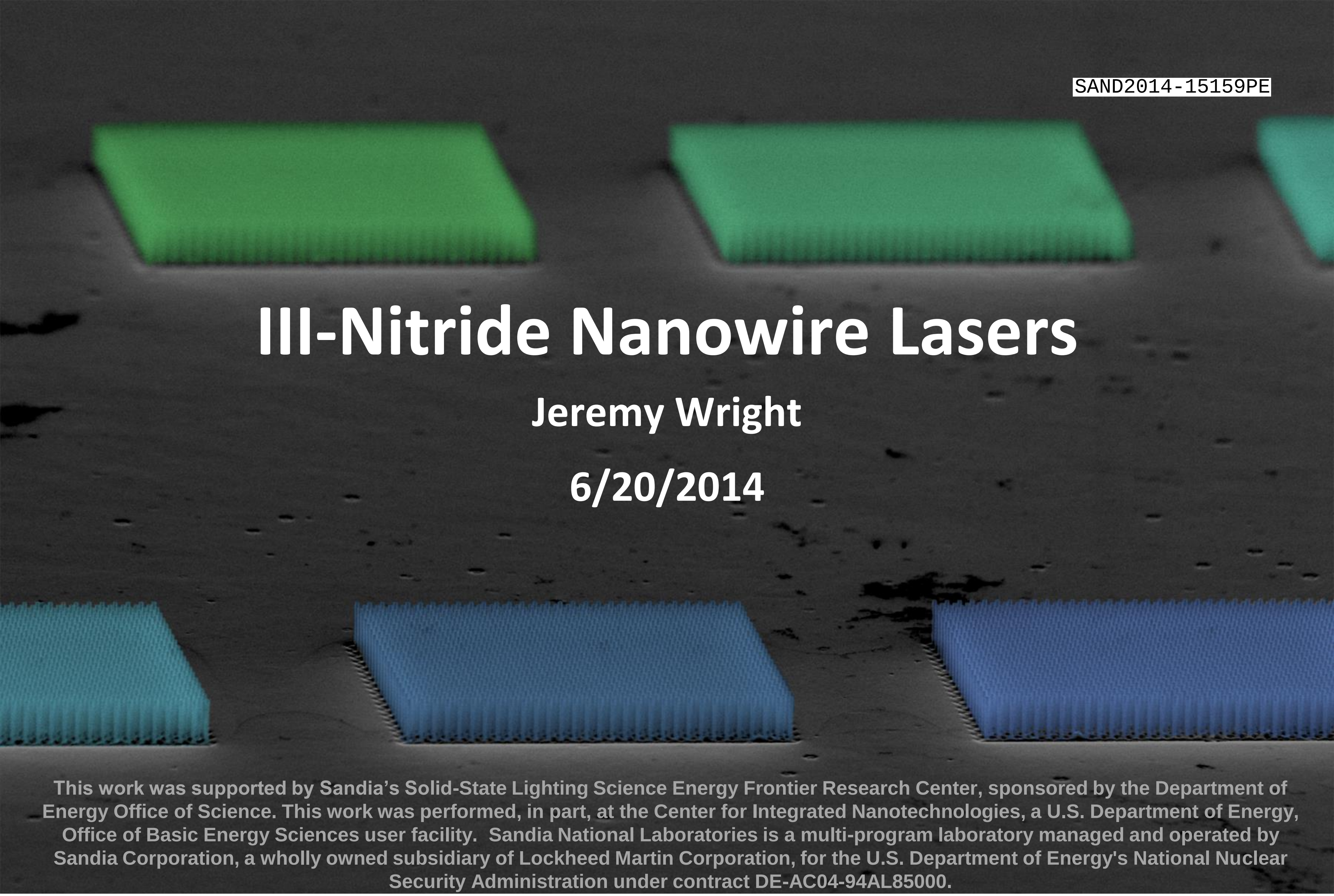
SAND2014-15159PE



III-Nitride Nanowire Lasers

Jeremy Wright

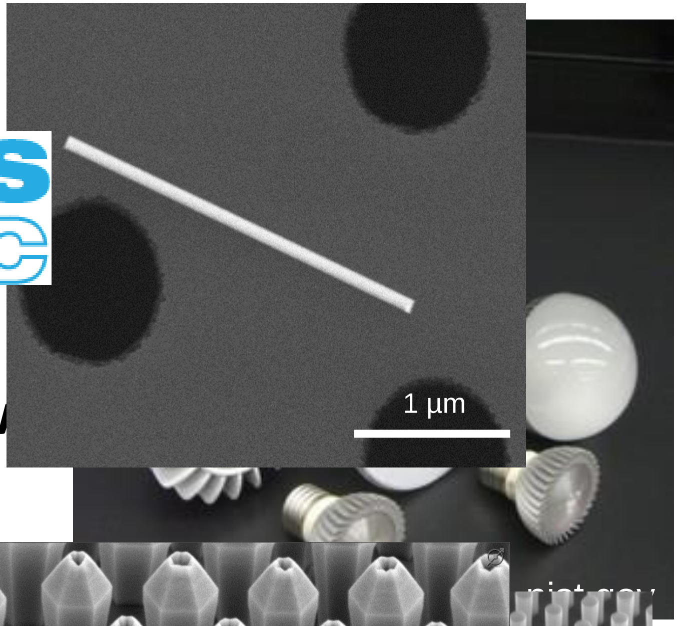
6/20/2014

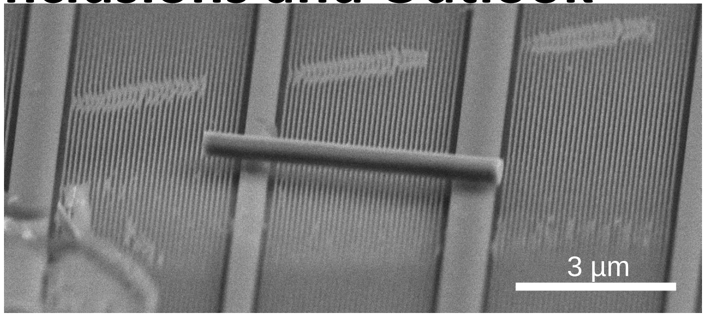
This work was supported by Sandia's Solid-State Lighting Science Energy Frontier Research Center, sponsored by the Department of Energy Office of Science. This work was performed, in part, at the Center for Integrated Nanotechnologies, a U.S. Department of Energy, Office of Basic Energy Sciences user facility. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

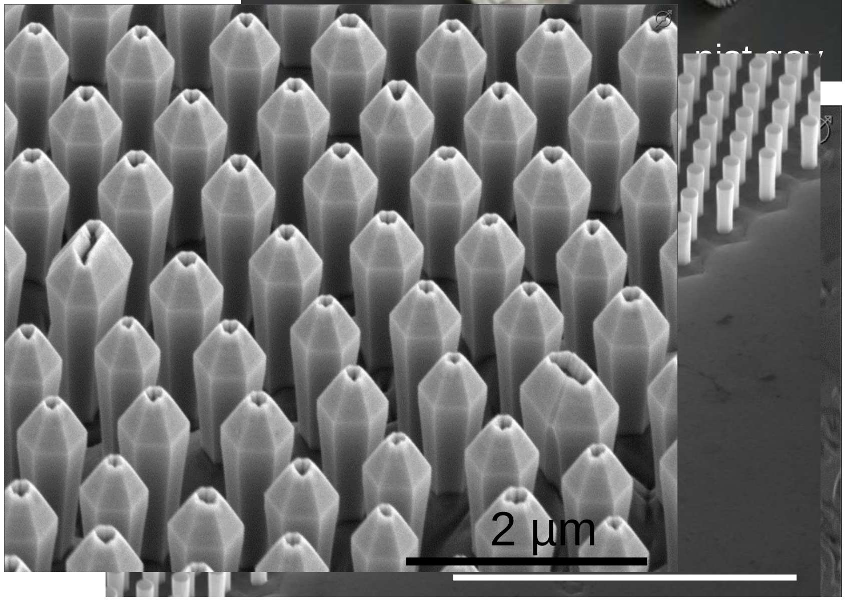
SSLS EFRC | CHTM Center for High Technology Materials | THE UNIVERSITY of NEW MEXICO | Sandia National Laboratories

Outline

- **Motivation**
  - **Solid state lighting**
  - **Nanowire lasers**
  - **Top-down nanowires**
- **Single-mode lasing from single nanow**
  - **Geometric reduction**
  - **Distributed feedback**
- **Photonic crystal laser "pixels"**
- **Conclusions and Outlook**

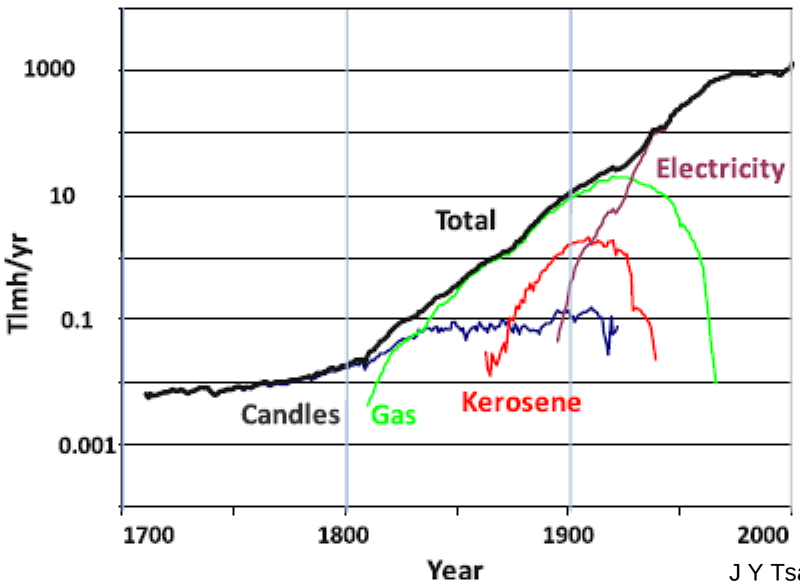


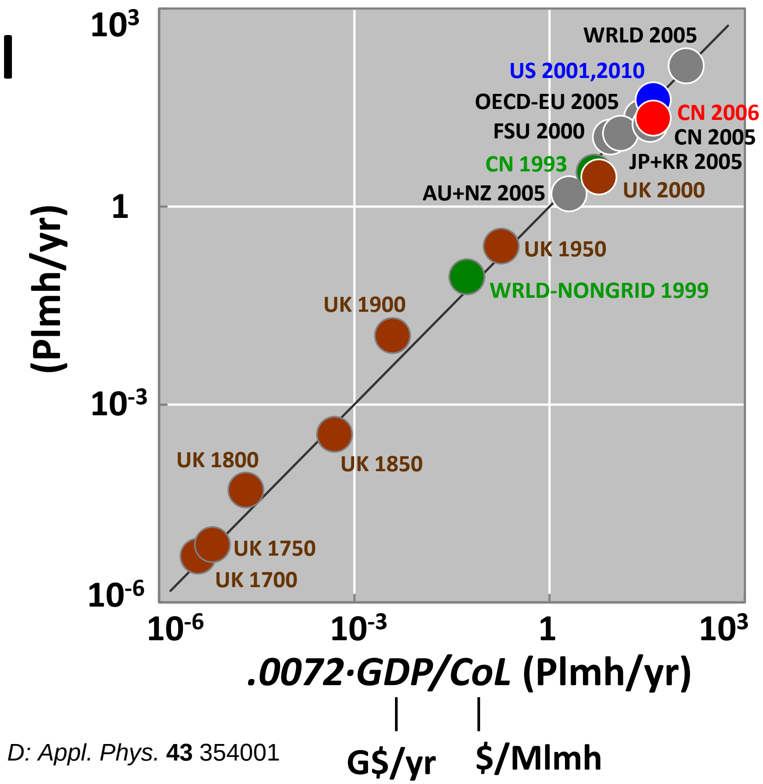




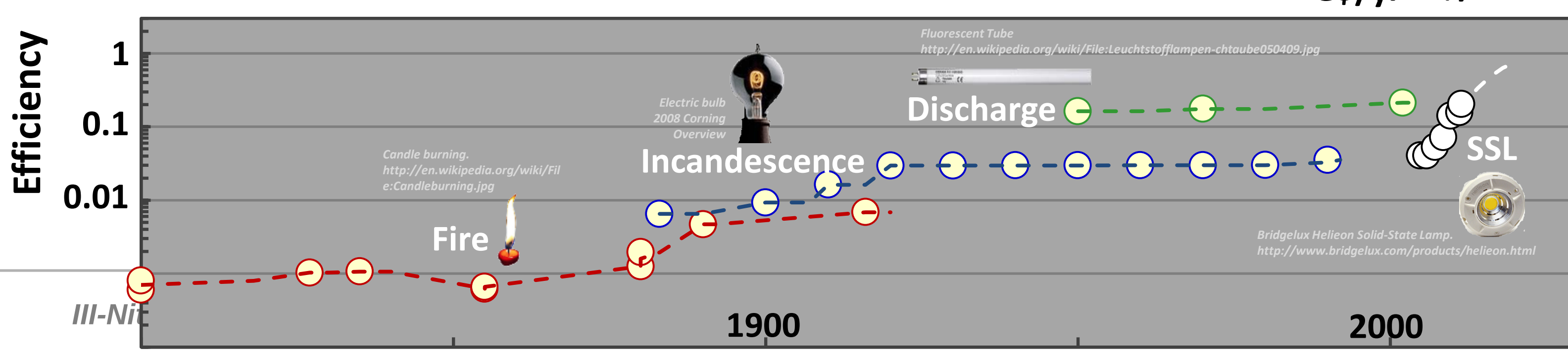
The consumption of light

- Human productivity is tied to light
- The global demand for lighting is still increasing





J Y Tsao *et al* 2010 *J. Phys. D: Appl. Phys.* **43** 354001



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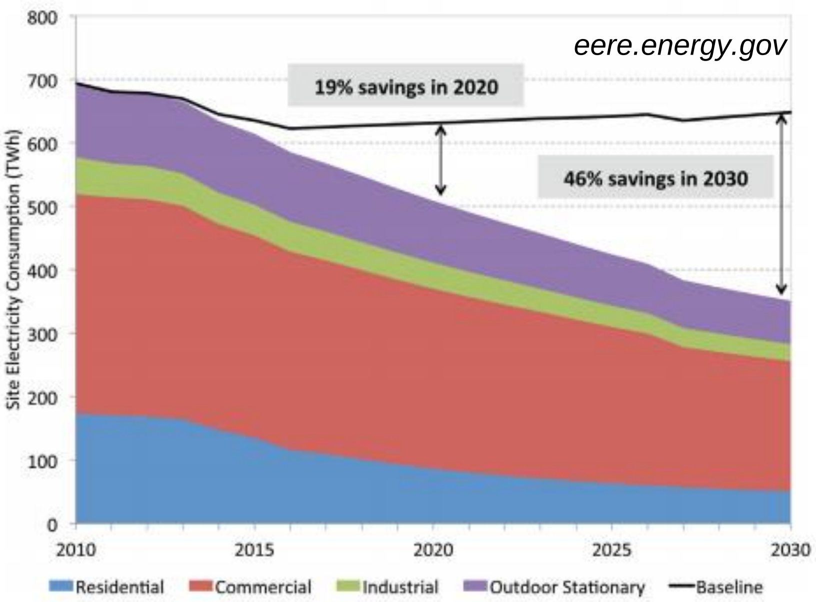
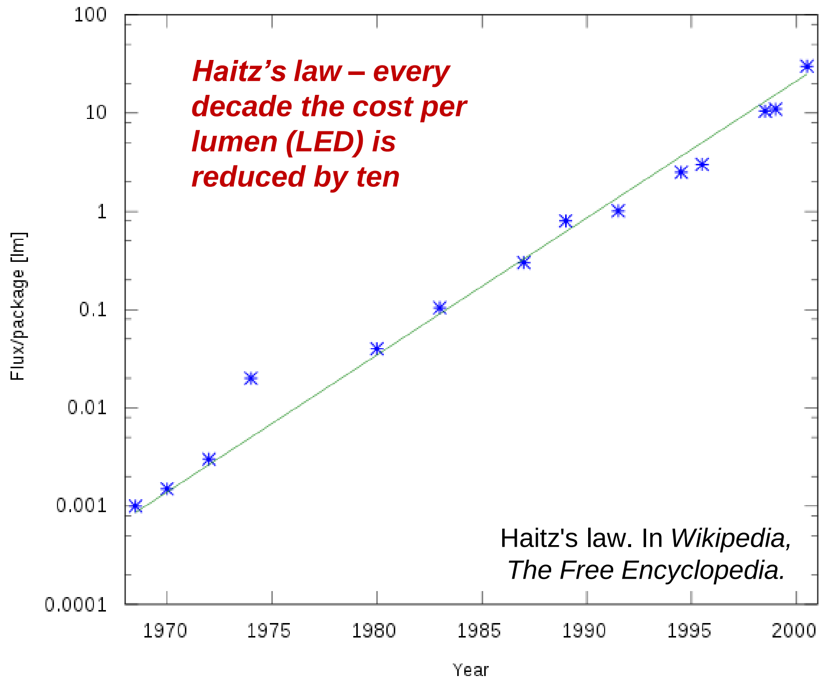
Benefits of Solid State Lighting (SSL)

It is estimated that switching to SSL over the next two decades could save the country:

- **$250 billion in energy costs over that period**
- **Reduce the electricity consumption for lighting by nearly one half**
- **Avoid 1,800 million metric tons of carbon emission.**





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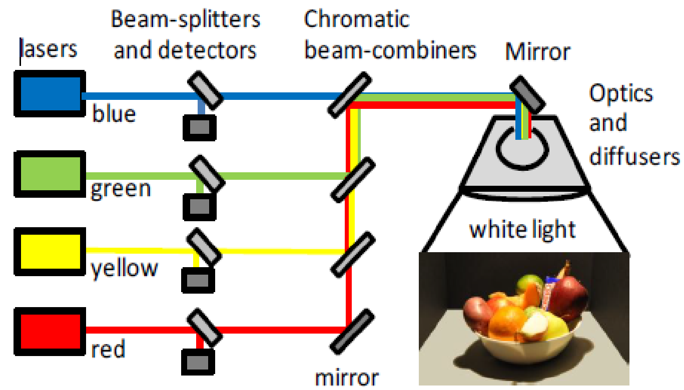
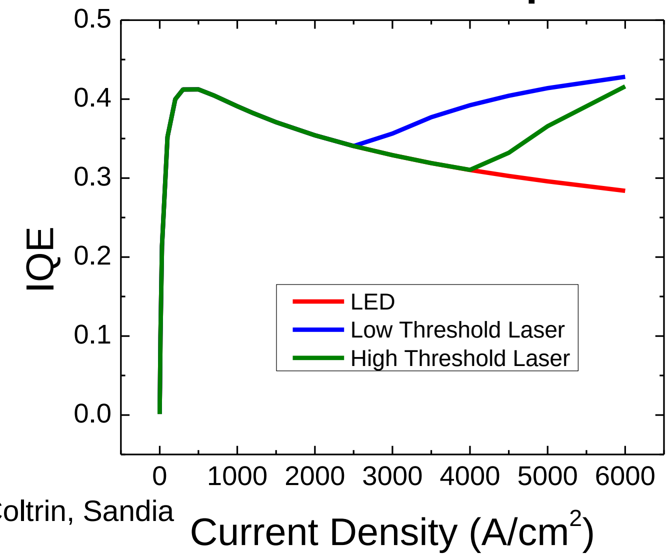
Lasers for lighting?

- **The "efficiency droop"**
  - **InGaN LEDs exhibit a decrease in efficiency at high drive currents**
    - **This is worsened with In content**
  - **Limits the operating current density**
    - **Operated near peak IQE**
  - **Increases the cost per lumen**



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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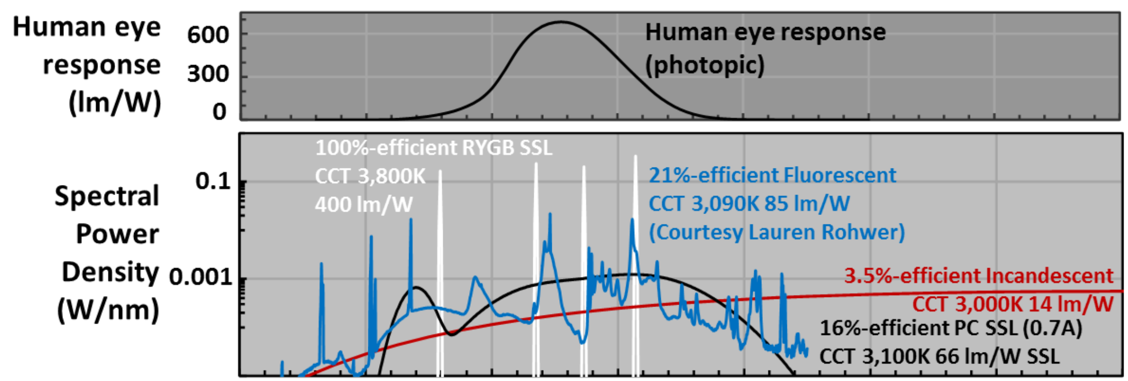

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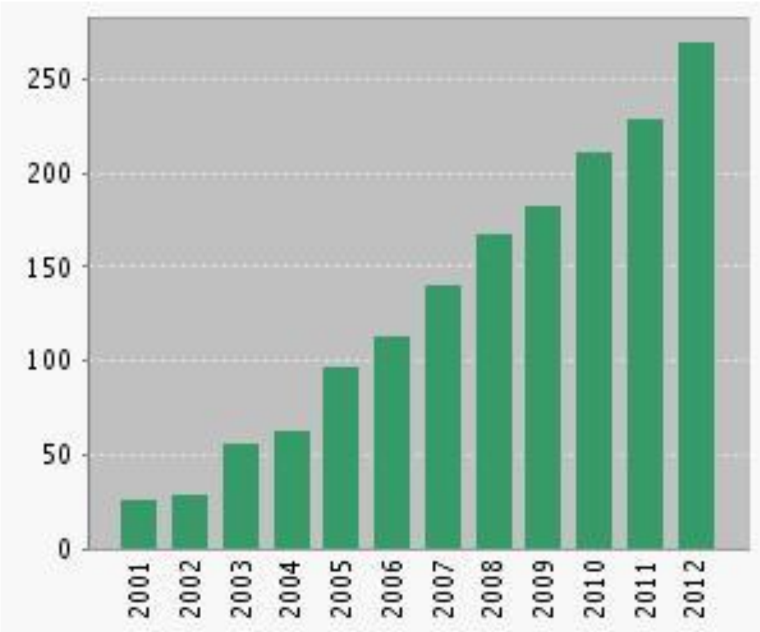
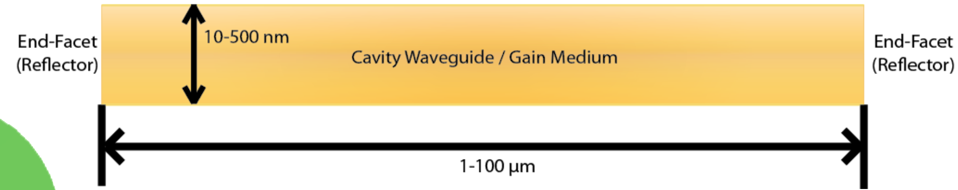
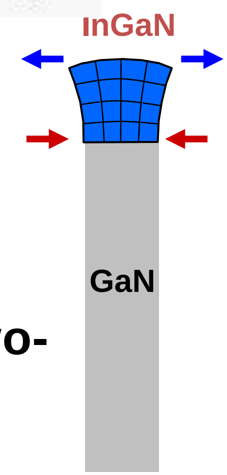
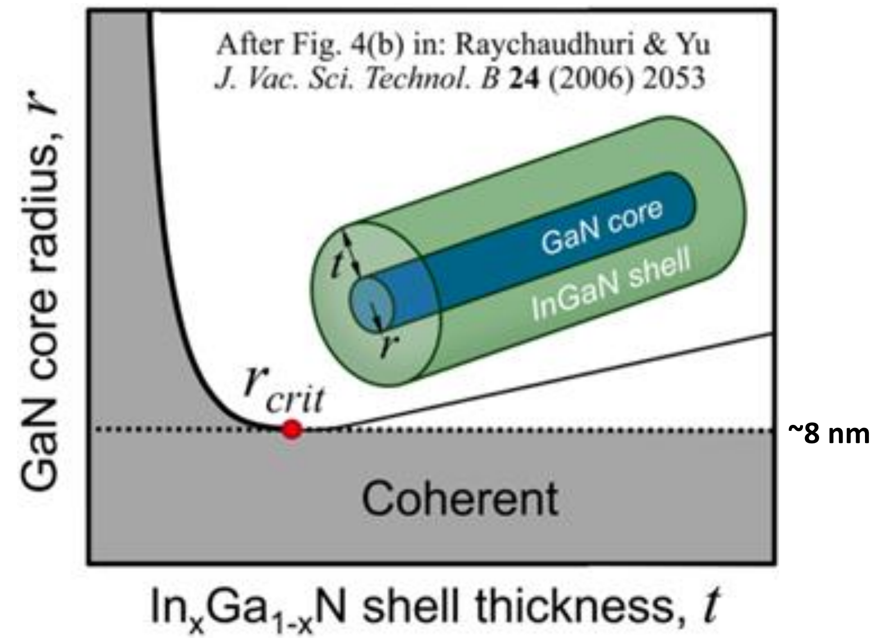
Nanowire lasers





