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Nanophotonic structures to control propagation, emission and topological behavior of light

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Collaborators/Acknowledgements

SNL

- Nicholas Karl
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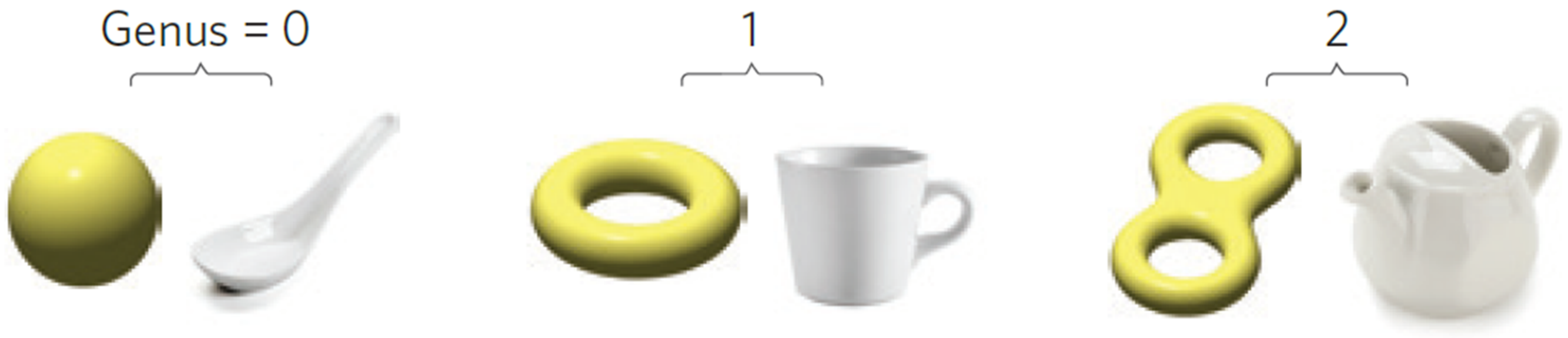
- Jason Dominguez
- Anthony James

- P. Duke Anderson(Leonardo DRS)
- Stavroula Foteinopoulou (UNM)
- Daniel Feezell (UNM)
- Elizabeth Delong (UNM)

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.



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

- 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).

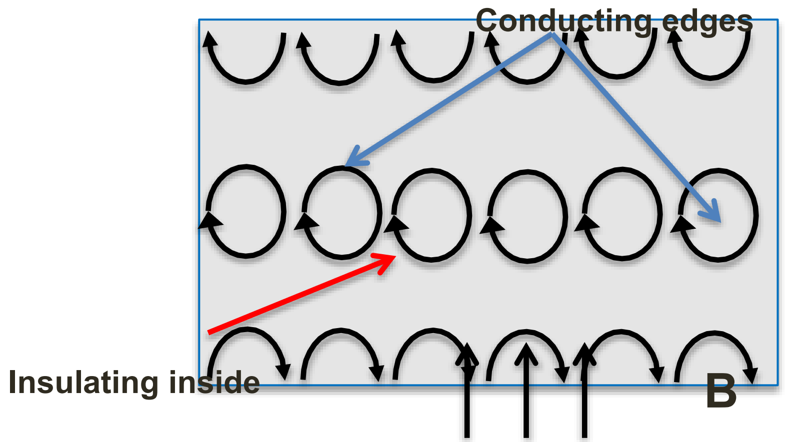
Topological Systems in Electronics

<u>Electronic Topological Insulators</u> : Systems exhibiting Quantum Hall Effect → 2DEGs

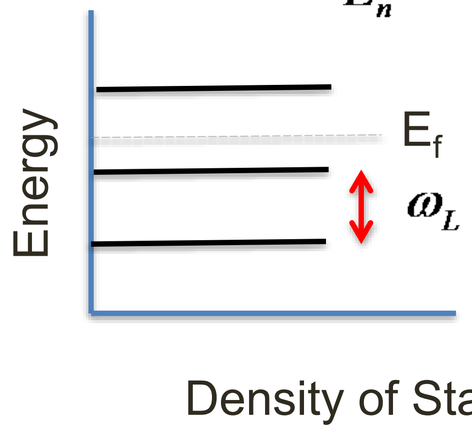
❖ Time reversal symmetry is broken by applying magnetic (B) field

- Discrete highly degenerate Landau Levels
- Conducting edge states within insulator gap
- Topologically protected “one way” electronic transport

- *Needs high B fields*
- *Low temperatures*



Landau Levels $E_n = \left(n + \frac{1}{2}\right)\frac{heB}{m}$



$\omega_L = \frac{eB}{m}$

❖ Time reversal protected system : Z_2 type topological with spin-momentum locking

Topological Photonics Research Activities

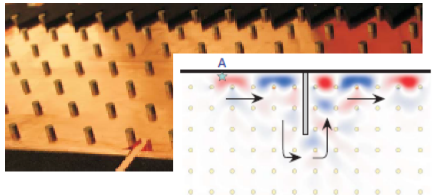
PHYSICAL REVIEW A 78, 033834 (2008)

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

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

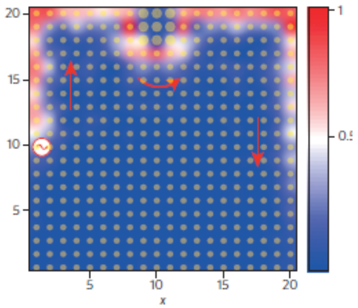
F. D. M. Haldane
Department of Physics, Princeton University, Princeton, New Jersey 08544-0708, USA

One- way transport at microwave frequency



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

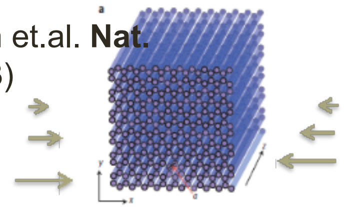
One-way edge transport



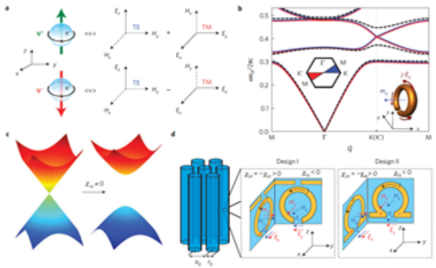
K.Fang, Z. Yu , S.H.Fan , **Nat. Phot. 6 ,** (2012)

Strain induced pseud mag. field in optical fiber arrays

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

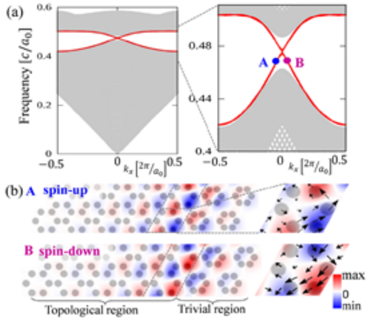


Metamaterial PTI



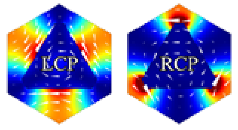
A. B. Khanikaev et.al. Nat Mater **12** (3), 233-239 (2013).

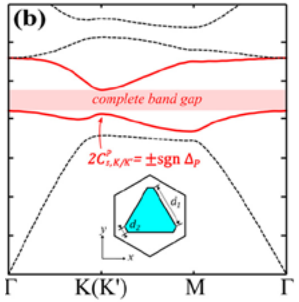
Topological Photonics Spin Hall in Dielectric PC



Long-Hua Wu and Xiao Hu, Phys. Rev. Lett. 114 (22), 223901 (2015).

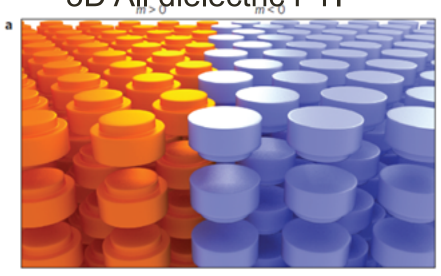
Valley hall PTI





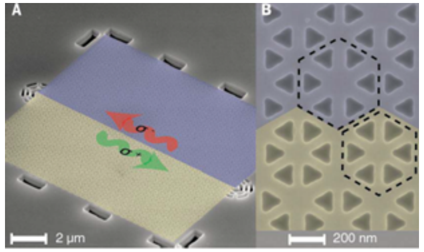
M. Tzuhsuan and S. Gennady, NJP.**18** (2), 025012 (2016).

3D All dielectric PTI



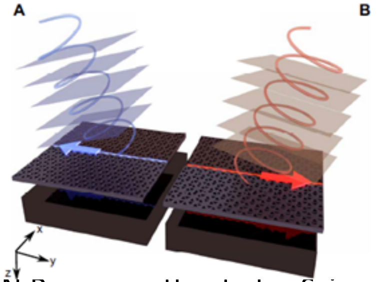
A. Slobozhanyuk, et.al. , Nat Photon **11** (2), 130-136 (2017).

Topological edge states in III-V



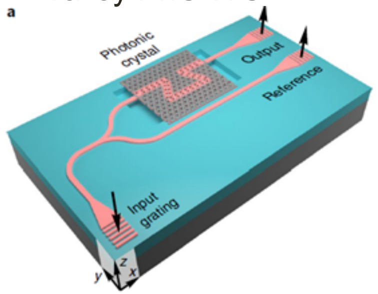
Barik, S. *et al.*. *Science* **359**, 666 (2018).

Topological Photonics in Si PhC



N.Parappurath, et.al. , Science Advances 6 (10), eaaw4137 (2020)

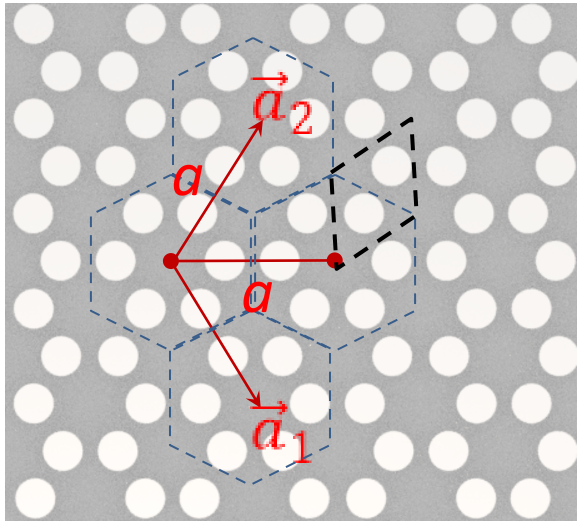
Valley PhC WG

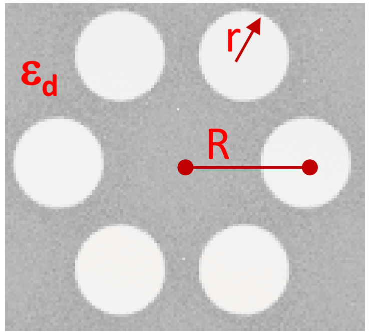


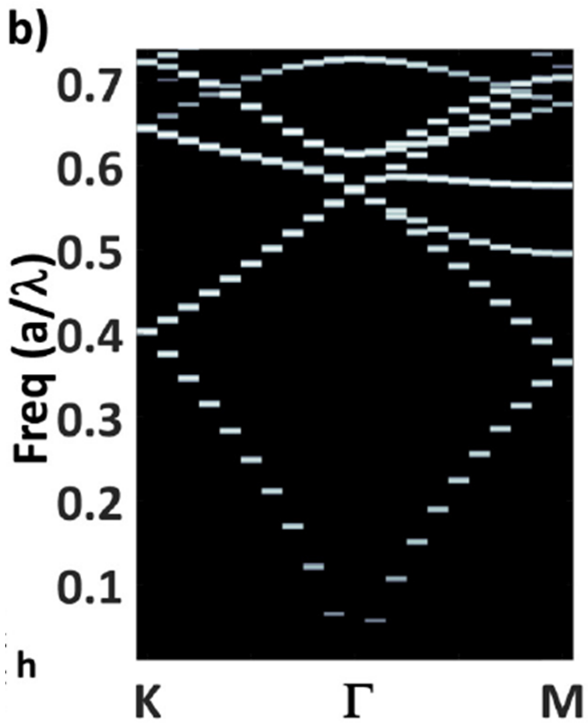
M.I.Shalaev et. al., Nature Nanotechnology 14 (1), 31 (2019).

