

Mode and Polarization Control in Gallium Nitride Nanowire Lasers

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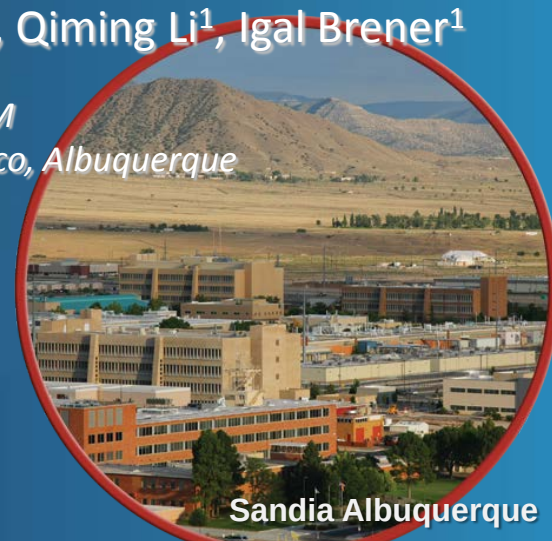
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e-mail: gtwang@sandia.gov

<http://www.sandia.gov/~gtwang>

Sandia MESA Facility

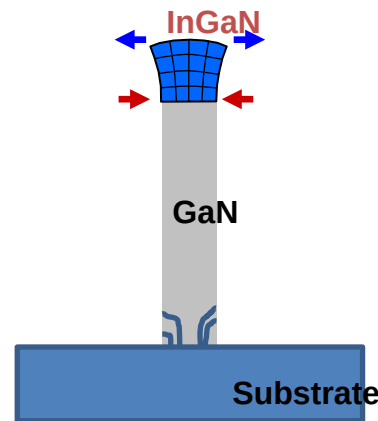
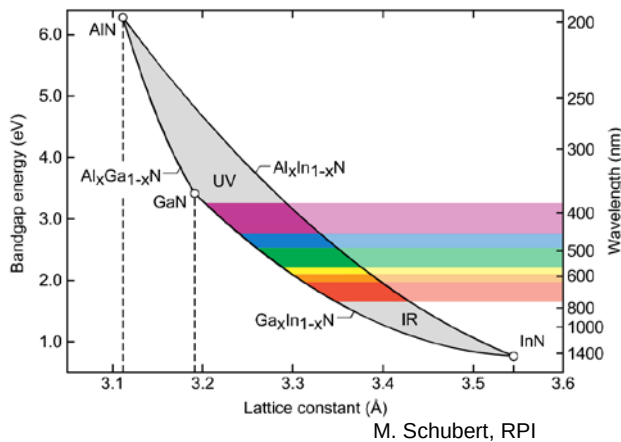
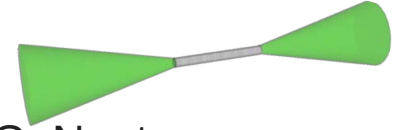


Sandia Albuquerque

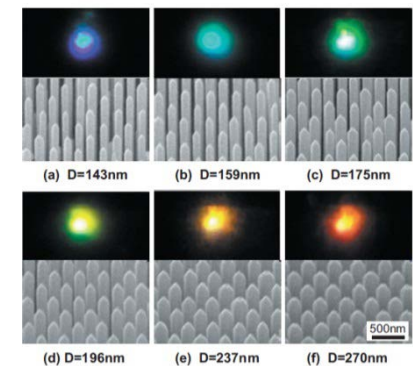
Funding Acknowledgment: Sandia's Solid-State-Lighting Science Energy Frontier Research Center (DOE BES) and Sandia's LDRD program; European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° PLOF-GA-2010-273822.

Nanowire Lasers

- Nanowire forms a freestanding, low loss optical cavity
- Optically pumped nanowire lasers: ZnO, CdS, GaAs, GaSb, GaP, GaN, etc.
- Most commonly Fabry-Perot type lasing from end facets
- Compact and low power due to small mode volume
- Strain accommodation in GaN nanowires opens up possibility of high efficiency lasers over a wide spectral range (incl. green and yellow) through facile In incorporation



Multi-color [spontaneous] emission



Sekiguchi et al., APL **96**, 231104 (2010) – Sophia U.