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





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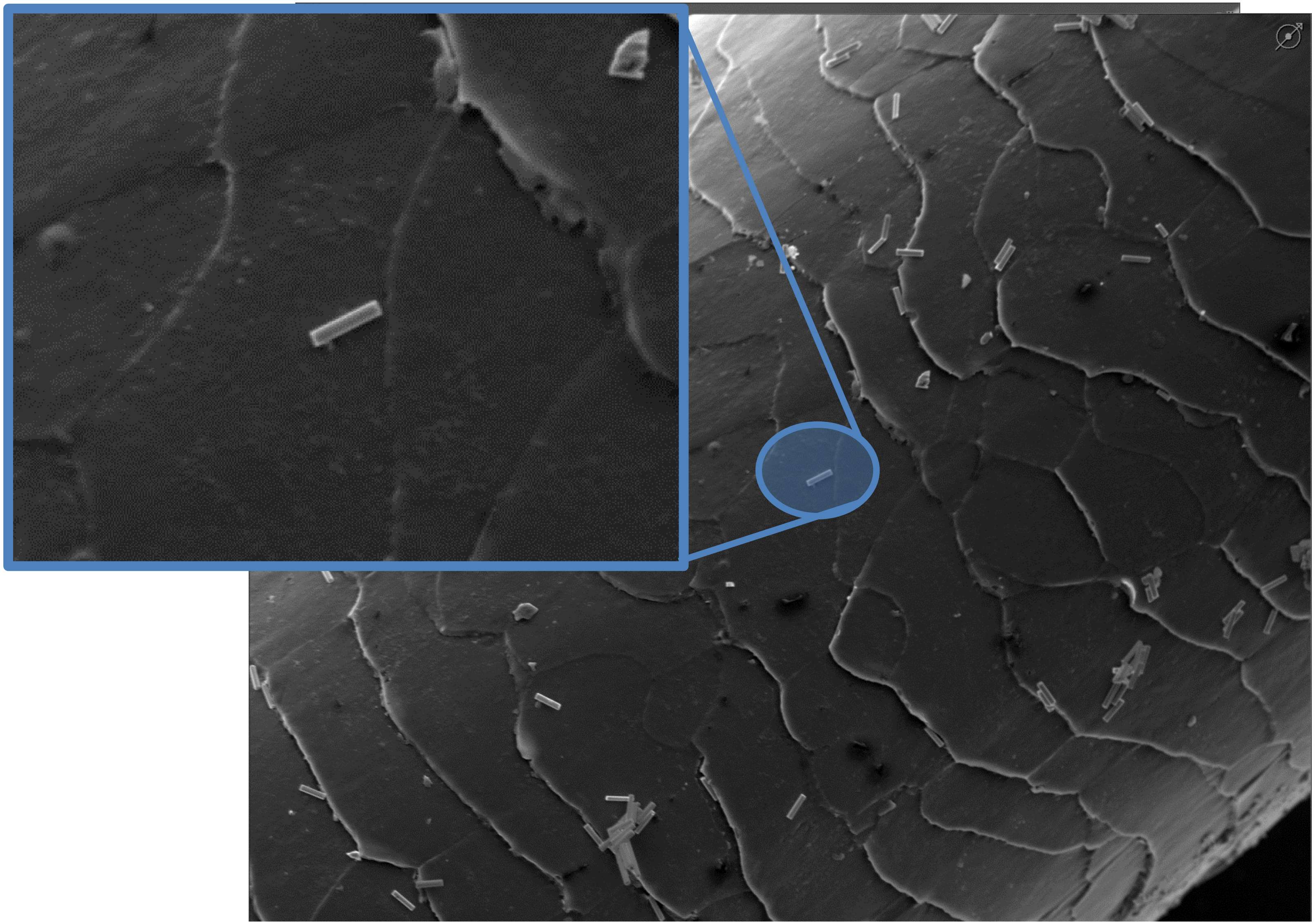
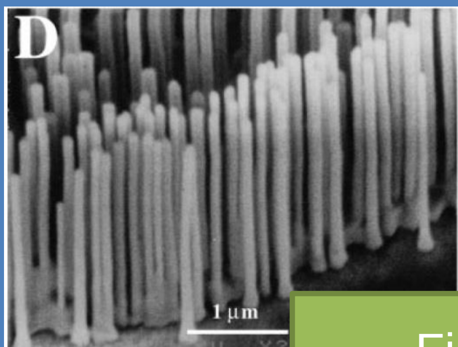
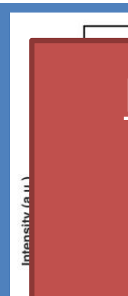
Nanowire Scale | A size comparison



Previous Nanowire Lasers

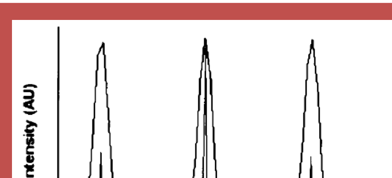
First demonstration of lasing from an ensemble of nanowires (ZnO)

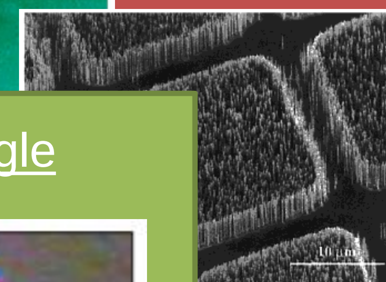




Room-Temperature U
Nanowire Nanolasers
M. H. Huang *et al* Scie
June 2001: **292** (5523
189

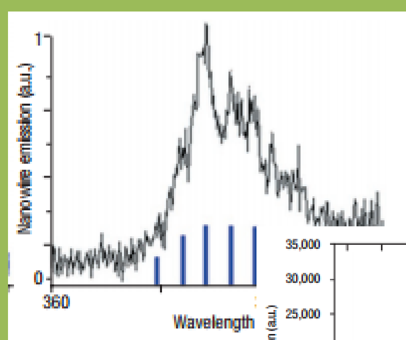
First demonstration of lasing from a single nanowire (ZnO)

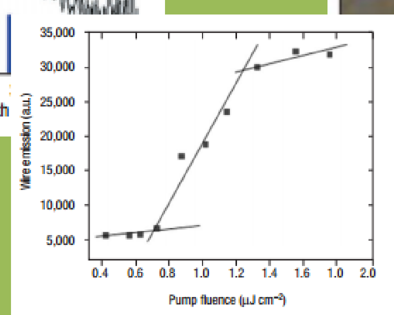


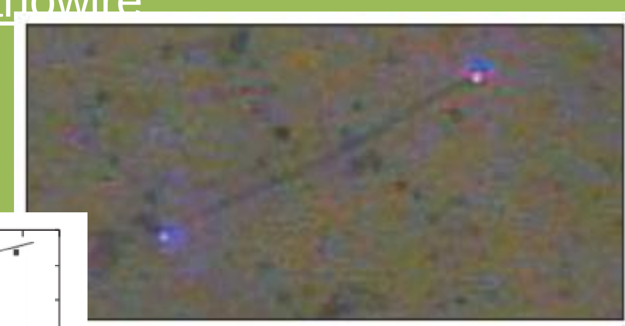


nal of Physical
1387-11390

First demonstration of lasing from a GaN single nanowire



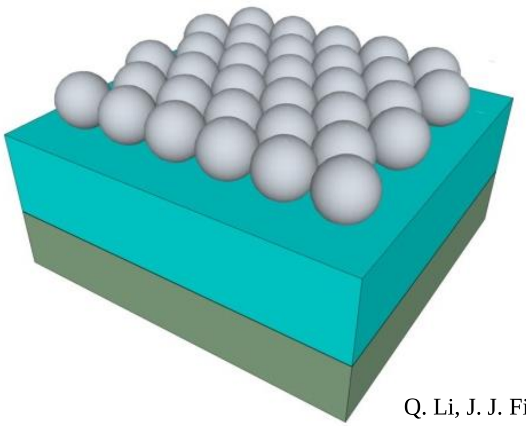


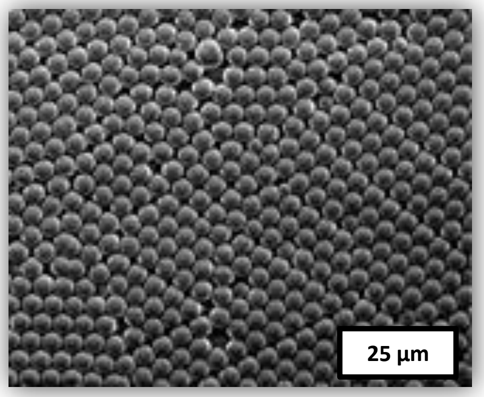


Single gallium nitride nanowire lasers
J. C. Johnson *et al*.
Nature Materials **1**, 106 - 110 (2002)

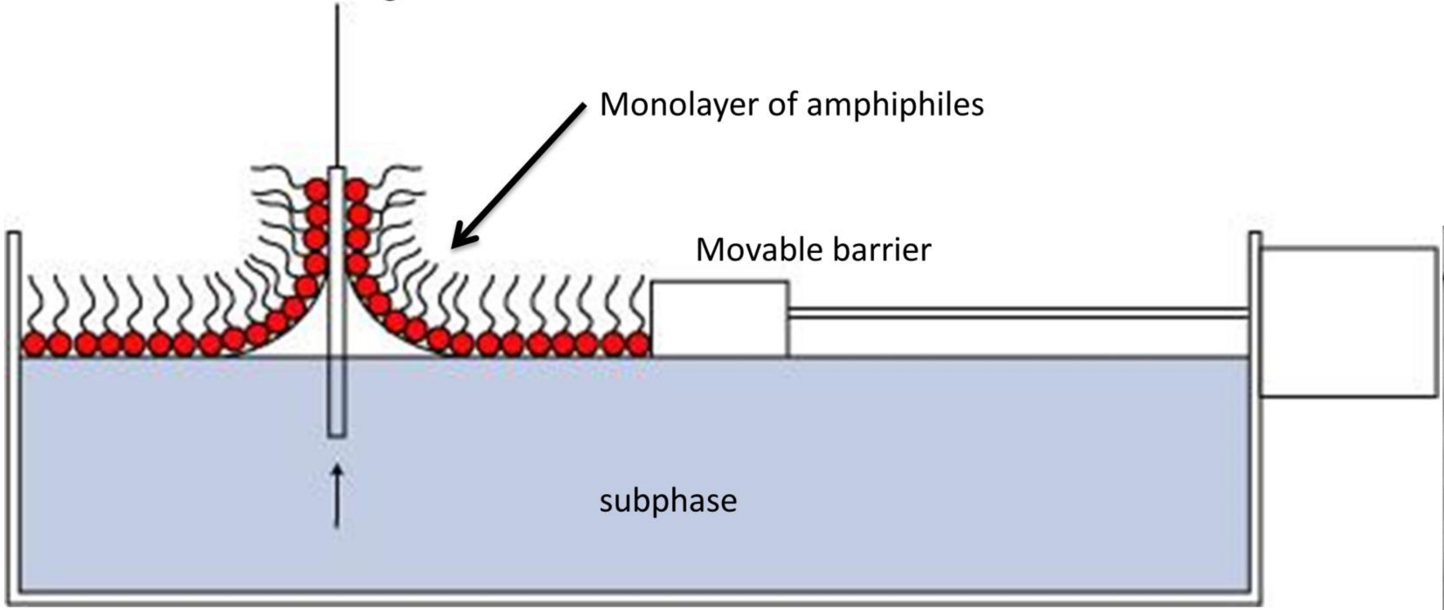
Top-down Nanowire Fabrication | Patterning

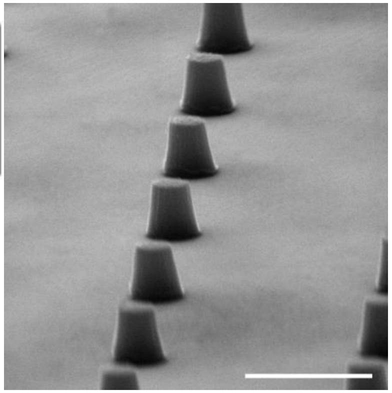
- Silica Microsphere Patterning
  - Self-assembly
  - Wafer-Scale
  - Locally ordered
  - Fixed diameter/spacing ratio





Q. Li, J. J. Figiel, G. T. Wang, Appl. Phys. Lett., **94**, 231105 (2009).





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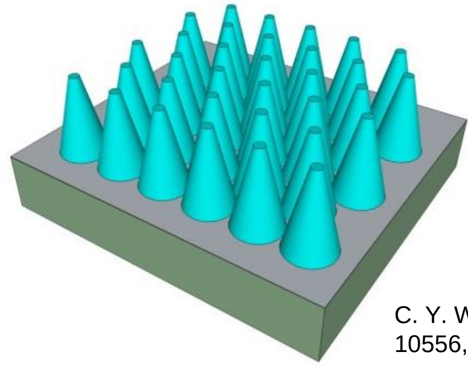
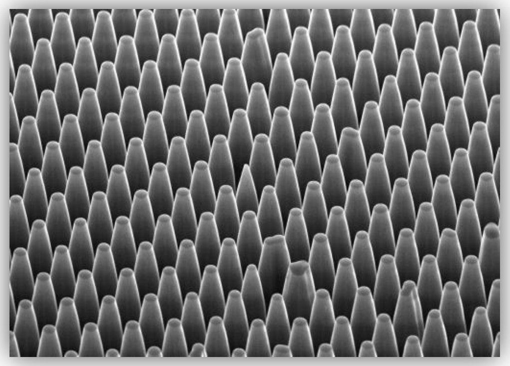
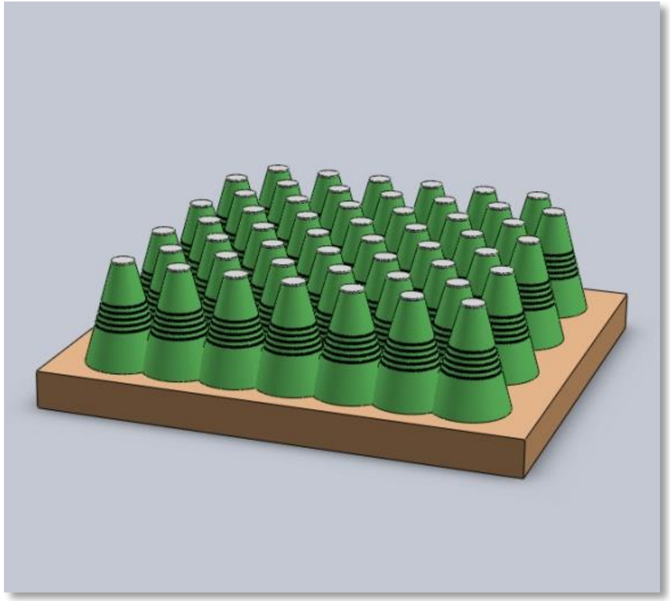
Top-down Nanowire Fabrication | top-down 2-step etch process – dry etch

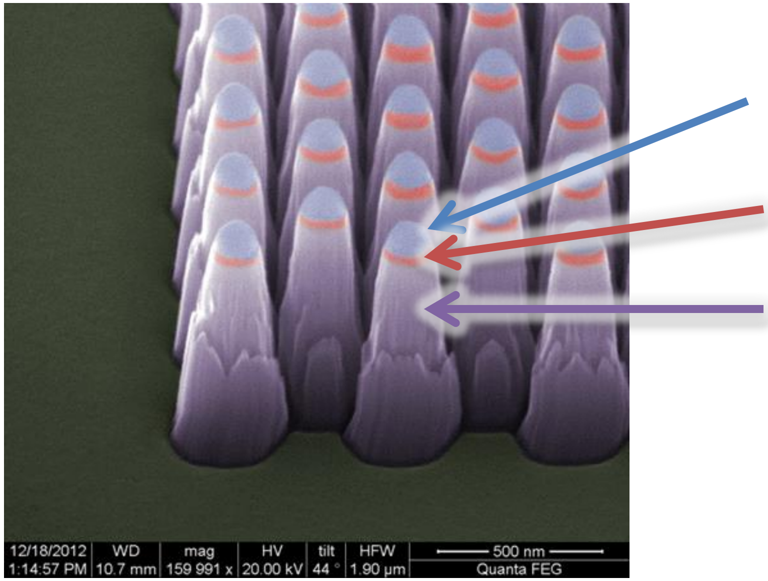
- **Dry inductively coupled plasma etch (ICP)**
  - **Transfers pattern into the epitaxial material**



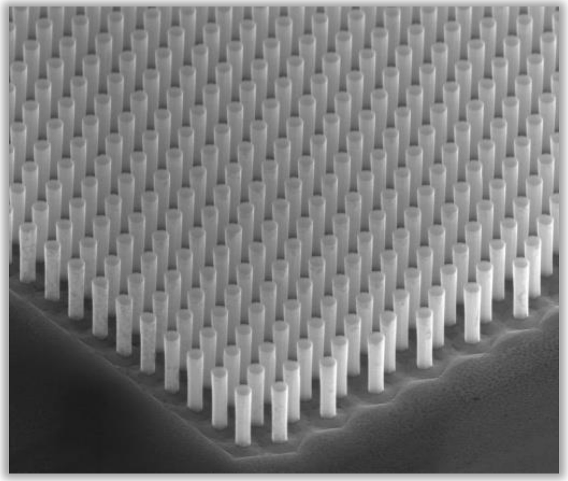


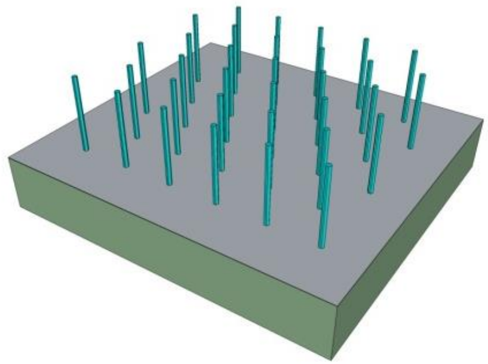
C. Y. Wang et al., Opt. Expr. *16,* 10549–10556,2008.

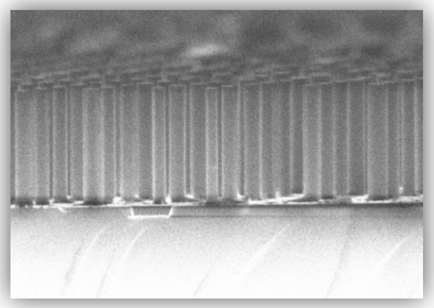


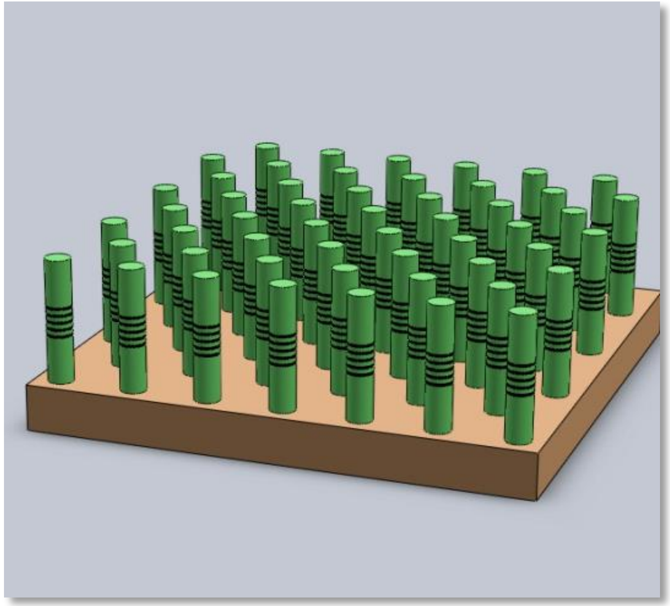


Top-down Nanowire Fabrication | top-down 2-step etch process – wet etch

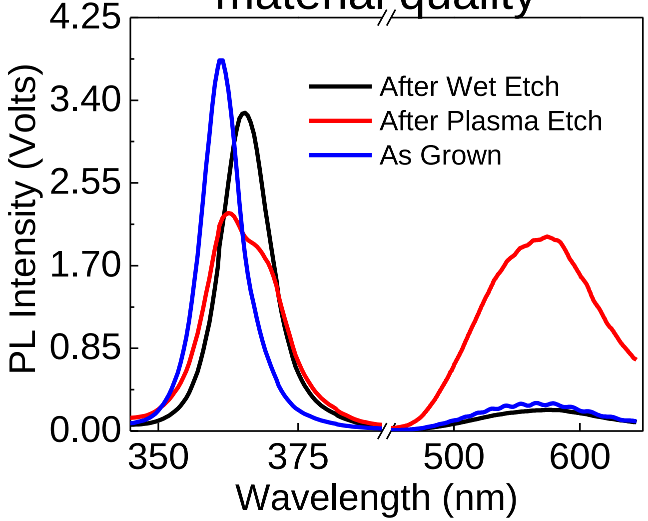


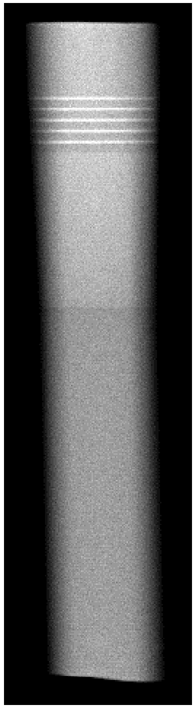






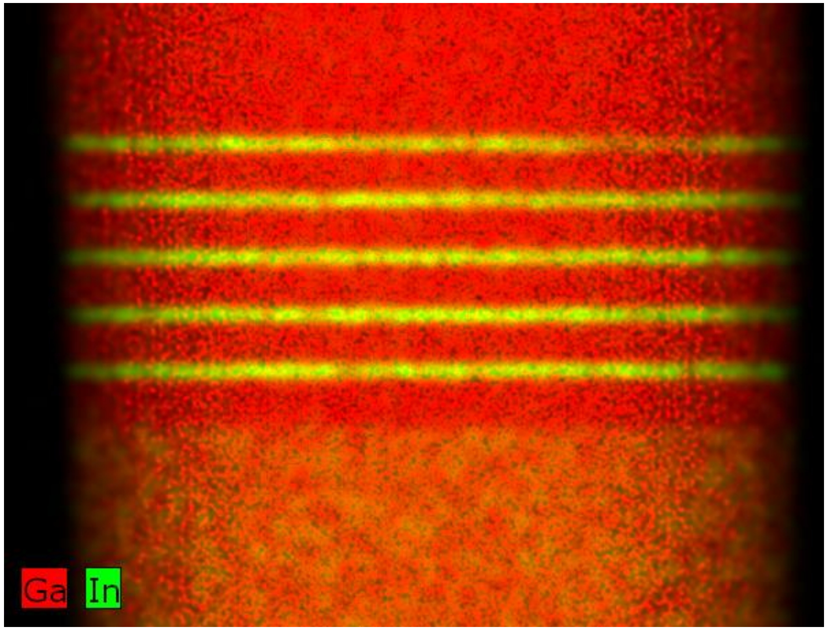
The wet etch improves the material quality

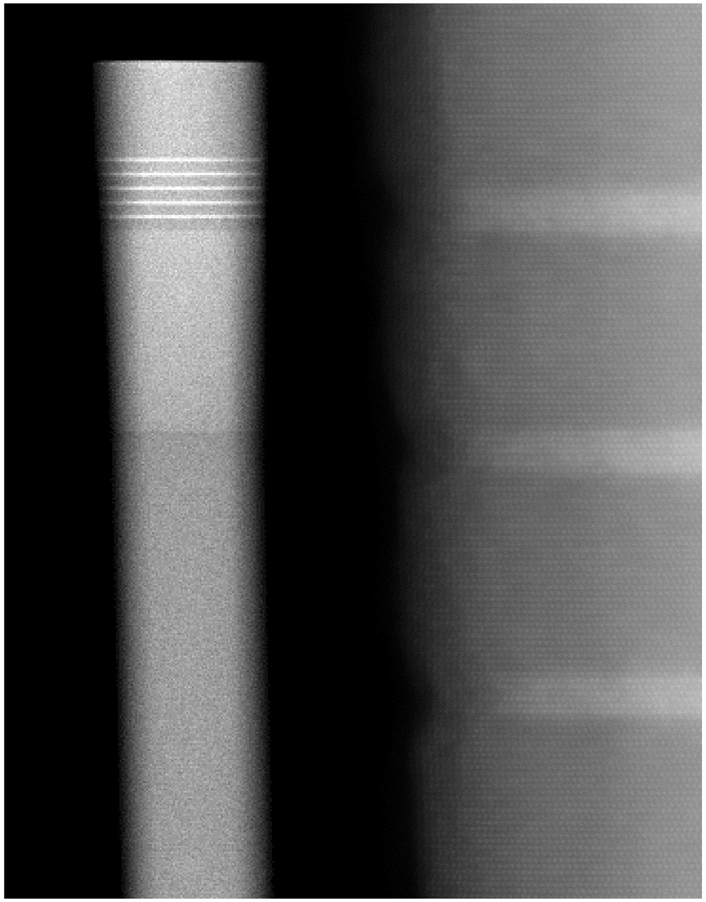




TEM of a single nanowire taken from an array

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





Ping Lu, Sandia

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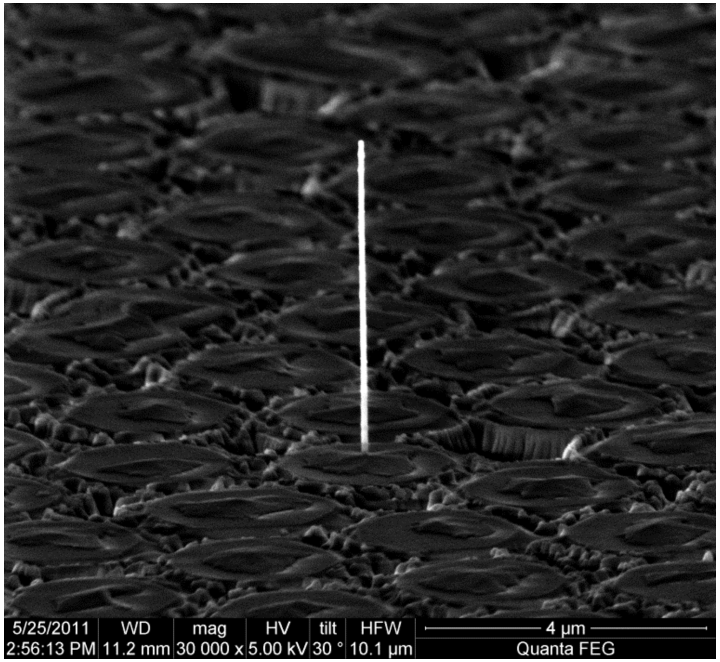
Outline

- Motivation
- Single-mode lasing from single nanowires
    - Geometric reduction
    - Distributed feedback
- Photonic crystal laser “pixels”
- Conclusions and Outlook



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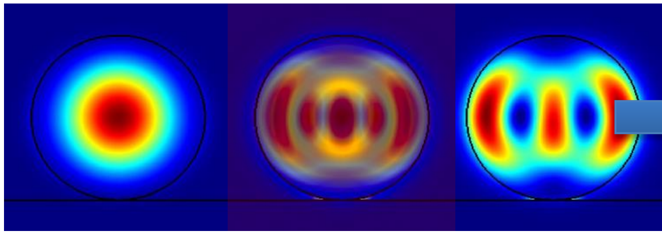
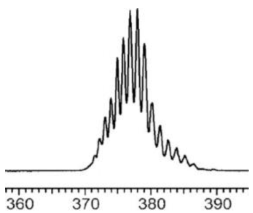
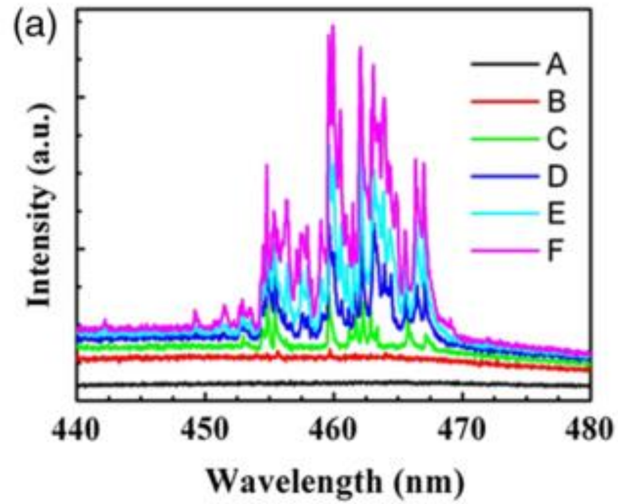
Motivation | Why single-mode nanowire lasers?