Review: S. Iwamoto, Y. Ota, and Y. Arakawa, "*Recent progress in topological waveguides and nanocavities in a semiconductor photonic crystal platform [Invited],*" Optical Materials Express **11,** 319-337 (2021)

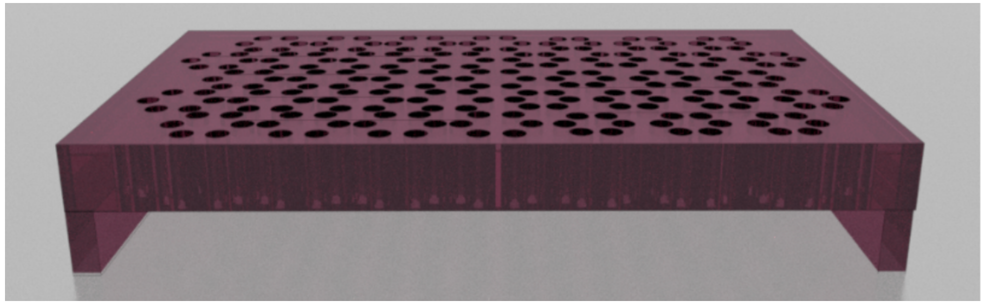
Thin-slab Honeycomb Photonic Crystal Design







h = 0.25a



a/R = 3.0

r=0.13a

6

Calculated with FDTD (Lumerical ®)

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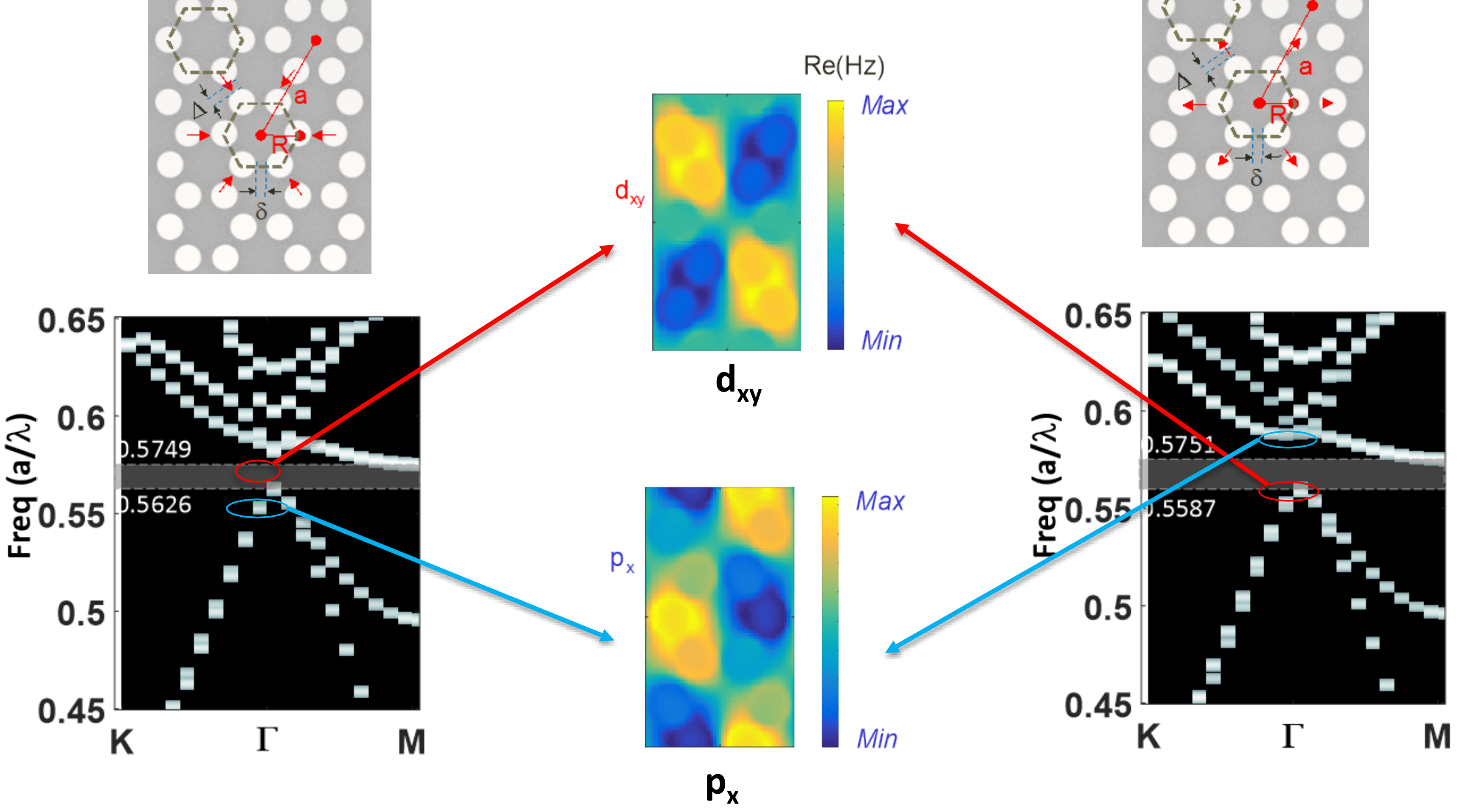
Modification off Honeycomb Lattice

Compressed lattice a/R = 3.1
Topologically Trivial PhC

Expanded lattice a/R = 2.9
Topologically non-Trivial PhC

Δ=a-2 (R+r) δ=R -2r



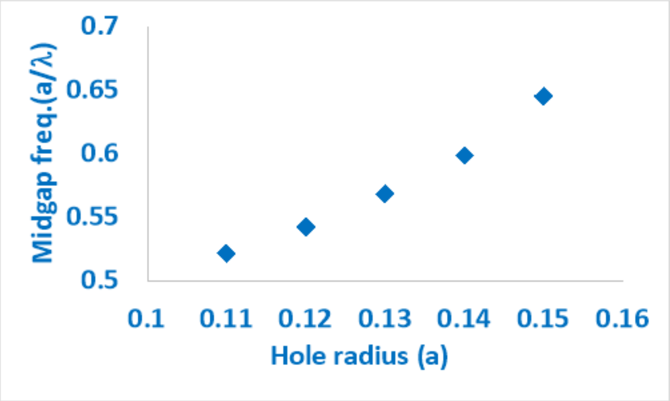
P. D. Anderson and G.Subramania, Optics Express **25** (19), 23293 (2017).

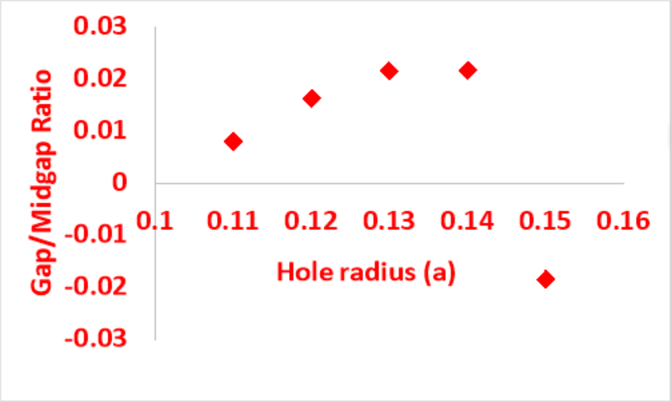
Circular Hole Array Honeycomb Lattice Photonic Crystal

