359**(6376): 666.

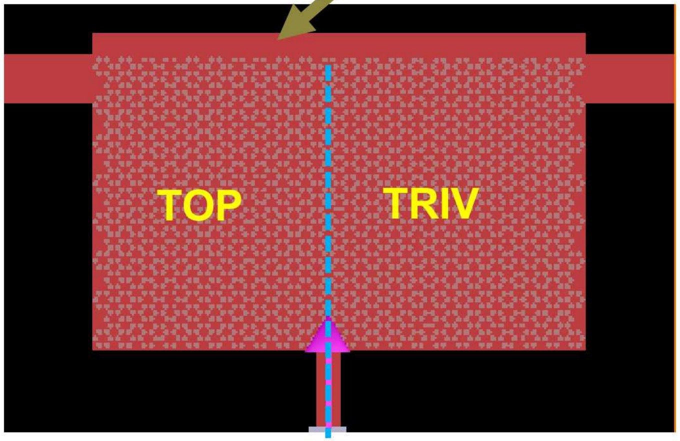
- Create a quantum dot inside the structure
- Apply high B field to split energy level as well as helicity
- Unidirectional propagation of single photon source
- Bandwidth difficult to demonstrate

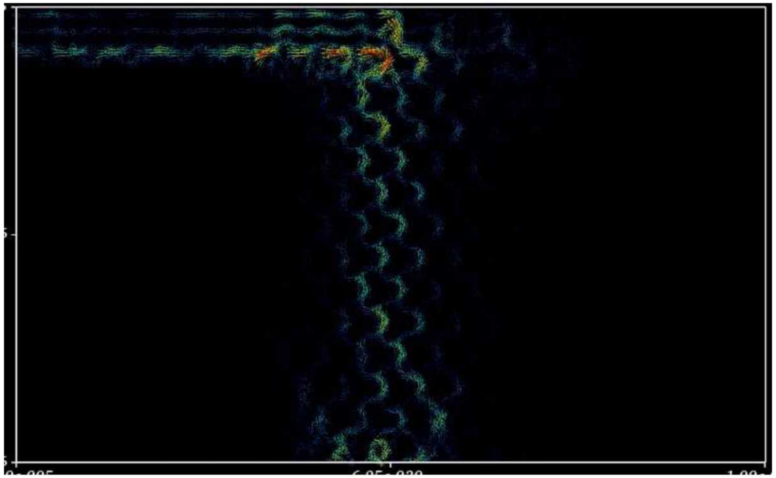
What about a passive structure to manipulate light incident from elsewhere?



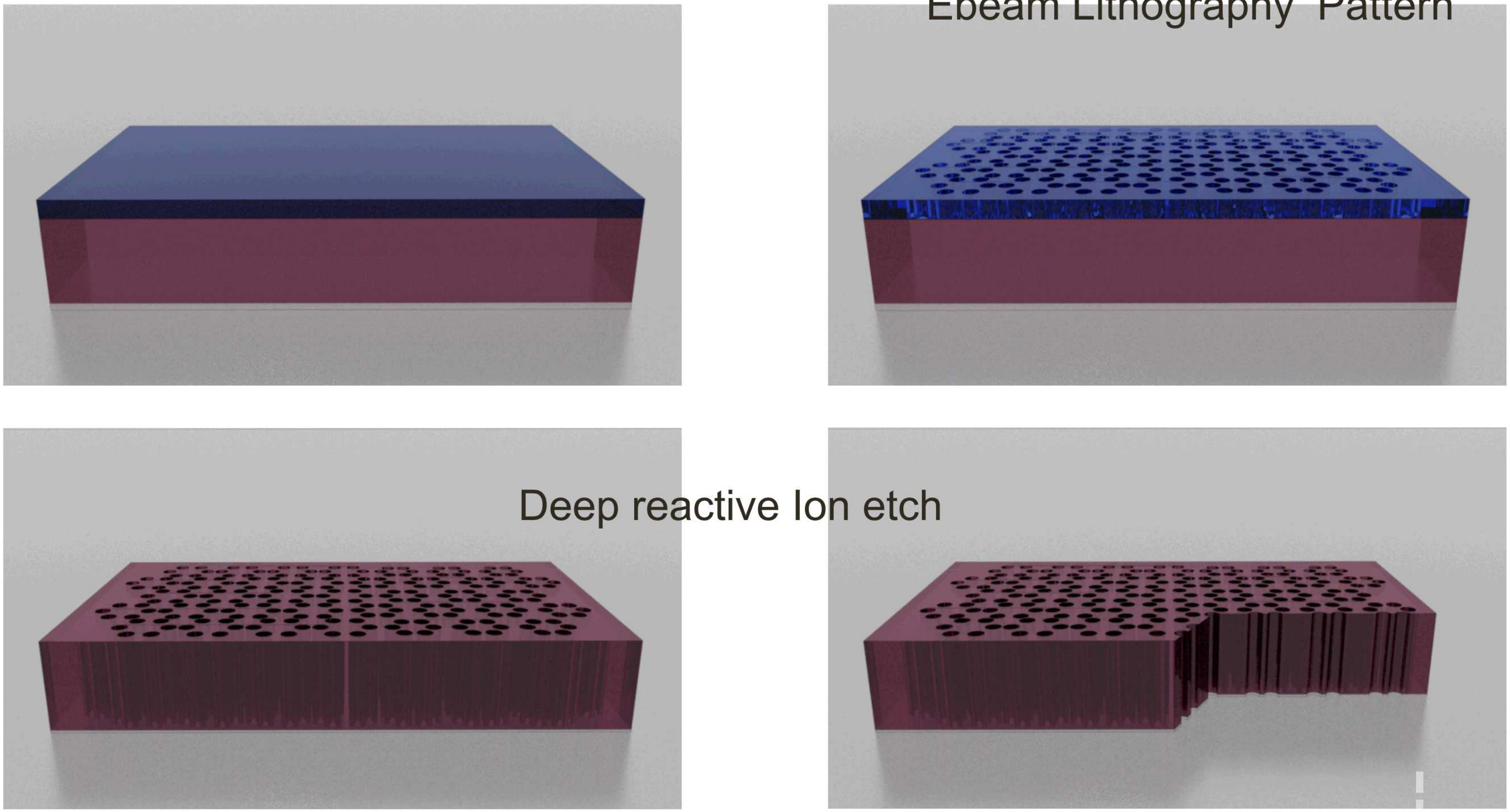


High index trivial medium





Fabrication on Thick Si using deep etch



This can be challenging fabricate and may not always be compatible with typical Si photonics designs.