See also: S. Arafin, X. Liu, Z. Mi, "Review of recent progress of III-nitride nanowire lasers," *J. Nanophotonics* **7**, 074599-1 (2013)

Why Nanowire Lasers?

Integrated coherent nanophotonic elements for communications, sensing, imaging, lithography, lighting, etc.

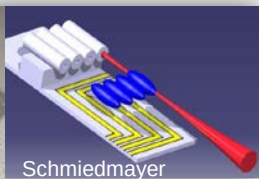
Integrated nanophotonics, atom trapping, optical MEMS

Optical nanoprobes & chem/bio detection/sterilization

atom trap



P. Schwindt (1725)

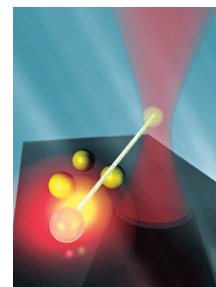


Schmiedmayer

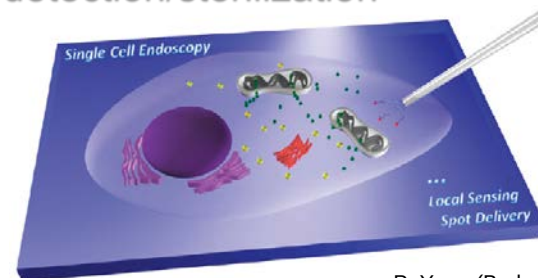


J. Ford, Lucent

Small UV-visible laser for trapping, interconnects, switching, etc.



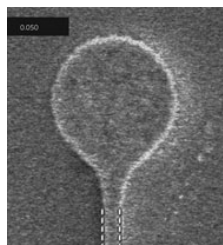
Sub- λ resolution probes for localized excitation, detection



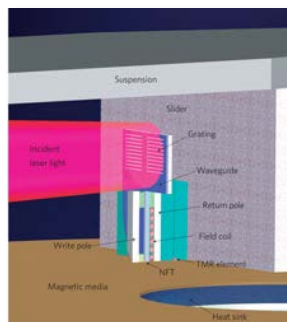
P. Yang (Berkeley)

Nanolithography & Heat-assisted Magnetic Recording

Lighting, projection, & holographic displays



Nature Photonics 3, 220 (2009)



Seagate

Subwavelength & efficient laser spot

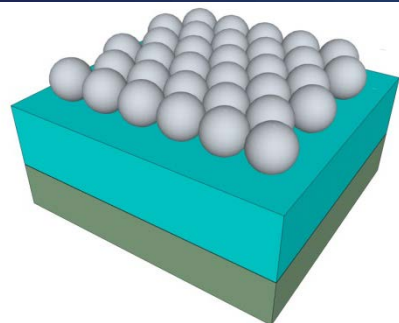


Sony Crystal LED Display prototype

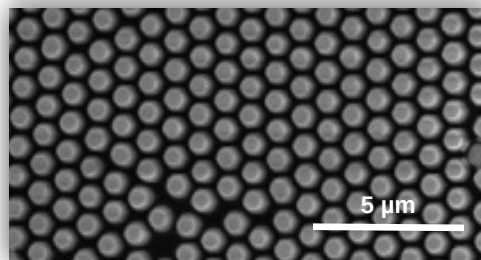
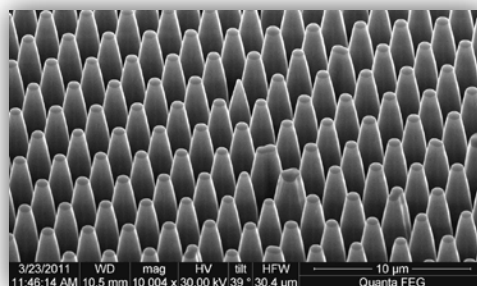
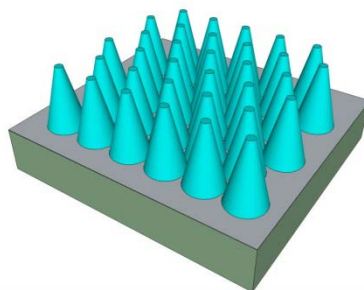
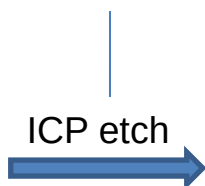
Low-power, speckle-free low coherence (random laser), multicolor pixels



