Tunable Blue-Violet III-Nitride Nanowire Photonic Crystal Lasers

SAND2013-4688C

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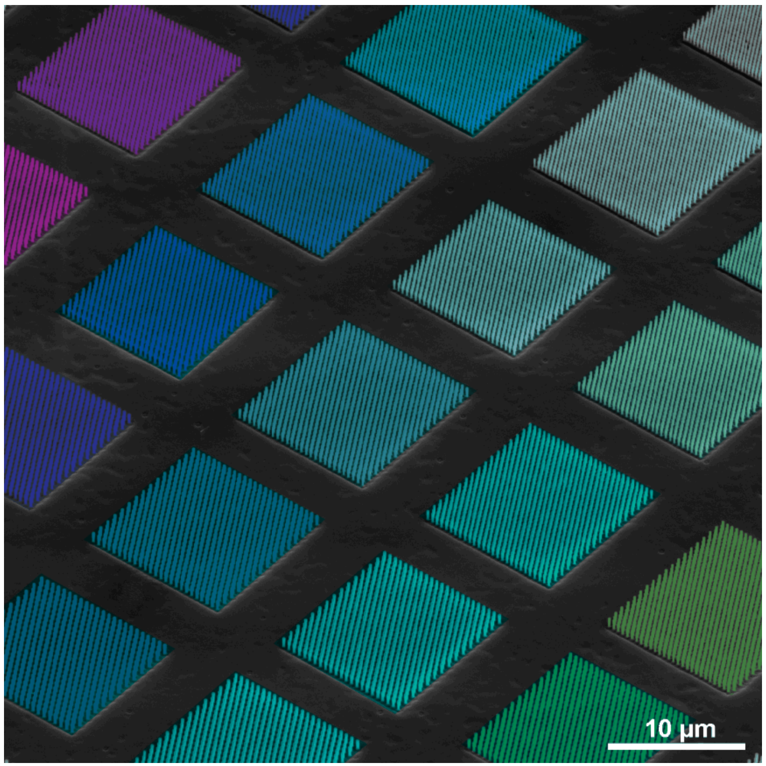

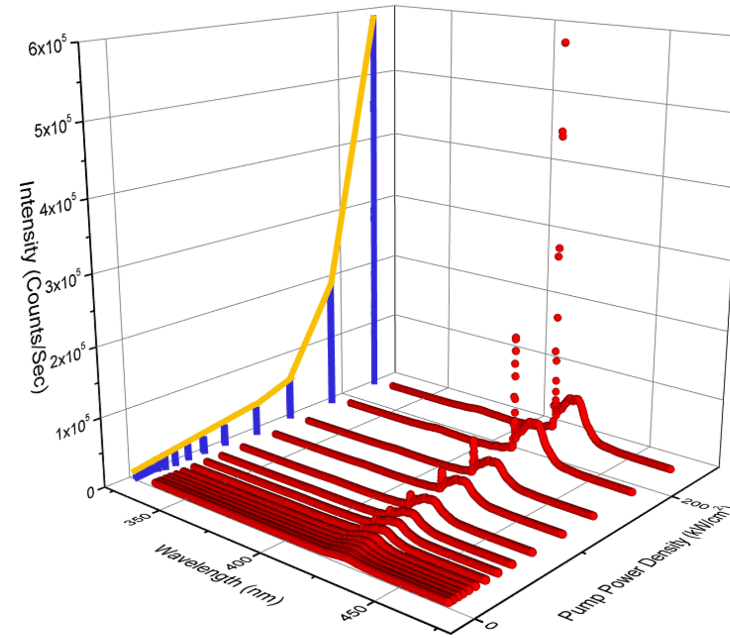

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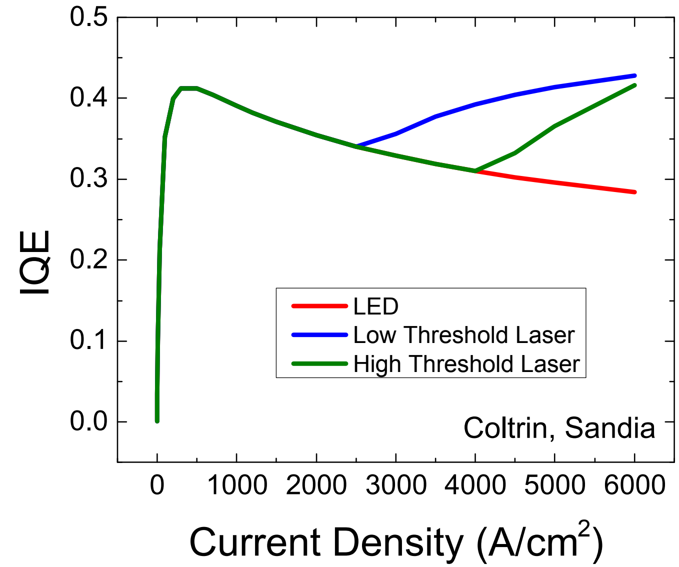
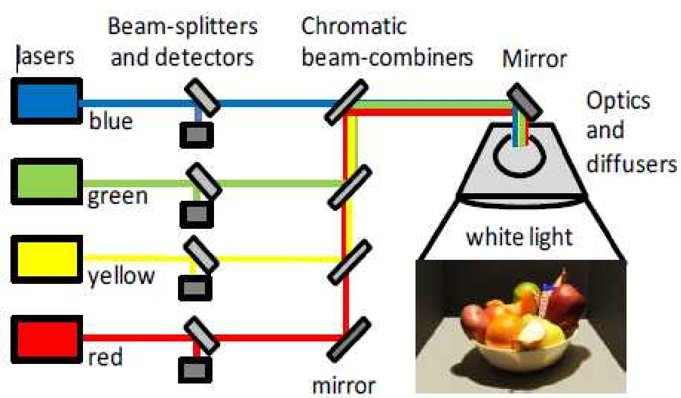
SSLS EFRC | CHTM Center for High Technology Materials | THE UNIVERSITY of NEW MEXICO | Sandia National Laboratories

Why lasers in solid state lighting?

- **The "efficiency droop"**
  - **InGaN LEDs exhibit a decrease in efficiency at high drive currents**
  - **limits the operating current density**
  - **increases the cost per lumen**



4-Color Laser Illuminant



A. Neumann et al., "Four-color laser white illuminant demonstrating high color-rendering quality," Opt. Express, vol. 19, pp. A982-A990, 2011.

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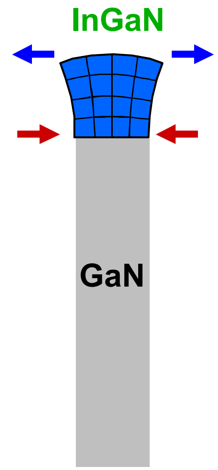
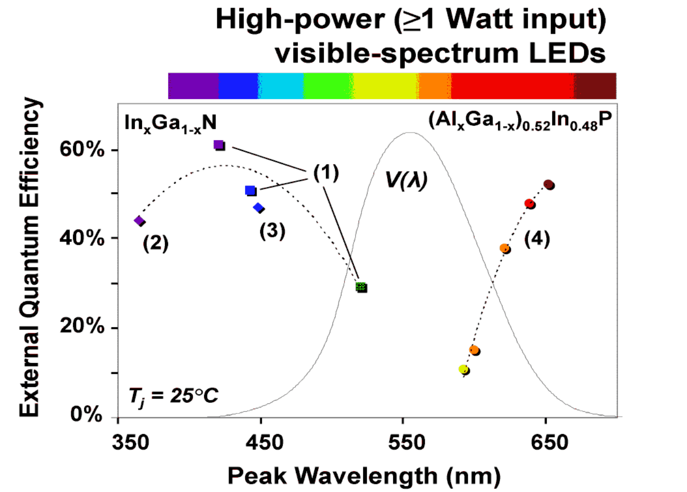
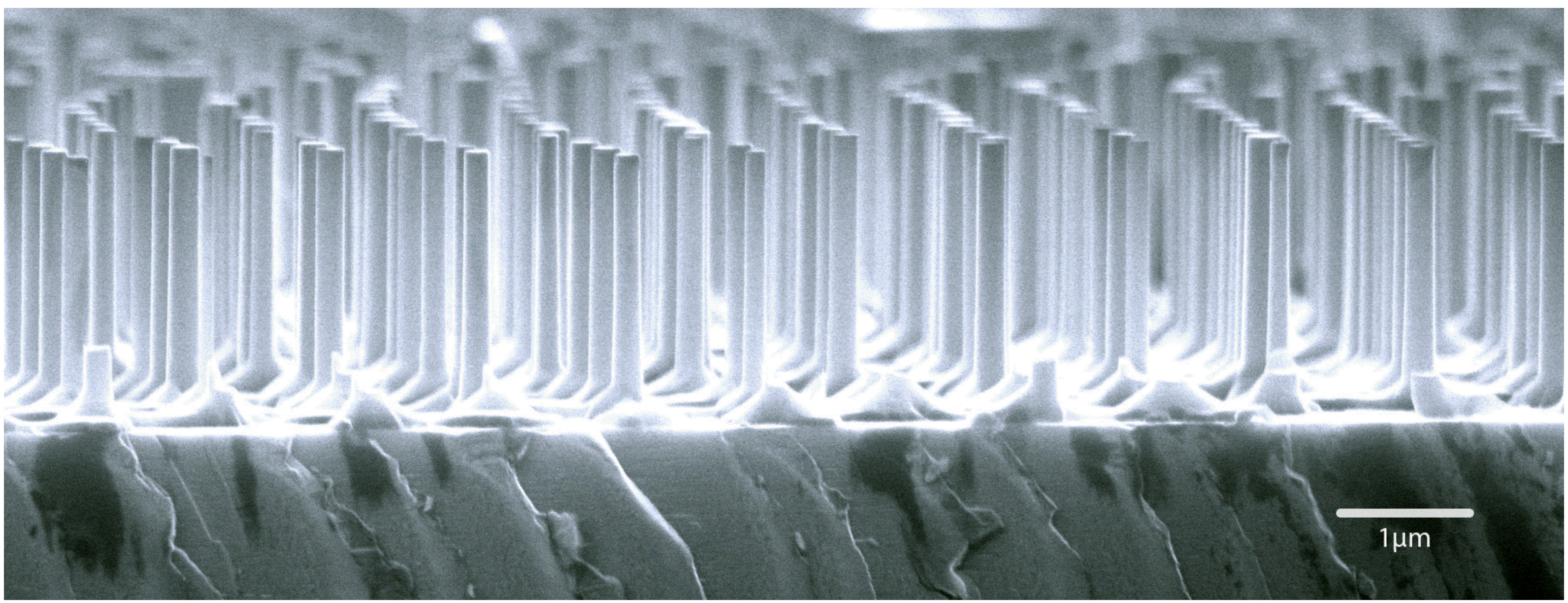
Why Nanowires for Lasing?