Multiple transverse modes

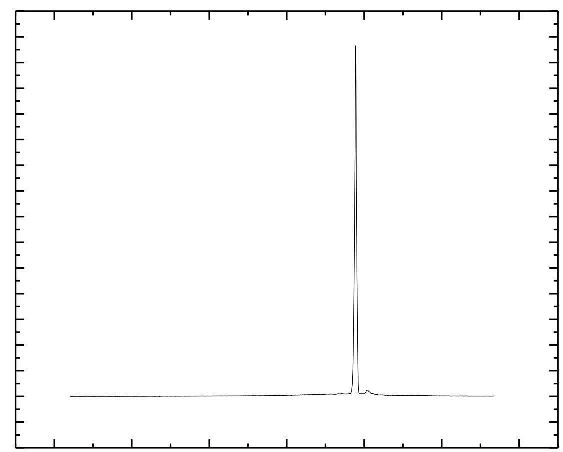


Multiple longitudinal modes



Single-Mode Lasing
(Transverse and Longitudinal)

High Beam Quality + Single Frequency Operation



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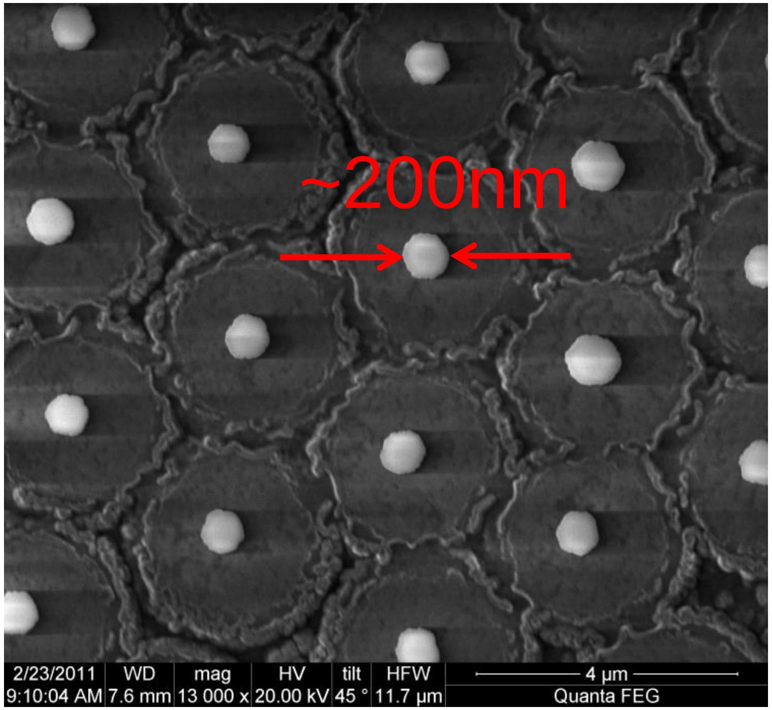
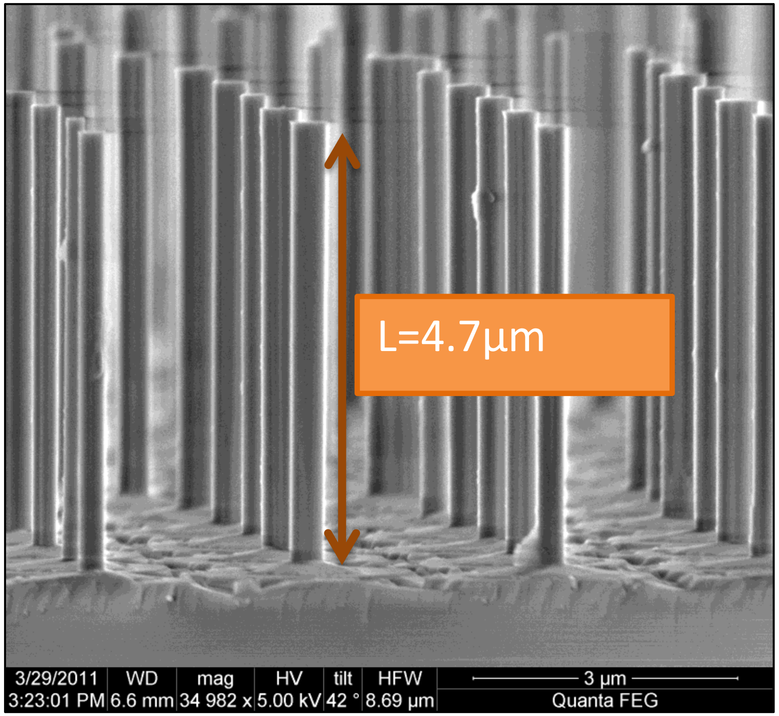
Cavity Geometry of the Top-Down Nanowire

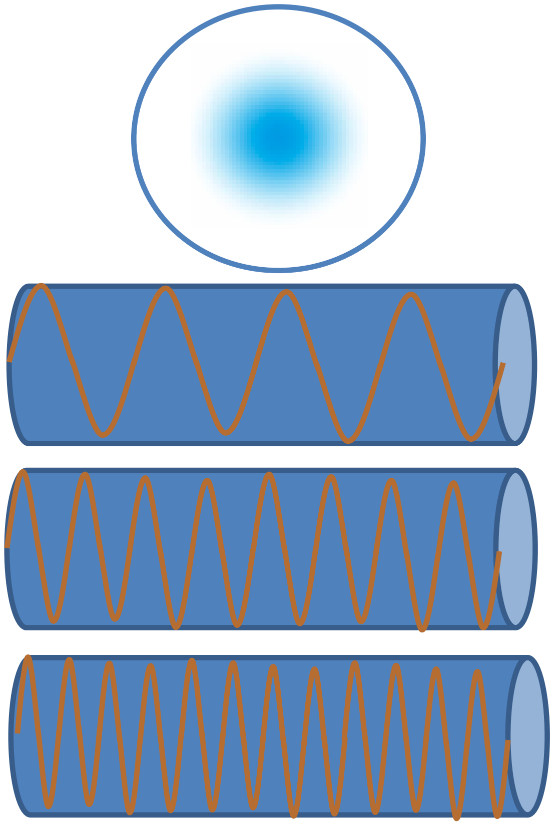


Since the C-plane is not etched, the wires are uniform in length and the length is fixed to the thickness of the epitaxial layer.

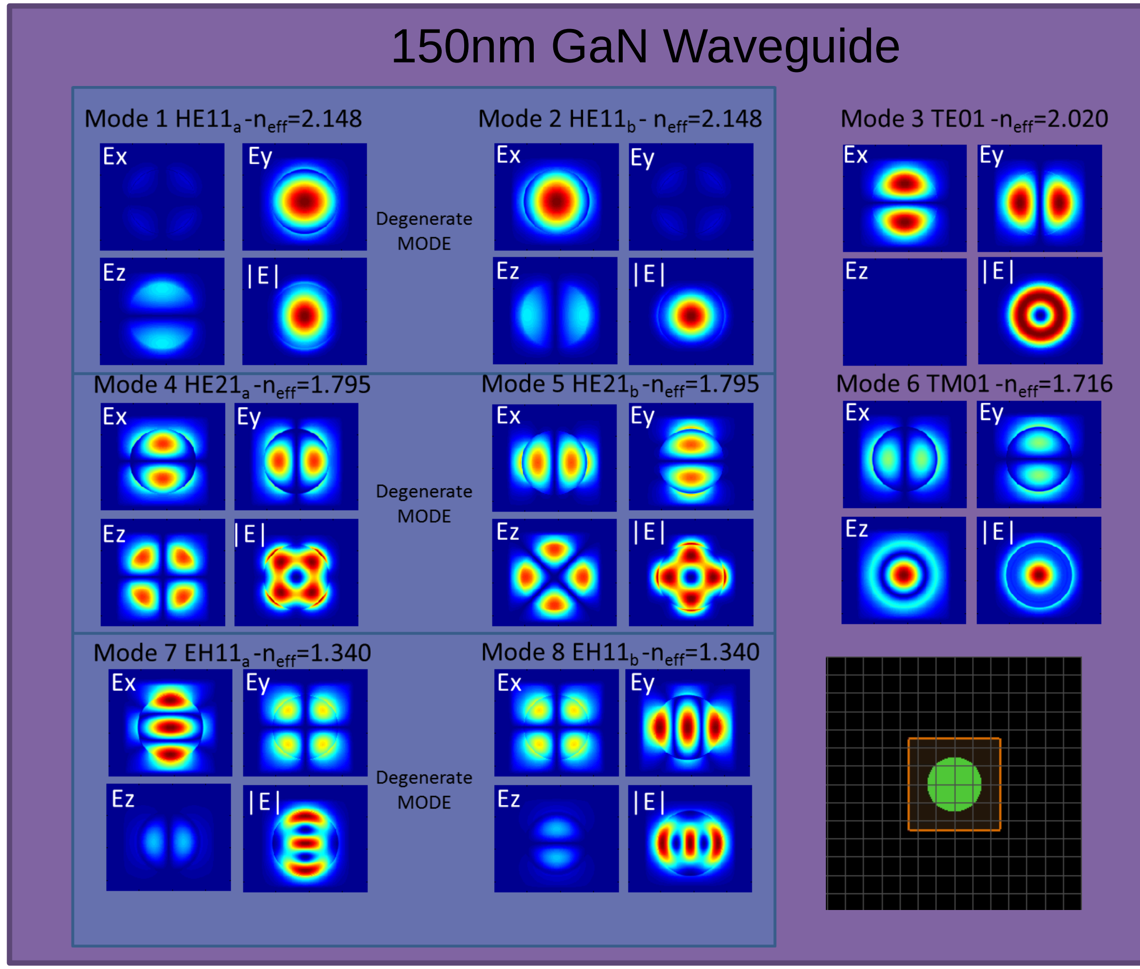


Modal Distributions for Circular Waveguides

1st Transverse Mode



$$E_{m,n,p}(x,y,z)=E_0u_{m,n}(x,y)e^{-jk_pz}$$



Simulations show two supported modes for a 130nm nanowire.

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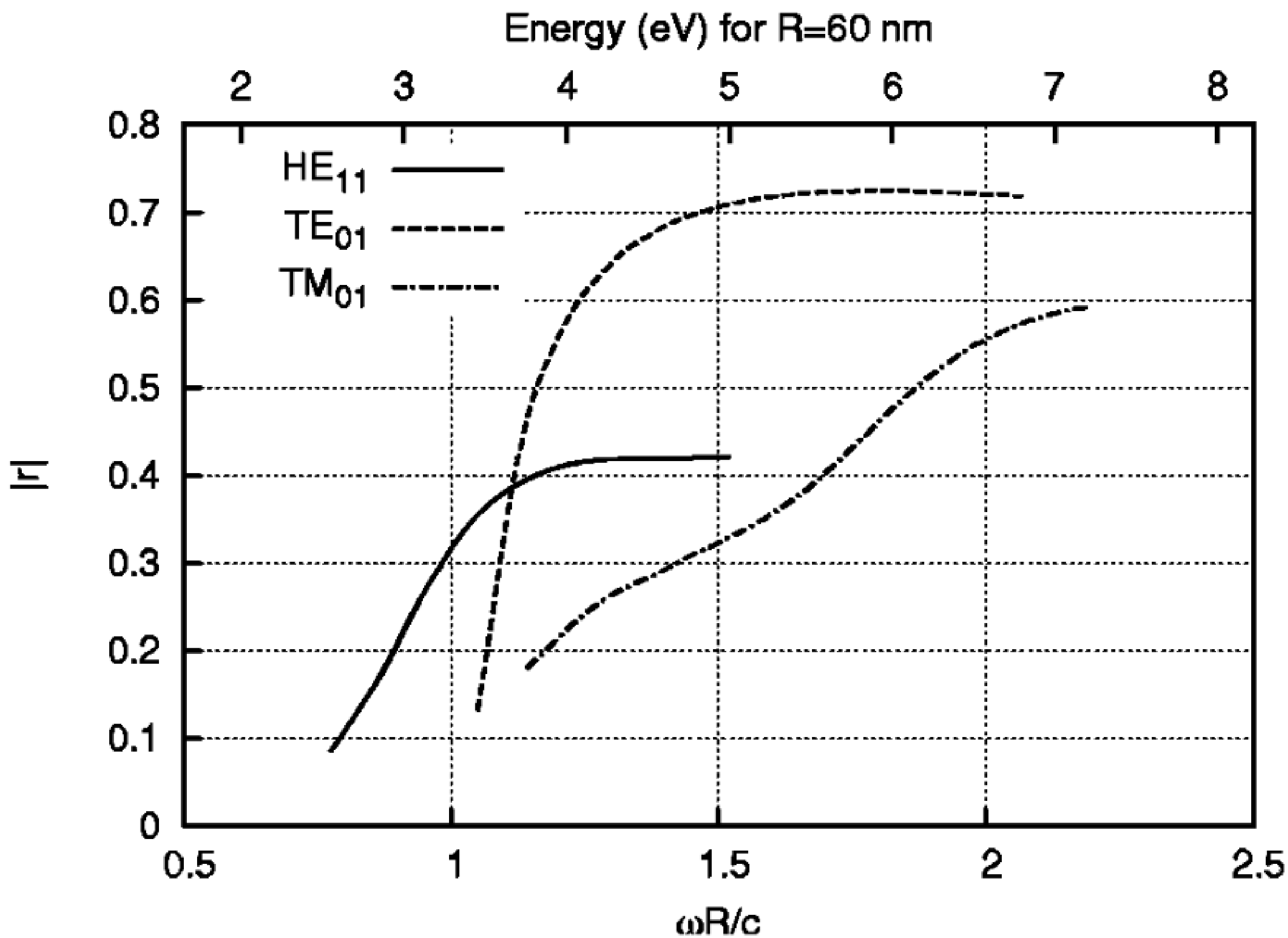
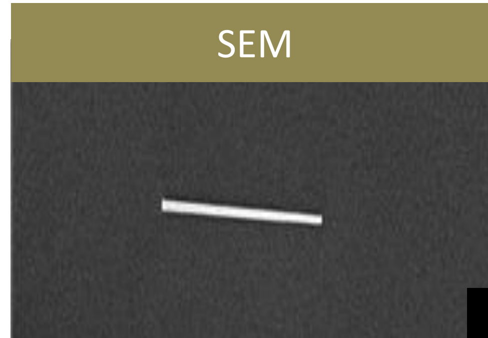
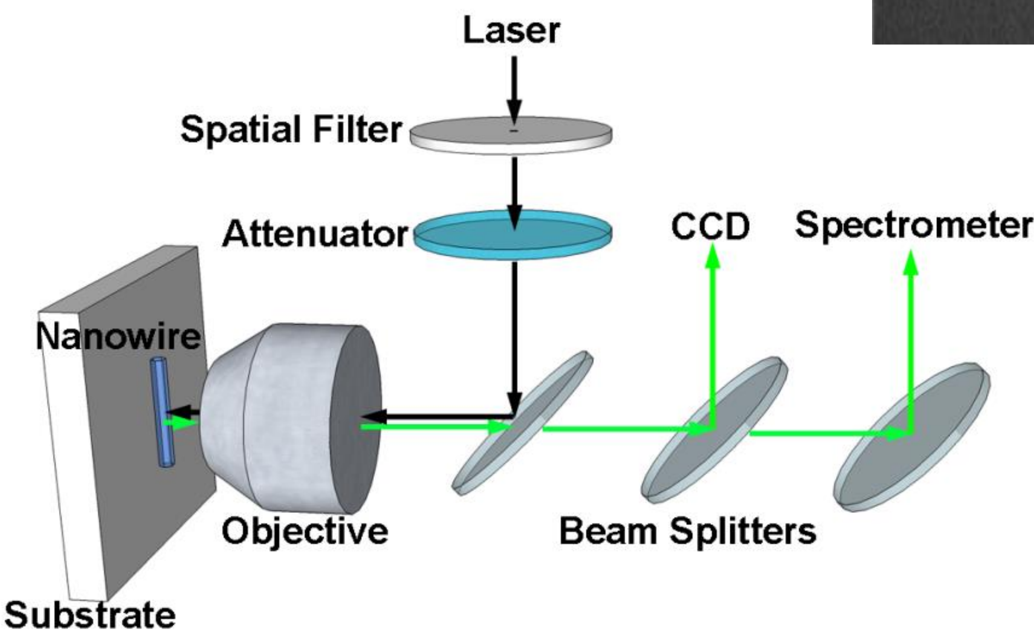
Modal Reflectivity

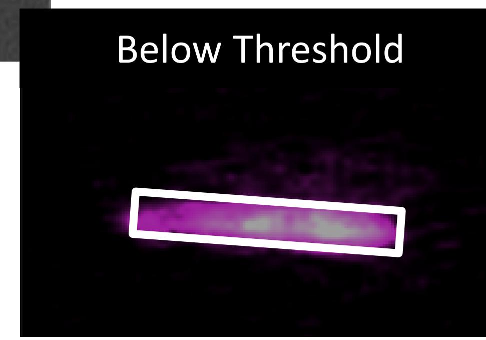


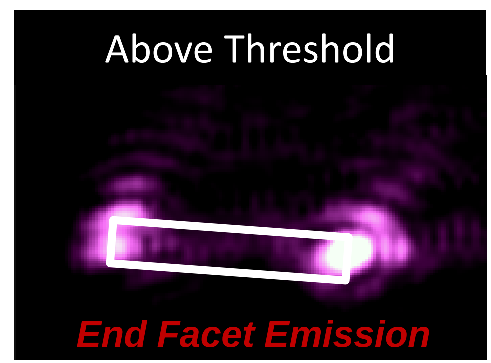
Spectral Characterization of Single Nanowires

Average Power: 5.2mW
Pulse Width: 0.4ns
Rep Rate: 9.08 kHz
Pulse Energy: 0.64µJ



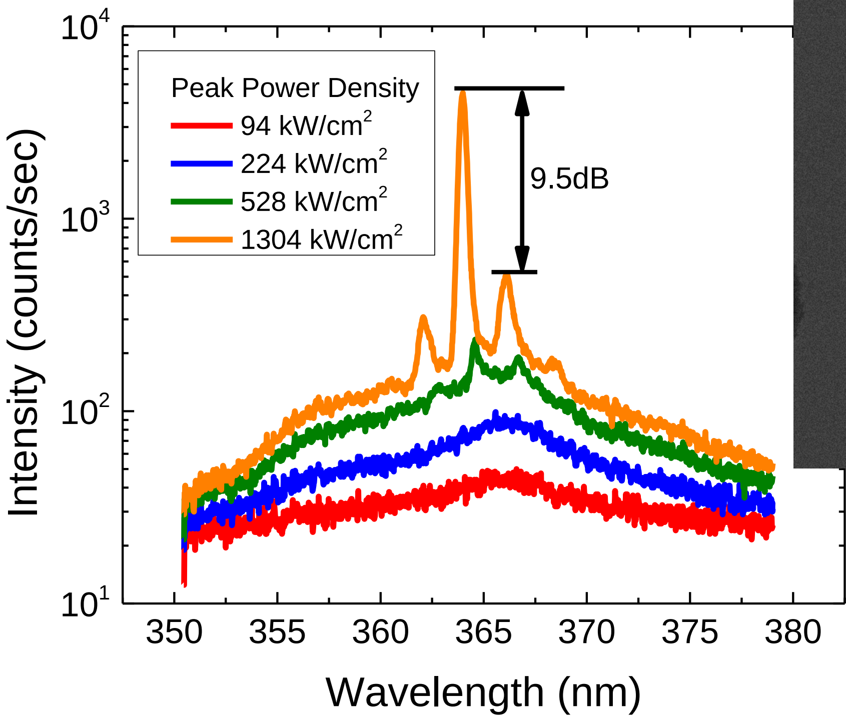


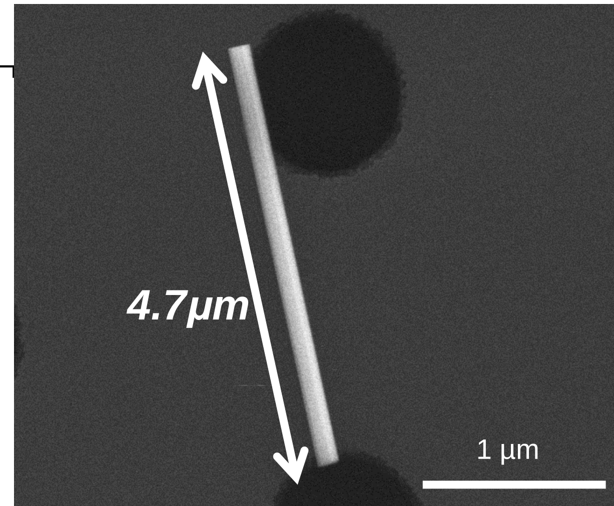


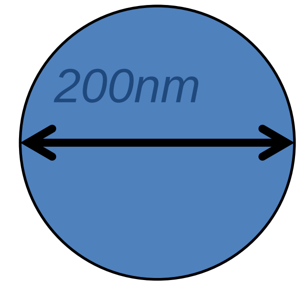


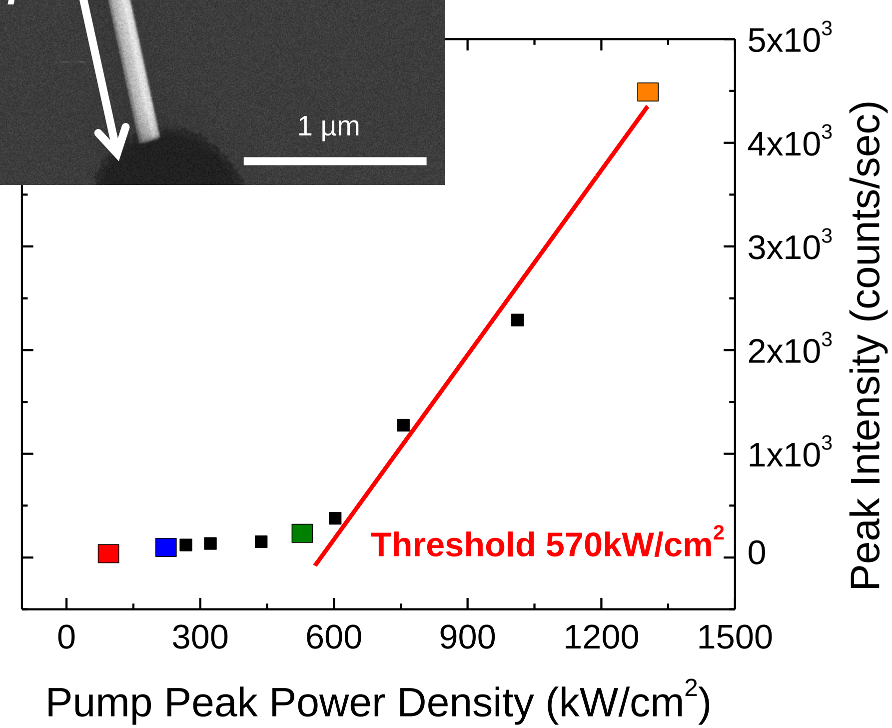
- **Pump power densities range from <1kW/cm^2 to >10MW/cm^2 over a 5µm spot**

Lasing From a Large Diameter Single Nanowire









Broad linewidth indicates multiple transverse mode lasing.