New dry + wet top-down ordered nanowire fabrication process

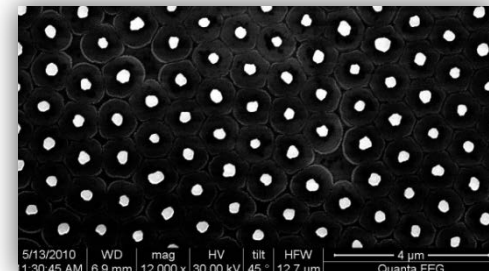
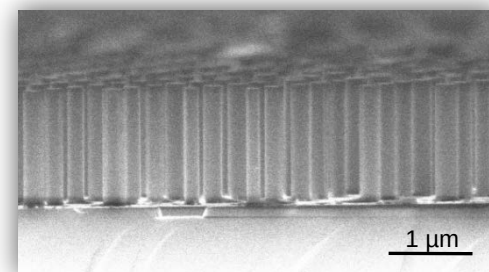
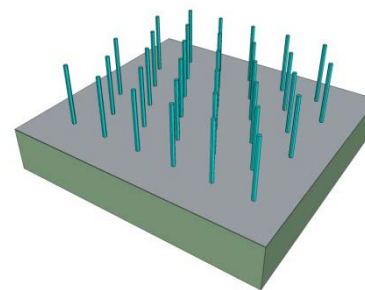


(0001) GaN on sapphire

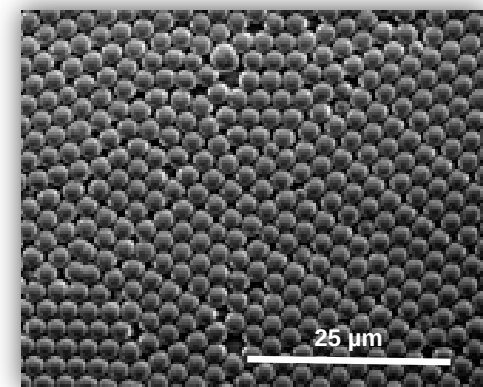


Plasma etch causes sidewall damage
C. Y. Wang et al., Opt. Expr. 16, 10549–10556, 2008.
Tapered; no well-defined facets

Selective wet etch
(AZ-400K developer)



Wet etch: straight sidewalls,
removes sidewall damage



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



Straight GaN nanowires with controllable geometries

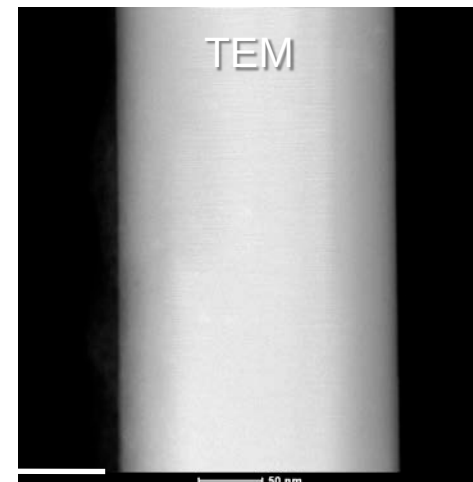
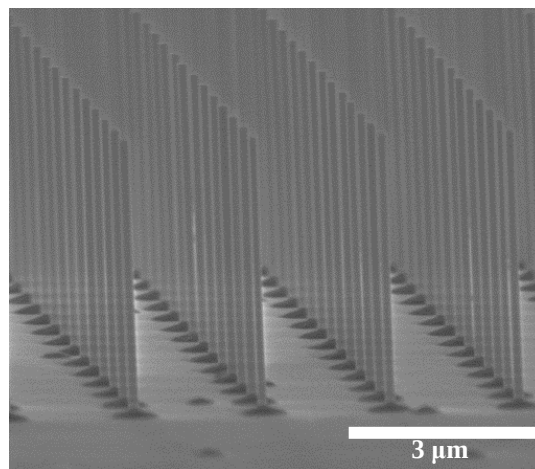
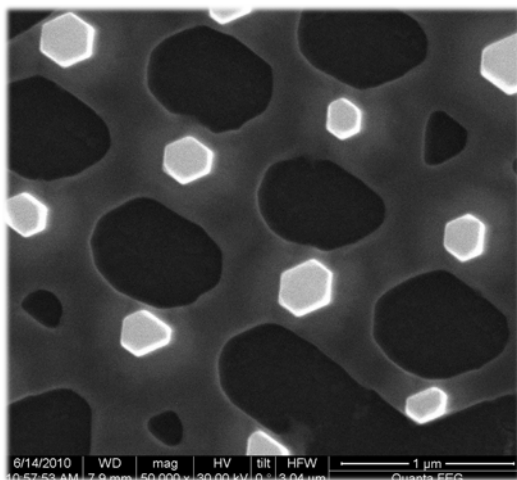
Wet etch rate negligible for top (Ga-polar) c-face & fast for [10-10], leads to nominally hexagonal NWs with **straight & smooth** *m*-facets