- **Reduced strain**
  - Greater range of alloy compositions
- **Easily integrated into two-dimensional arrays**





M. Krames, Philips Lumileds



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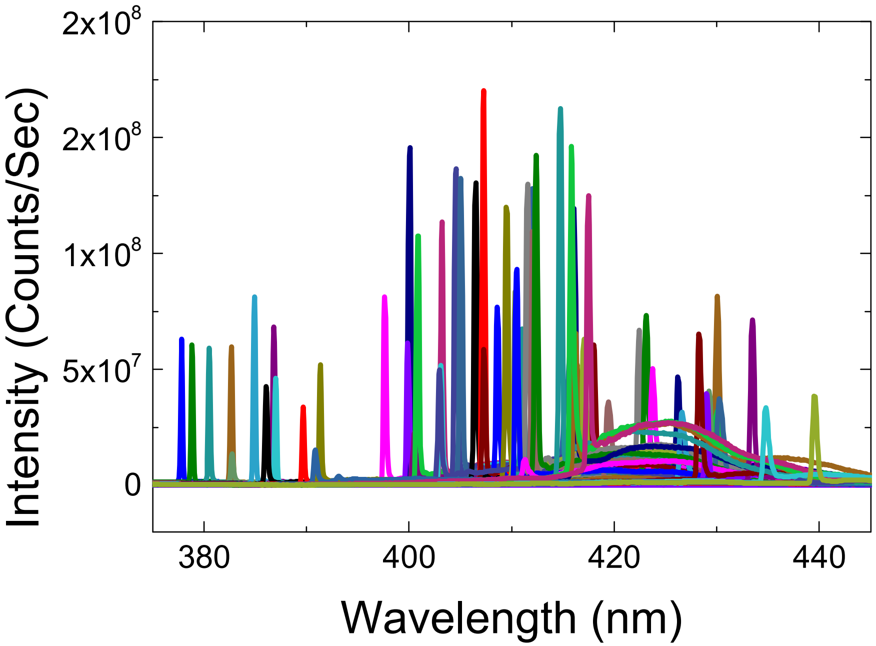
Outline

- **Design: Slow Group Velocity Modes**

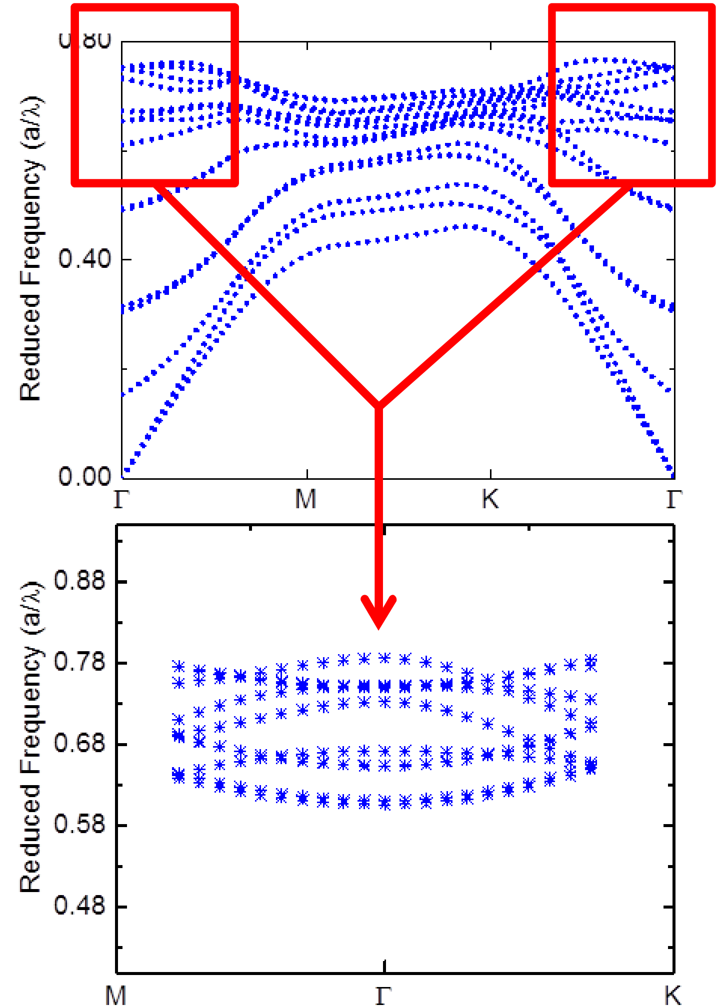
  - **Fabrication: Top-down Nanowire Photonic Crystals**

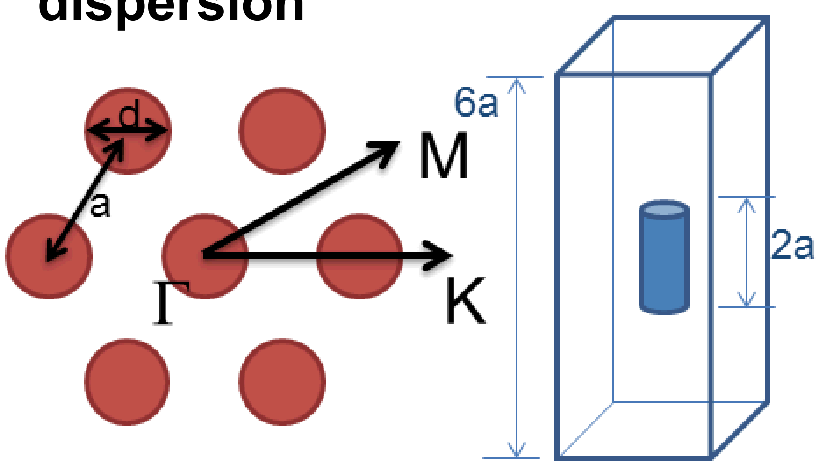


- **Optical Characterization and Results**

Designing vertically emitting photonic crystal lasers.

- **We desire low group velocity**
  - **enhances the light matter interaction**
  - **forms standing waves within the gain medium**
  - **First described by Sakoda (1999)**
- **We designed high order bands designed to have low dispersion**