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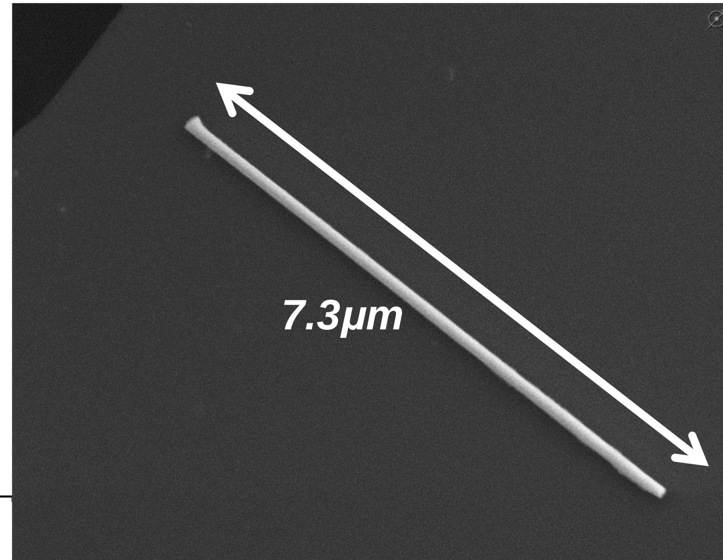
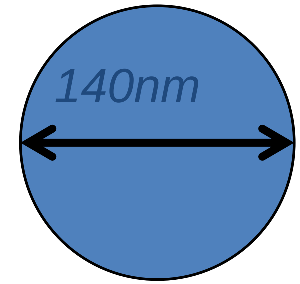
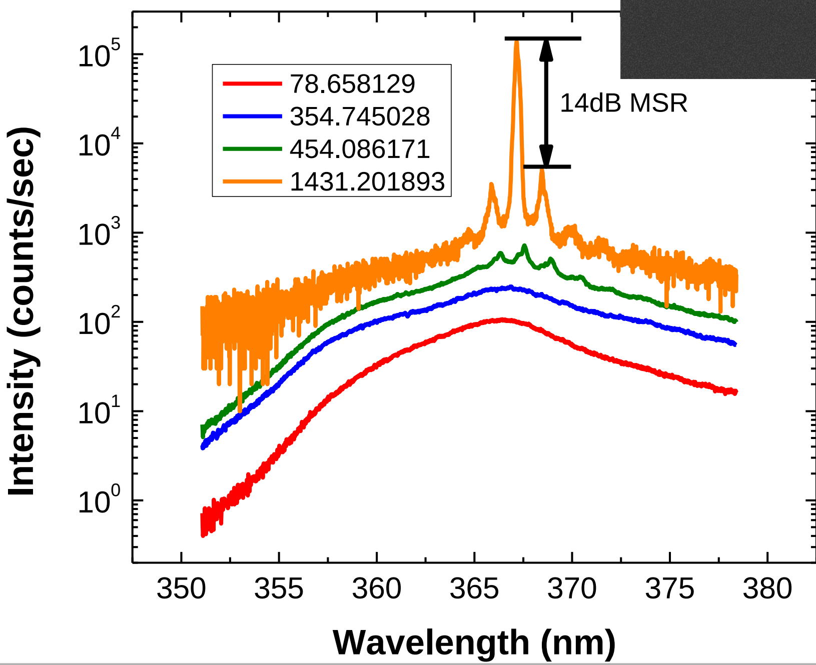
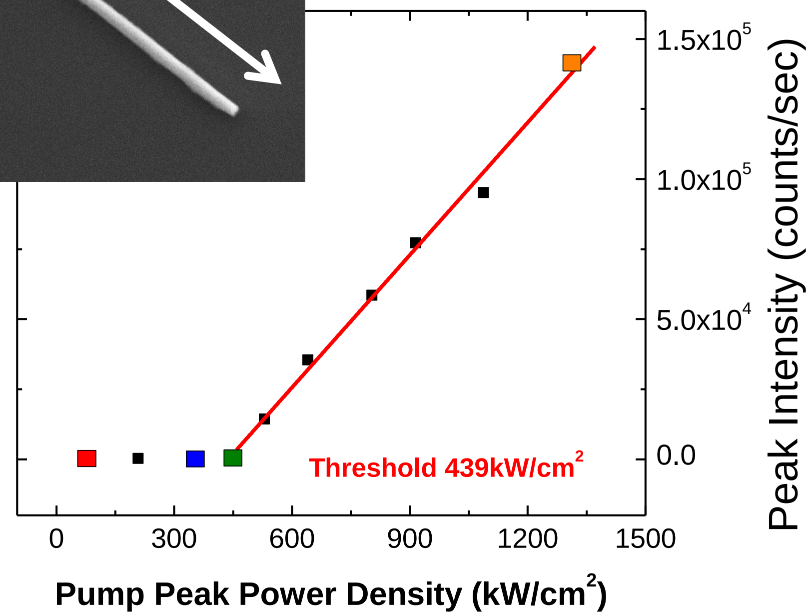
Lasing from a 7µm Long Single Nanowire

Multiple peaks appear within the gain bandwidth.









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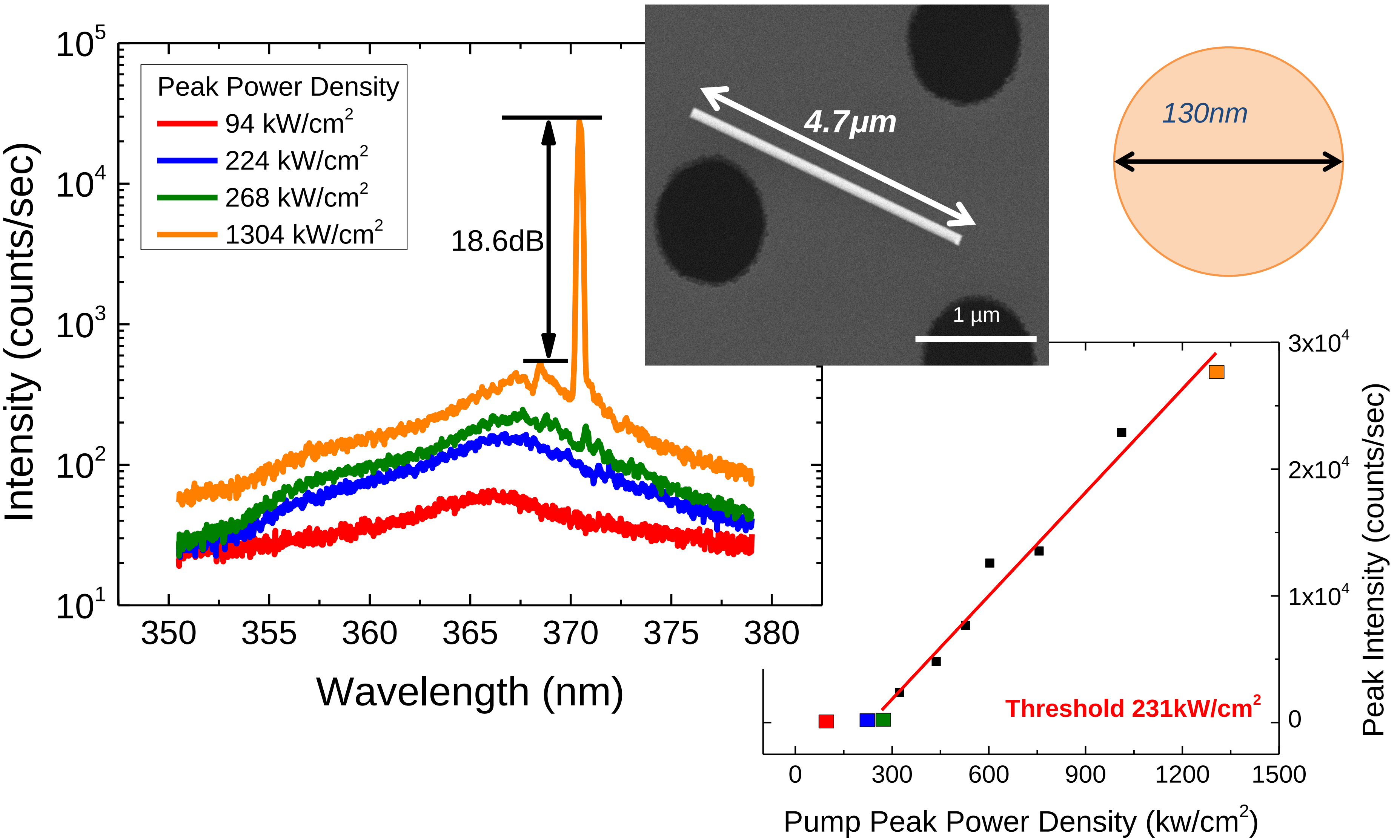
Lasing from a Small Diameter Nanowire



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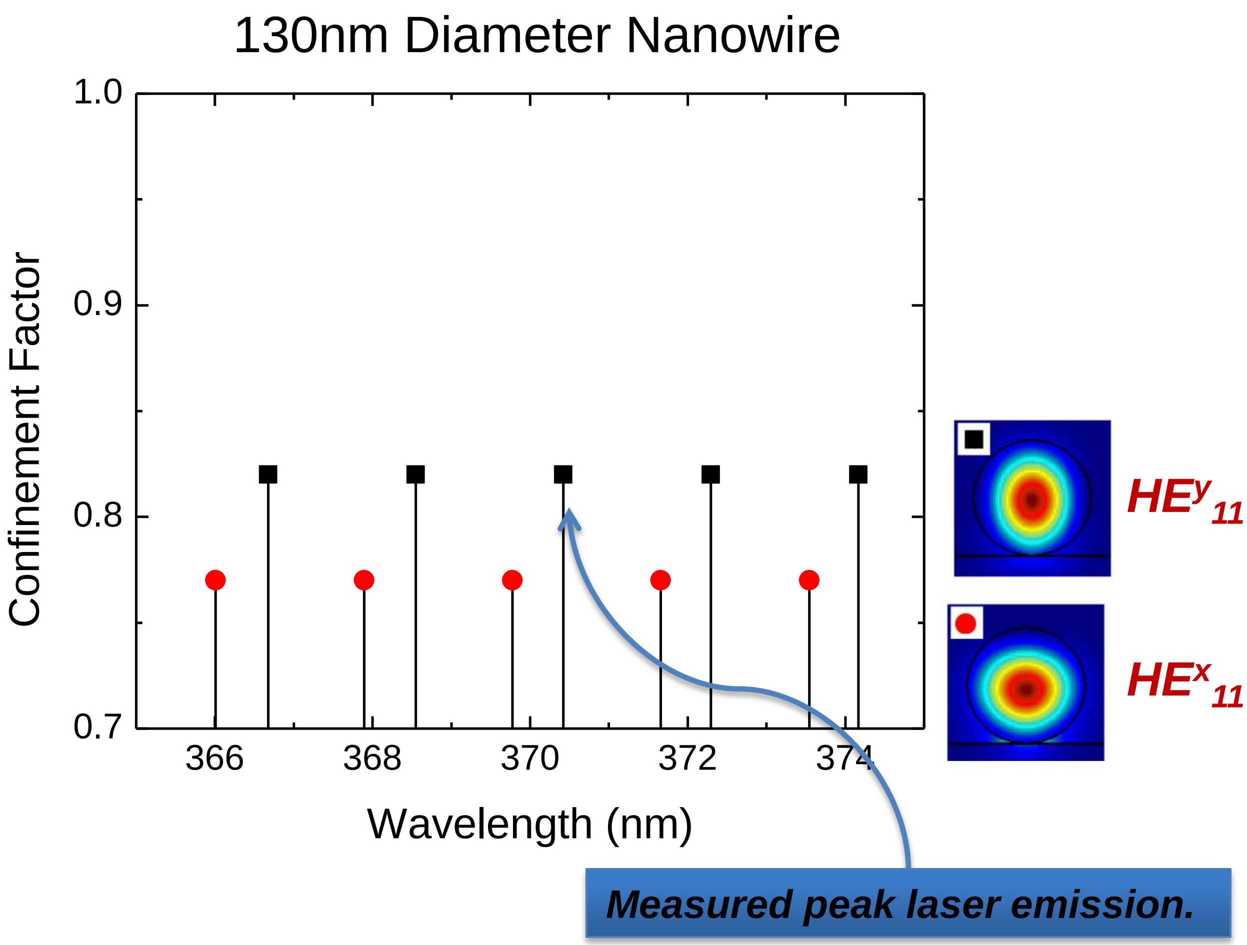
Locations of the Transverse and Longitudinal Modes for a 130nm Nanowire

The location of the competing cavity modes are calculated relative to measured peak laser emission.

$$\Delta\lambda_{FSR} \approx \frac{\lambda_0^2}{2 \cdot l \cdot n_{eff-g}}$$



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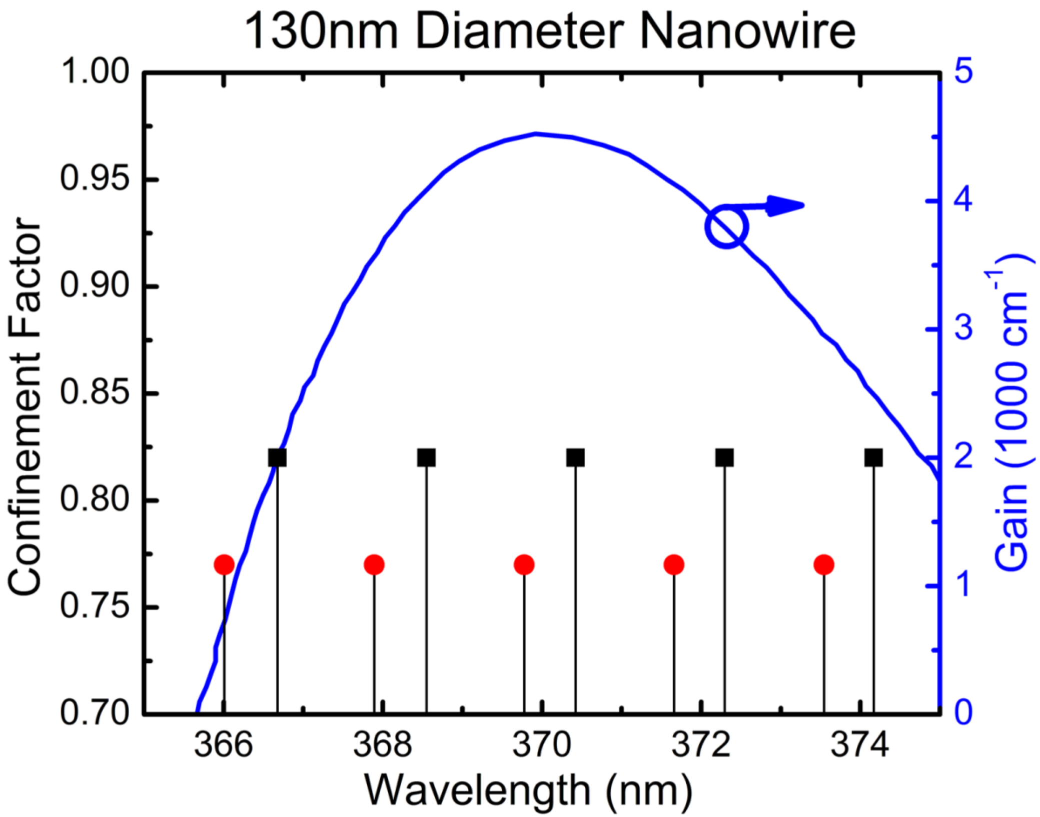
Locations of the Transverse and Longitudinal Modes for a 130nm Nanowire

$$g_{th} \approx \frac{1}{2\Gamma L}\ln\left(\frac{1}{R^2}\right)$$



The gain spectra is compared to spectral mode distribution and associated confinement factors.

Wiesmann, D., et al. Applied Physics Letters **69(22): 3384-3386 (1996).**

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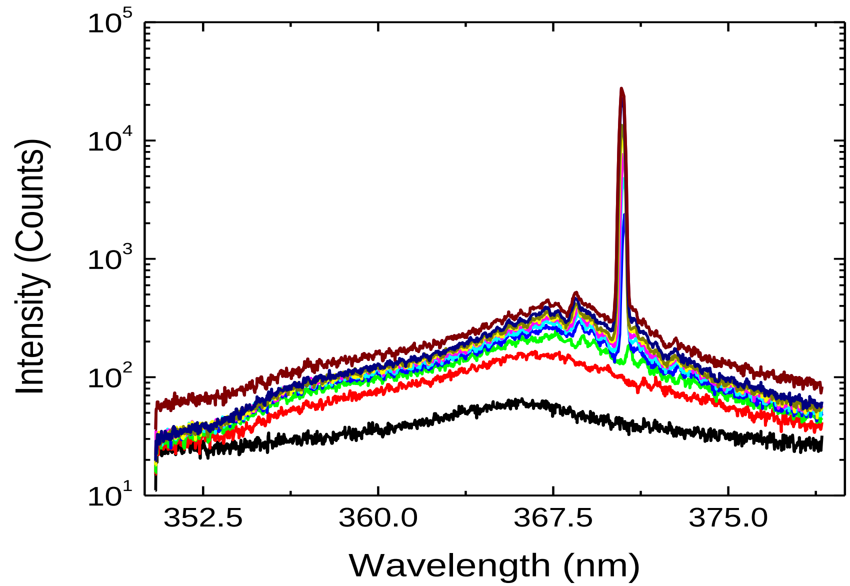
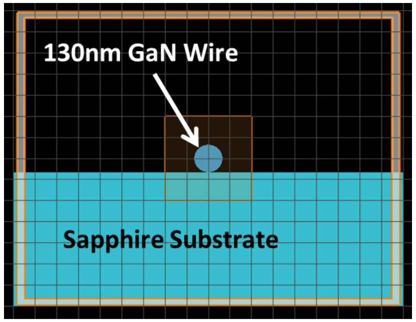
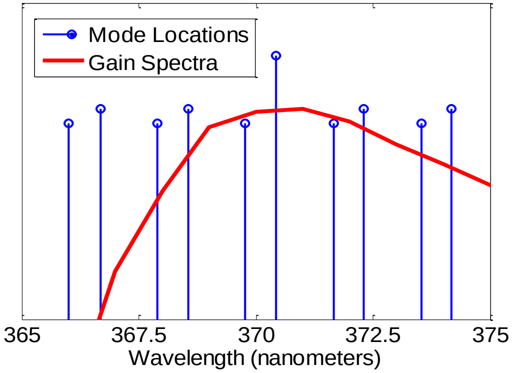
Single-mode Single Nanowire Lasers | Achievements

- Observed lasing from individual top-down fabricated nanowires
- In a small diameter nanowire observed single-mode operation
- Modeling of the nanowire modal properties







Q. Li, J. B. Wright, W. W. Chow, T. S. Luk, I. Brener, L. F. Lester, et al., "Single-mode GaN nanowire lasers," Optics Express, vol. 20, pp. 17873-17879, 2012.

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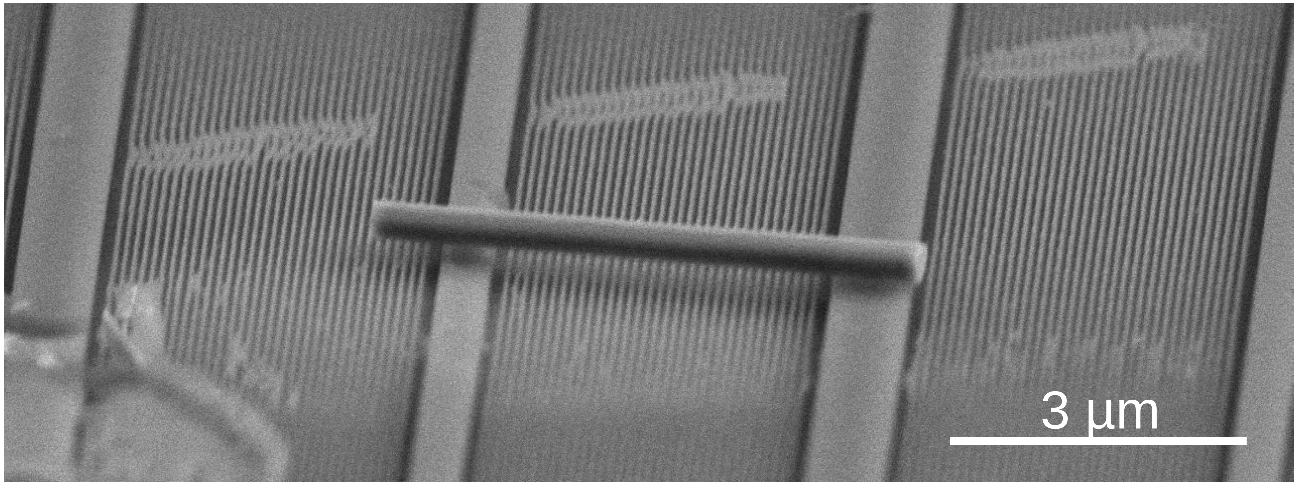
Outline

- **Motivation**
- **Single-mode lasing from single nanowires**
  - **Geometric reduction**
  - **Distributed feedback**
- **Photonic crystal laser “pixels”**
- **Conclusions and Outlook**



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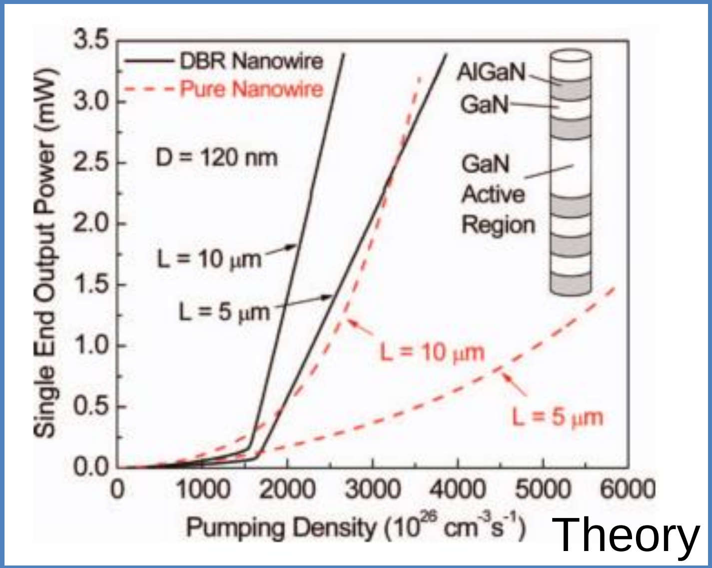
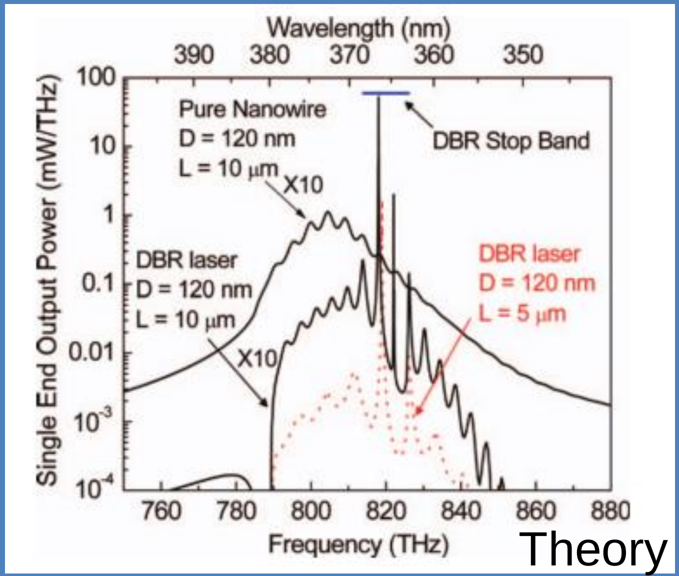
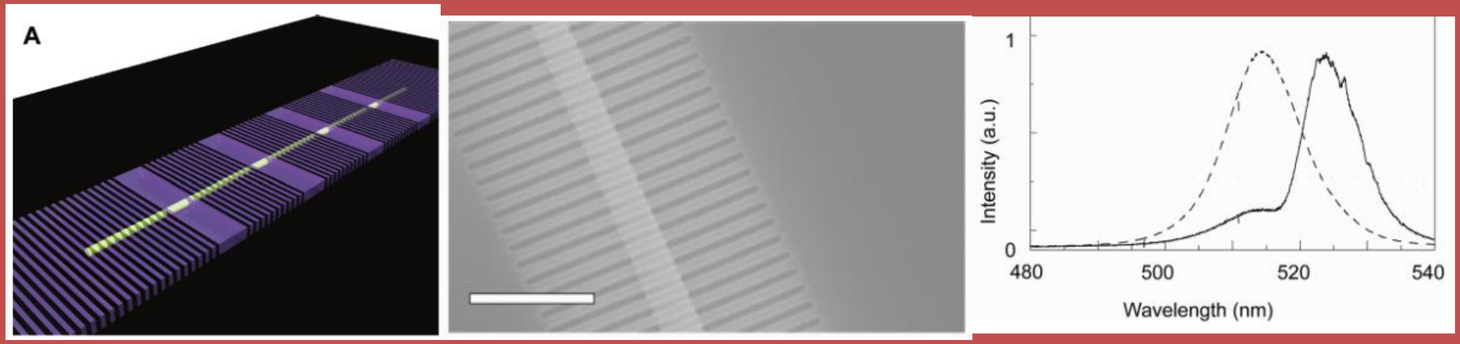
Previous Work – Nanowires with gratings