Hole radius 'r' dependence

Membrane thickness 'h' = 0.25a

Compressed a/R = 3.1

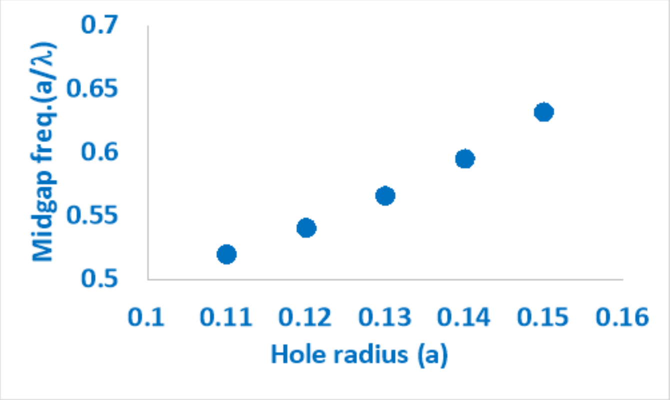


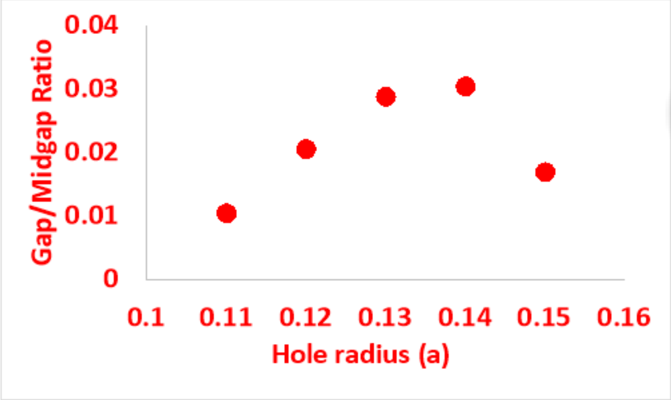


At λ ~ 1500nm

$\Delta\lambda$ ~ 30nm

Expanded a/R = 2.9





At λ ~ 1500nm

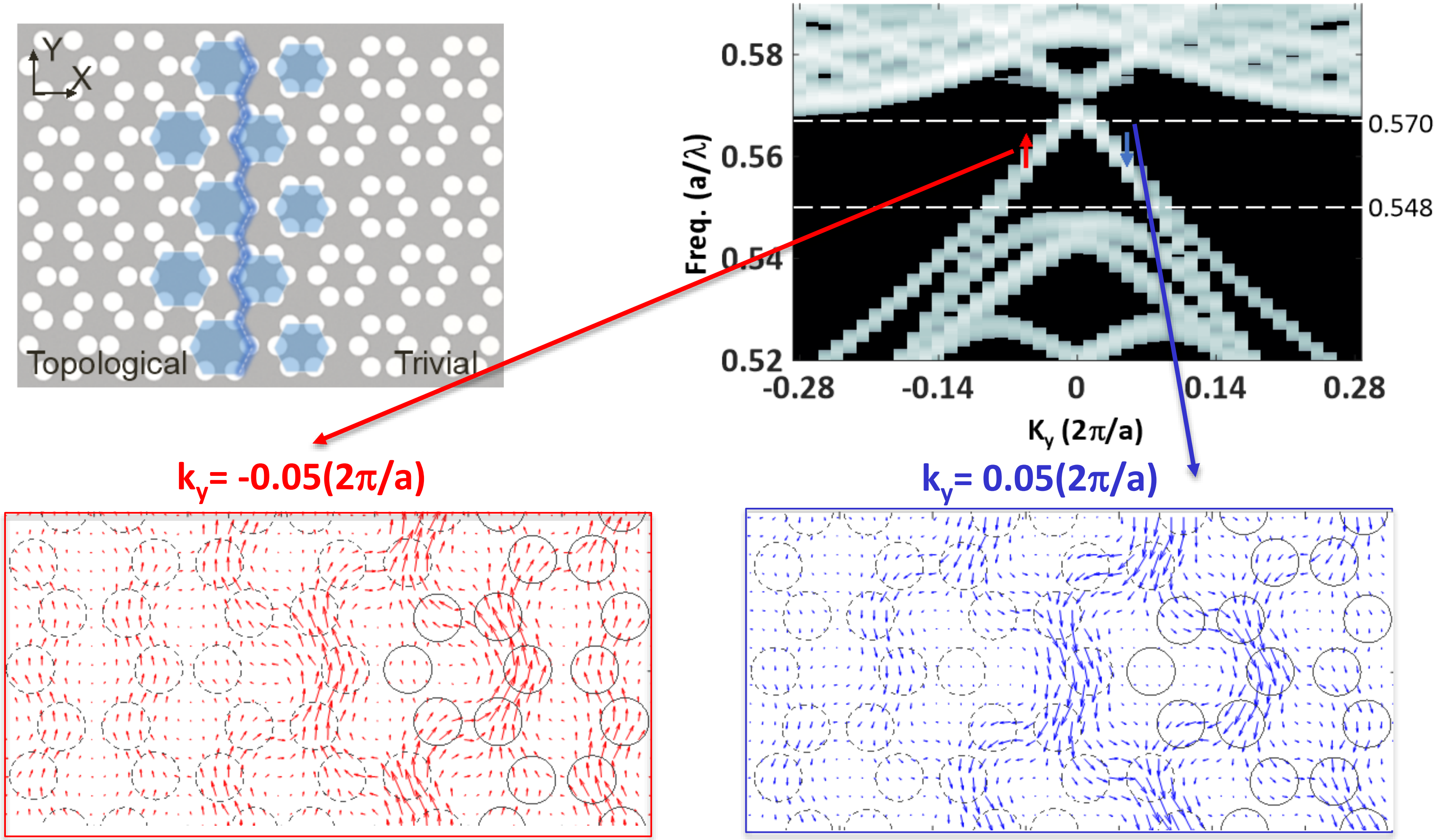
$\Delta\lambda$ ~ 45nm

Reasonable operational bandwidth possible at the telecom frequencies

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

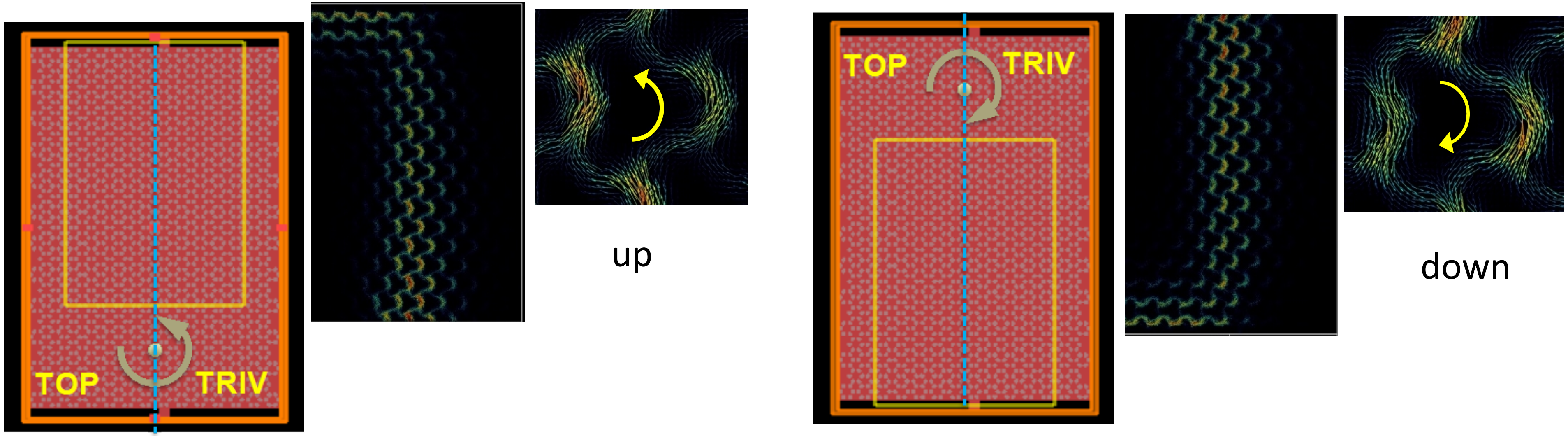
Unidirectional Edge State Propagation

Zig-zag interface

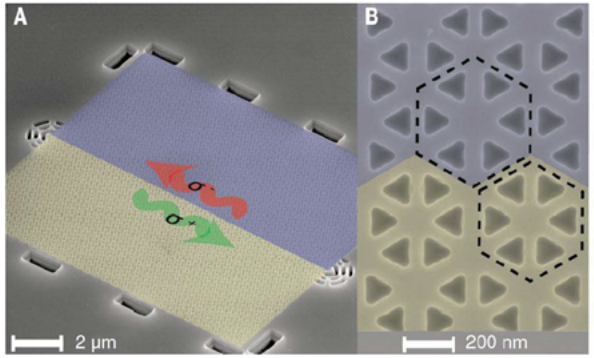


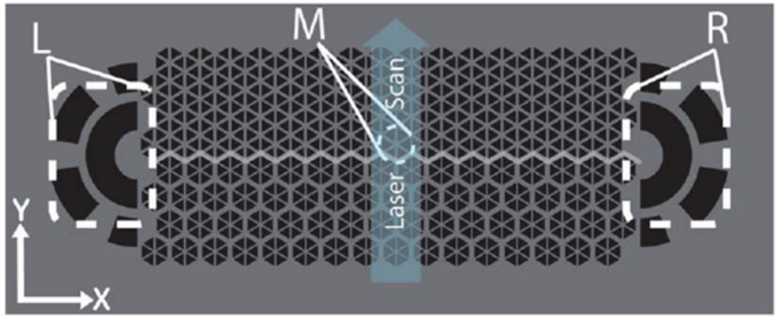
P. D. Anderson and G.Subramania, Optics Express **25** (19), 23293 (2017).

Unidirectional Propagation with Helical Sources



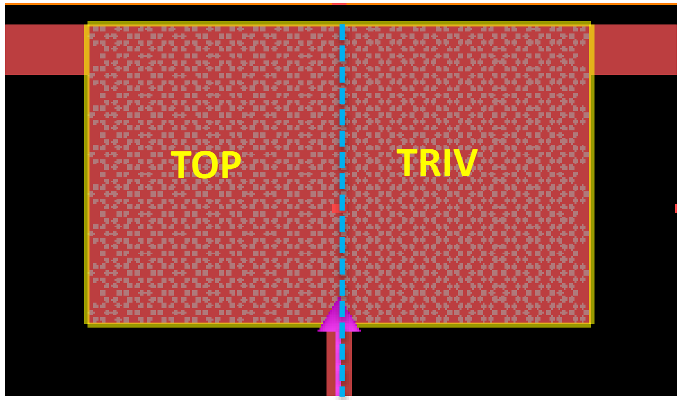
Quantum Dot based Helical Sources

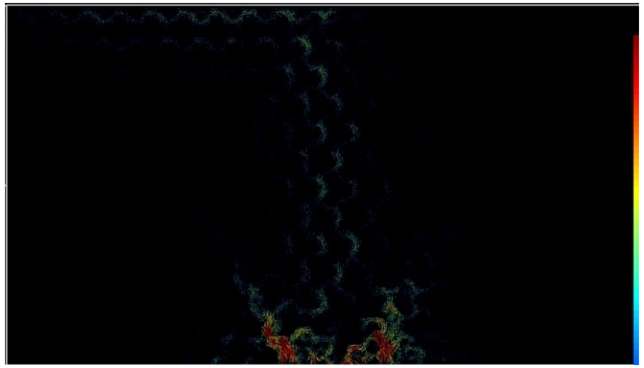




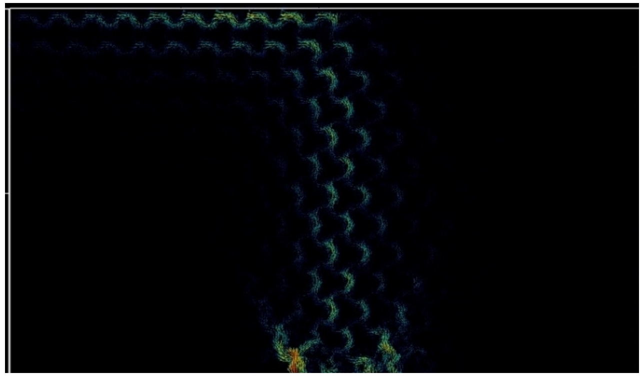
Barik, S., et al. (2018). "A topological quantum optics interface." Science **359**(6376): 666.

Demonstrating Topological Behavior in a Waveguide System

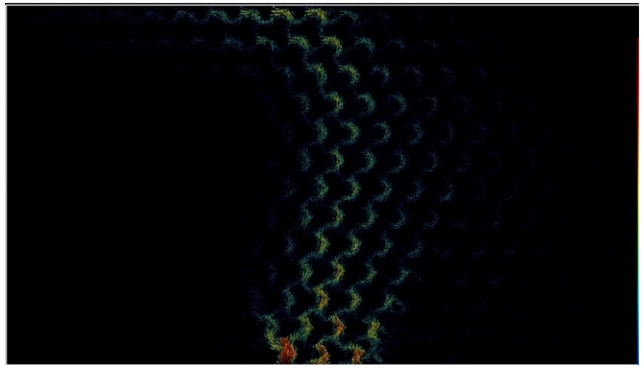




a/λ ~ 0.557



a/λ ~ 0.552



a/λ ~ 0.543

- Direct edge coupling
- Coupling not optimal

Fabrication on Silicon on Insulator (SOI) - Membrane

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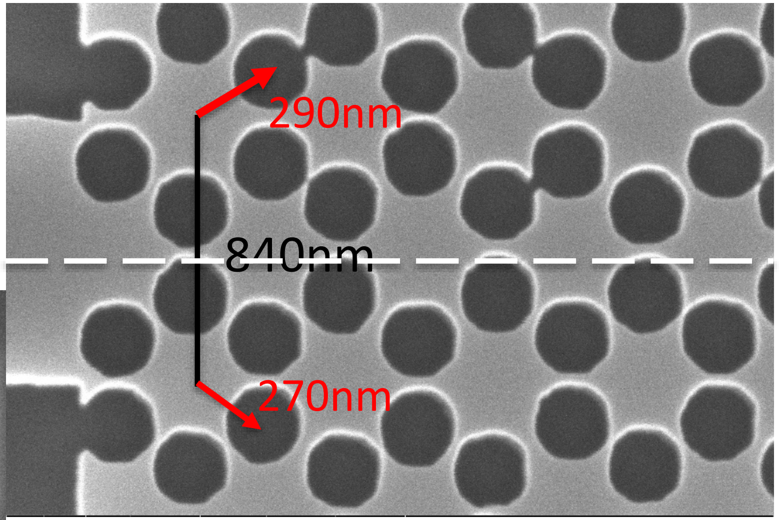
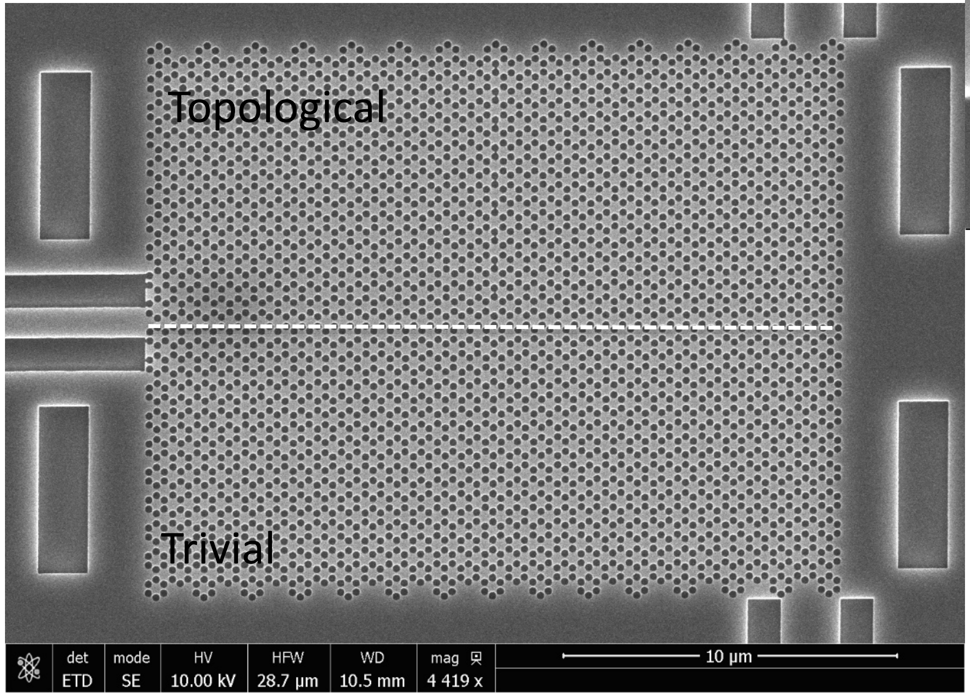
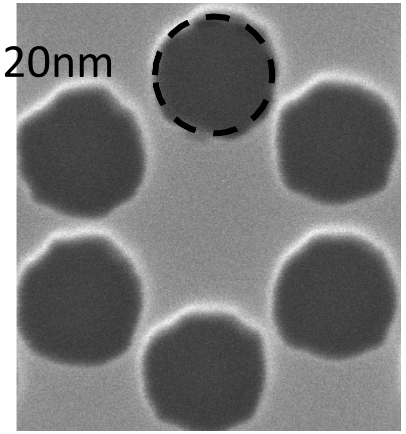
Pattern transfer to Si

- ~ 50 nm SiO_2 is used as hardmask for pattern transfer
- Highly selective HBr based RIE for Si etch

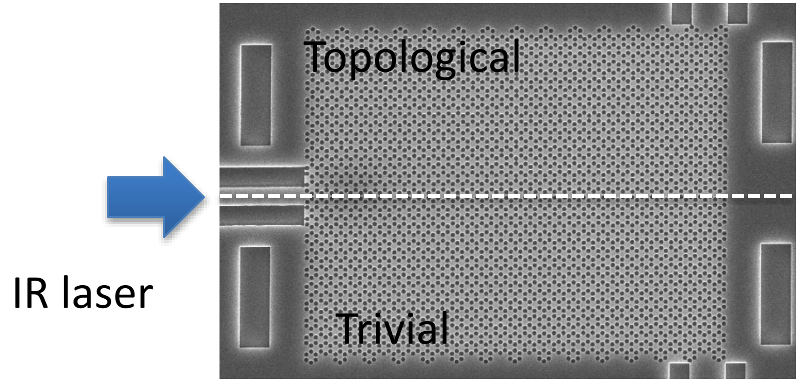


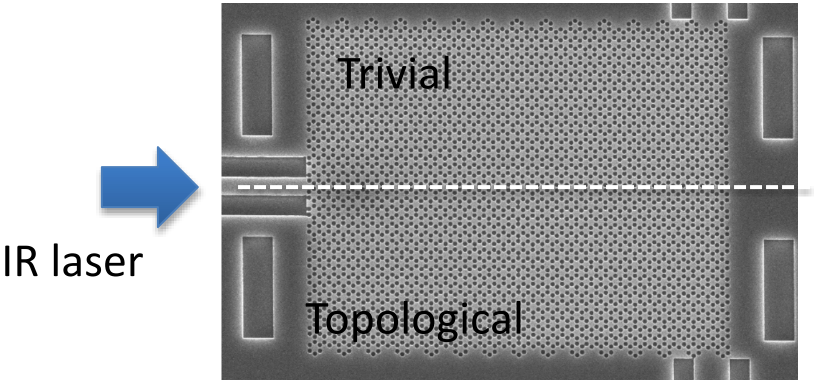


d = 220nm



Optical Measurement





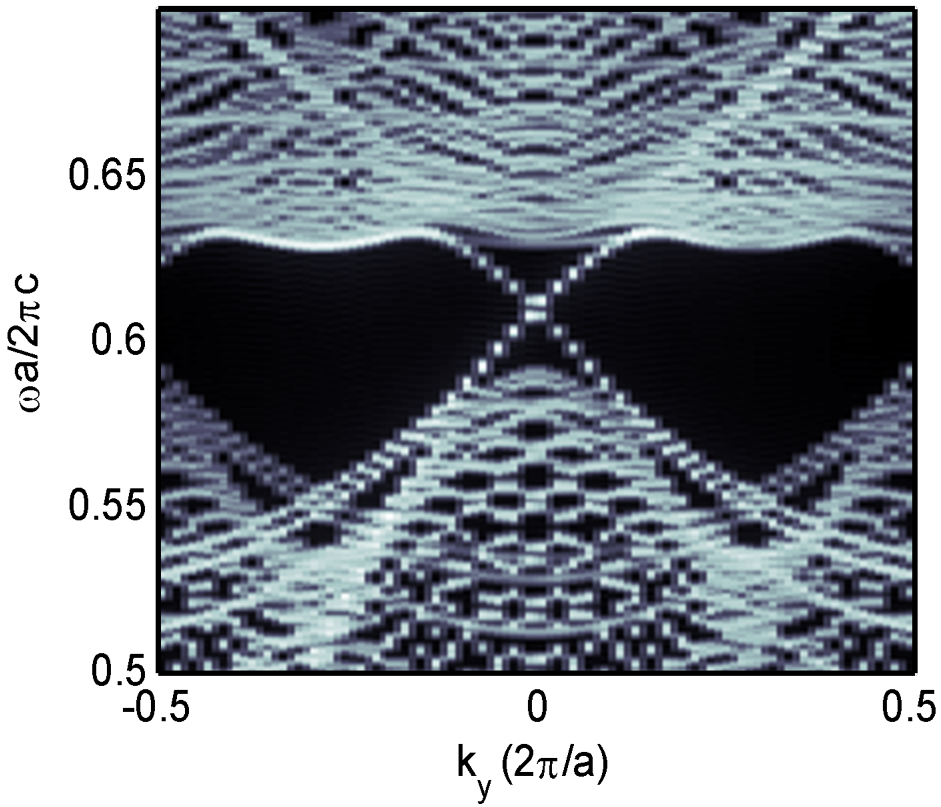
λ ~ 1536nm

- Light propagation shows clear distinction based on orientation of the Topological PhC relative to the Trivial PhC
- In progress …