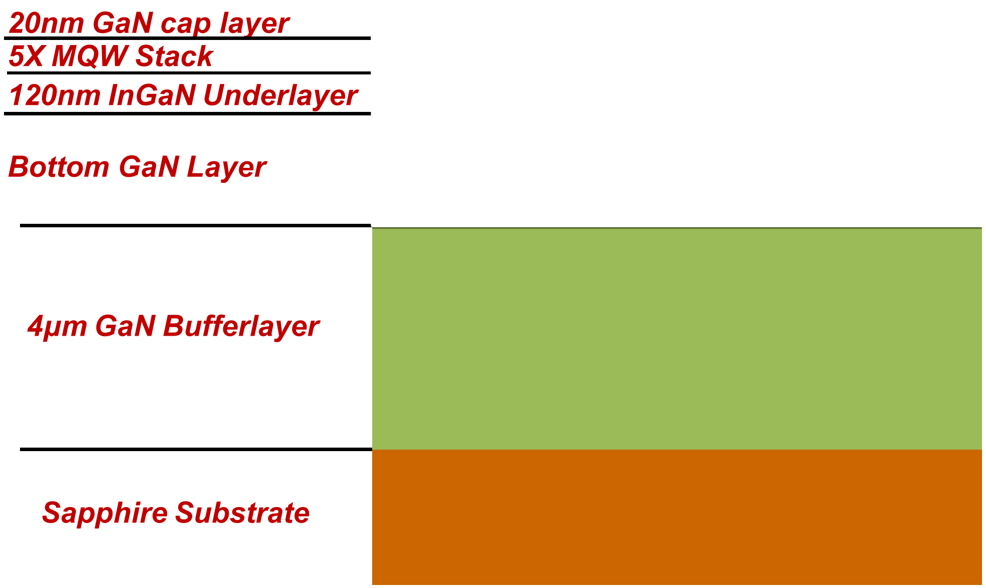


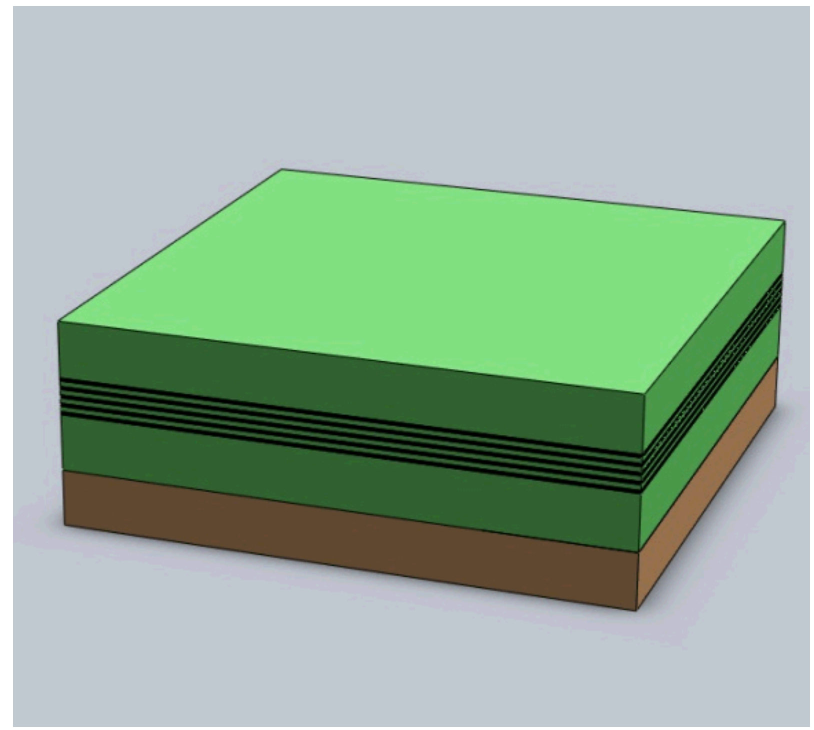


Plane Wave Expansion Super Cell

Fabrication | Growth of III-N active material

- 4µm GaN bufferlayer
- 2% In Underlayer
- 5 MQW InGaN/GaN near the surface





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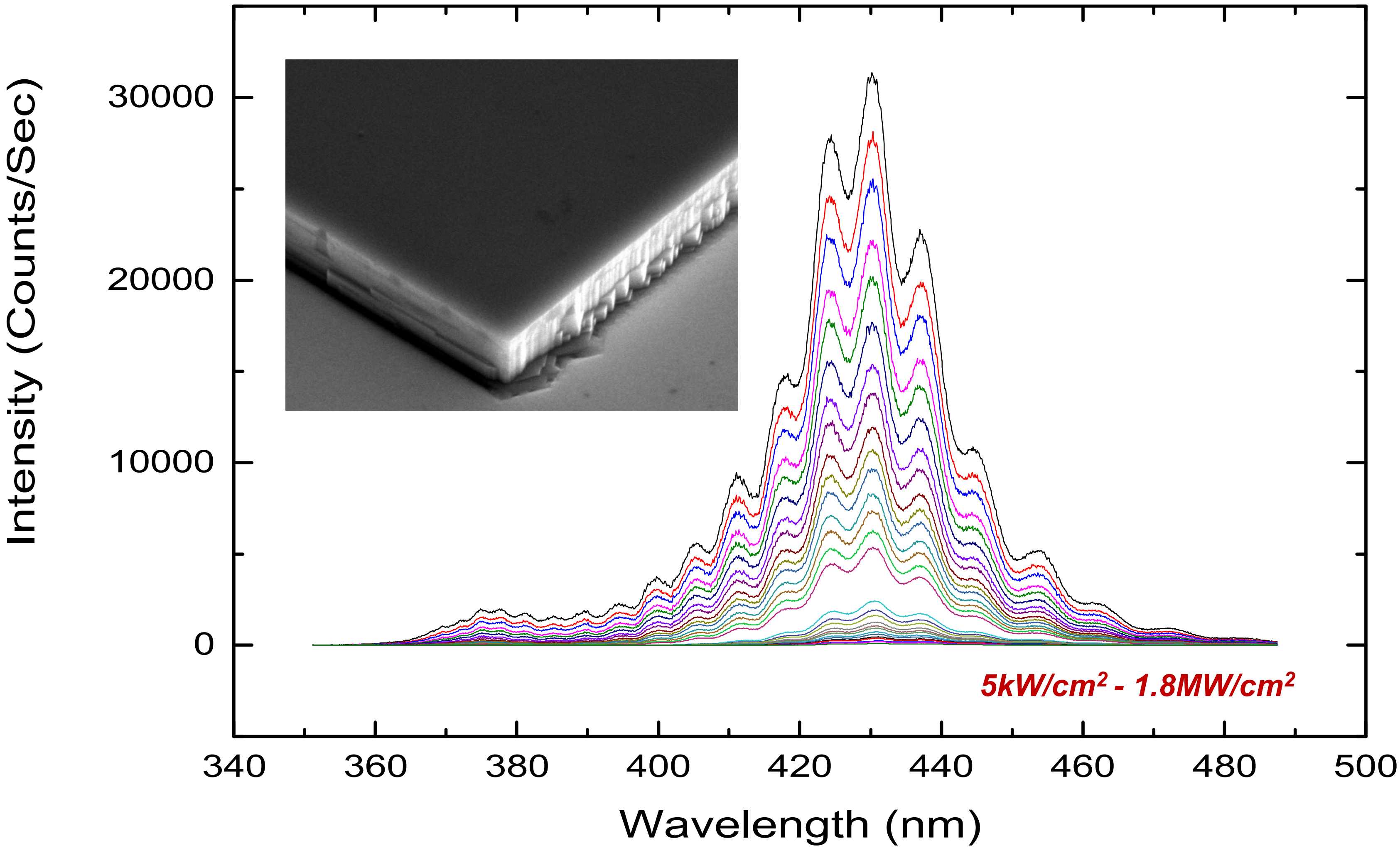
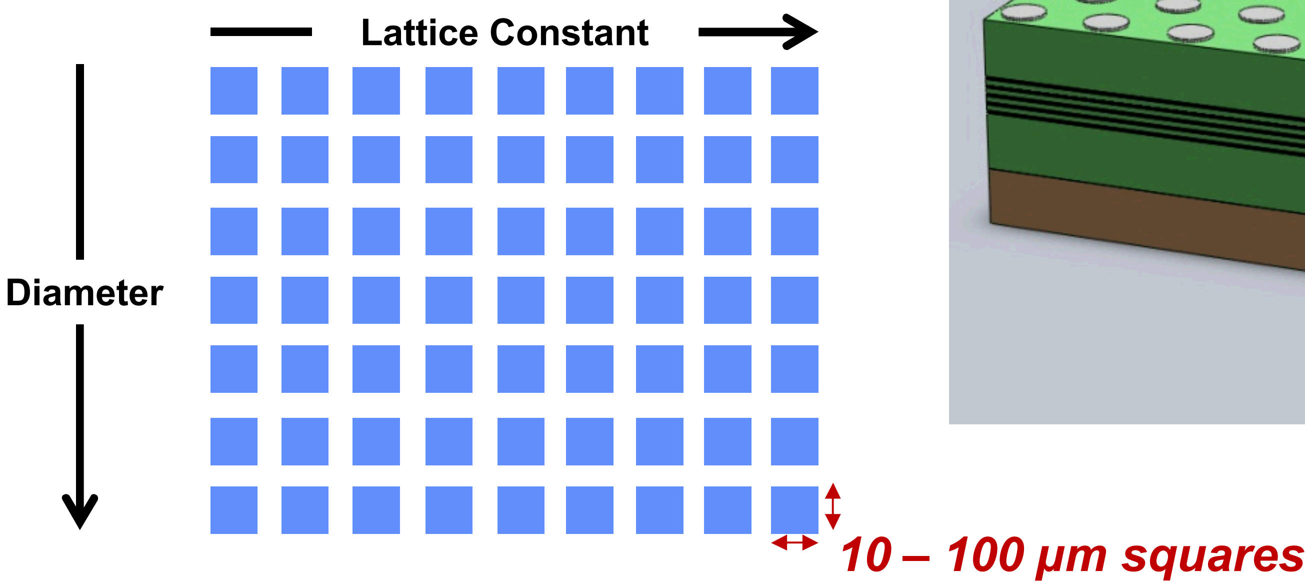
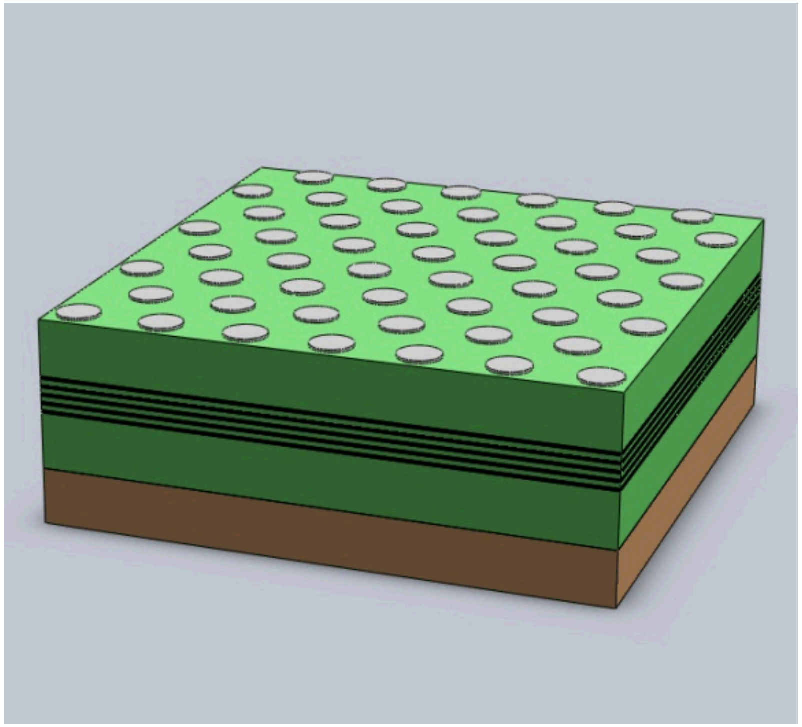
Photoluminescence from a non-etched reference region.



Fabrication | Patterning of 2DPC using e-beam

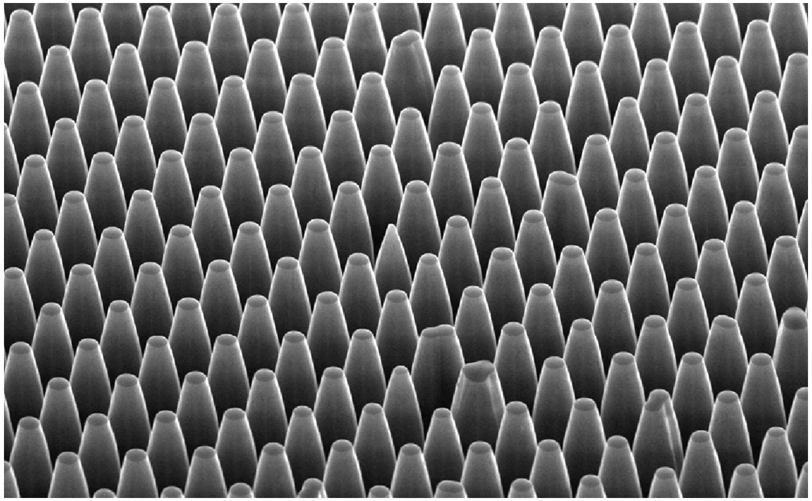
- E-beam Patterning
- Triangular Lattice of Ni Dots
- 9x7 array

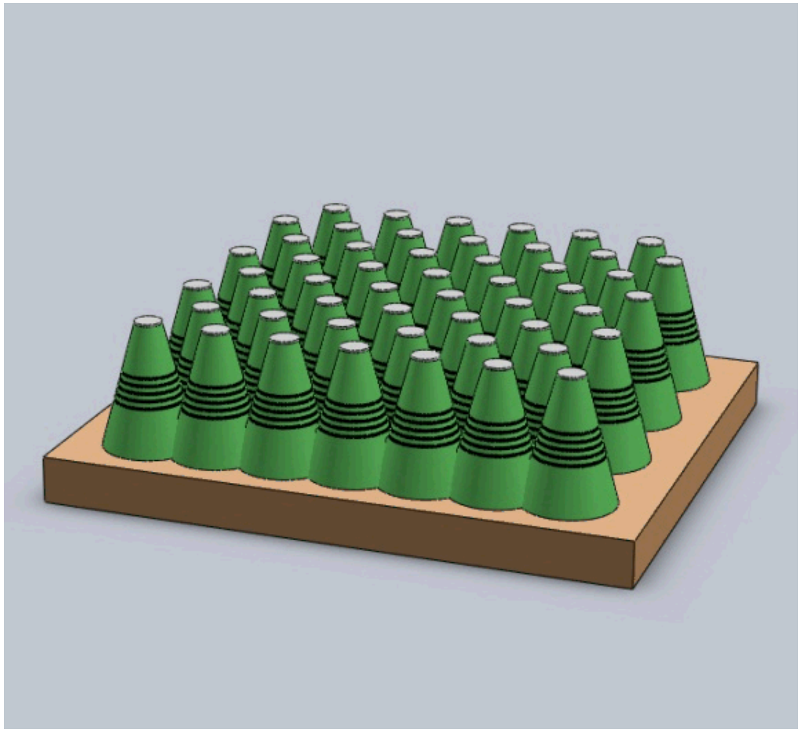




Fabrication | top-down 2-step etch process

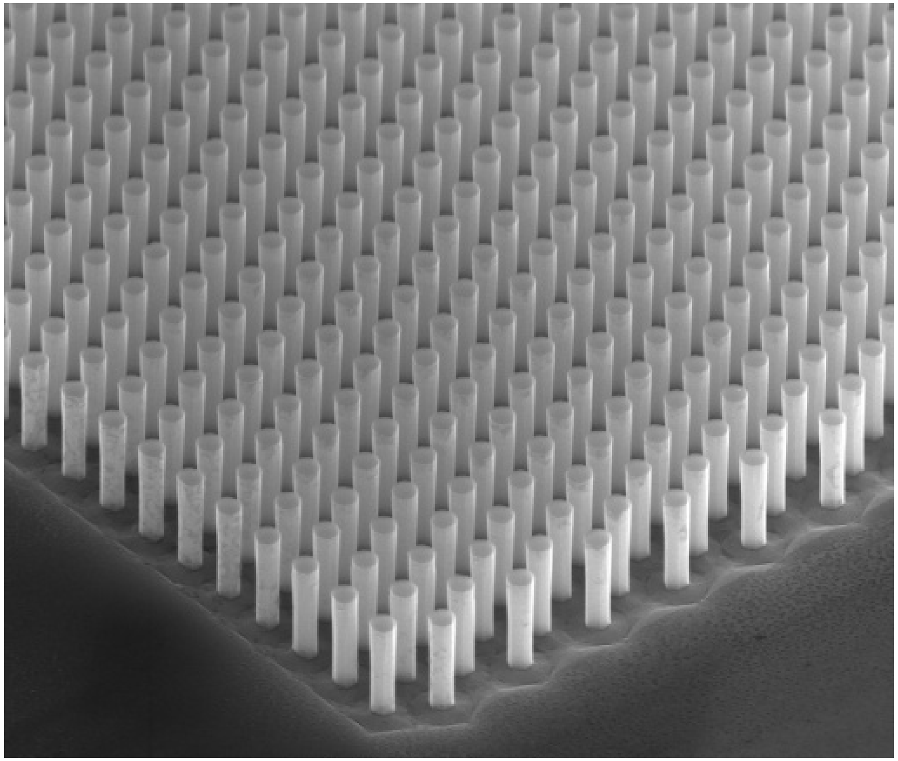
- **Same process as our top-down nanowires**
- **Dry (ICP) followed by wet (KOH) process**