Nanowire lasers with distributed-Bragg-reflector mirrors
L. Chen and E. Towe, *Applied Physics Letters, vol. 89, pp. 053125-3, 07/31/ 2006.*



Hybrid single-nanowire photonic crystal and microresonator structures
C. J. Barrelet et al, *Nano Letters, vol. 6, pp. 11-15, Jan 2006.*

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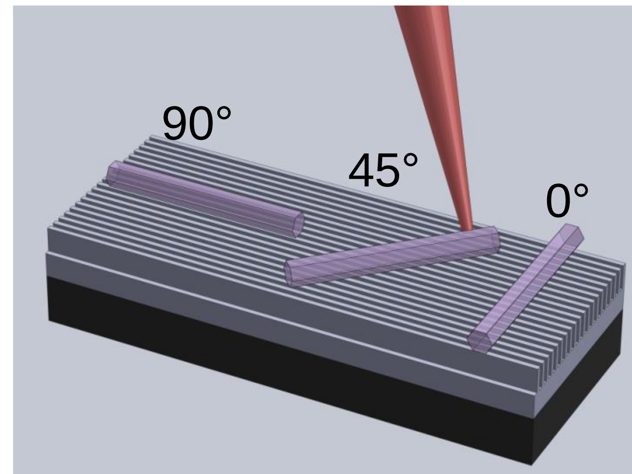
Single nanowire with distributed feedback

- Single nanowires are coupled to a silicon nitride grating substrate to achieve distributed feedback
- Stop-band tuned via nanomanipulation of the angular alignment
- Modeling using mode solver and TMM



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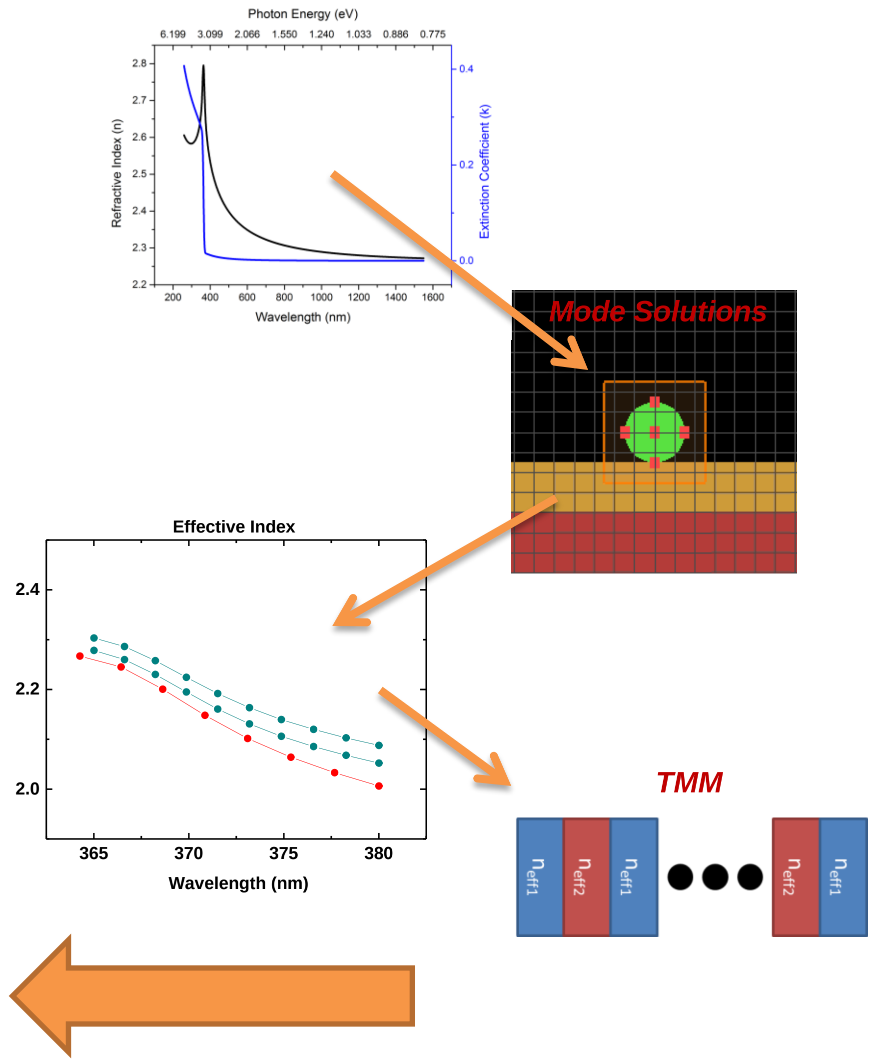
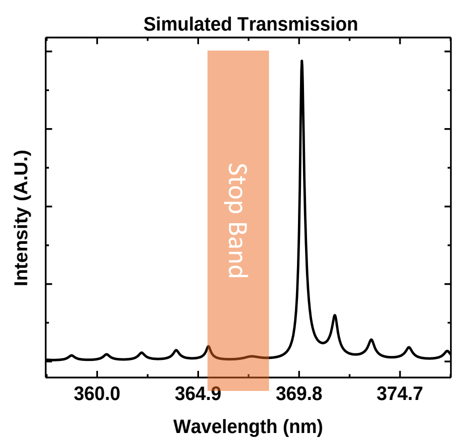
Model Development of DFB Nanowire

1. **Ellipsometry**
   1. **retrieve optical constants**
2. **Mode solutions**
   1. **effective indices**
3. **Transfer Matrix Method (TMM)**
   1. **Stop band vs angle**





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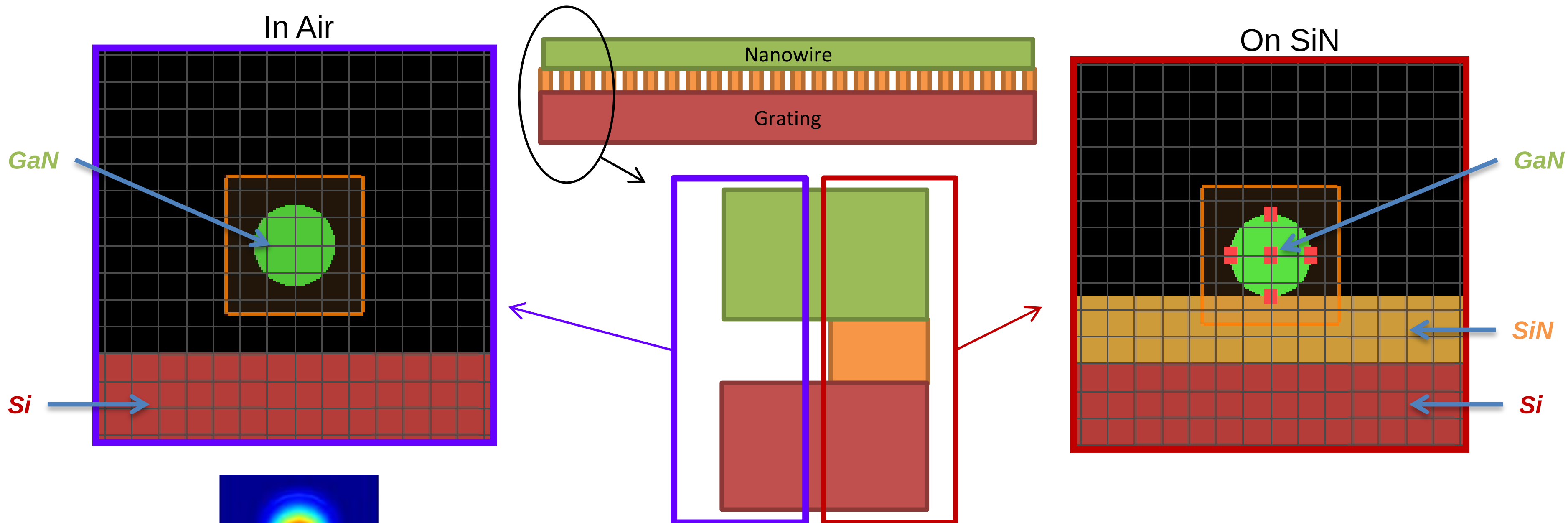
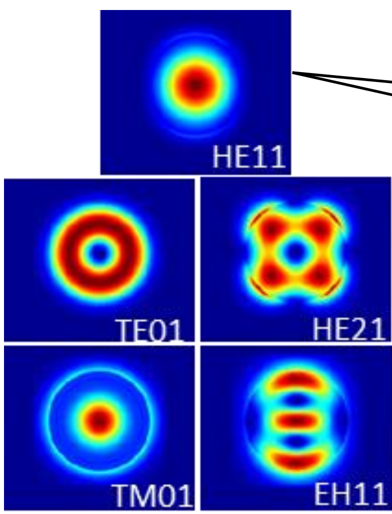
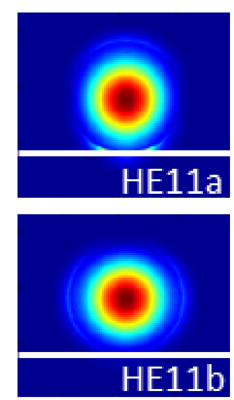
DFB Nanowire Simulations – Mode Theory



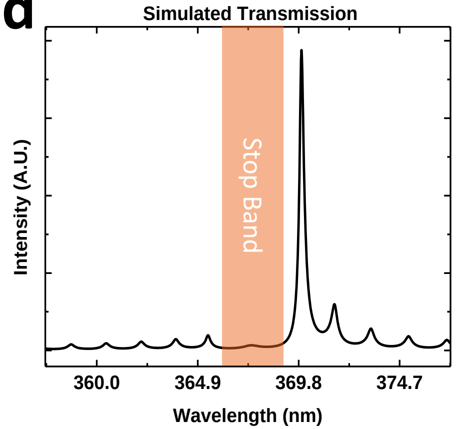


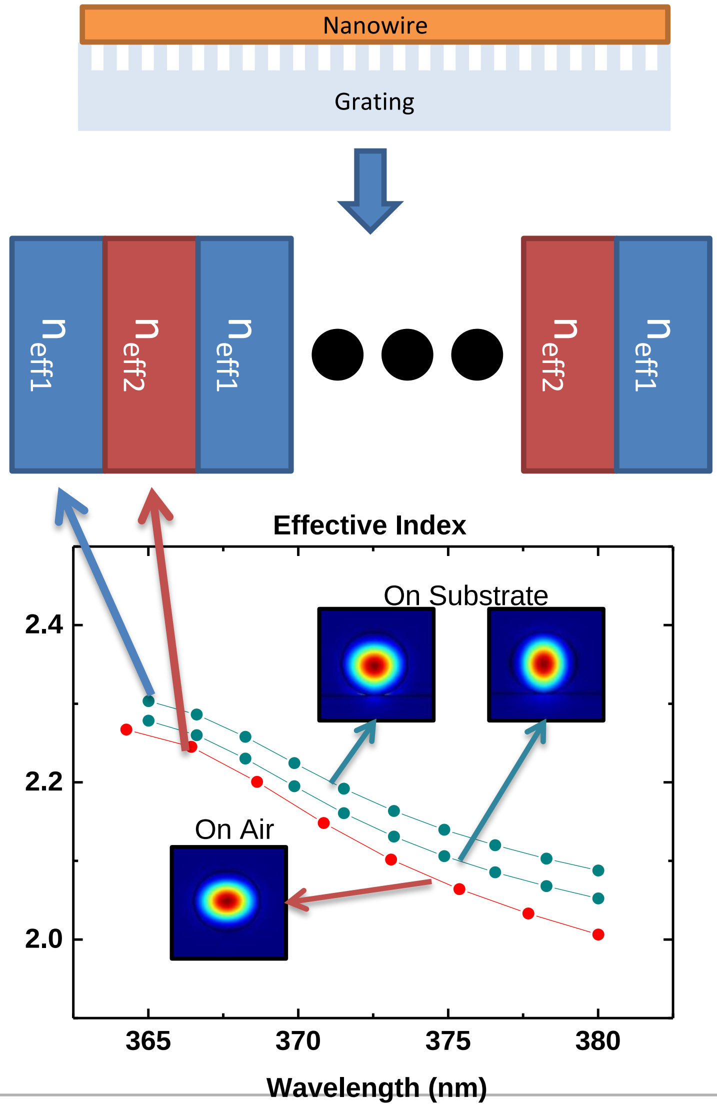


- The higher order modes are suppressed by the SiN layer
- The addition of the SiN in contact breaks the degeneracy of HE11

Distributed feedback transfer matrix method

- **TMM- Transfer Matrix Method is used to estimate the stop-band**





- **The coupled system is treated as a stack of dielectric layers**
- **The index of each layer is extracted from the modal model**

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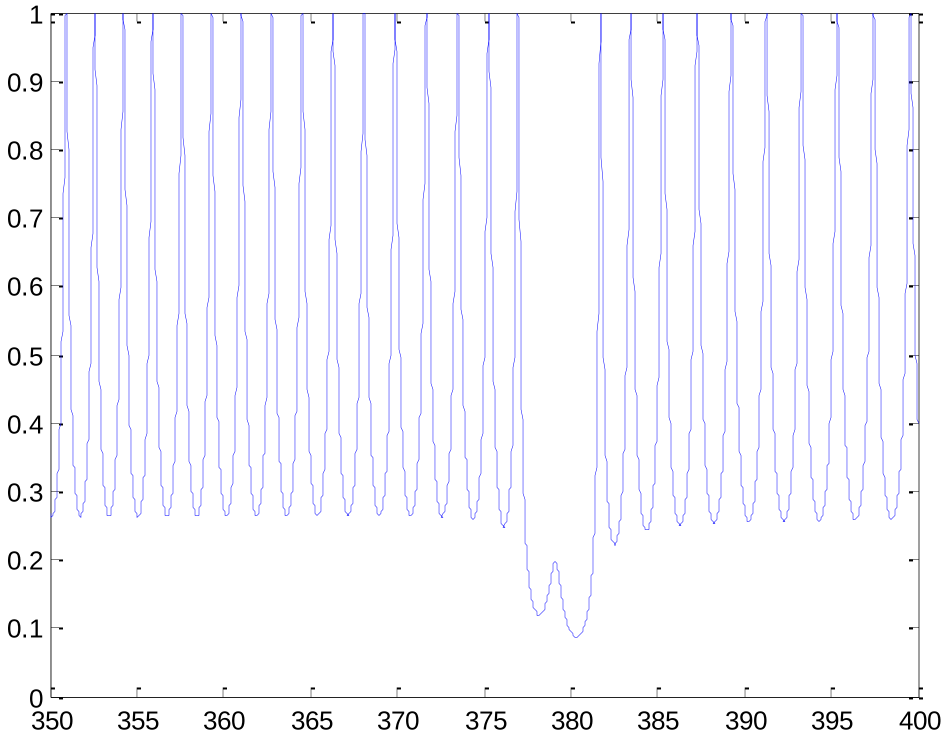
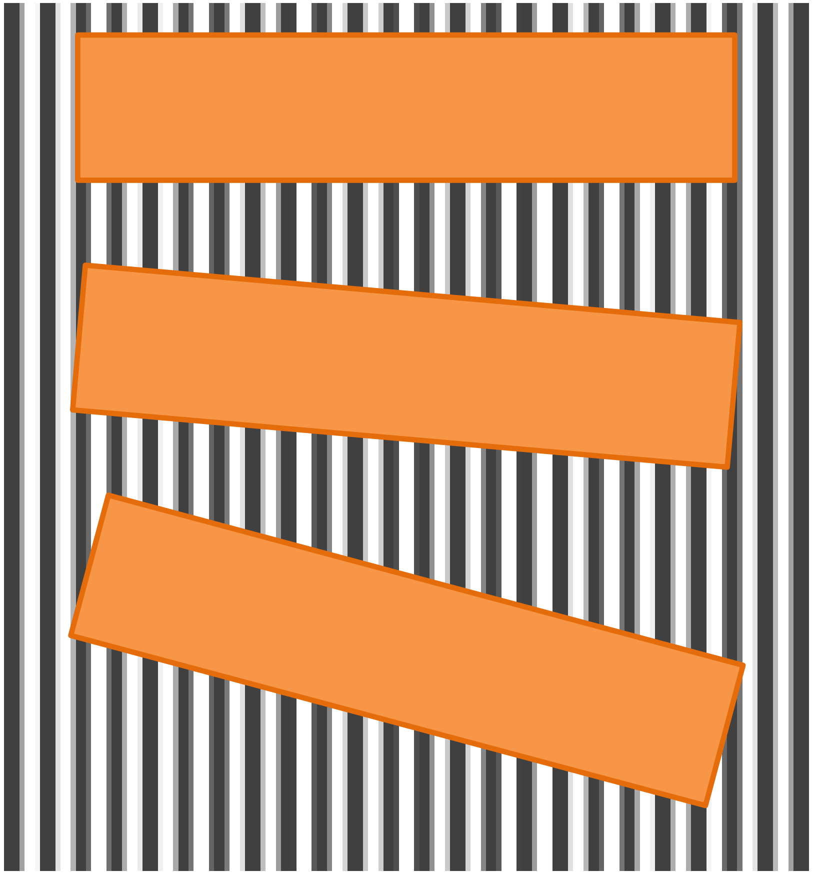
Stop-band vs. Alignment Angle

The alignment angle is varied in the model by changing the layer thicknesses.

0° ➡ 5° ➡ 15°





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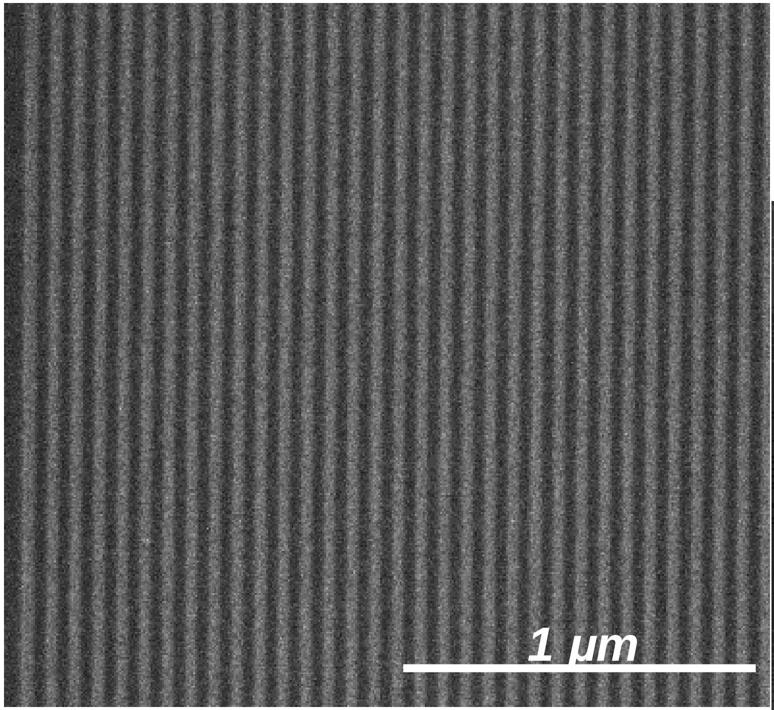
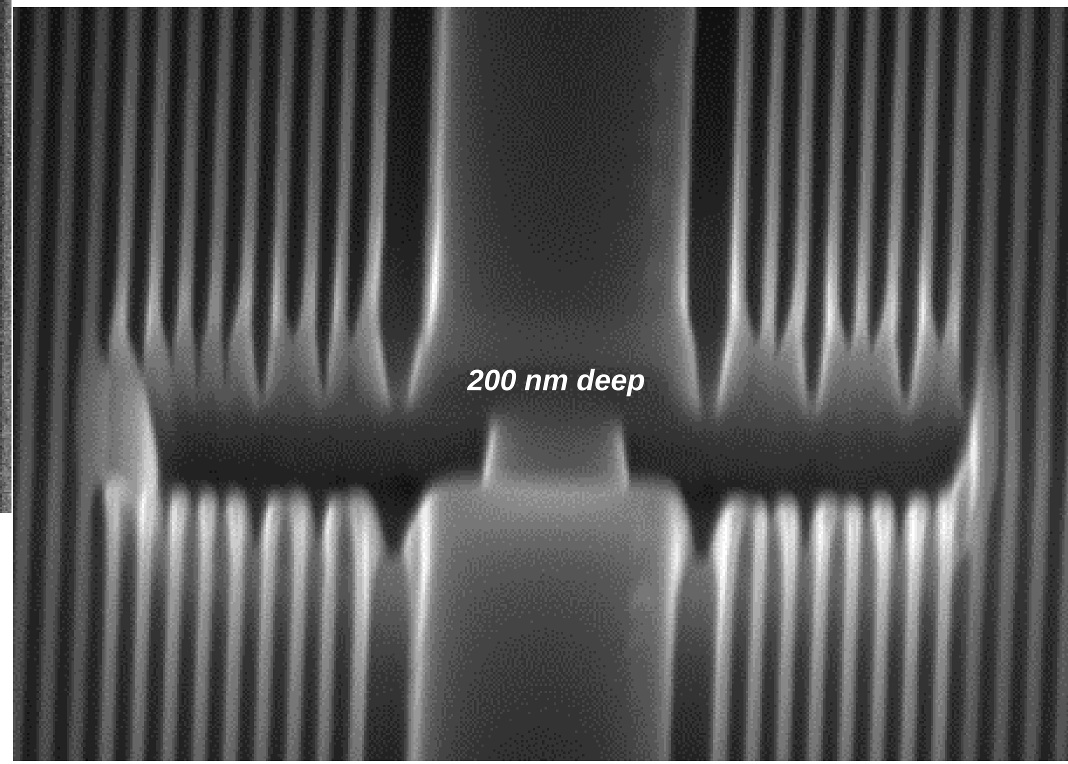
Silicon Nitride Grating Substrate