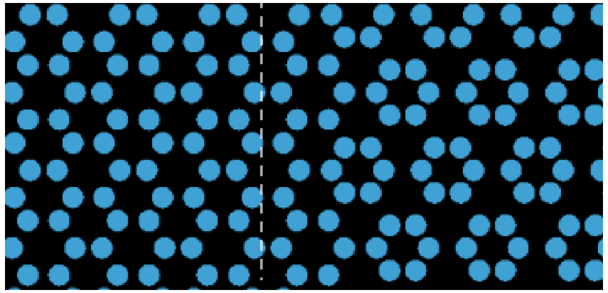
Topological edge state in honeycomb lattice structure in III-Nitride

Modeling

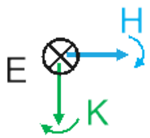
Band Structure

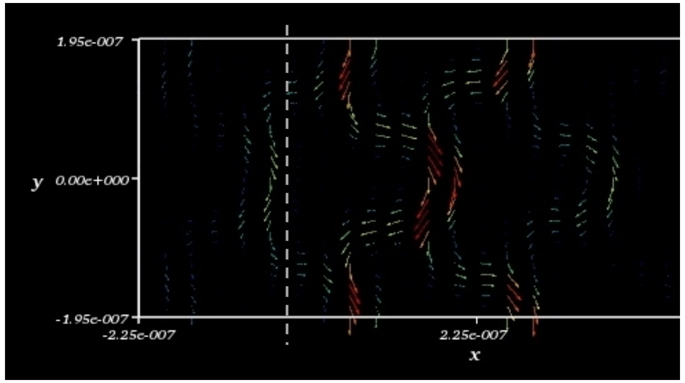


- Opens up possibility of topological light emission and lasing in the visible and ultraviolet

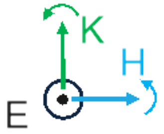


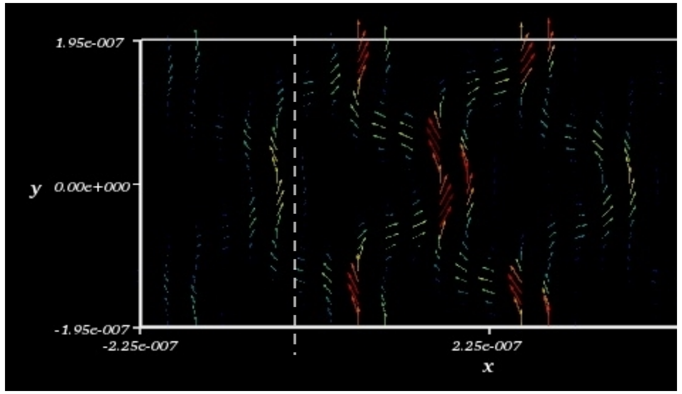
Spin-down state
a/λ = 0.618





Spin-up state
a/λ = 0.60





Light emission from photonic topological structures

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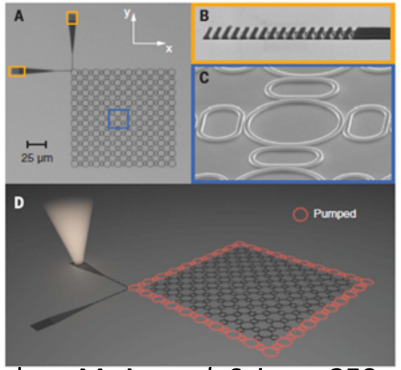
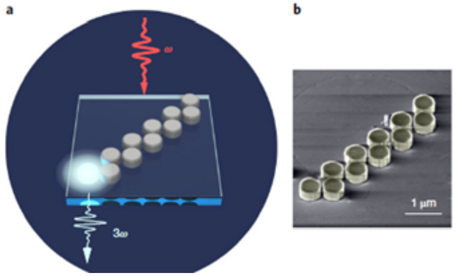
PTI lasing



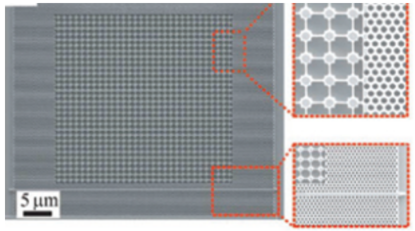
Bandres, M. A. *et al*. *Science* **359**, eaar1231 (2018).

Nonilinear light generation



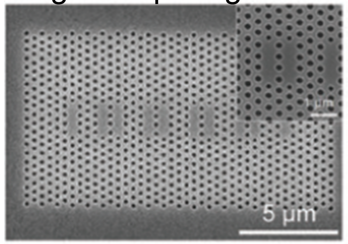
Sergey Kruk, et. Al. Nature Nanotechnology **14**, 126 (2019).

Non-reciprocal lasing



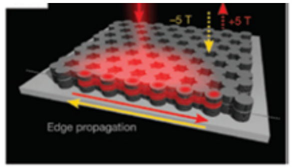
Bahari B, et. al., Science **358**, 636 (2017)

Lasing in Top. edge states



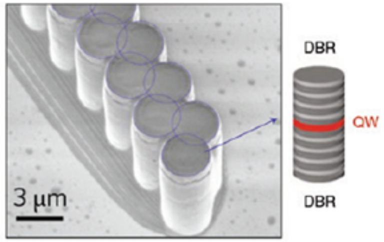
Han C et. al. , Light Sci Appl **8**, 40 (2019).

Exciton-polariton topological insulator



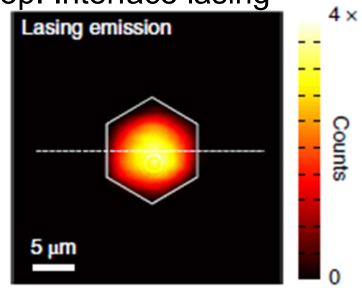
Klembt S et. al., Nature 562:552(2018).

Top. lasing in 1D



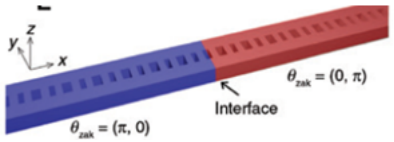
St-Jean P, et. al. Nat Photonics,**11**,651(2017).

Top. Interface lasing



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

Top. Nanocavity laser

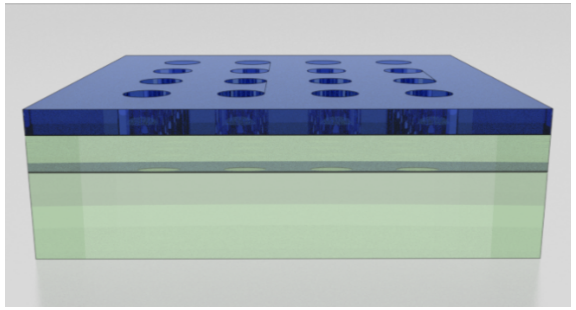


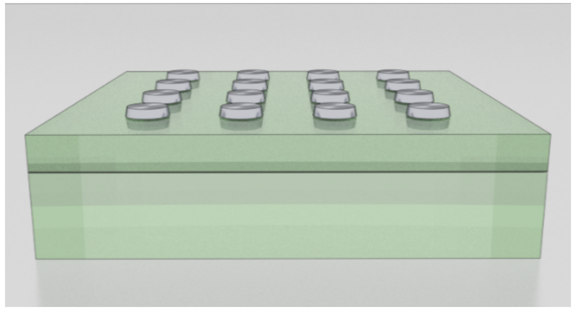
Ota Y, et. al. Commun Phys **1**, 86 (2018).

<u>Review:</u> Y. Ota, K. Takata, T. Ozawa, A. Amo, Z. Jia, B. Kante, M. Notomi, Y. Arakawa, and S. Iwamoto, "*Active topological photonics*," Nanophotonics 9, 547-567 (2020).

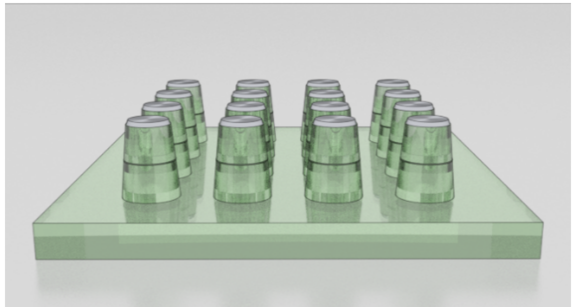
Top down nanofabrication or nanowire array in GaN