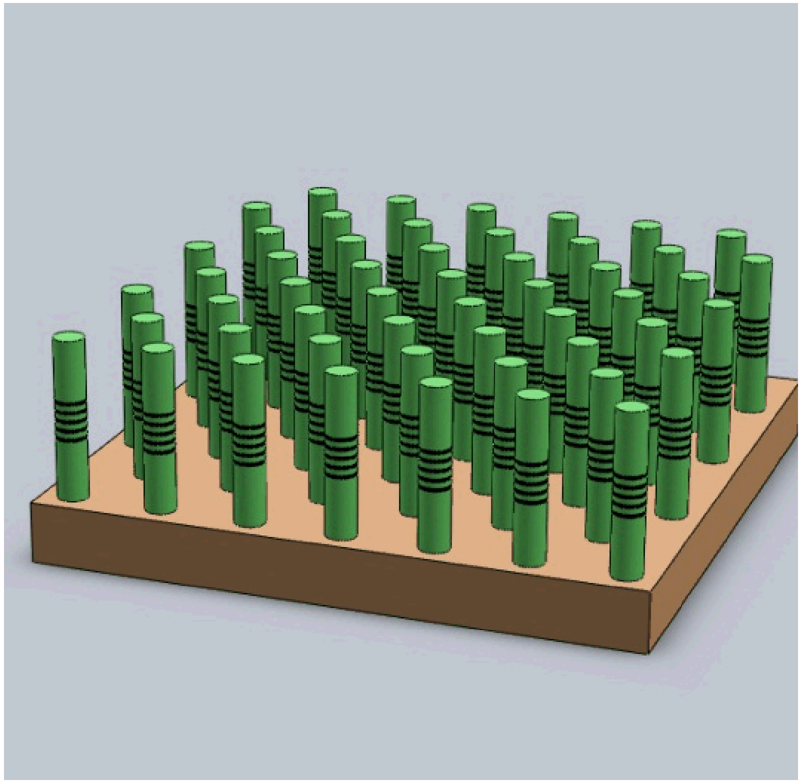




Li, Q. *et al. Optical performance of top-down fabricated InGaN/GaN nanorod light emitting diode arrays. Opt. Express* ***19, 25528-25534 (2011).***
Li, Q. *et al. Single-mode GaN nanowire lasers. Opt. Express* ***20, 17873-17879 (2012).***

Fabrication | Ordered arrays of anisotropic nanowires





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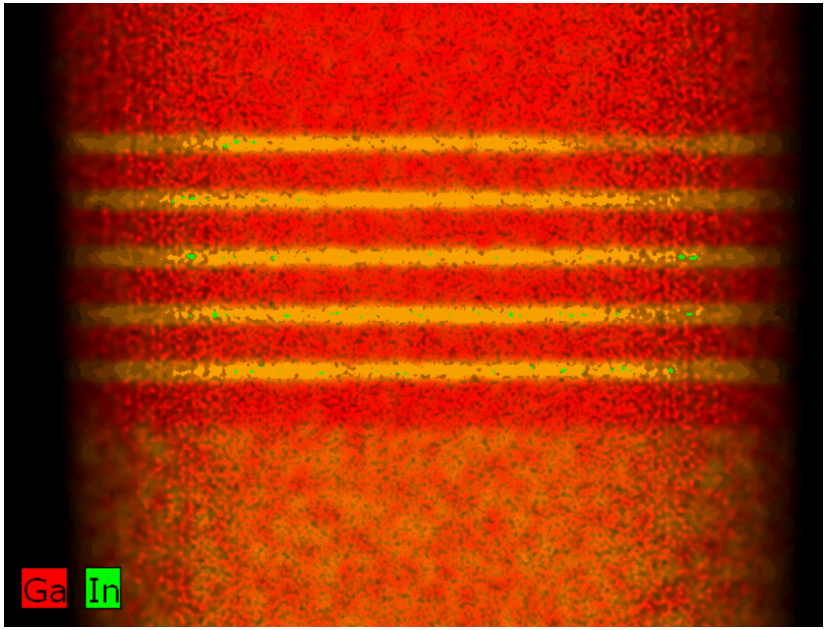
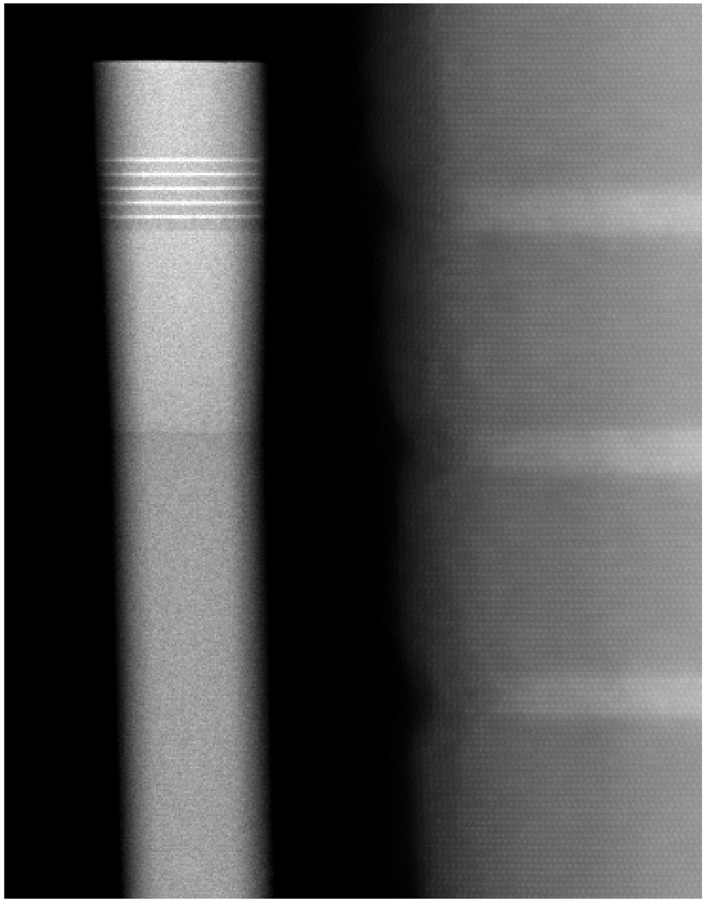
TEM of a single nanowire taken from an array

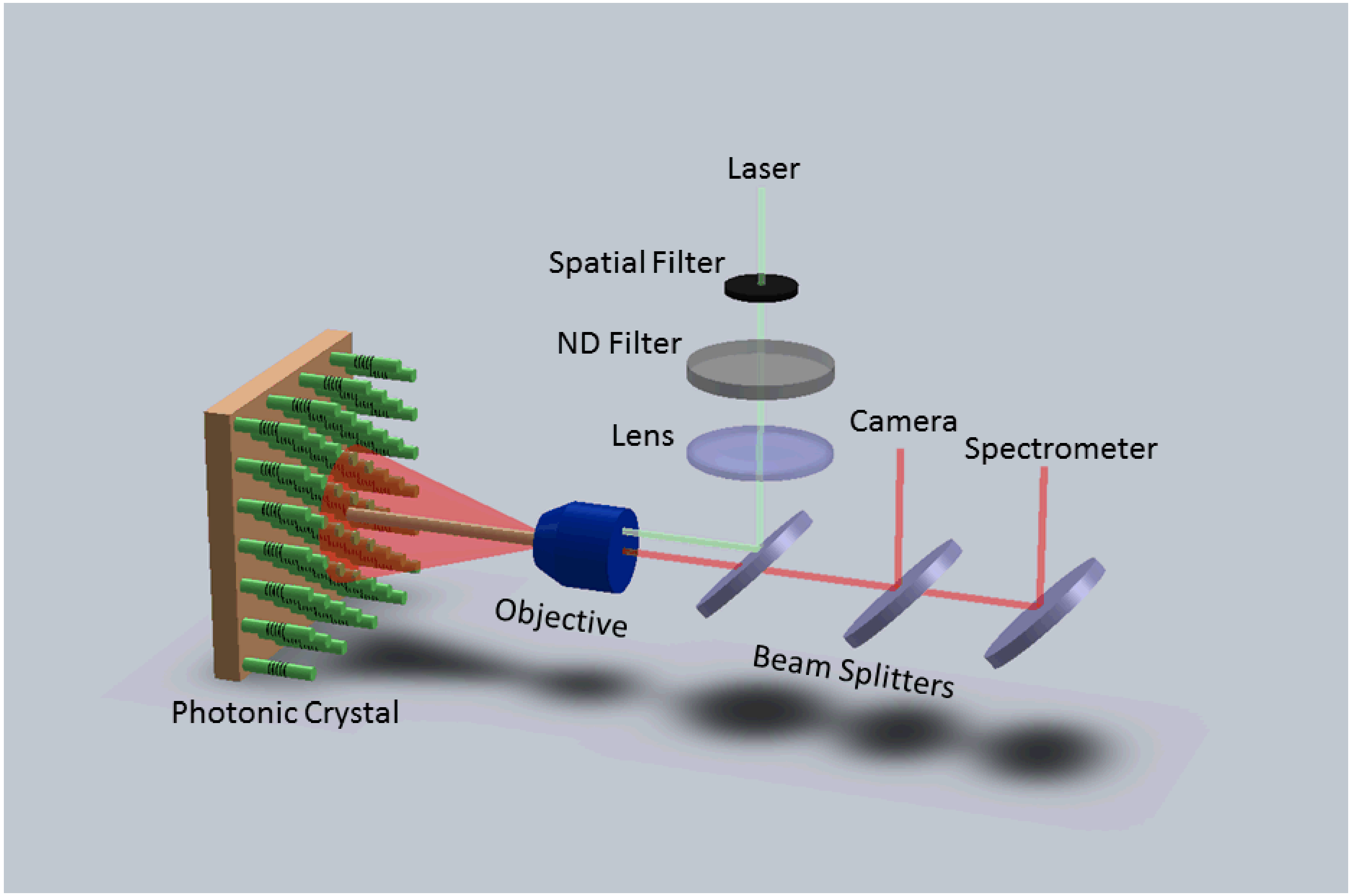
- 5x MQW InGaN Emission Centered at 430nm
- 2% In underlayer
- Slight taper from the InGaN quantum wells