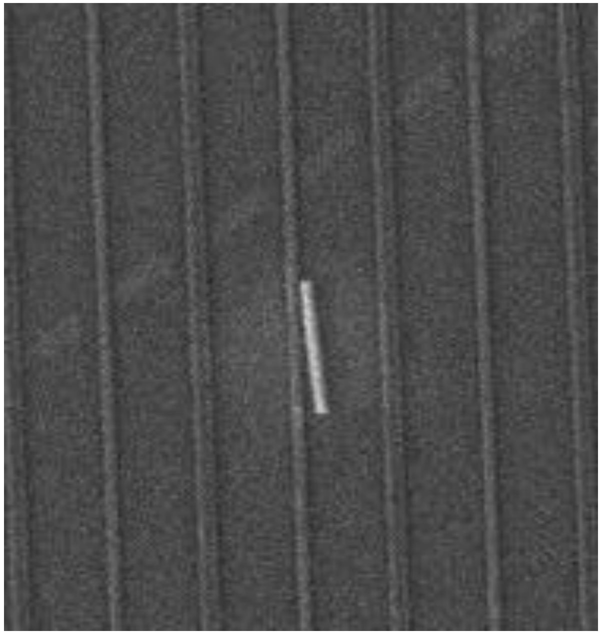
FIB Cross Section

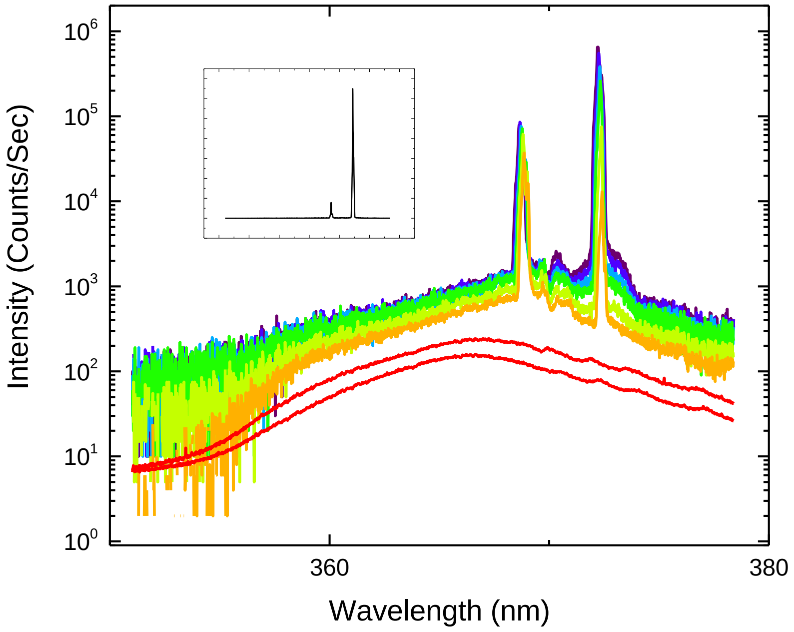


90nm period
~50% duty cycle

Out of Alignment – Multimode Operation

- **As placed – No alignment between the grating and the substrate**

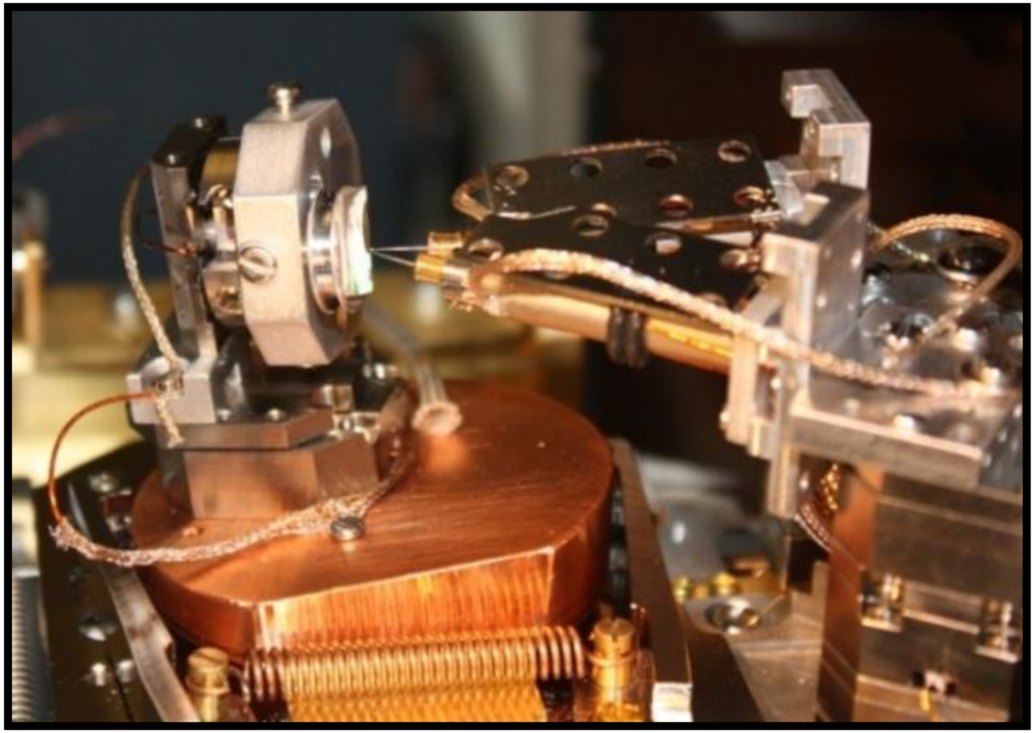


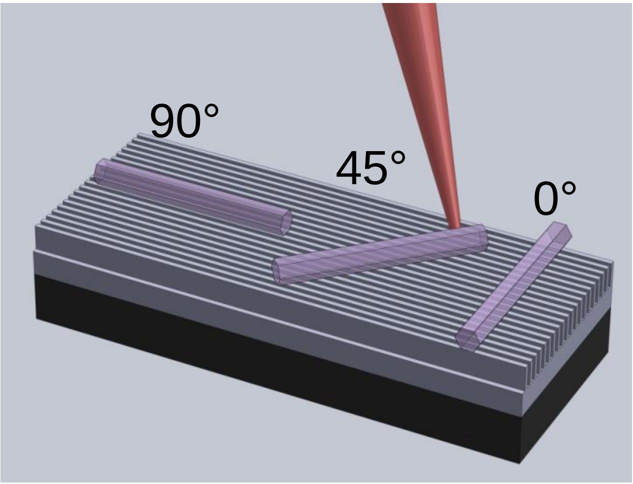


- ***Multi Mode - 5dB Mode Suppression Ratio***

SEM Manipulator Tool

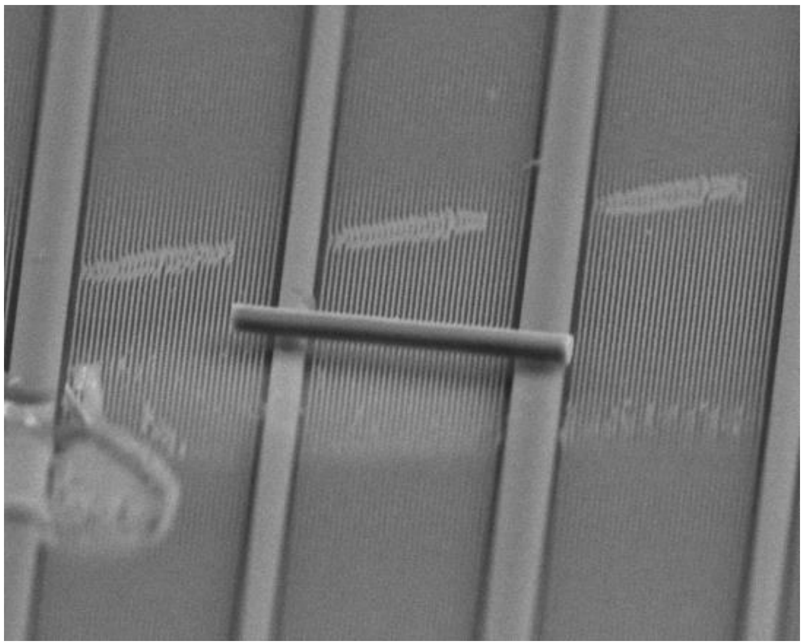
- Inside of an SEM
- Two piezo actuated 3-axis stages
- Two probes used simultaneously

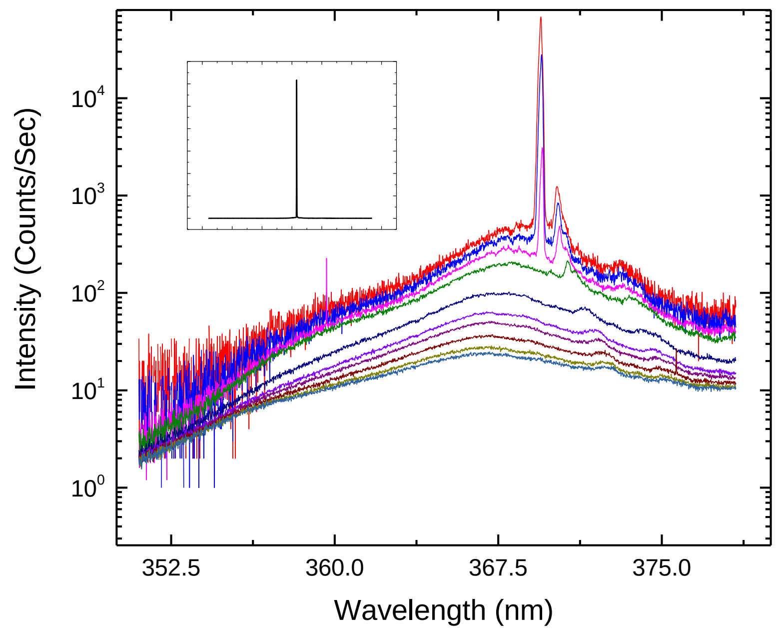




Single-mode Operation

- **After Rotation – the nanowire is rotated so that the designed periodicity of the grating is used.**





✓ ***Single Mode Lasing with 17dB Mode Suppression Ratio***

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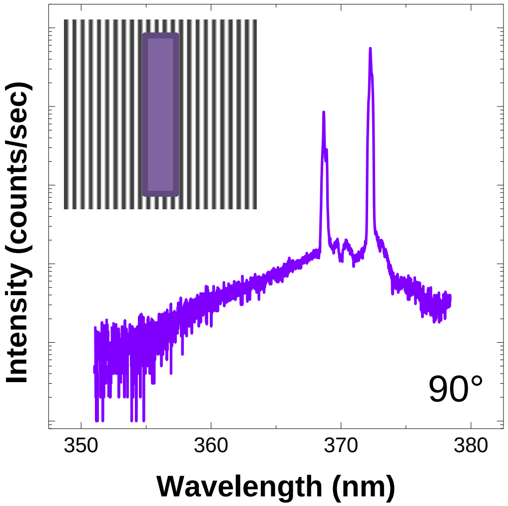
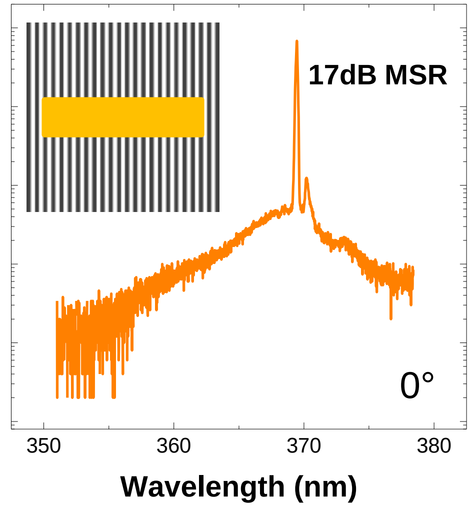
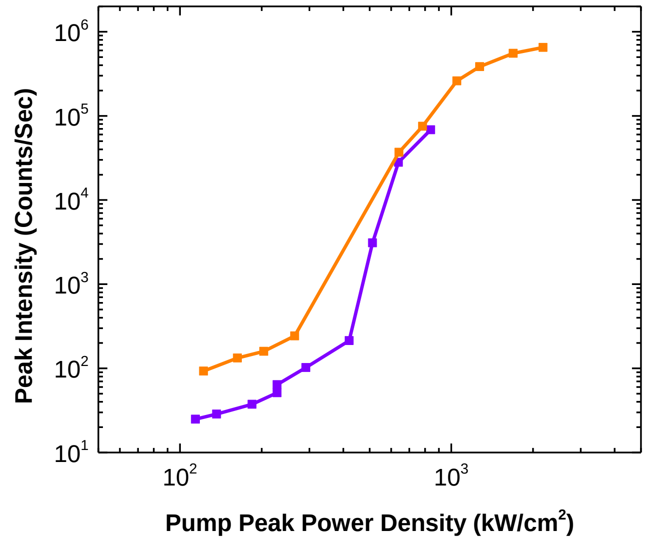
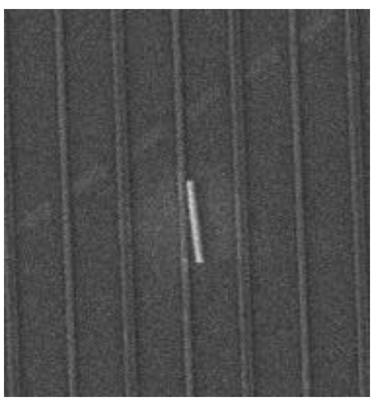
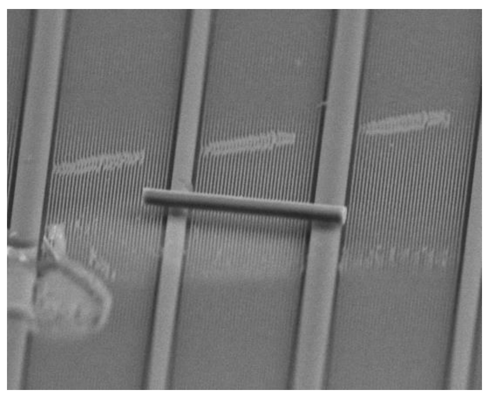
Distributed feedback nanowire laser | Summary









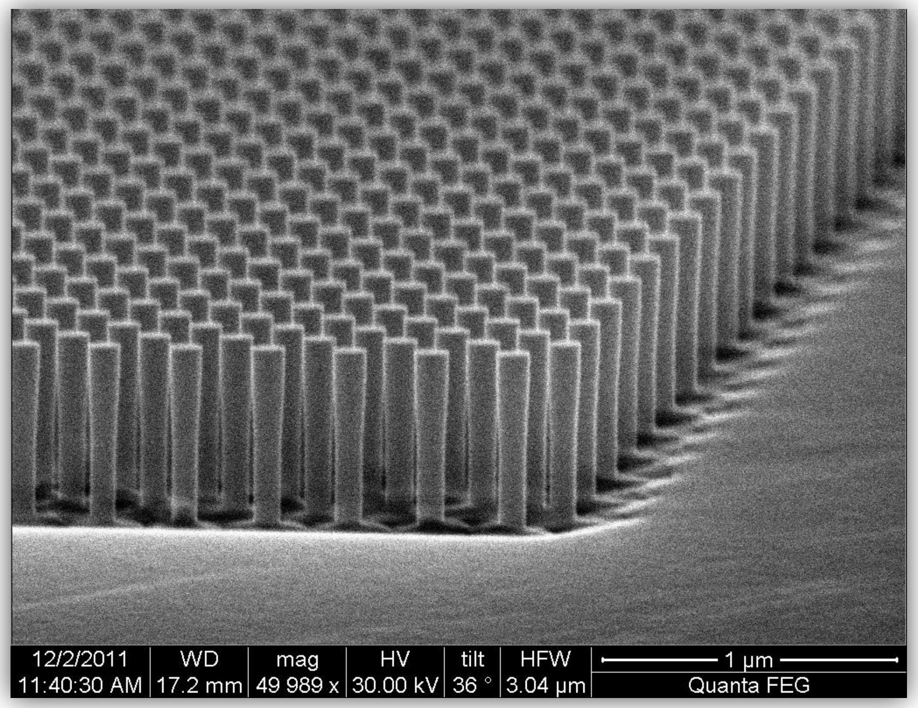


- ✓ Single-mode lasing with 17dB mode suppression ratio.
- ✓ Slight reduction in the lasing threshold
- ✓ Model development of nanowires with external gratings

J.B. Wright et al., APL 104 (4), 041107 2014.

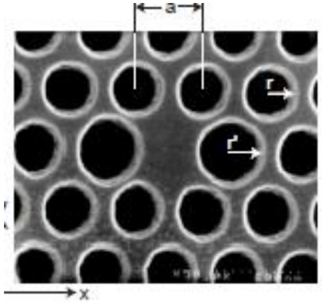
Outline

- **Motivation**
- **Single-mode lasing from single nanowires**
  - **Geometric reduction**
  - **Distributed feedback**
- **Photonic crystal laser “pixels”**
- **Conclusions and Outlook**

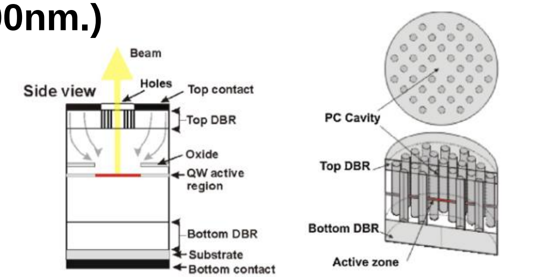


Previous Work

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

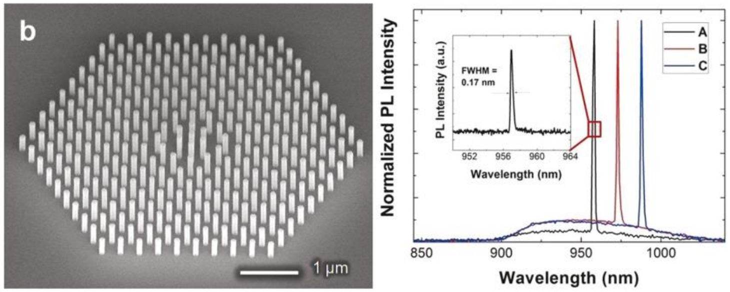


Painter, O. *et al. Science* ***284 (1999).***



Ivanov et al…0268-1242_27_9_094010

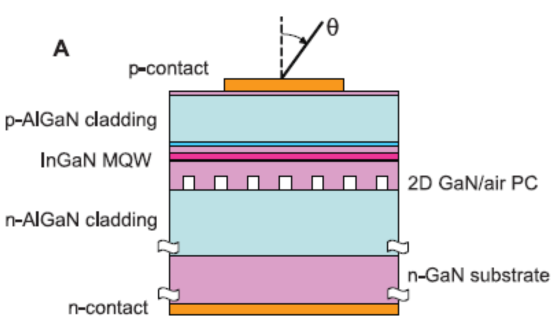
Previous tuning results limited to <30nm

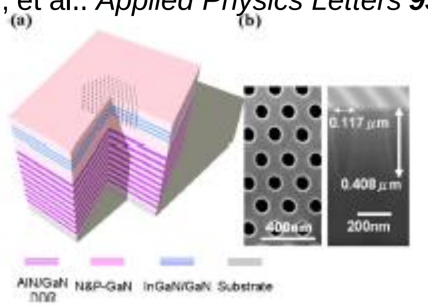


Scofield, A. C. *et al. Nano Lett.* ***11, (2011).***

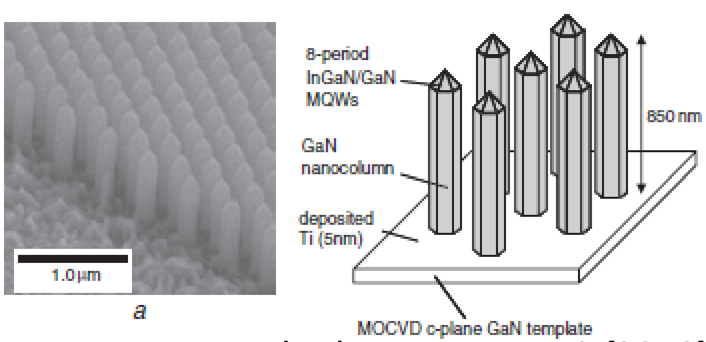
III-Ns

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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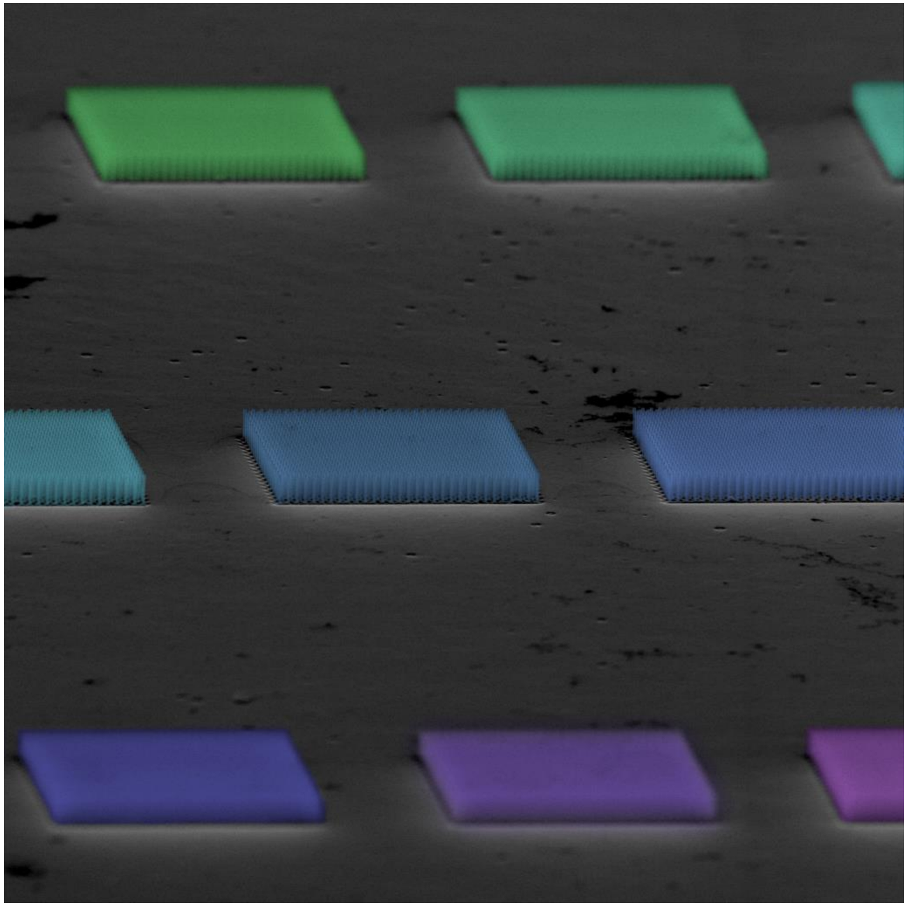
Photonic Crystal Nanowire Laser Pixels

- Fabricating an array of photonic crystal lasers that are composed of nanowires instead of holes
- Wavelength selection is decided purely by photonic crystal geometry
- Lateral feedback with low group velocity enables multiple gain sections and wide color tuning bandwidth



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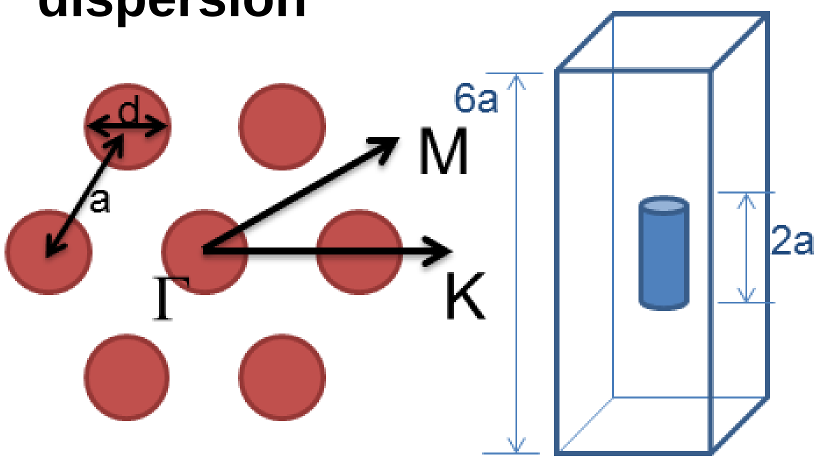
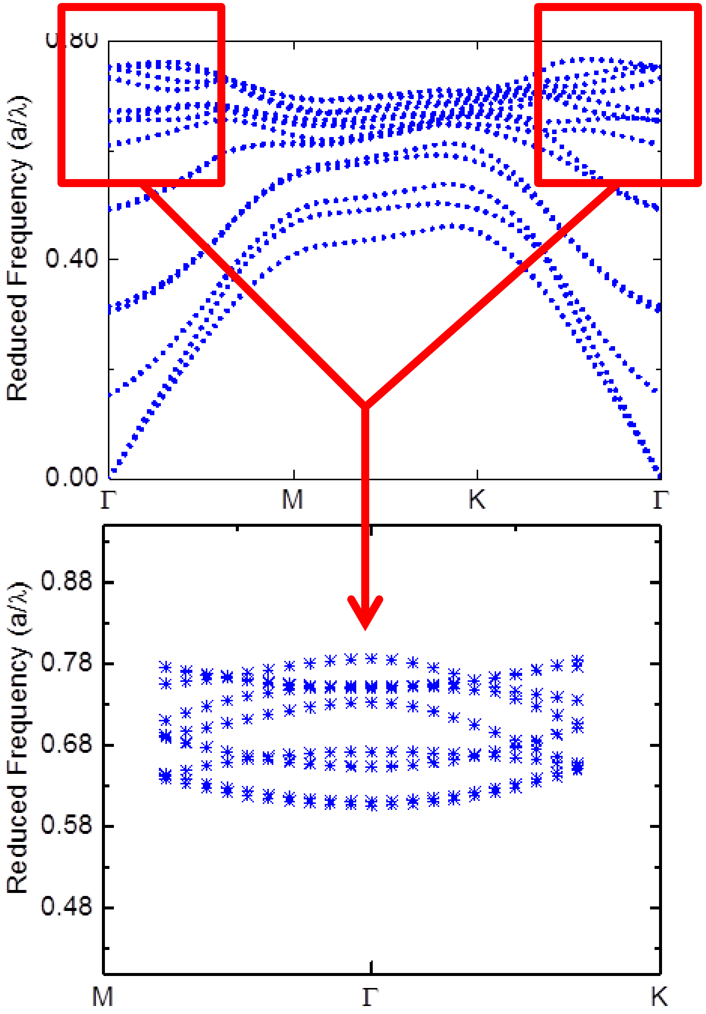
Designing vertically emitting photonic crystal lasers

- **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



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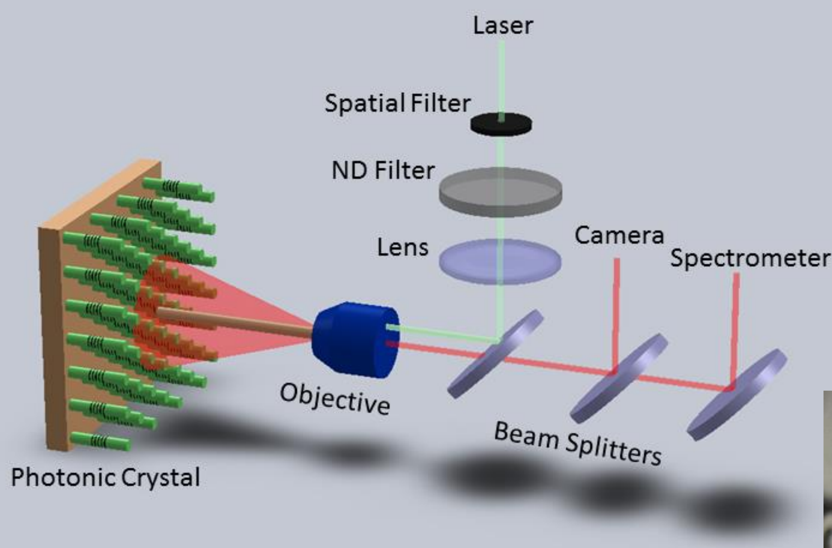
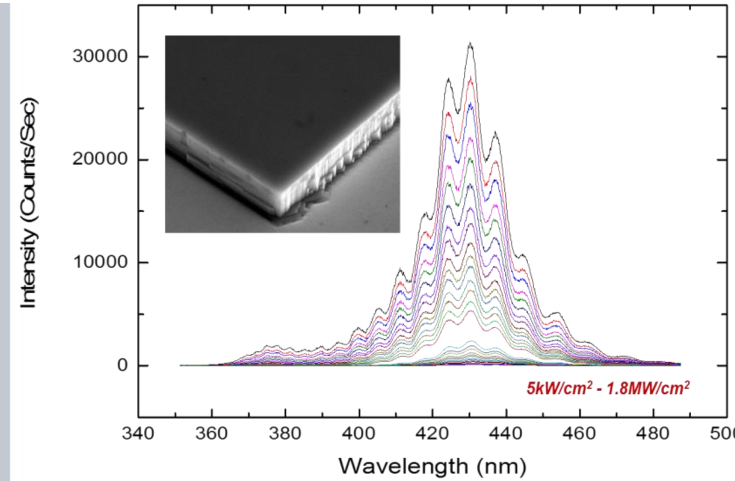
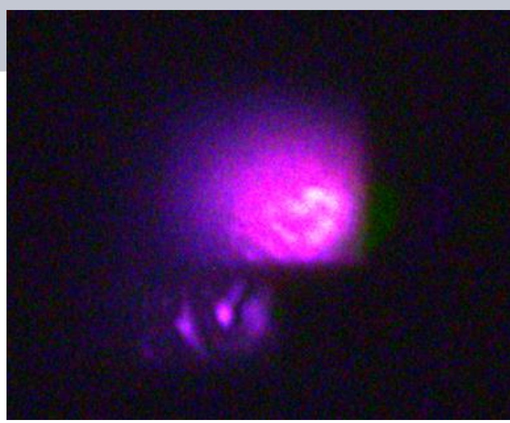
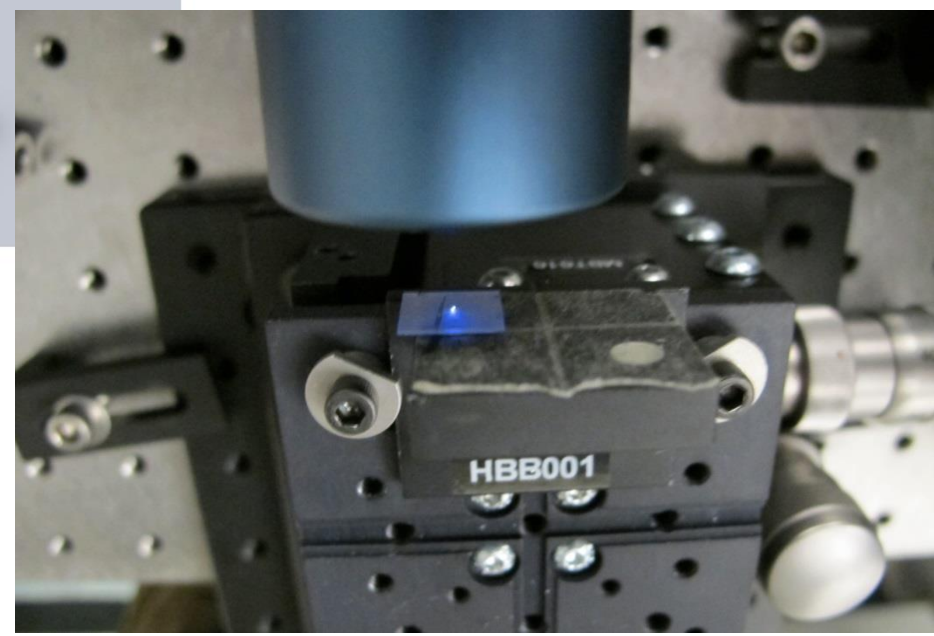
micro-Photoluminescent Optical Characterization

Pump spot is tunable in size and power density.