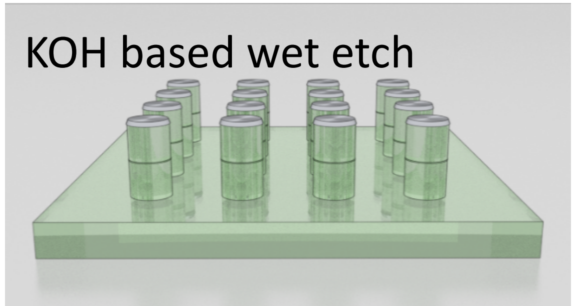
EBL pattern in PMMA



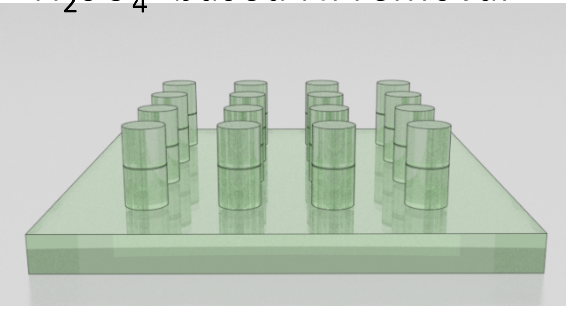


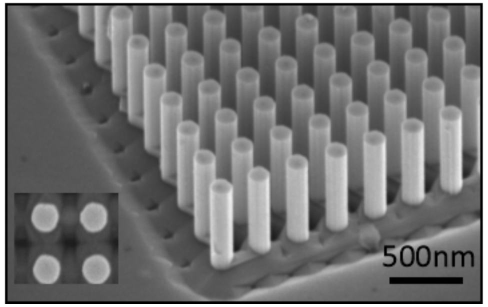
Cl2 based dry etch



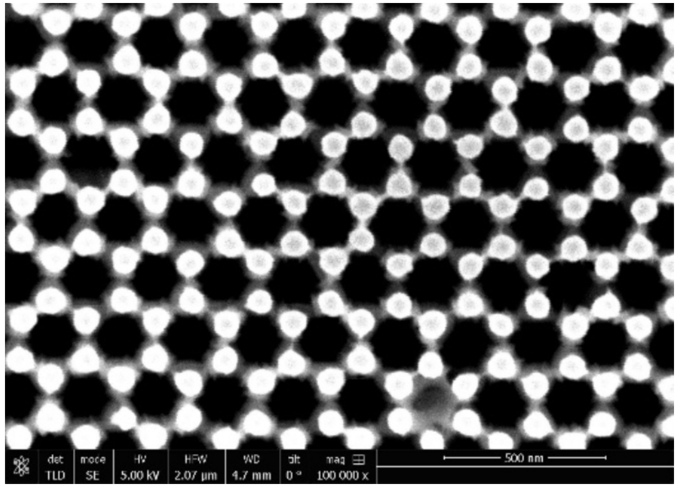


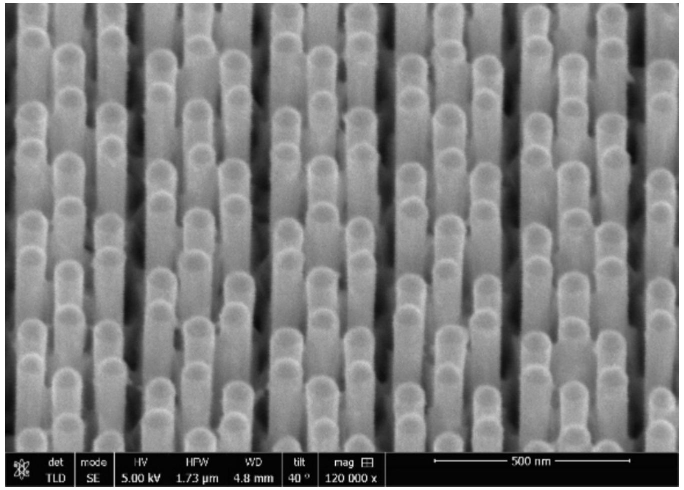
H_2SO_4–based Ni removal

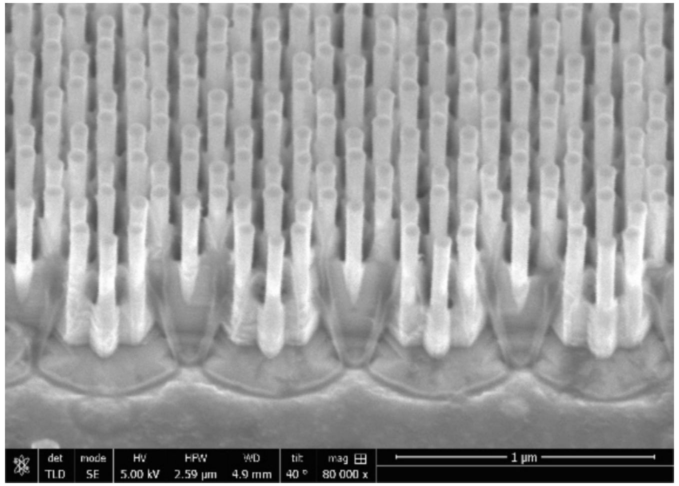




Topological/Trivial lattice interface structure in III-Nitride







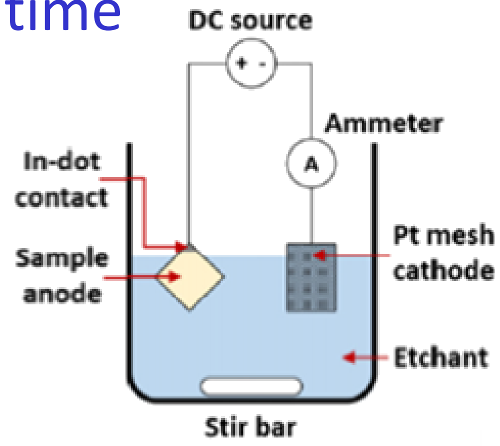
III-N Nanowires do not have low refractive index cladding to isolate from the high index substrate which is

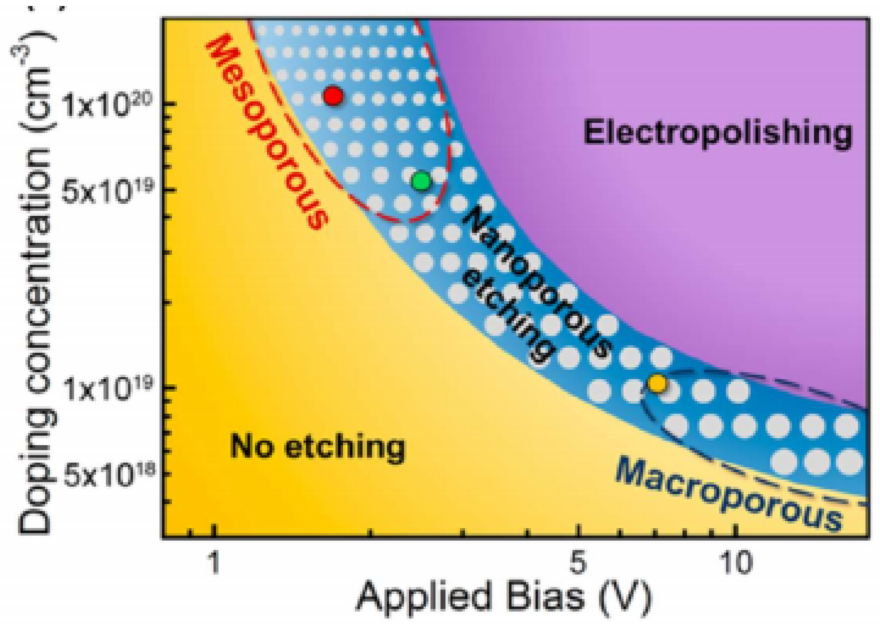
- No natural low-index compounds
- Utilize nanoporous interface

Nanoporous III-N Low Index Layer

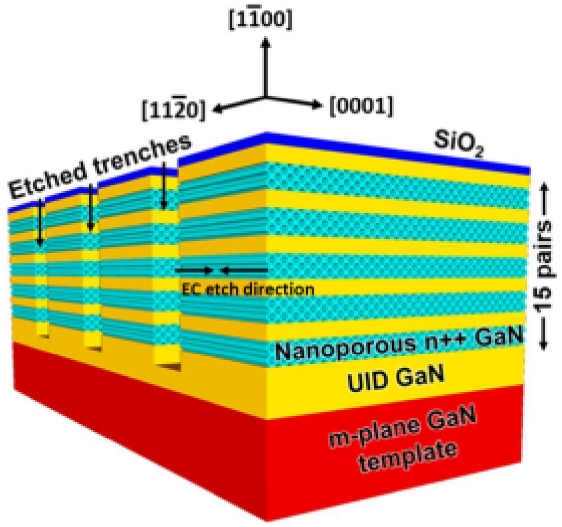
Electrochemical (EC) etching of doped III-N layer in chemical bath

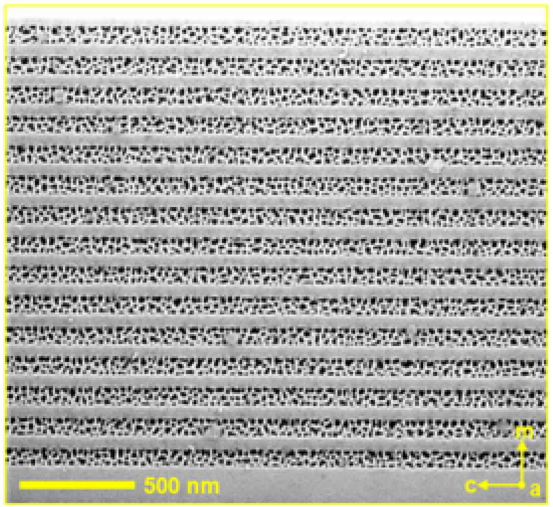
- Etching conditions - applied voltage, doping concentration, etching time





Feezell Group (UNM)





Approach is flexible and scalable

- **Enables control of porosity a through control of etch conditions**

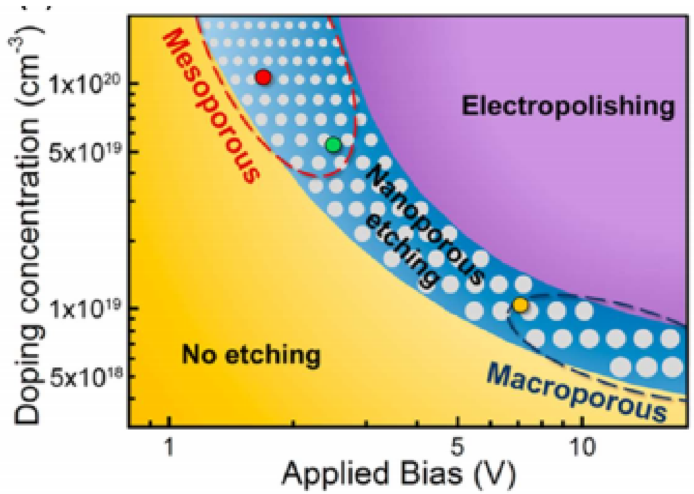
Figures adapted from Mishkat-Ul-Masabih, S et. al. *Applied Physics Letters* **2018,** *112* (4), 041109

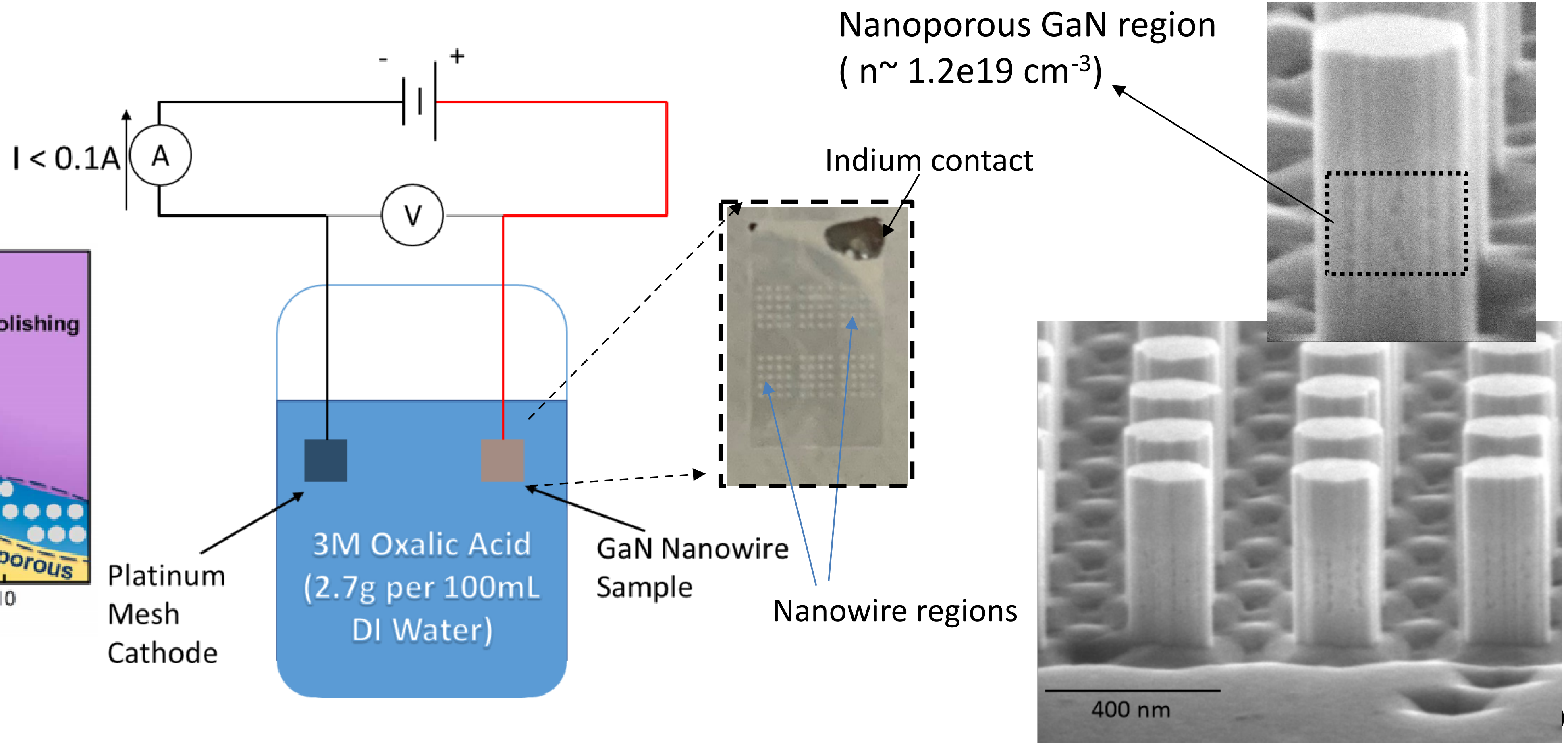
Electrochemical Etching Process

In collaboration with Prof. Daniel Feezell's group (UNM)

Electrochemical etching of doped GaN layer in acidic solution

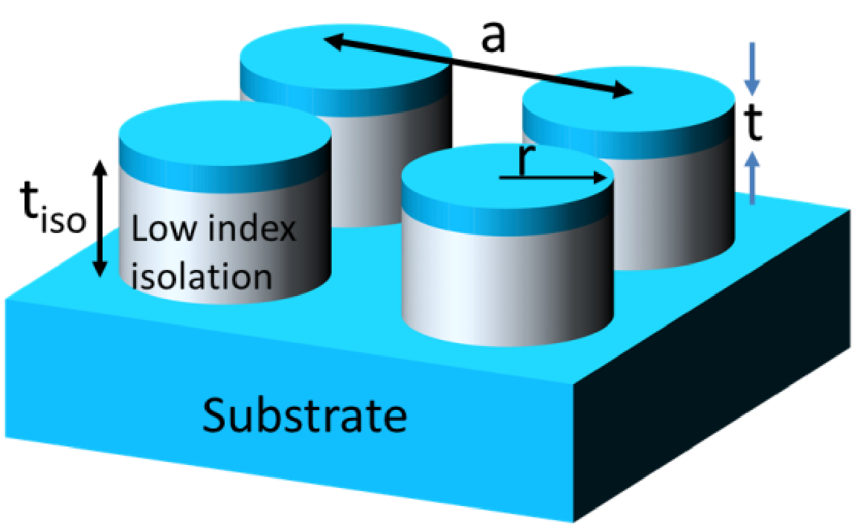
- Results in nanoporous region with lower effective refractive index