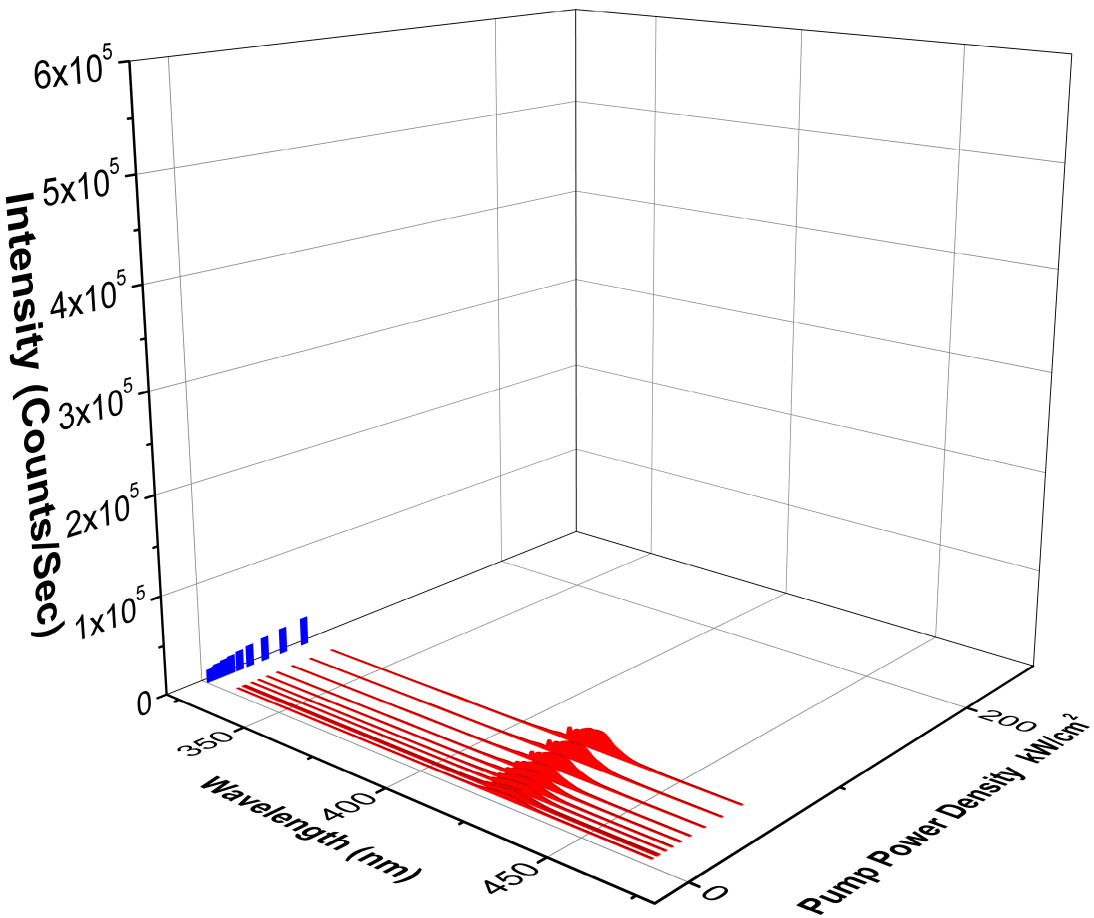
Ping Lu, Sandia

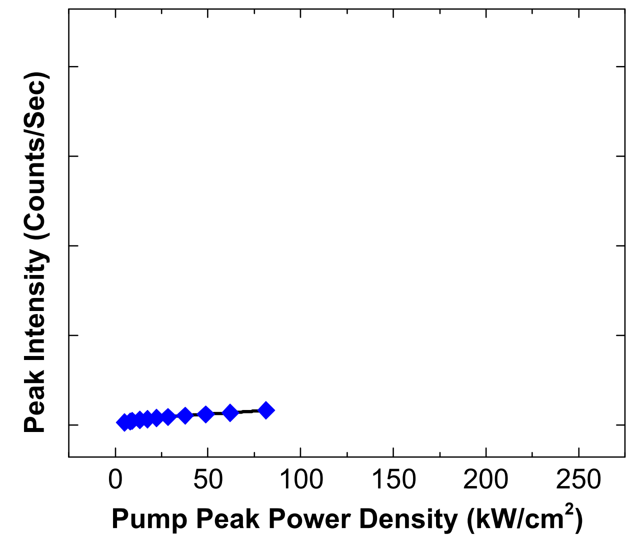
micro-Photoluminescent Optical Characterization

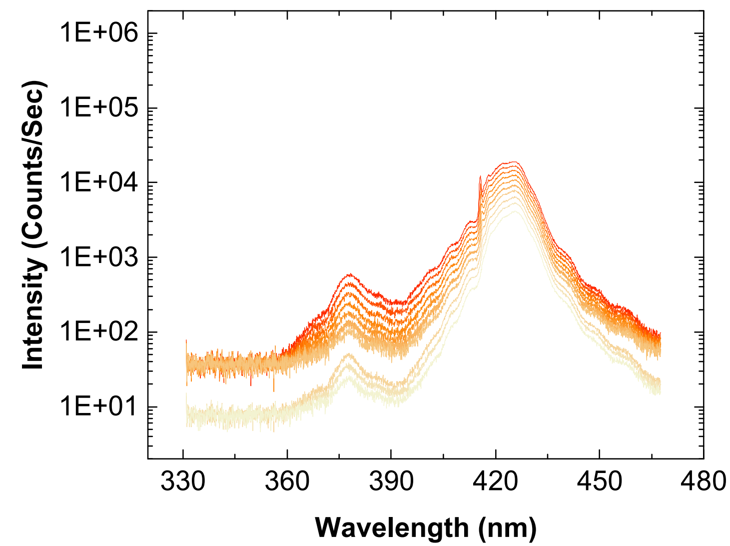


Pump spot is tunable in size and power density.

Below Threshold Spectra of a 2DPC Laser

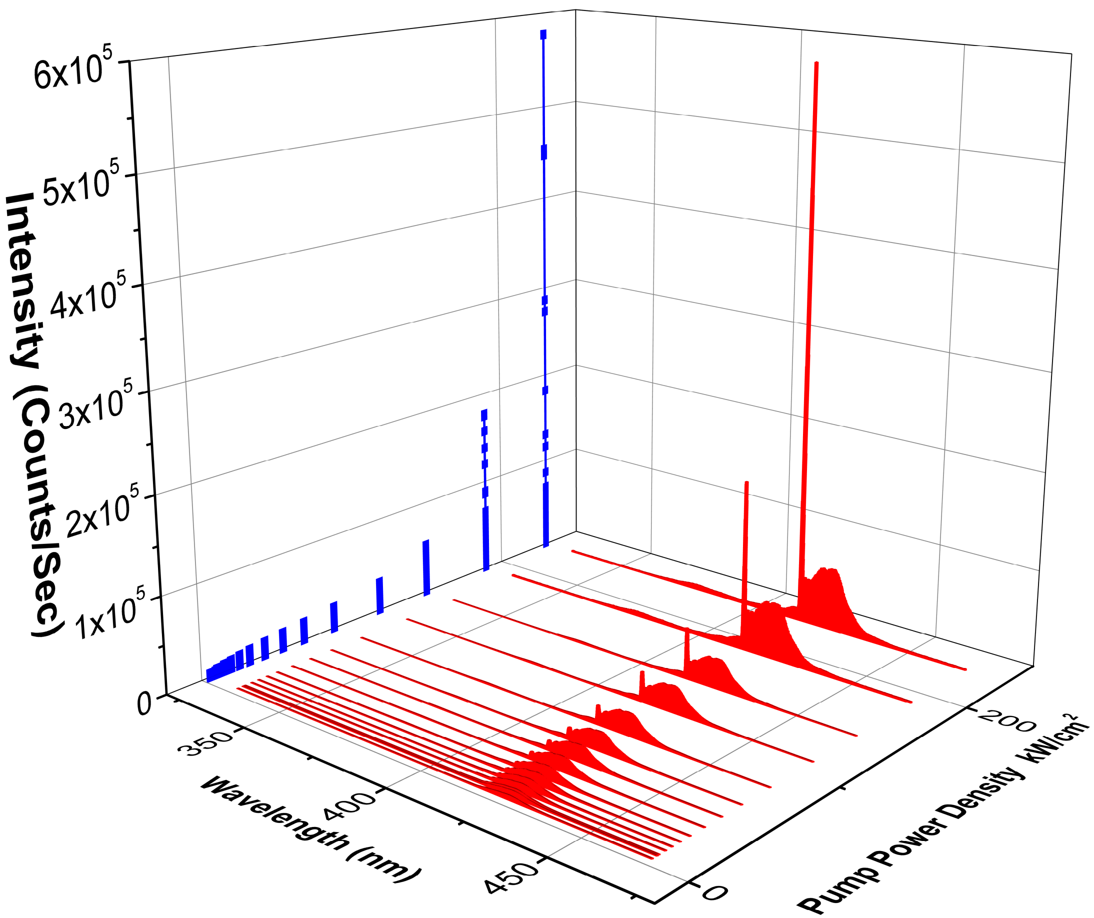


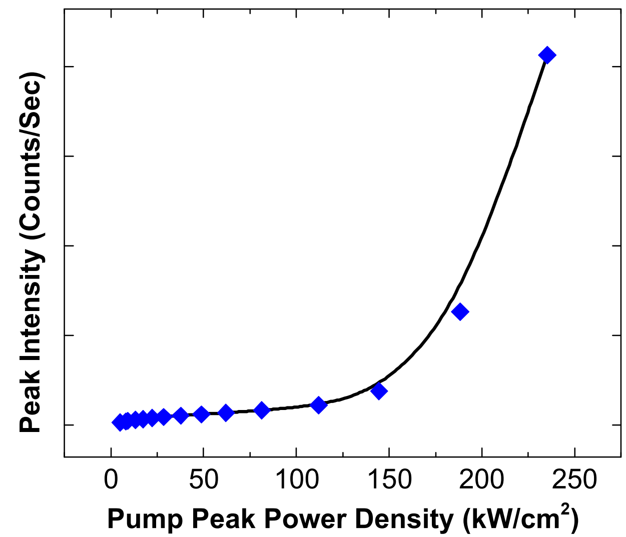


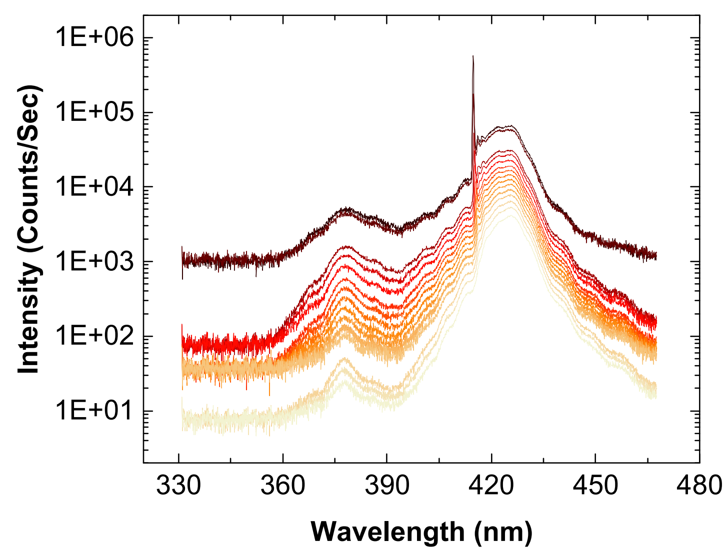


Array Element Dimensions: d=145 nm and a=320 nm.