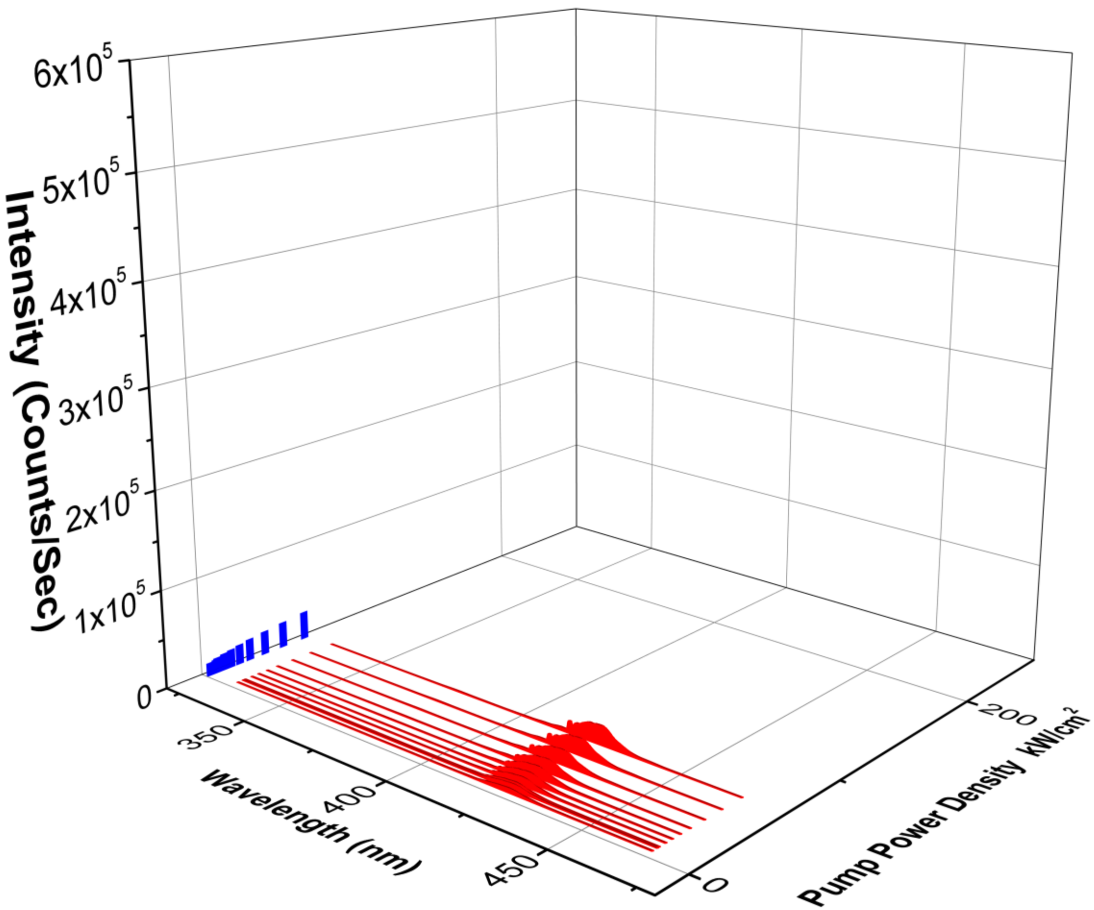


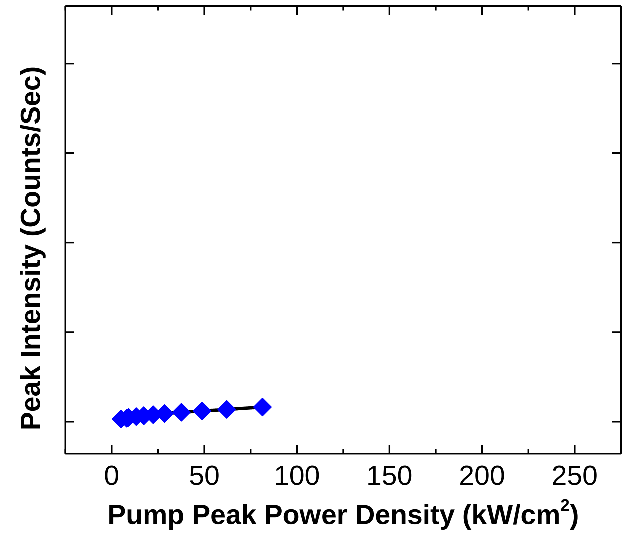


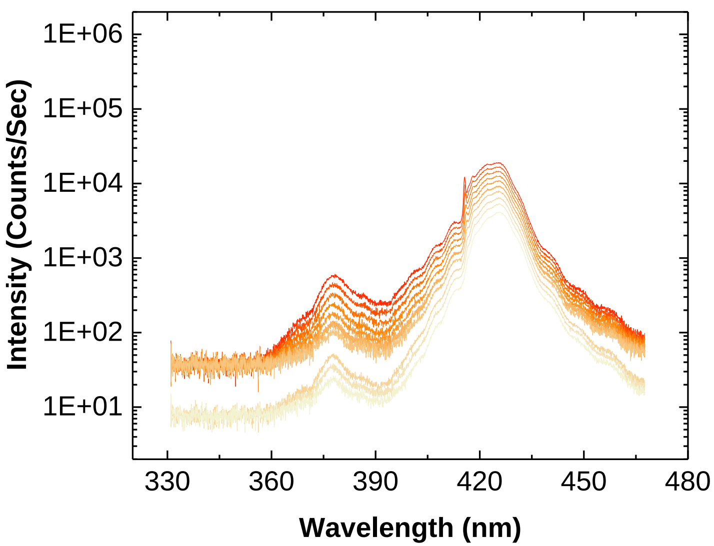




Below Threshold Spectra of a 2DPC Laser

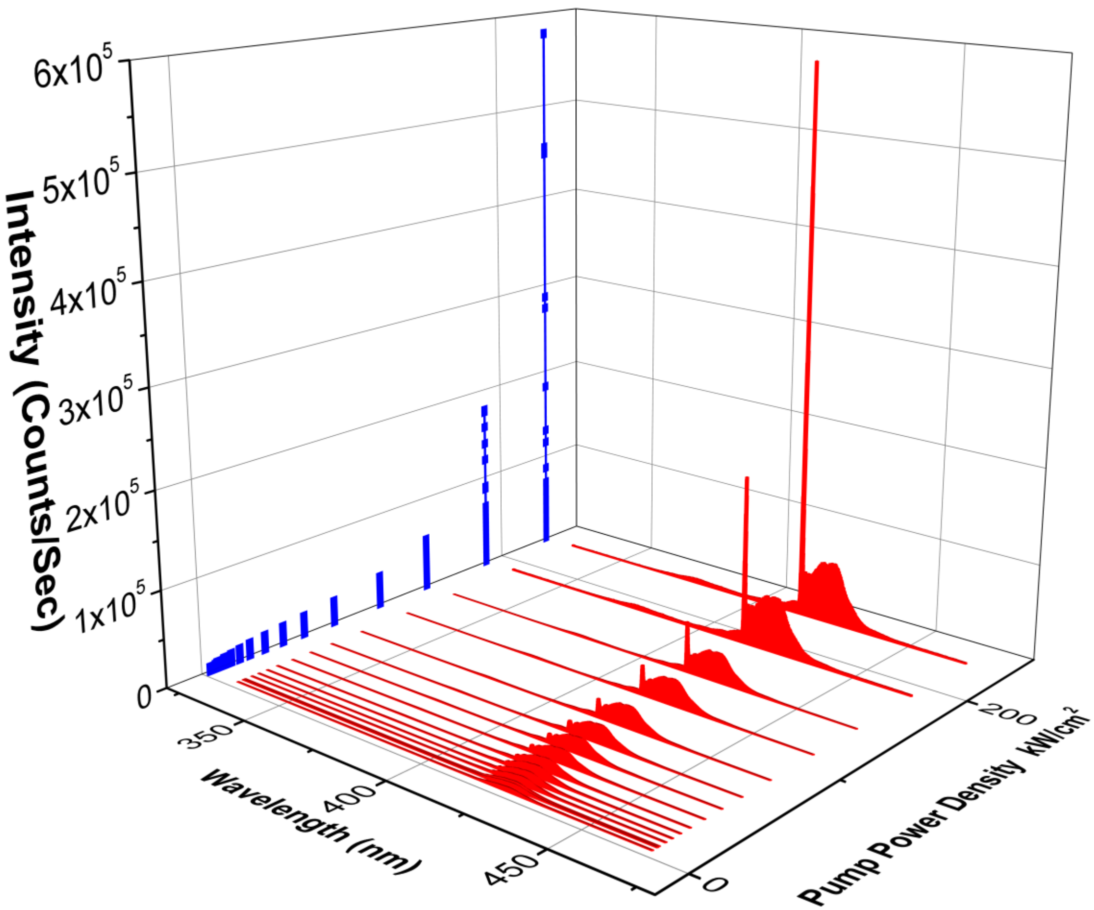


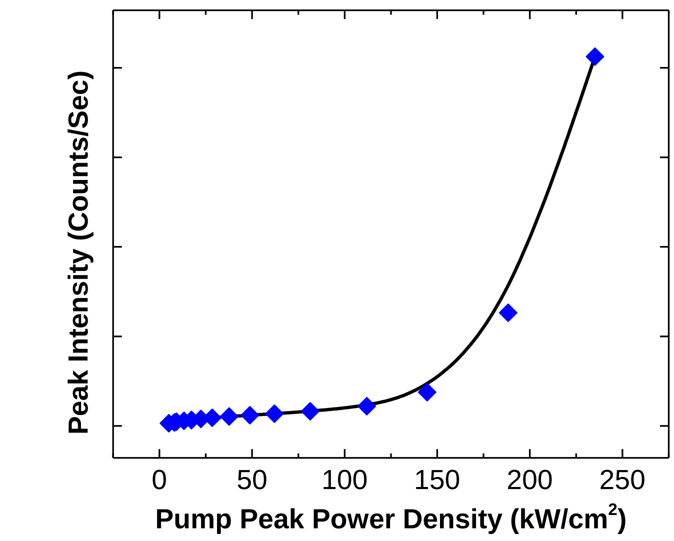


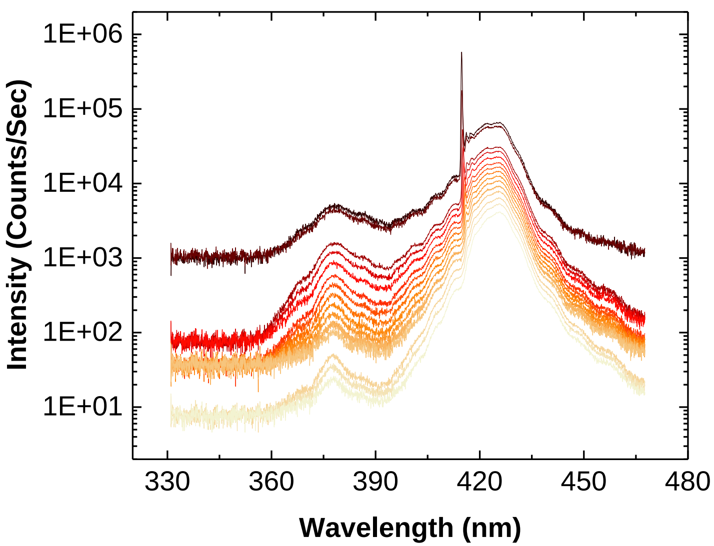


Array Element Dimensions: d=145 nm and a=320 nm.

Above Threshold Spectra of a 2DPC Laser

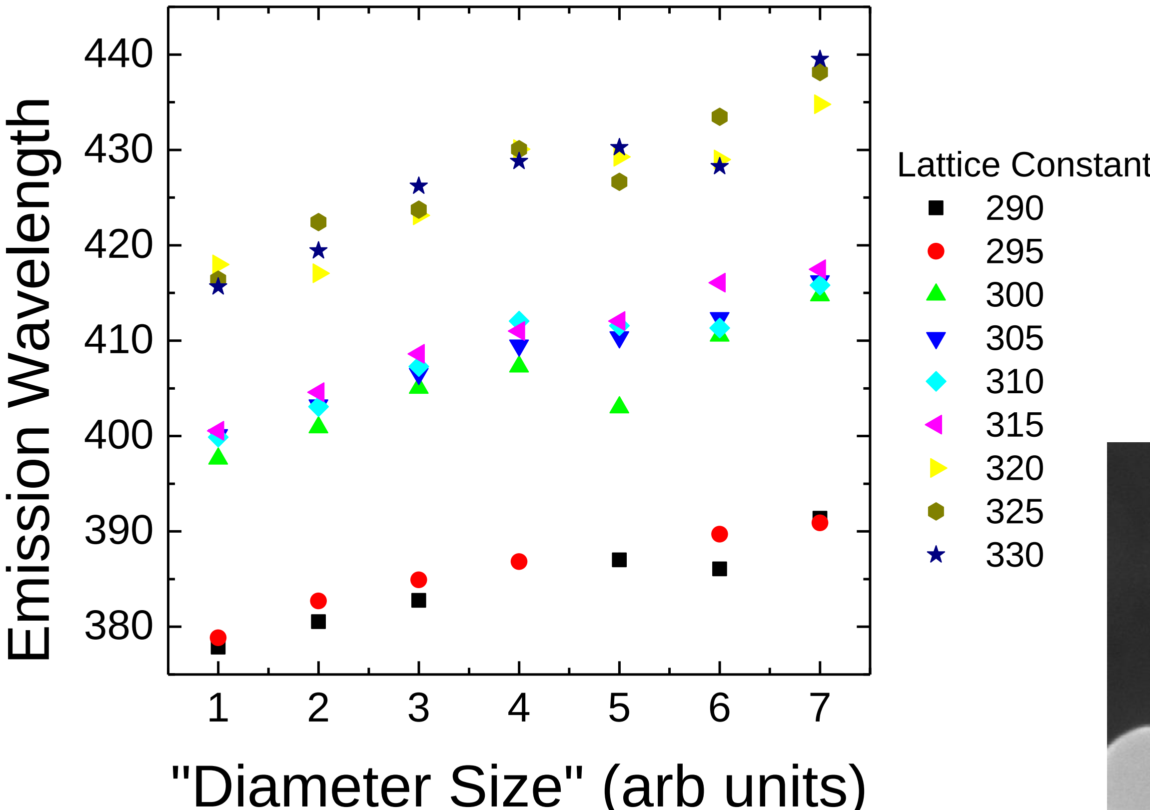


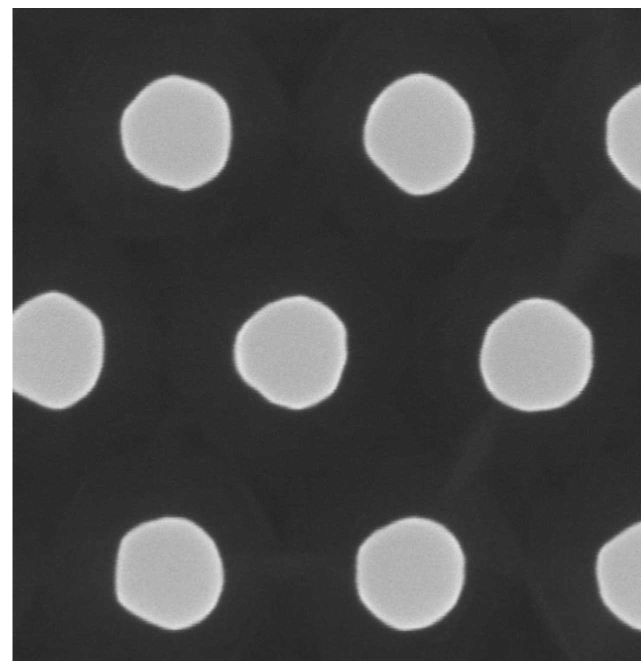




Array Element Dimensions: d=145 nm and a=320 nm.

Photonic crystal emission wavelength size dependence





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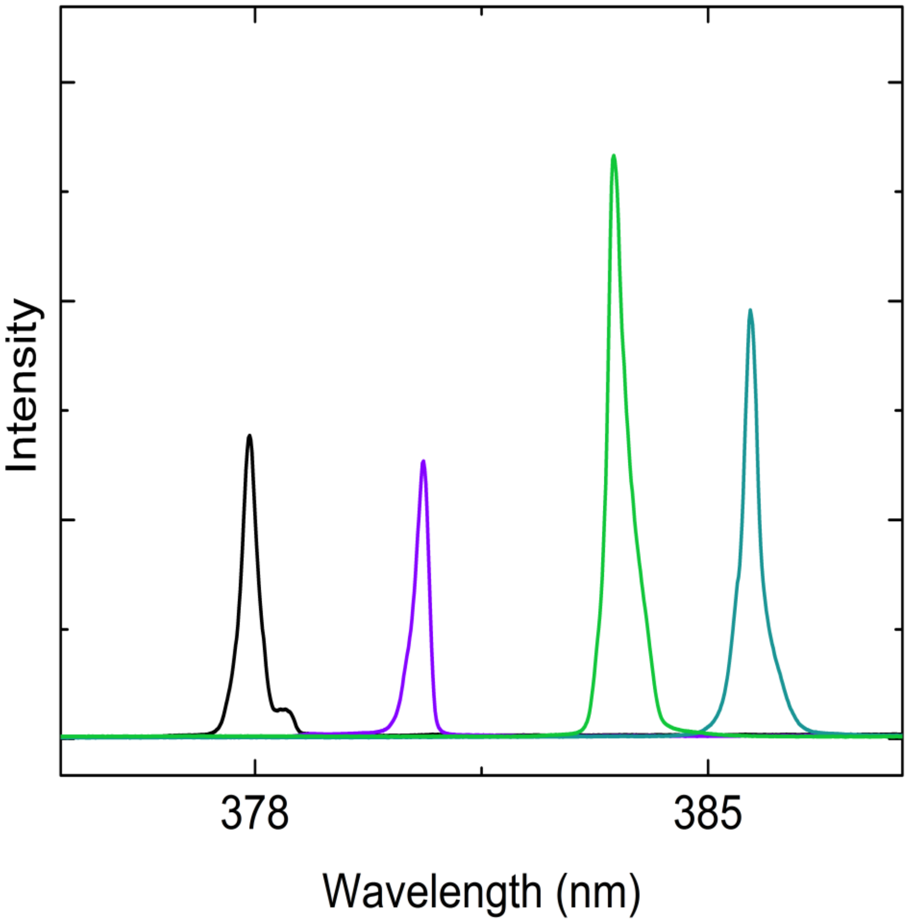
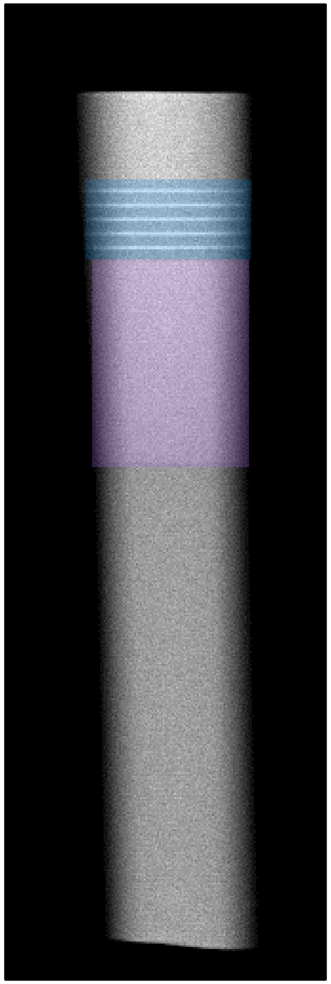
Gain is contributed from multiple sections





MQW Gain Section

Underlayer Gain Section

Incredibly the MQWs do not absorb the underlayer emission!

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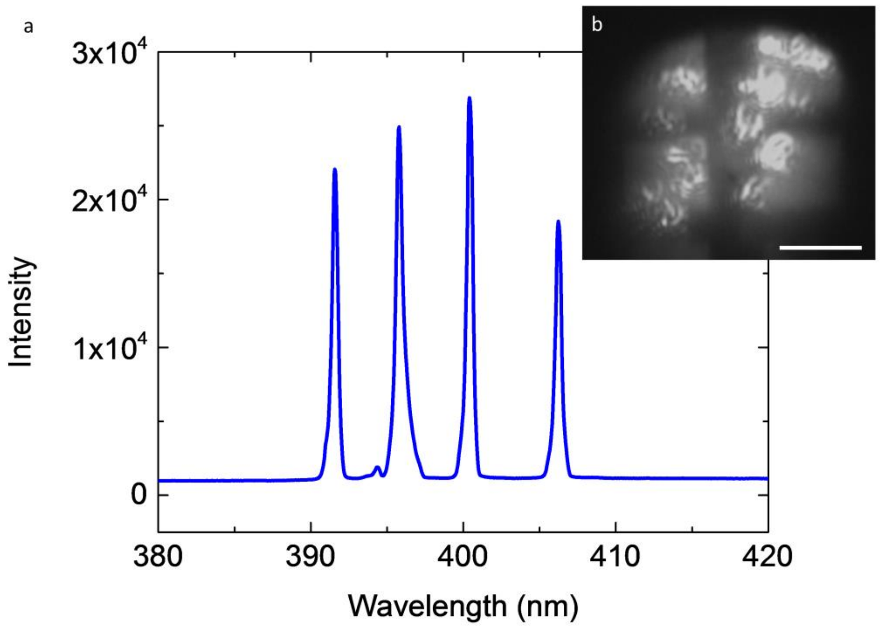
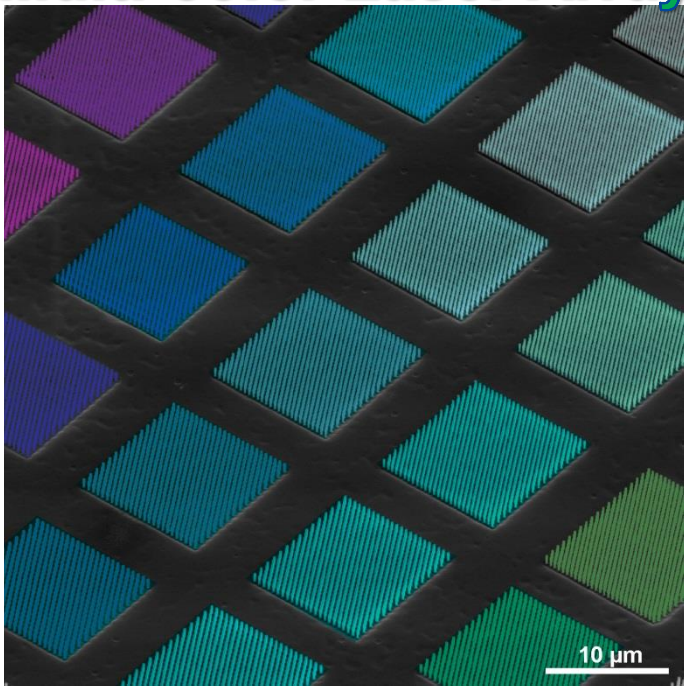
Photonic Crystal Laser Pixel | Achievements



Multi-color Laser Array



- Spectral Coverage from 380-440nm on a single die.
- Color mixing by pumping multiple pixels.
- Incorporation of multiple gain media to extend the spectral coverage.