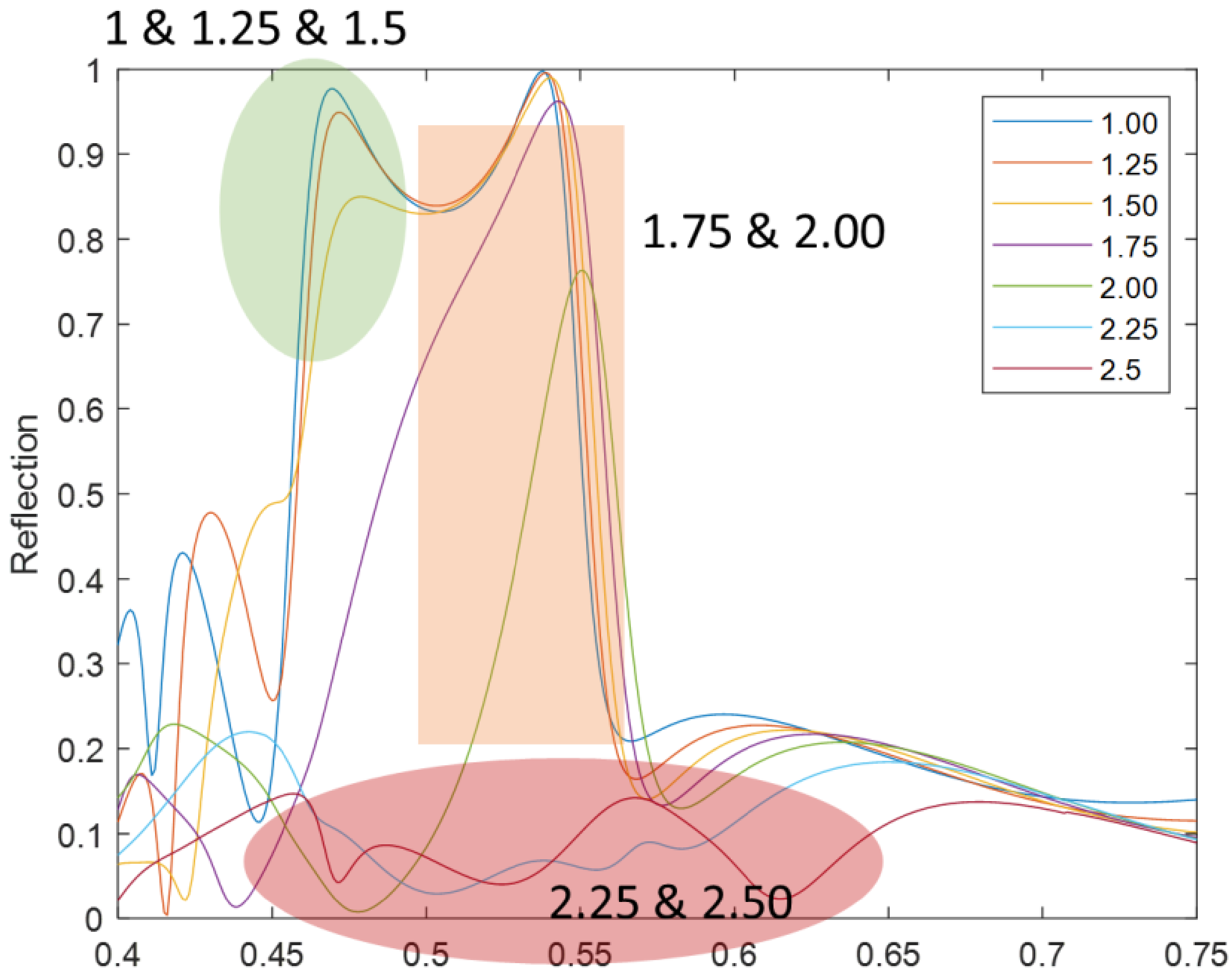




Design of Nanowire Resonator Arrays

➢ Unique reflectance signature from nanoresonator arrays corresponding to different effective cladding refractive index

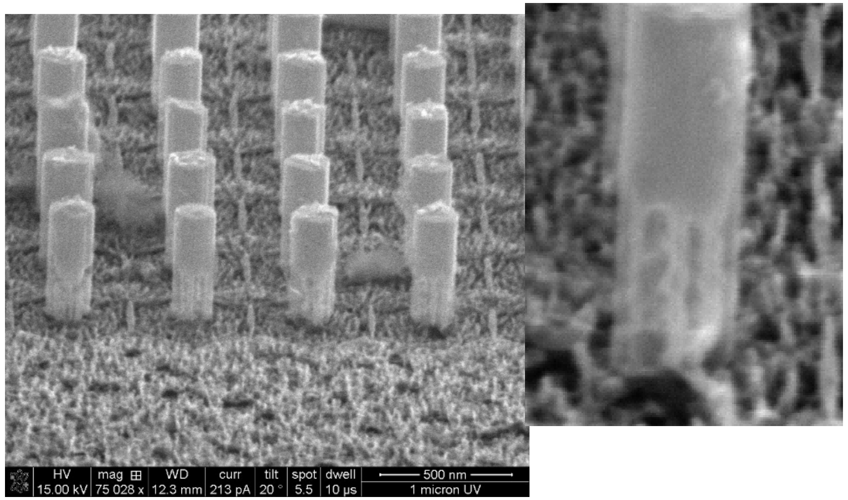




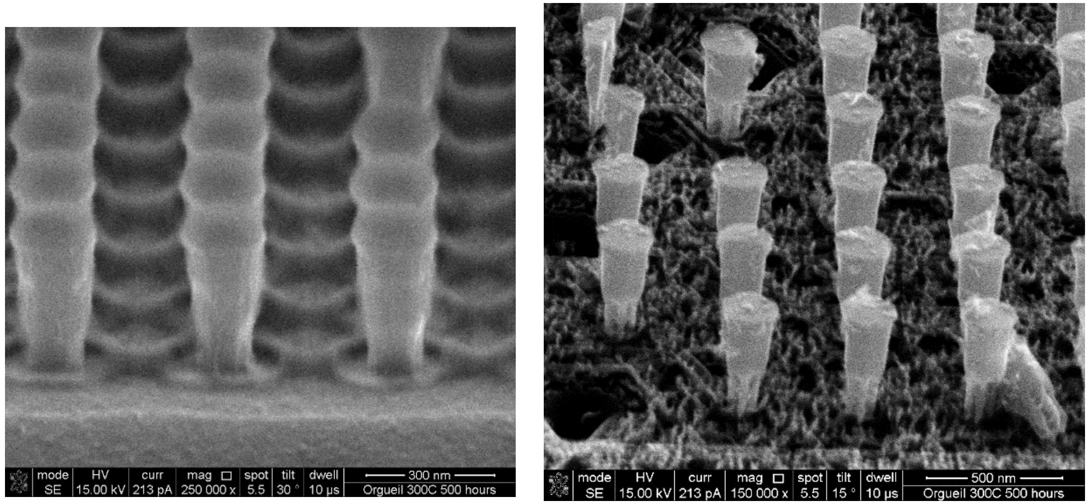
Porosity Characterization

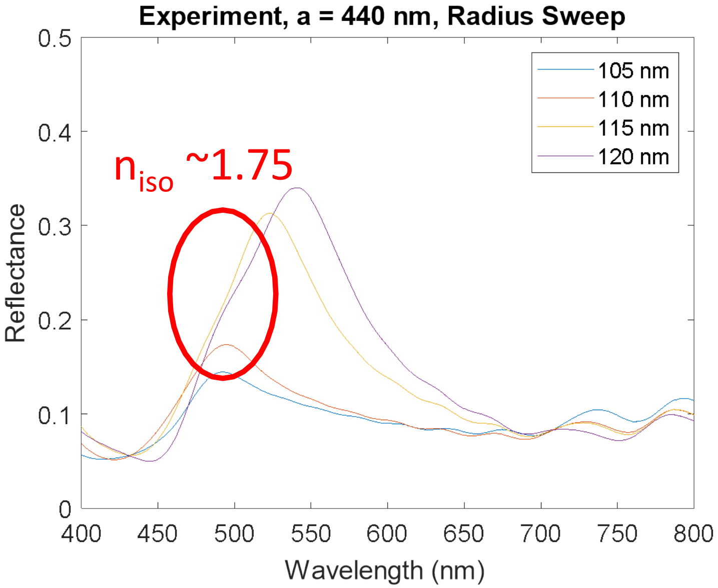
(24 V, 12 min)

EC etch



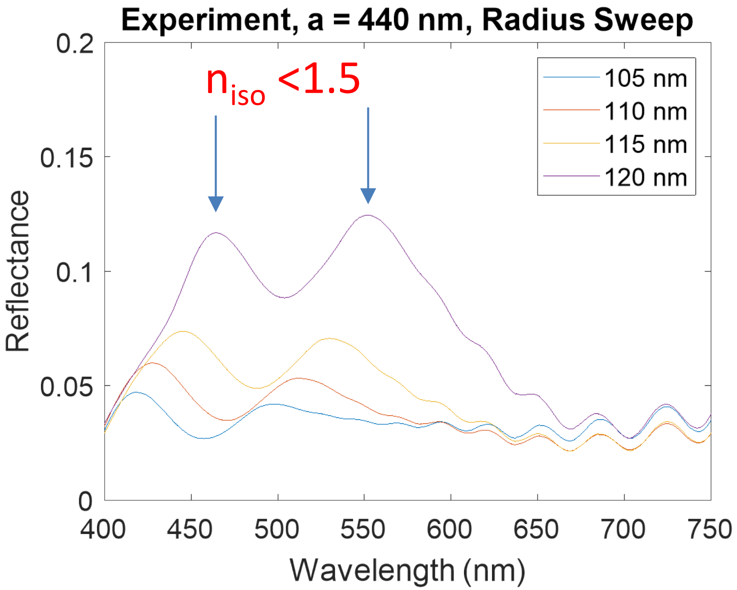
Blanket wet etch (KOH) + EC etch





Using our characterization design, the nanowire resonators show a clear reflectivity response enabling porosity/effective index characterization.

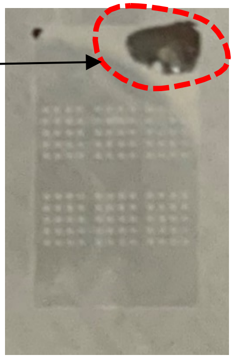
With the additional wet etch the porosity target enabling our Huygens' MS has been achieved!



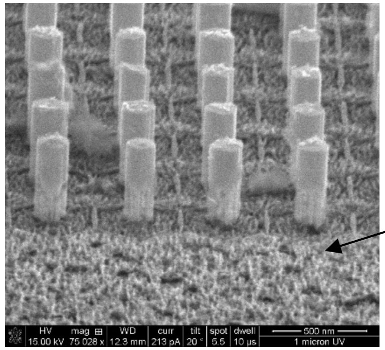
Improved EC etching approach

Sandia National Laboratories

- Controlled etch depth
- Indium contact annealed at 150^{o}C
- EC etch 24V, 12min