Above Threshold Spectra of a 2DPC Laser

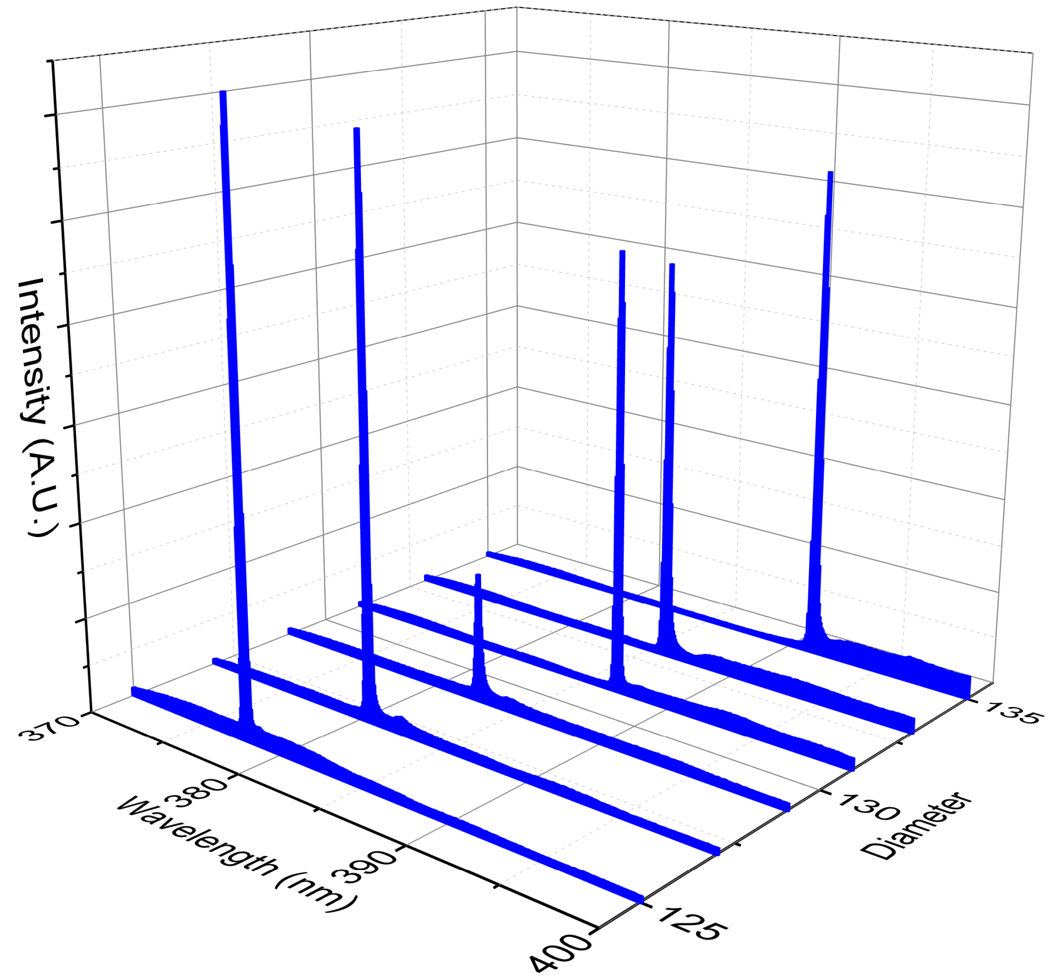




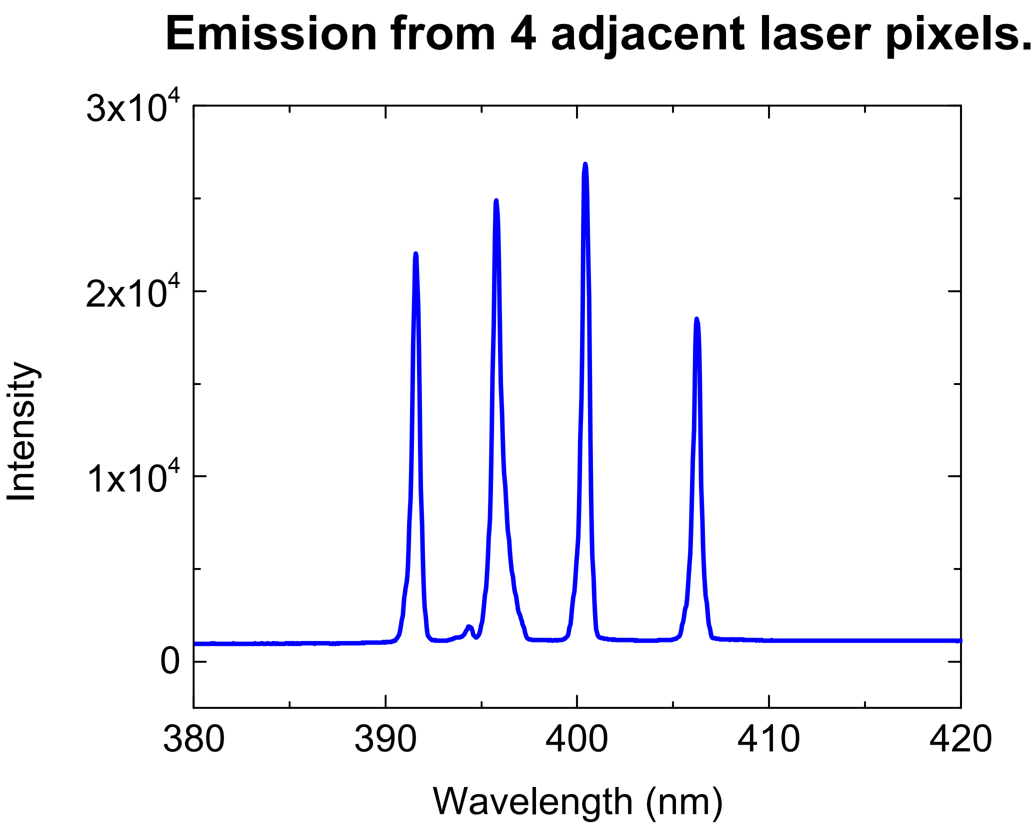


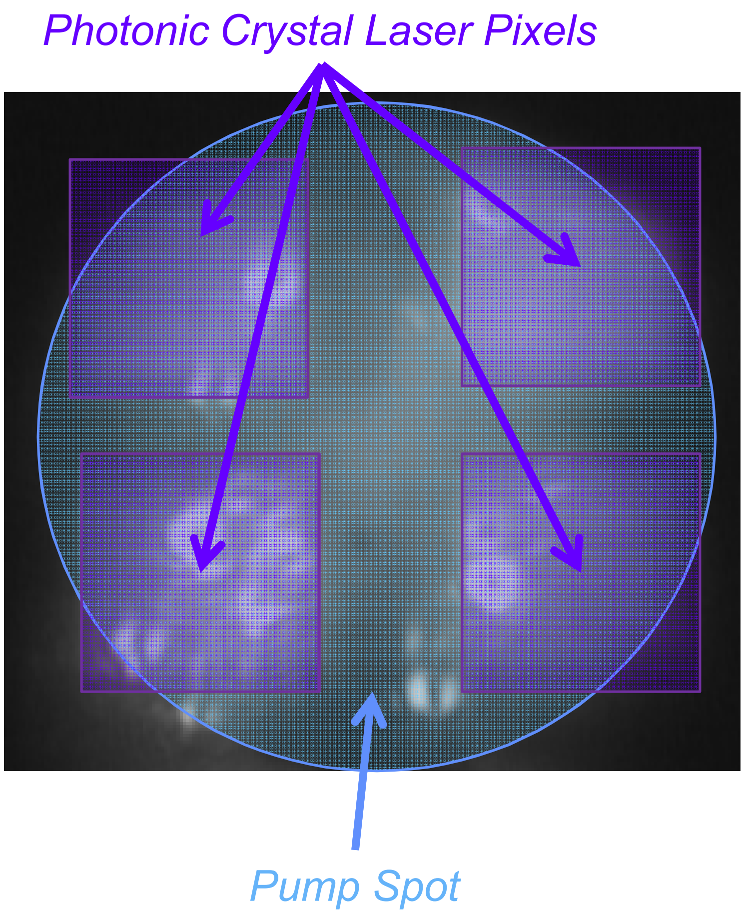
Array Element Dimensions: d=145 nm and a=320 nm.

Diameter Dependent Emission for a given Lattice Constant



Multiple Laser Pixels Coexcited





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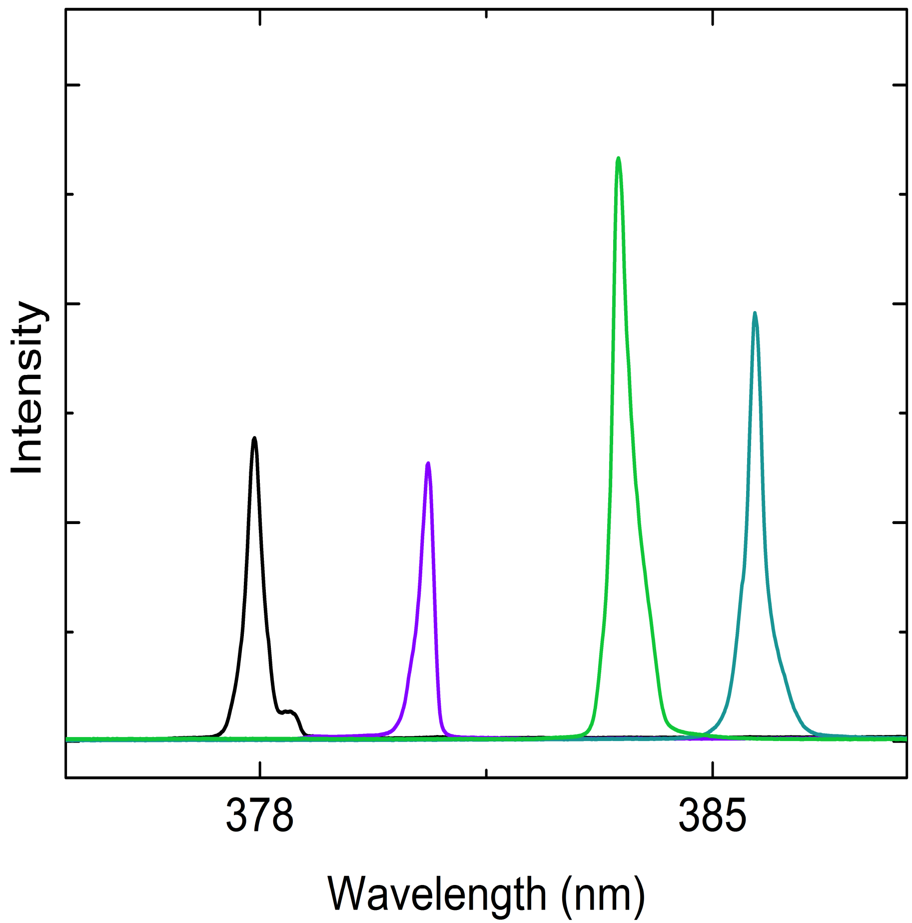
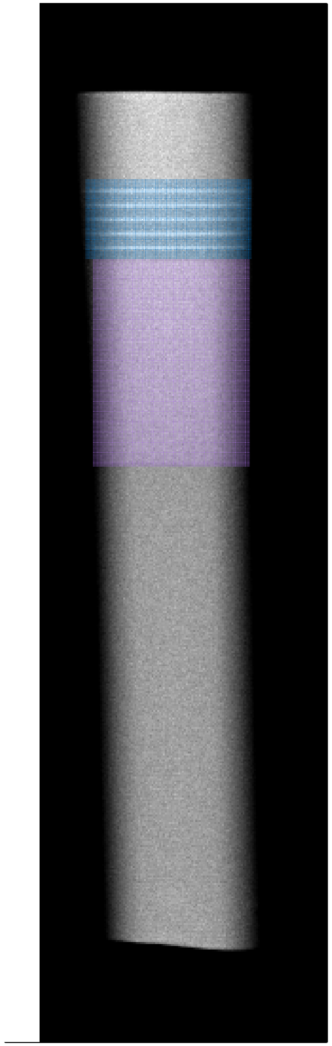
Gain from multiple sections