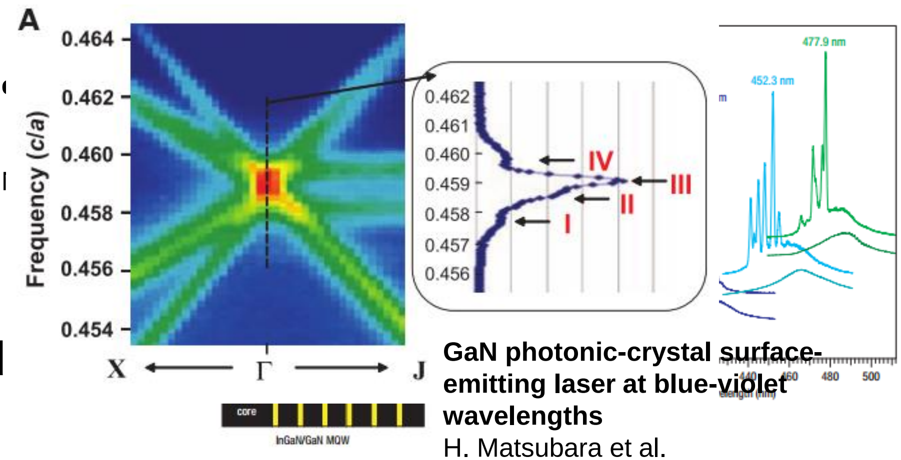
J. B. Wright, S. Liu, G. T. Wang, Q. Li, A. Benz, D. D. Koleske, et al., "Multi-Colour Nanowire Photonic Crystal Laser Pixels," Scientific Reports, vol. 3, 2013.

Outline

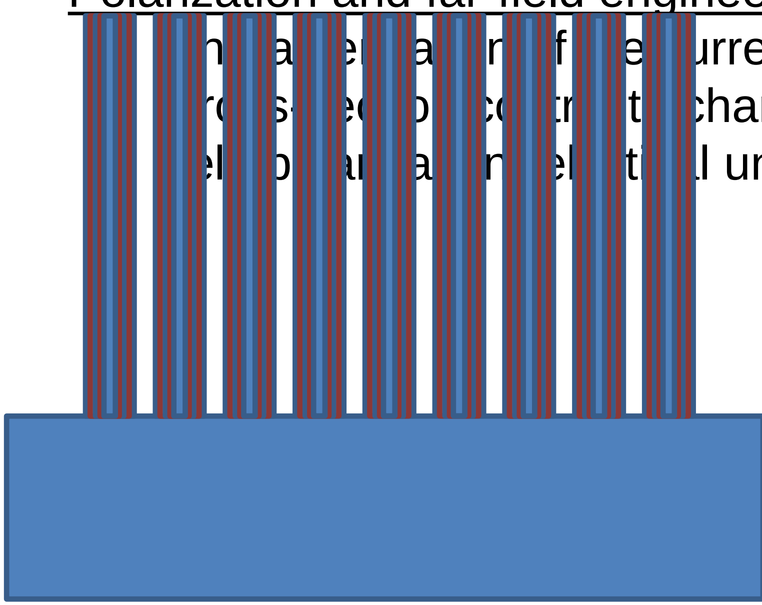
- **Motivation**
  - **Solid state lighting**
- **Single-mode lasing from single nanowires**
    - **Geometric reduction**
    - **Distributed feedback**
- **Photonic crystal laser "pixels"**
- **Conclusions and Outlook**

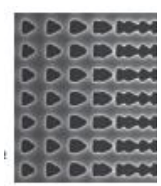
Future Work

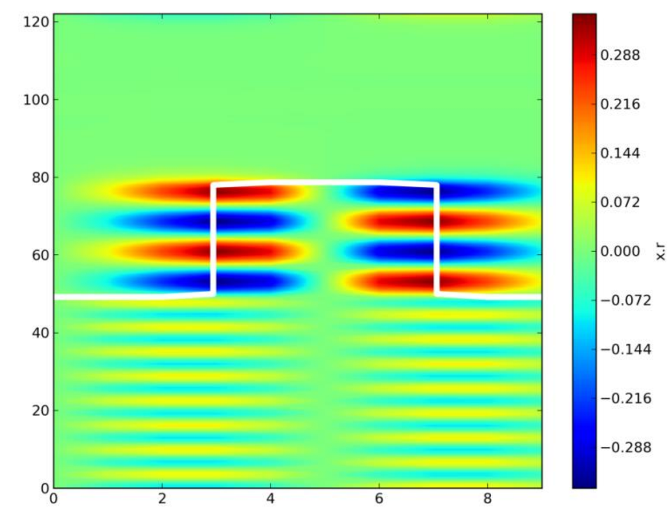
- **Photonic crystal laser pixels**
  - Regrown active regions
    - Core-shell MQW stacks
      - Higher field overlap -> lower thresholds
      - Non-polar QWs -> no QCSE
      - Strain relaxed -> possible redd wavelengths?
  - Polarization and far-field engineering
      - ... urrent PCLPs
      - ... change far-
      - ... l unit cells)



GaN photonic-crystal surface-emitting laser at blue-violet wavelengths
H. Matsubara et al.
Science, vol. 319, pp. 445-447, Jan







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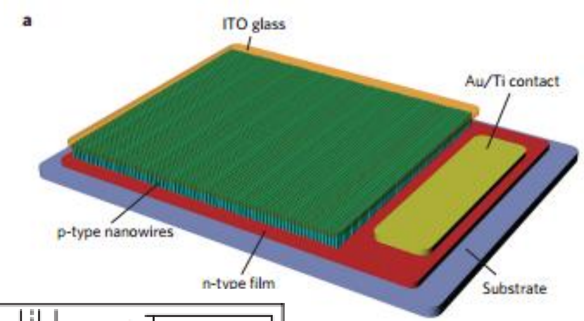
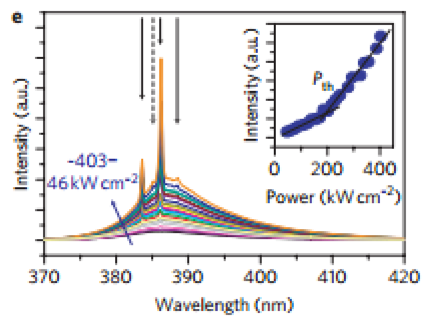
Possible Future Work

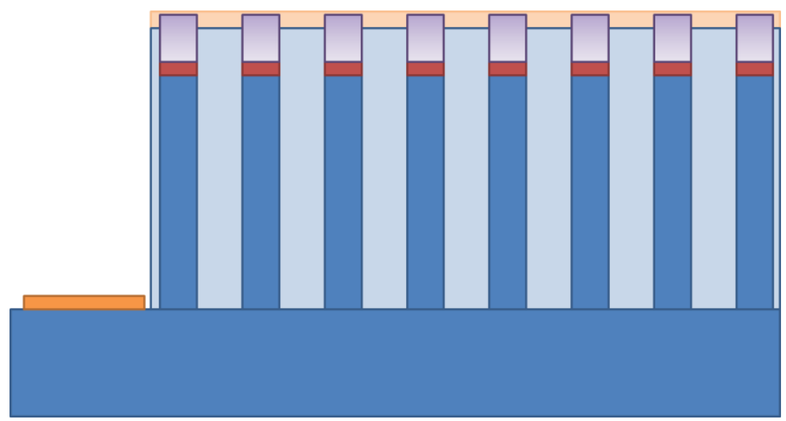
Electrical Injection

- **Redesign the lattice for planarization material**
- **Planarization and metallic contact**
- **Growth of new material with graded p-layers to limit absorption**





Electrically pumped waveguide lasing from ZnO nanowires
S. Chu, *et al.*
Nature Nanotechnology, vol. 6, pp. 506-510, Aug 2011.



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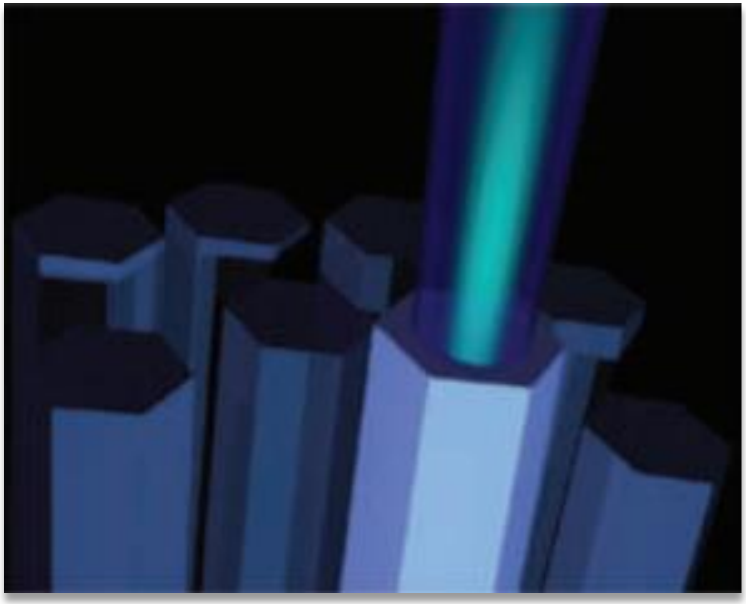
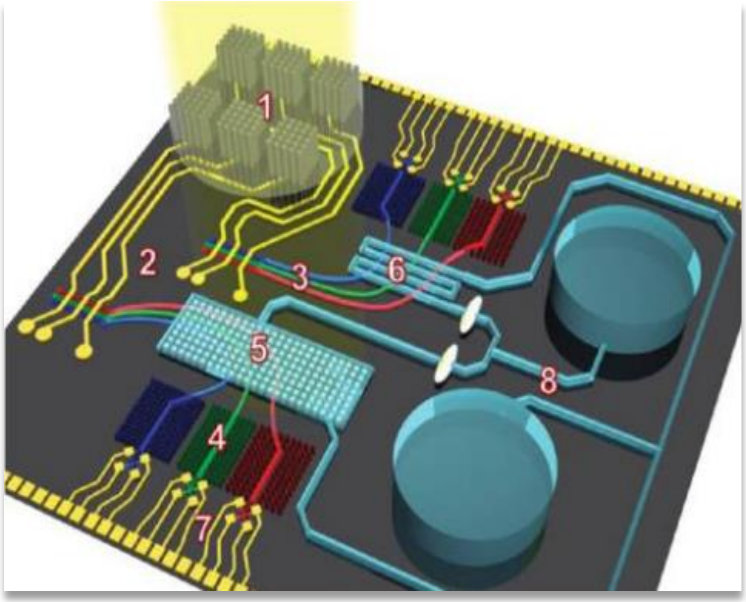
Outlook

- **Nanowire displays**
  - Ultra high resolution
  - Direct emitter



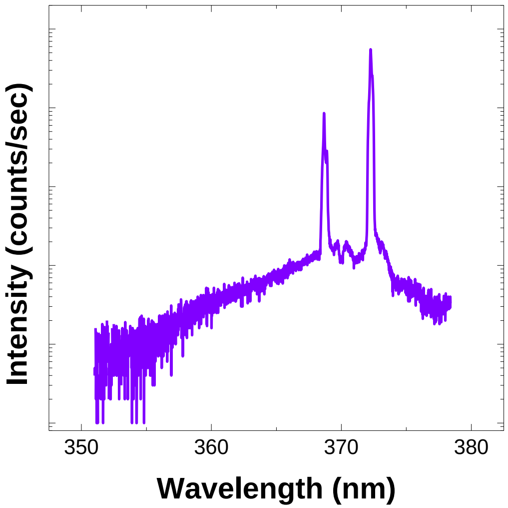
- **On chip light sources**
  - Low power
  - Substrate agnostic

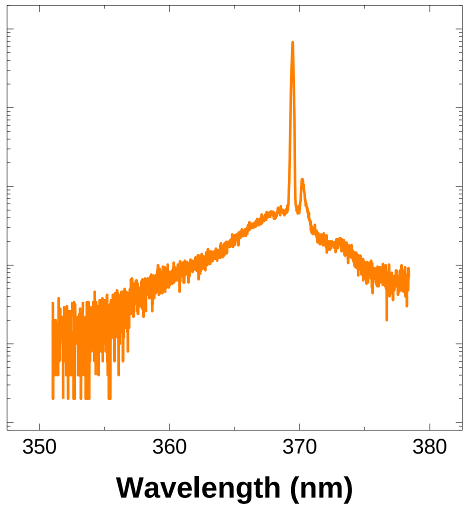


P. J. Pauzauskie, et al. Mat. Today 9(10), 36 (2006)
W. A. Challener, et al. Nat. Photonics 3(220), (2009)

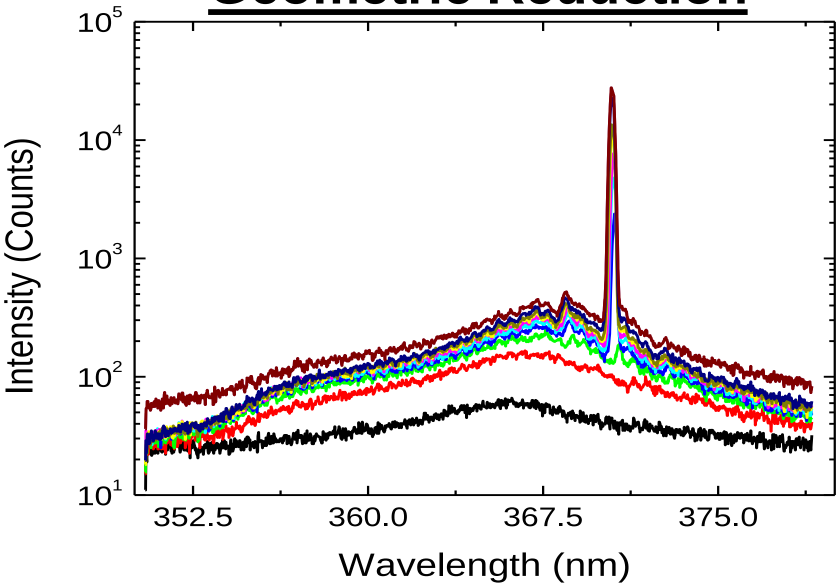
Summary

Grating Substrate

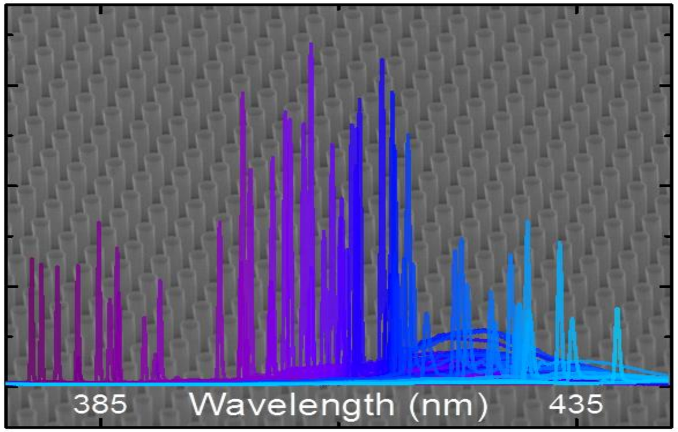




Geometric Reduction



Photonic Crystal Laser



THANK YOU

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SSLS EFRC

Relevant Publications

Refereed Journals

- **J. B. Wright**, S. Liu, G. T. Wang, Q. Li, A. Benz, D. D. Koleske, et al., "Multi-Colour Nanowire Photonic Crystal Laser Pixels," Scientific Reports, vol. 3, 2013.
- **J. B. Wright**, S. Campione, S. Liu, J. A. Martinez, H. Xu, T. S. Luk, et al., "Distributed feedback gallium nitride nanowire lasers," Applied Physics Letters, vol. 104, p. 041107, 2014.
- H. Xu, **J. B. Wright**, T.-S. Luk, J. J. Figiel, K. Cross, L. F. Lester, et al., "Single-mode lasing of GaN nanowire-pairs," Applied Physics Letters, vol. 101, p. 113106, 2012.
- H. Xu, **J. B. Wright**, A. Hurtado, Q. Li, T.-S. Luk, J. J. Figiel, et al., "Gold substrate-induced single-mode lasing of GaN nanowires," Applied Physics Letters, vol. 101, pp. 221114-221114-4, 2012.
- Q. Li, **J. B. Wright**, W. W. Chow, T. S. Luk, I. Brener, L. F. Lester, et al., "Single-mode GaN nanowire lasers," Optics Express, vol. 20, pp. 17873-17879, 2012.
- A. Kar, Q. Li, P. C. Upadhya, M. A. Seo, **J. B. Wright**, T. Luk, et al., "The influence of radial heterostructuring on carrier dynamics in gallium nitride nanowires," Applied Physics Letters, vol. 101, p. 143104, 2012.
- A. Hurtado, H. Xu, **J.B. Wright**, S. Liu, Q. Li, G. Wang, et al., "Polarization switching in GaN nanowire lasers," Applied Physics Letters, vol. 103, p. 251107, 2013.

Conference Papers

- **J. B. Wright**, Q. Li, T. Luk, I. Brener, G. Wang, K. Westlake, et al., "Single-mode lasing from top-down fabricated gallium nitride nanowires," in Photonics Conference (PHO), 2011 IEEE, 2011, pp. 529-530.
- **J. B. Wright**, Q. Li, I. Brener, T. S. Luk, G. T. Wang, W. W. Chow, et al., "Gallium Nitride Single-Mode Nanowire Lasers," in CLEO: Science and Innovations, 2012, p. CTh4M. 5.
- **J. B. Wright**, S. Liu, G. T. Wang, Q. Li, D. D. Koleske, P. Lu, et al., "Multi-Color Arrays of III-Nitride Photonic Crystal Nanowire Lasers on a Single Chip," in CLEO: Science and Innovations, 2013, p. CTh3G. 4.
- **J. B. Wright**, S. Campione, S. Liu, J.A. Martinez, H. Xu, G. T. Wang, Q. Li, et al., “Gallium Nitride Nanowire Distributed Feedback Lasers," in CLEO: Science and Innovations, 2014, *submitted*.
- A. Hurtado, H. Xu, **J. B. Wright**, S. Liu, Q. Li, G. T. Wang, et al., "Polarization Properties of GaN Nanowire Lasers," in CLEO: Science and Innovations, 2013, p. CW3G. 1.
- G. T. Wang, Q. Li, J. Wierer, J. Figiel, **J. B. Wright**, T. S. Luk, et al., "Top-down fabrication of GaN-based nanorod LEDs and lasers," in SPIE OPTO, 2012, pp. 827816-827816-6.

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nanowire
motivation
emission
achieve
nanowires
work
mode
single
2dpc
achievements
cavity
tunable
order
outline
characterization
velocity
array
new
feedback
research
multiple
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desired
2-step
fabricated
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lasers
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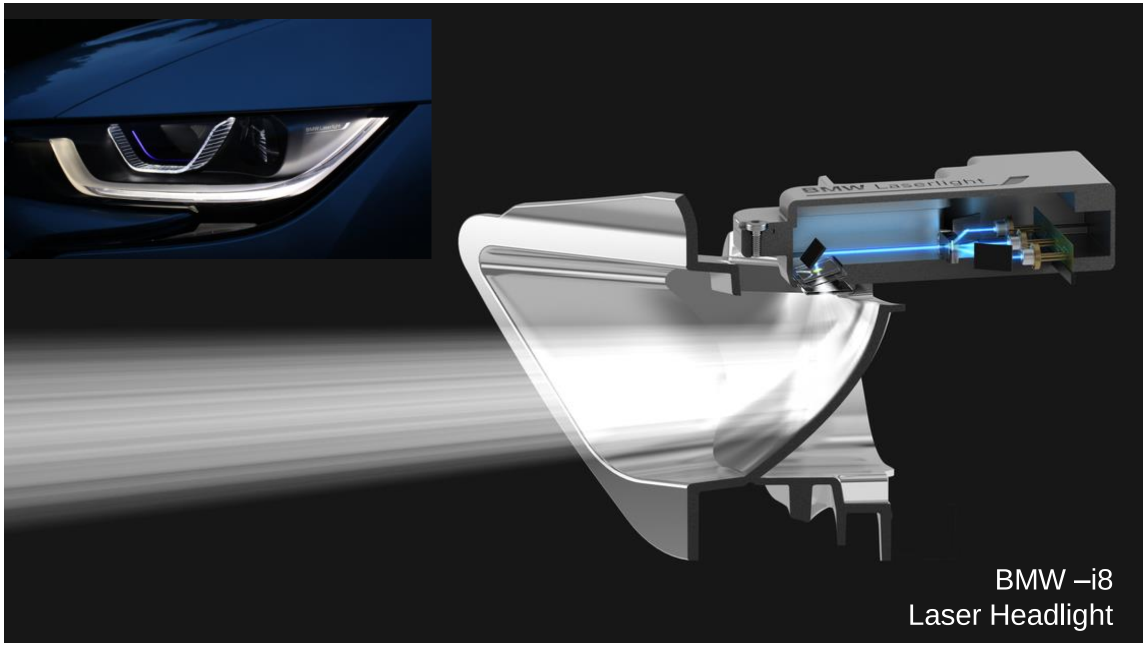
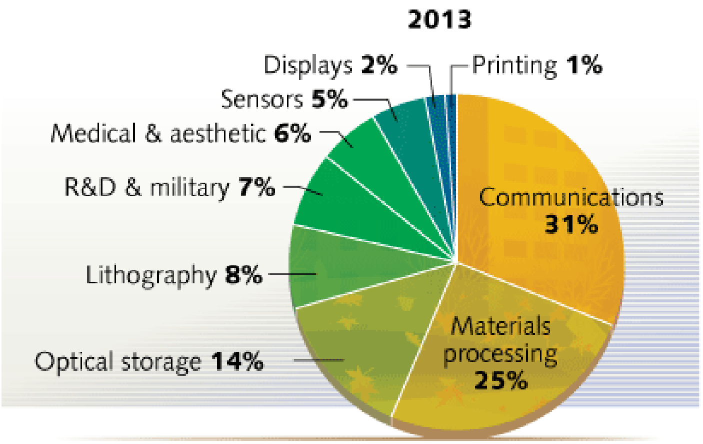
spectra
laser
pixels

Lasers in lighting markets



BMW –i8
Laser Headlight



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Multi-Mode Laser Theory Indicates Single-Mode Lasing

Single-mode lasing depends on two factors:

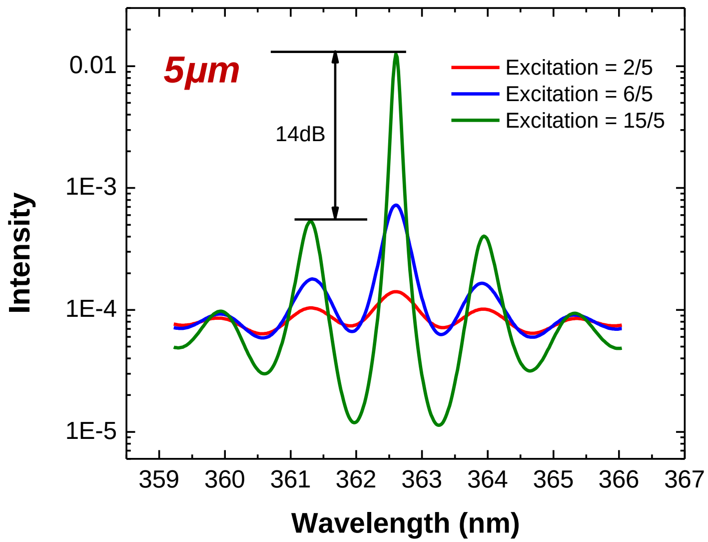
(1) Suppression of modes (e.g. transverse modes) close to the single lasing mode via mode competition, and

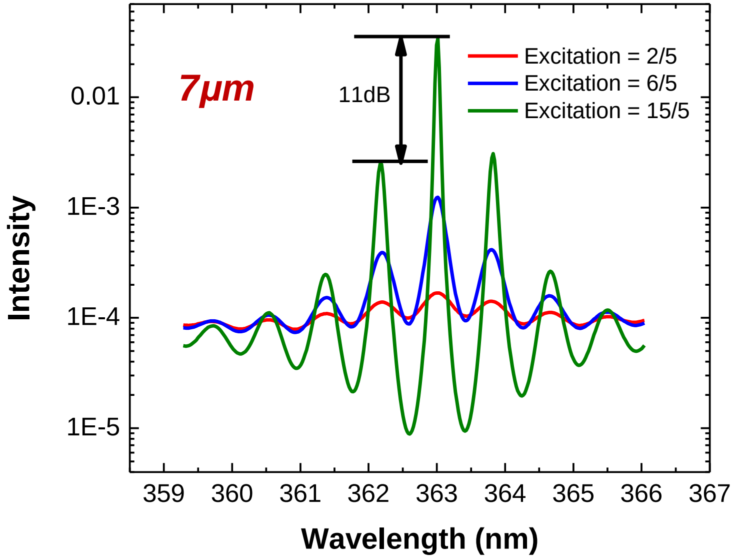
(2) Absence of net gain in the further lying modes because of large longitudinal mode spacing and finite gain bandwidth.

Material gain = 5.8×10^{3} cm^{-1}

Carrier density = 1.4×10^{19} cm^{-3}

Evidence for high material quality.





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Diameter Dependent Emission for a given Lattice Constant