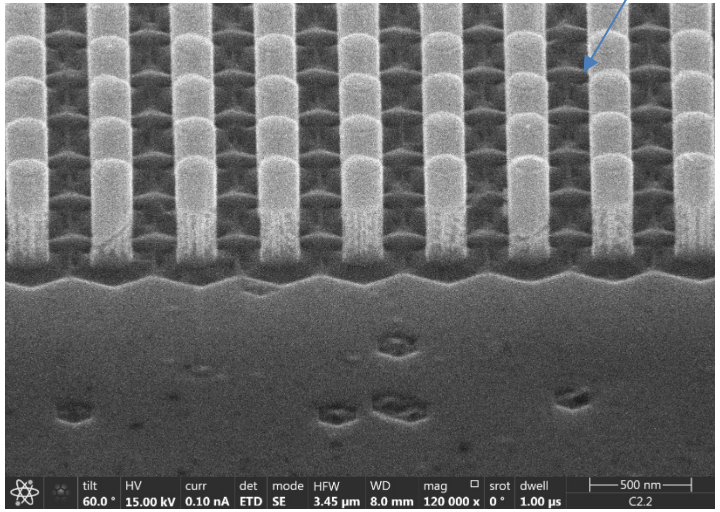
Previous

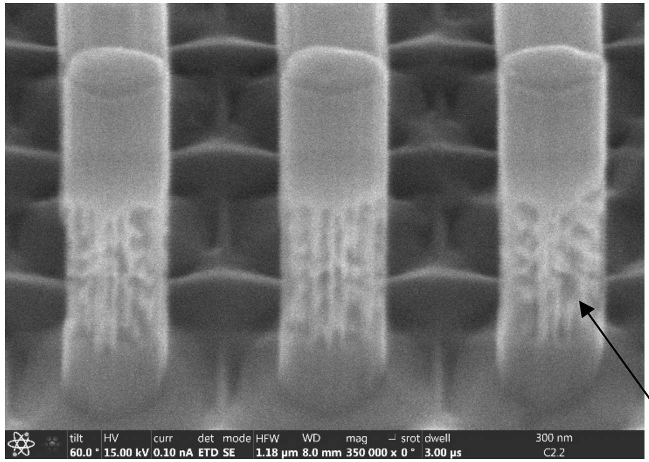


'grassy' surface

cleaner surface

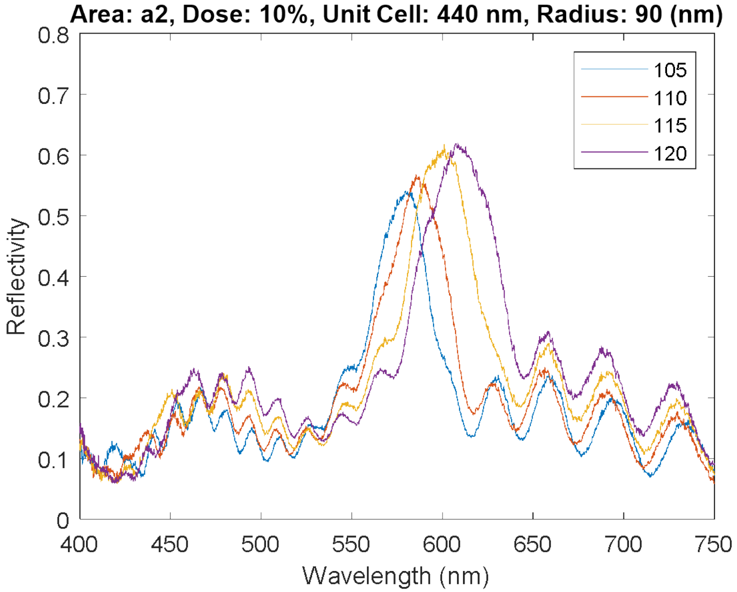
Current





Porous high

Considerably improved reflectivity response from resonators



N. Karl et. al. (in-preparation)

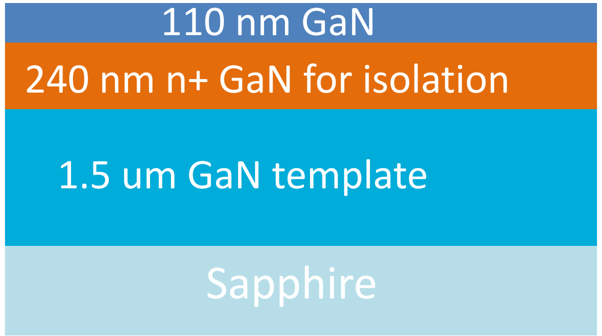
Summary

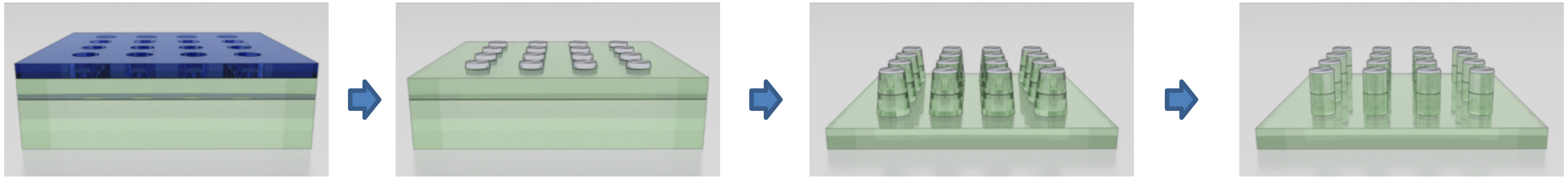
- ❑ Topological photonic behavior in hole array dielectric membrane PhC
- ❑ Implementation in a silicon-on-insulator system
- ❑ Topological light emission
- ❑ Implementation in III-nitride

Thank you for your attention !

Extras ..