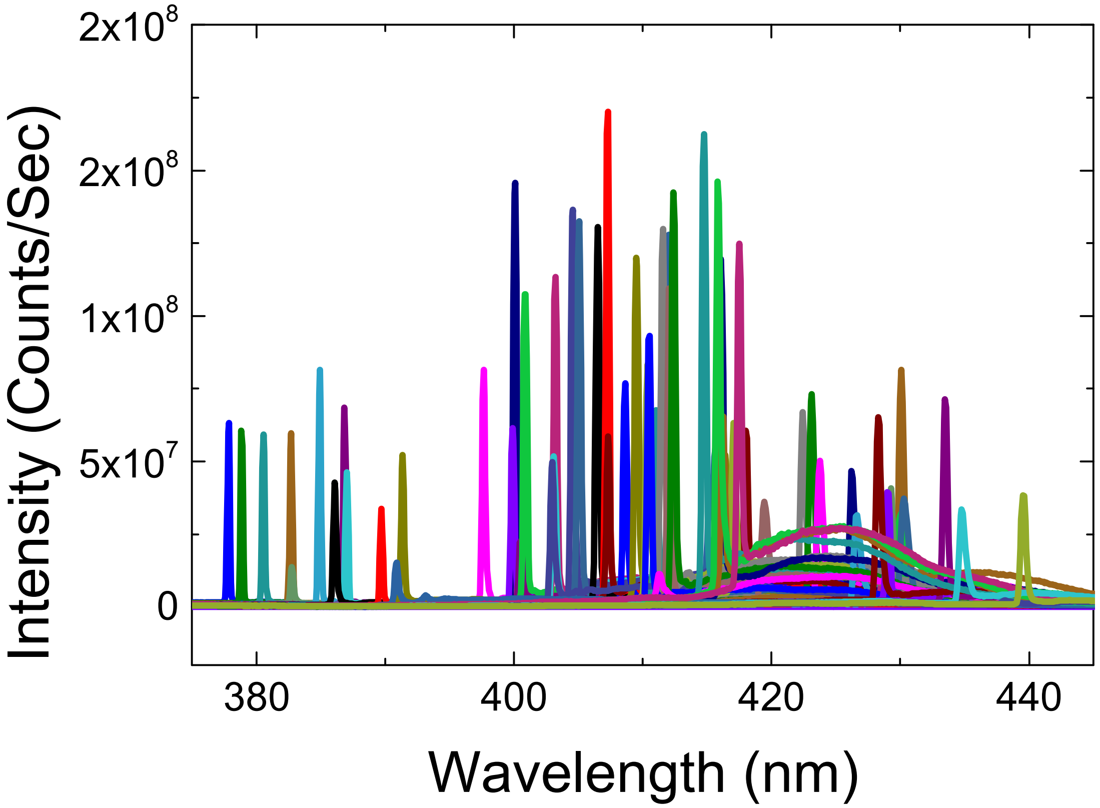




MQW Gain Section

Underlayer Gain Section

Multi-color Laser Array



- **Spectral Coverage from 380-440nm.**
- **Thresholds are reasonable compared to other optically pumped III-N nanowire devices. (<500kW/cm² for all devices)**

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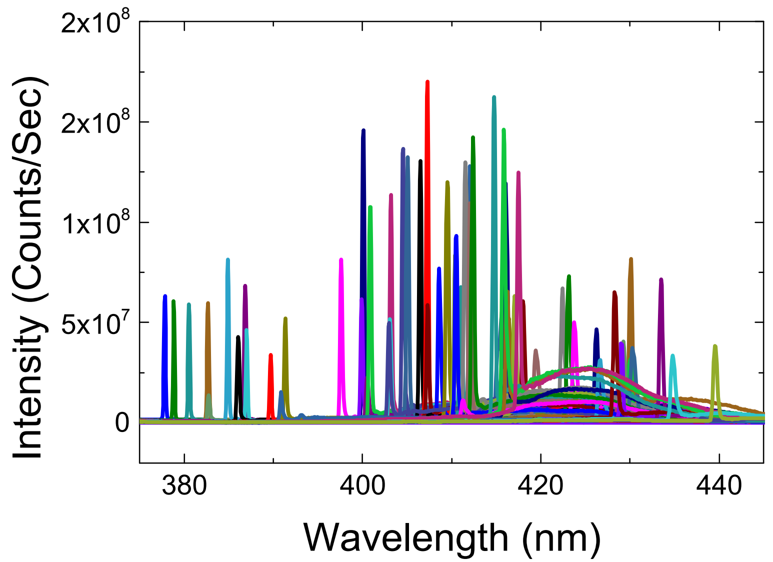
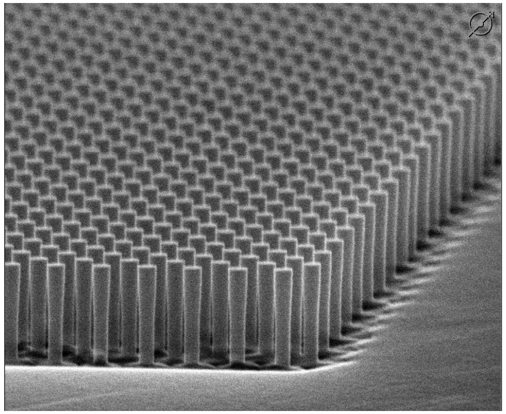
Summary

- **Fabricated laser arrays that span a broad spectral range**
  - **Near-Vertical single-mode emitters**
  - **Thresholds are non-homogeneous but remain reasonable for optical pumping experiments**
  - **Possible to fabricate high density of emitters with a larger wavelength span**
- **Technology implications**
  - **Lasers for SSL**
  - **Displays and projectors**





Thank you for your attention!

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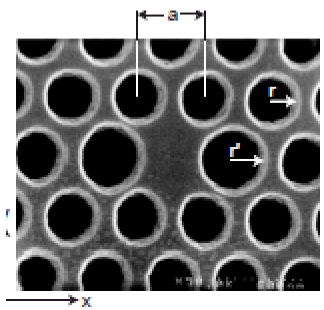
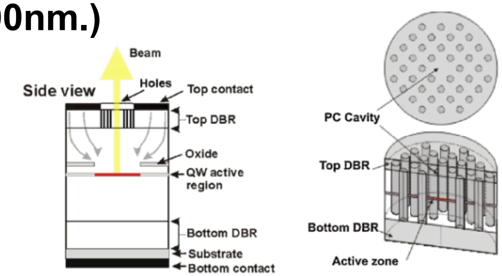
BACKUP MATERIAL

Previous Work

Most work on PCLs has been limited to Phosphides, Antimonides, and Arsenides. (λ>700nm.)

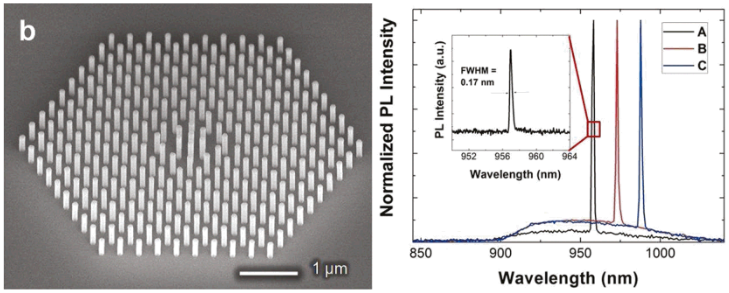


Painter, O. *et al. Science* ***284 (1999).***



Ivanov et al…0268-1242_27_9_094010

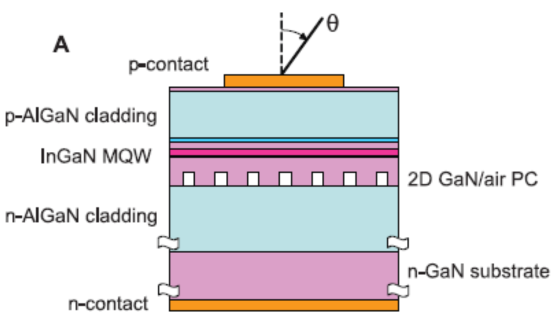
Previous tuning results limited to <30nm

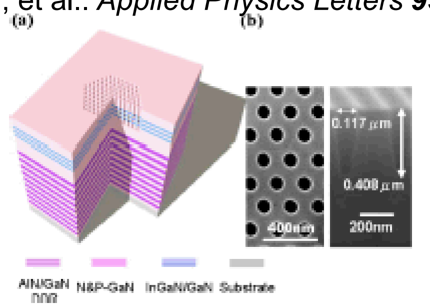


Scofield, A. C. *et al. Nano Lett.* ***11, (2011).***

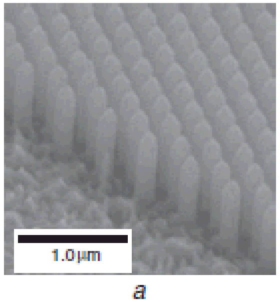
III-N difficult to fabricate or lack of tuning

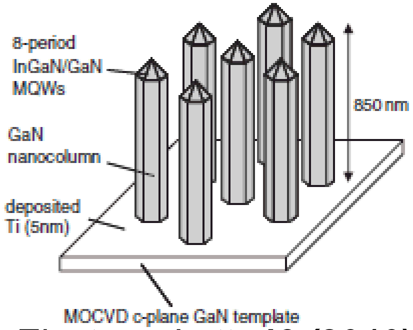
Lu, T.C., et al.. *Applied Physics Letters* ***93 (2008).***





Matsubara, H. *et al.. Science* ***319, 445-447, (2008).***





Kouno, T. *et al. Electron. Lett.* ***46 (2010)***

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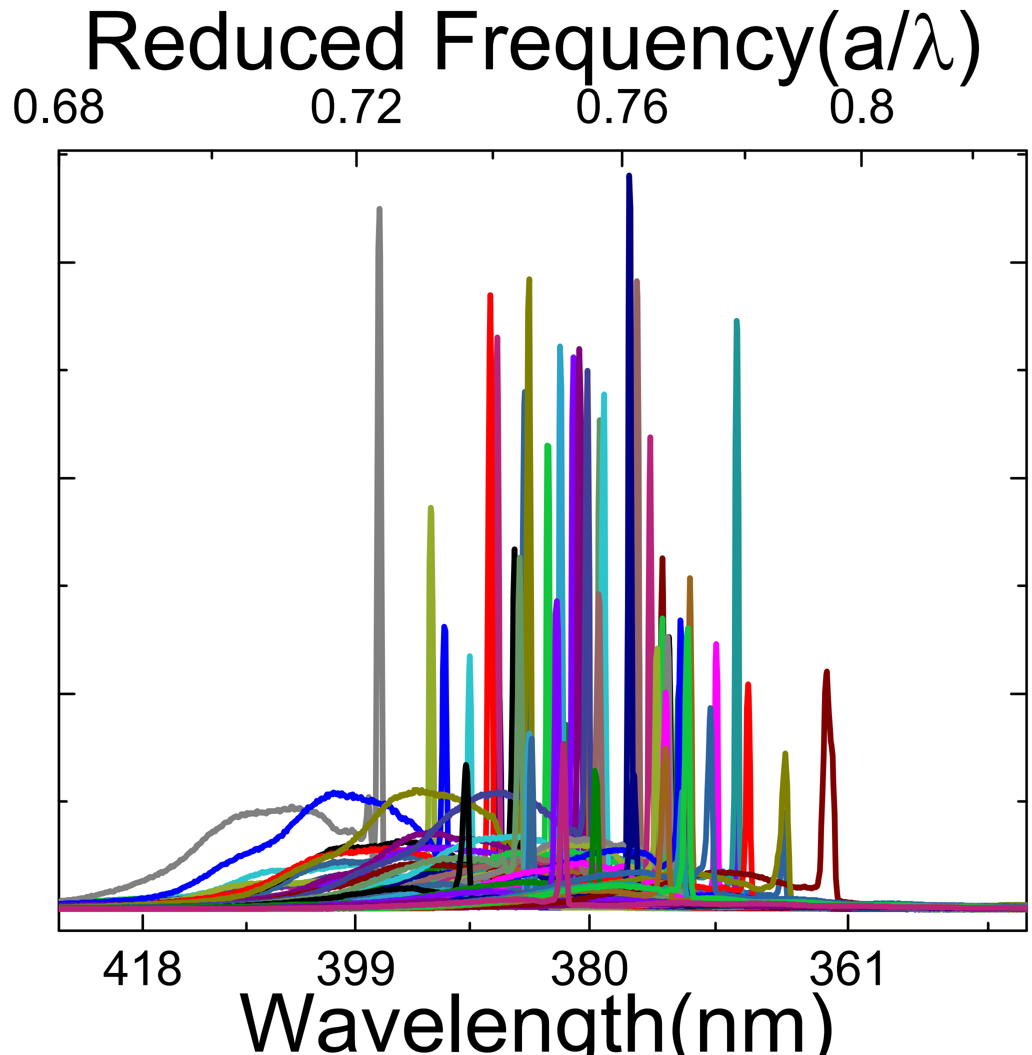
Lasing as a function of reduced frequency



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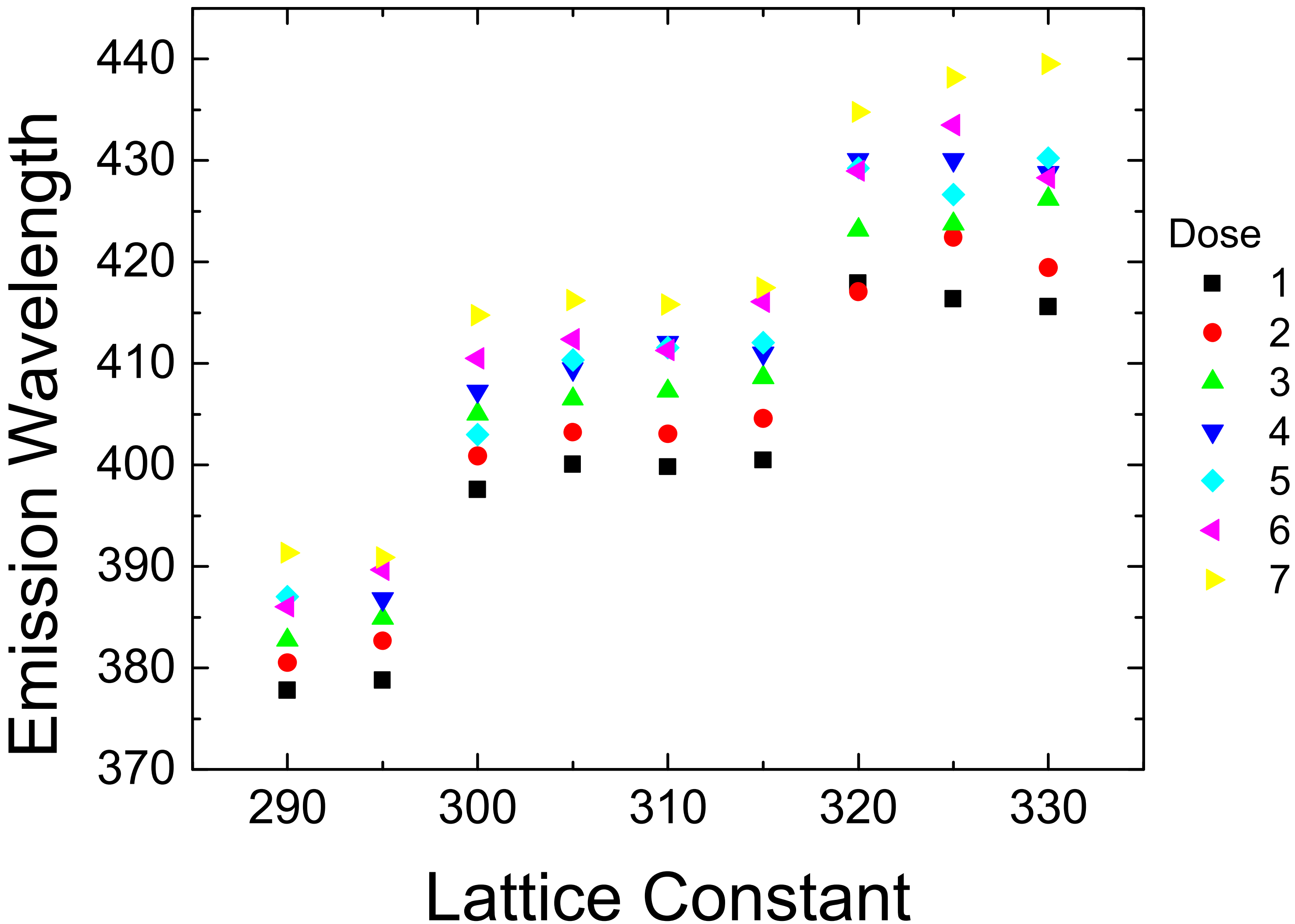
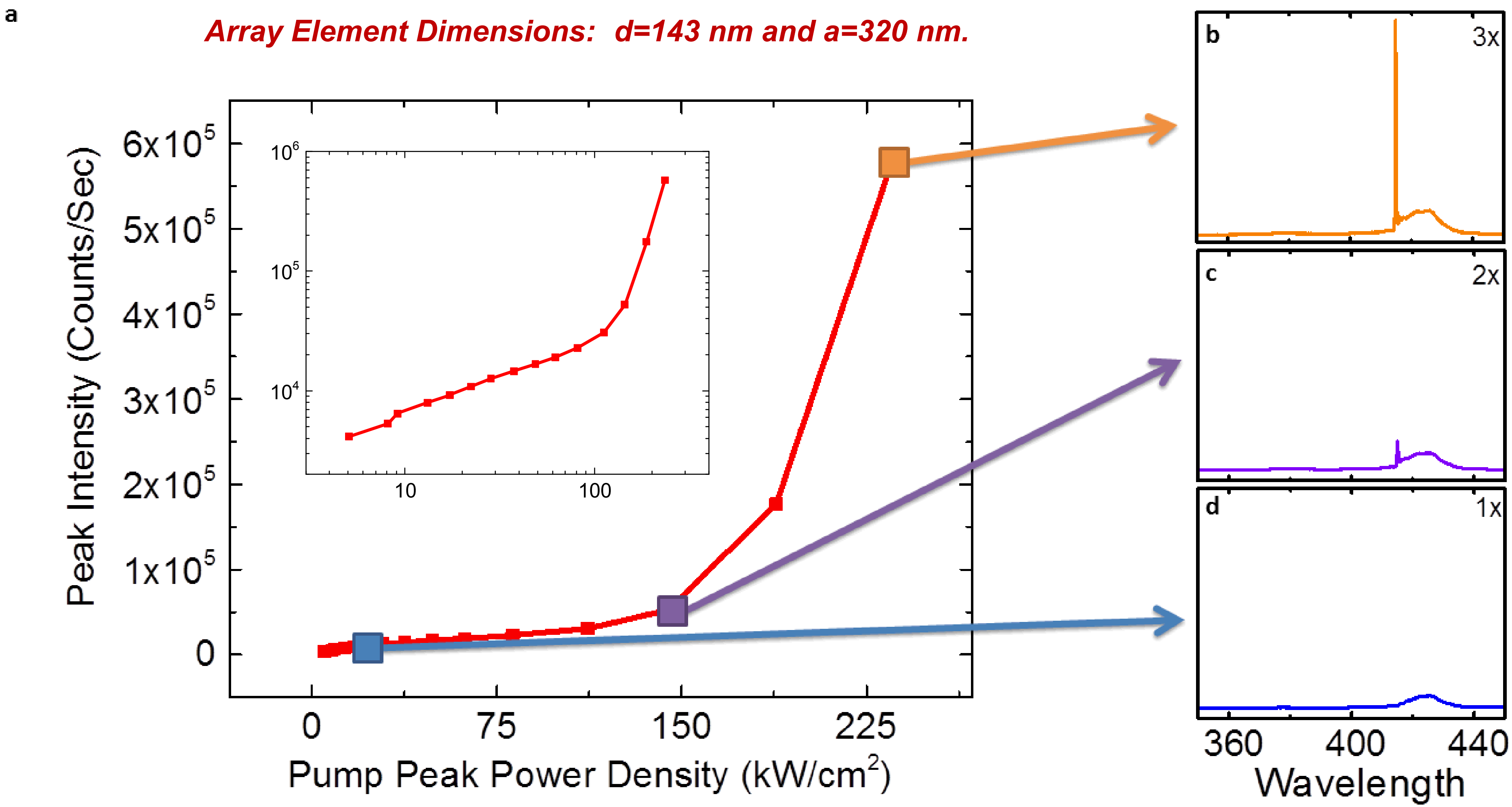
Lasers



Emission Wavelength
440
430
420
410
400
390
380
370
290
300
310
320
330
Lattice Constant
Dose
1
2
3
4
5
6
7

Optical Results from a single array element

Array Element Dimensions: d=143 nm and a=320 nm.



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Motivation

- Fabricate an array of different color lasers on a single chip that emit vertically with single-mode operation.
- Ideal spectral coverage would span the visible wavelengths.
- Optical Information Processing, Biology, Solid State Lighting, and Displays