III-N Nanowire Array Resonators



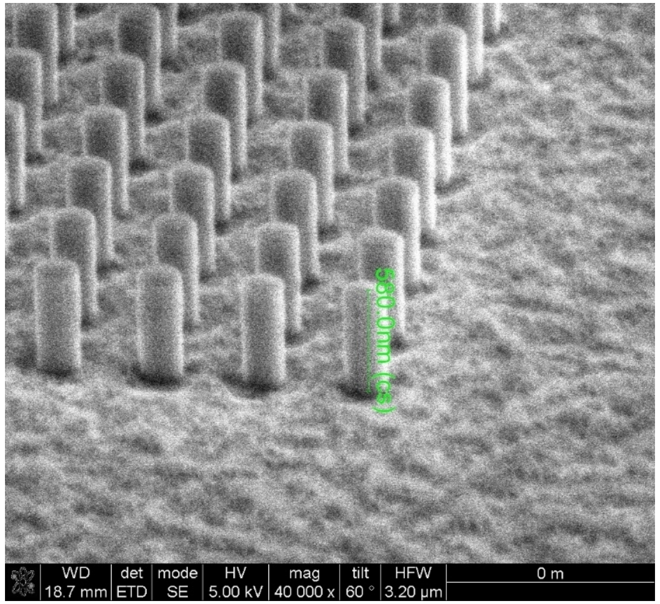


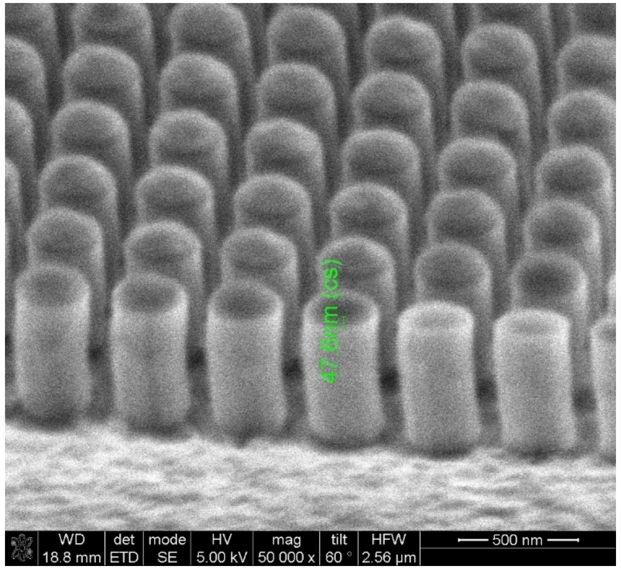
EBL pattern in PMMA

Ni evaporation and lift-off

Cl_2 based dry etch

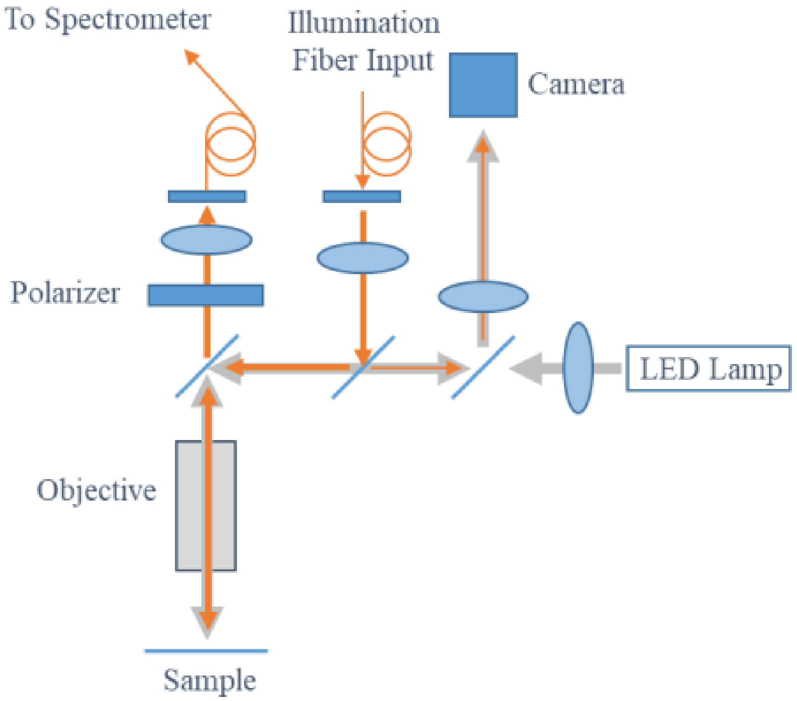
KOH based wet etch



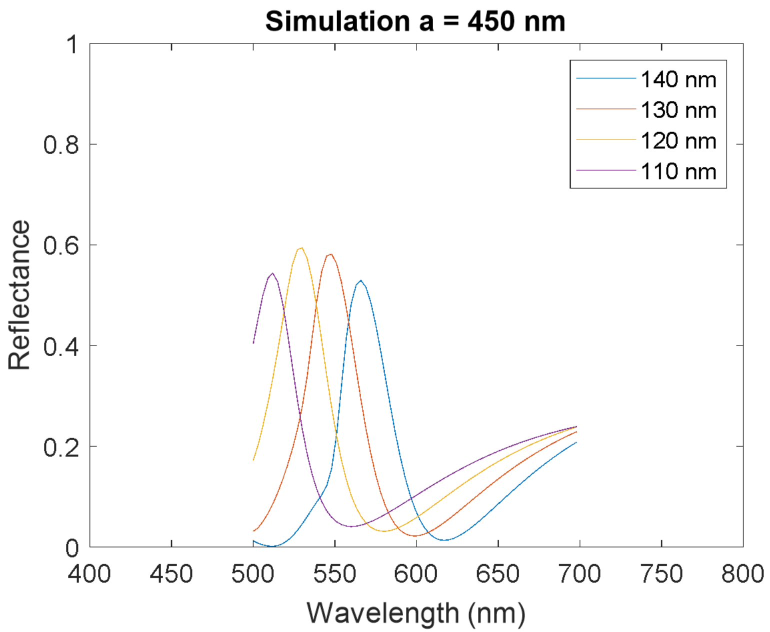


Demonstration of cylindrical GaN nanowire array with smooth side walls

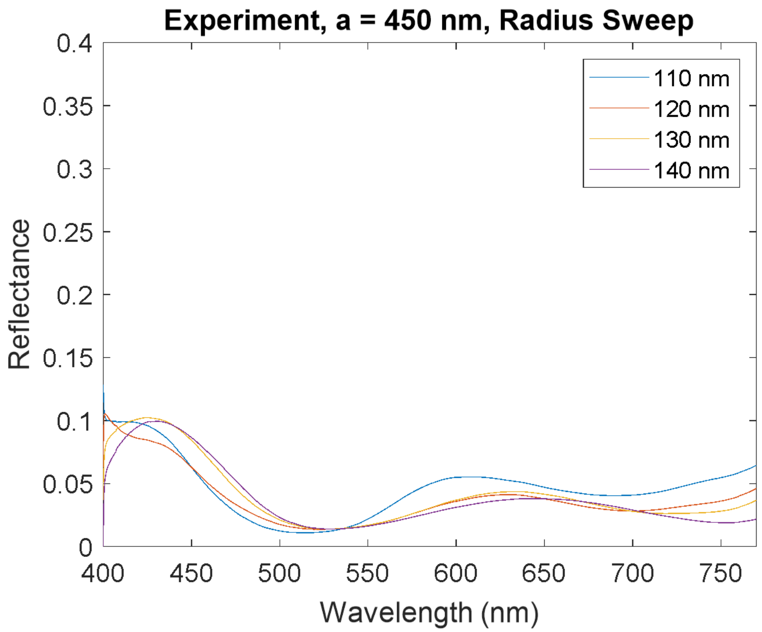
Optical Reflectance



EM simulation

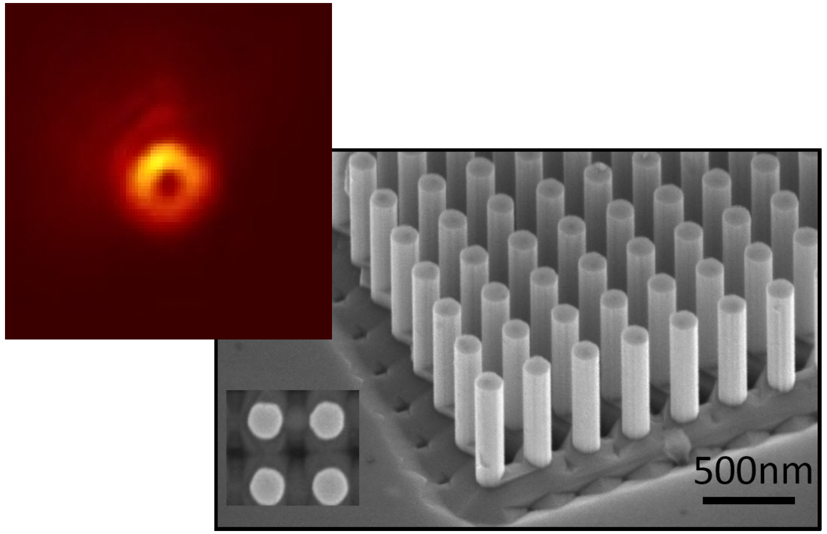


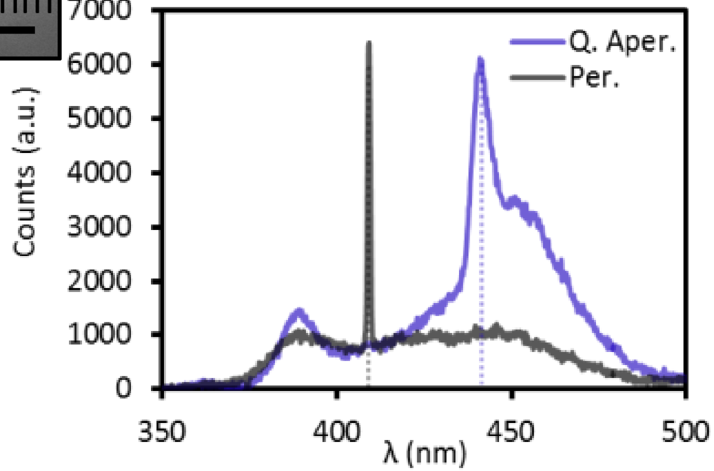
Optical measurement

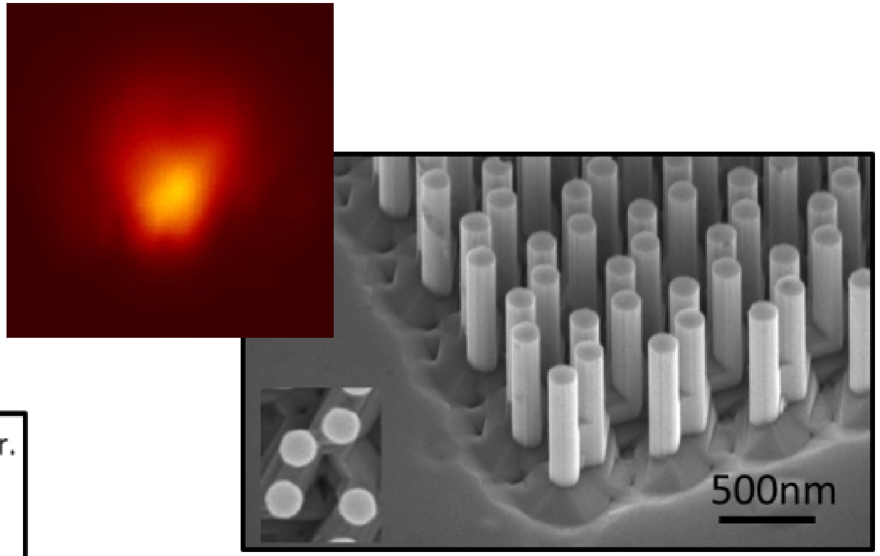


➢ Weak reflectivity response made porosity characterization difficult

Opportunities in InGaN MQW/GaN system



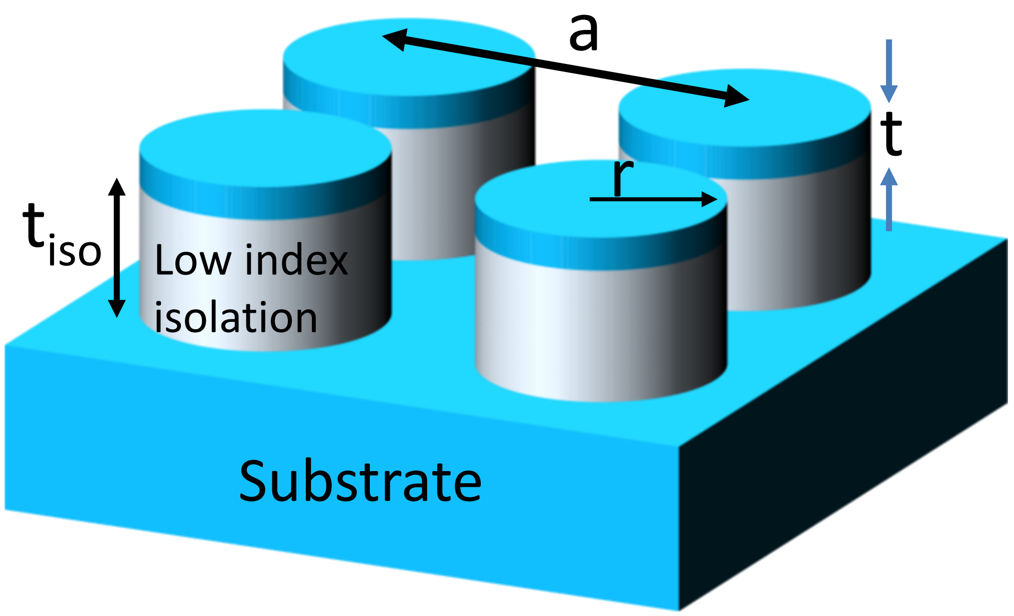




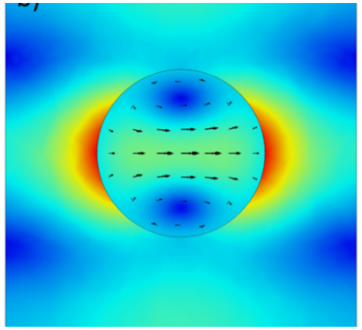
P. D Anderson, et. al.Optical Materials Express, **7** , 3634(2017).

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

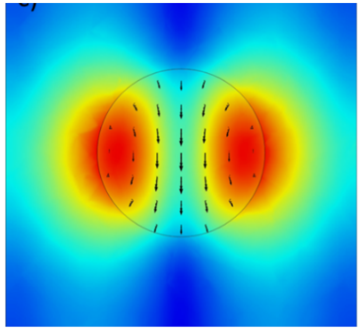
Huygen’s Metasurface Design

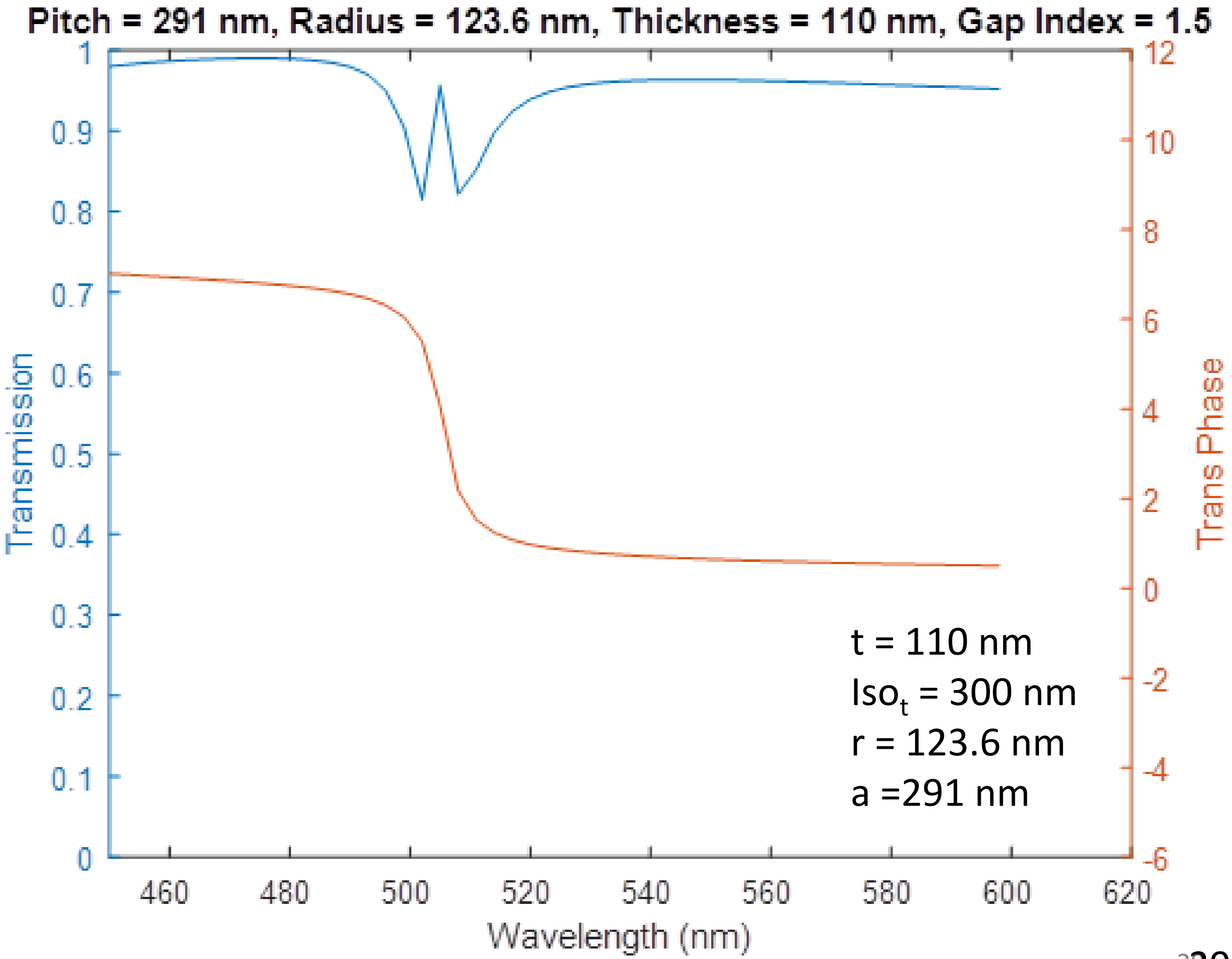


Electric dipole



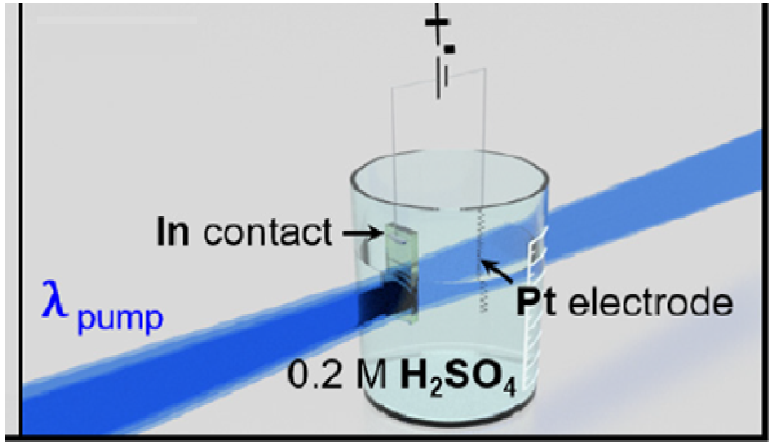
Magnetic dipole

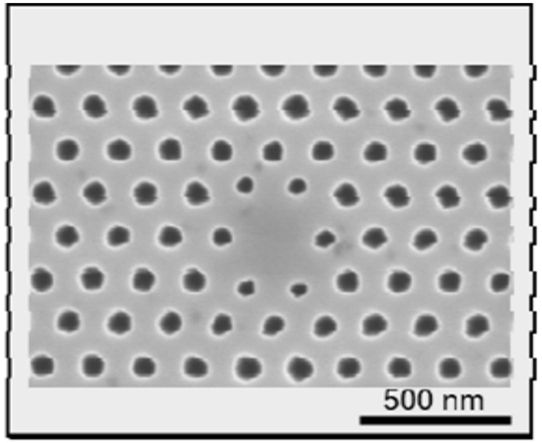


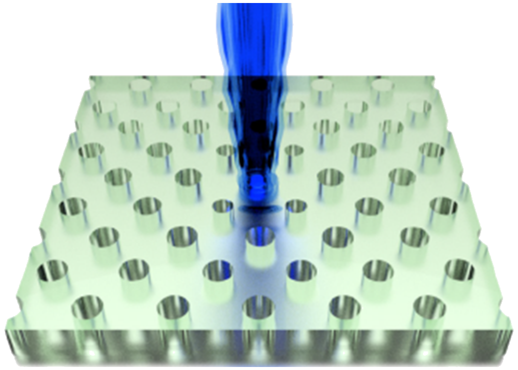


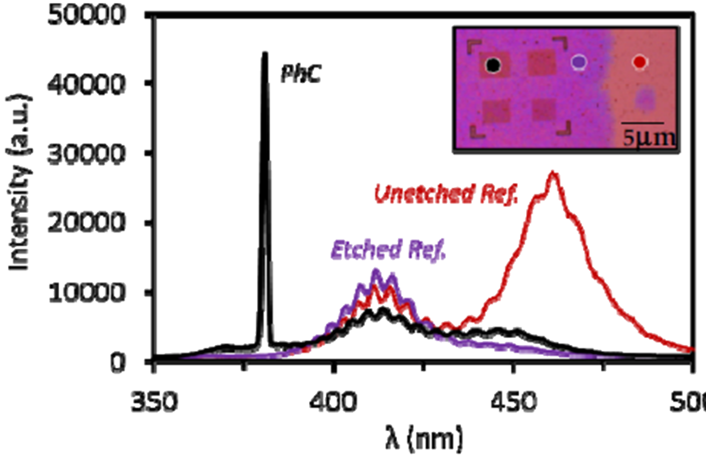
Photoelectrochemical Etching (PEC)

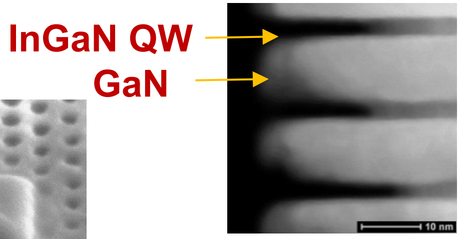
- Electrochemical etch is performed under laser illumination
- Laser wavelength is selected such that it is shorter than the energy gap of 16% InGaN but longer than that of 10% InGaN
- Selective etching of 16% InGaN MQW
- Creates low index cladding layer

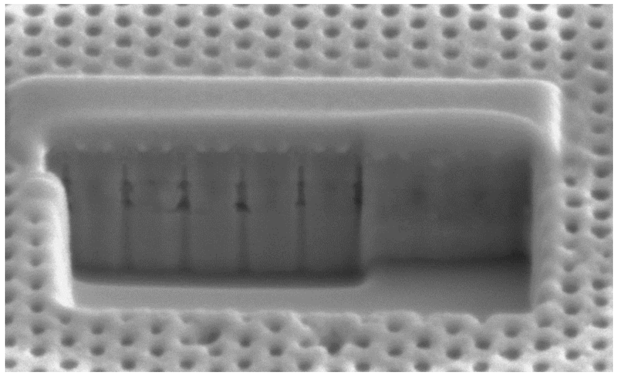












- Removal of InGaN QWs by PEC reduces cladding layer index but procedure is challenging
- Hard to scale for thicker cladding

Anderson, P. D.; Fischer, A. J.; Koleske, D. D.; Gunning, B. P.; Subramania, G., *Optical Materials Express* **2018,** *8* (11), 3543-3550.