Superior and independent control of:

Height (dry etch depth)

Diameter (wet etch time)

Pitch/arrangement (defined by masking template)

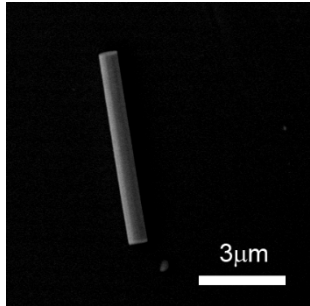


Smooth sidewall created by wet etch

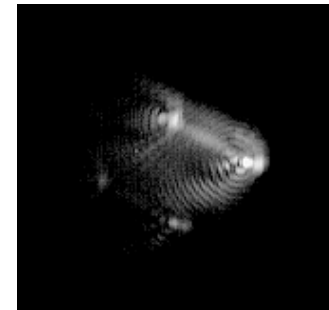
TEM: Ping Lu, SNL

See: Q. Li et al., *Optics Express* **19**, 25528 (2011)

Typical GaN Nanowire Lasing: Multimode Operation



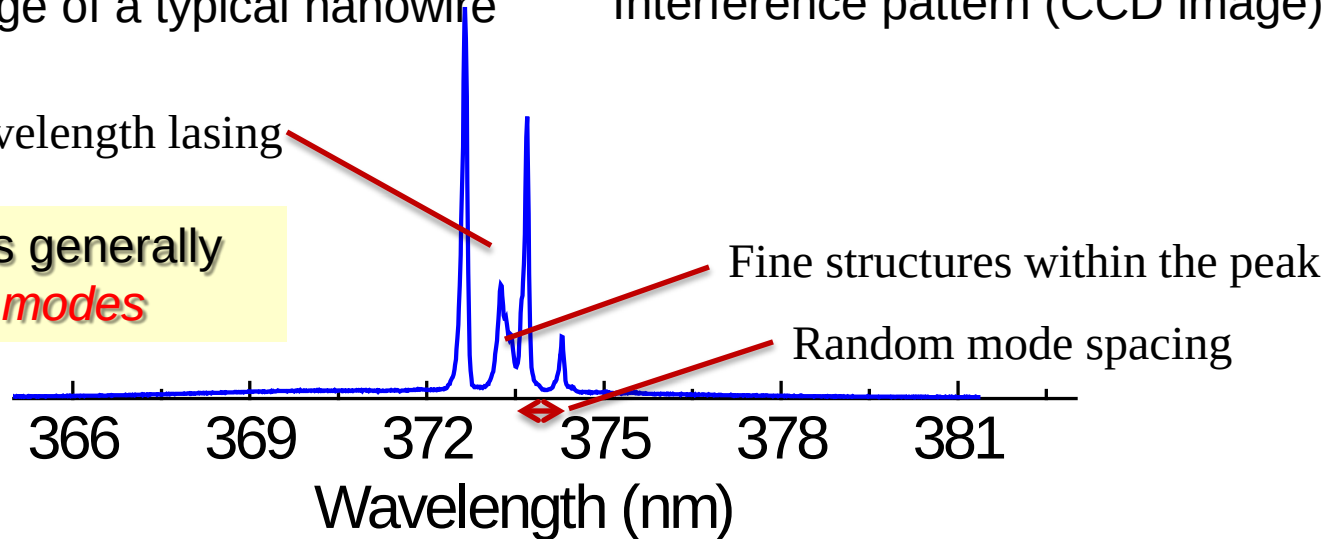
SEM image of a typical nanowire



Interference pattern (CCD image)

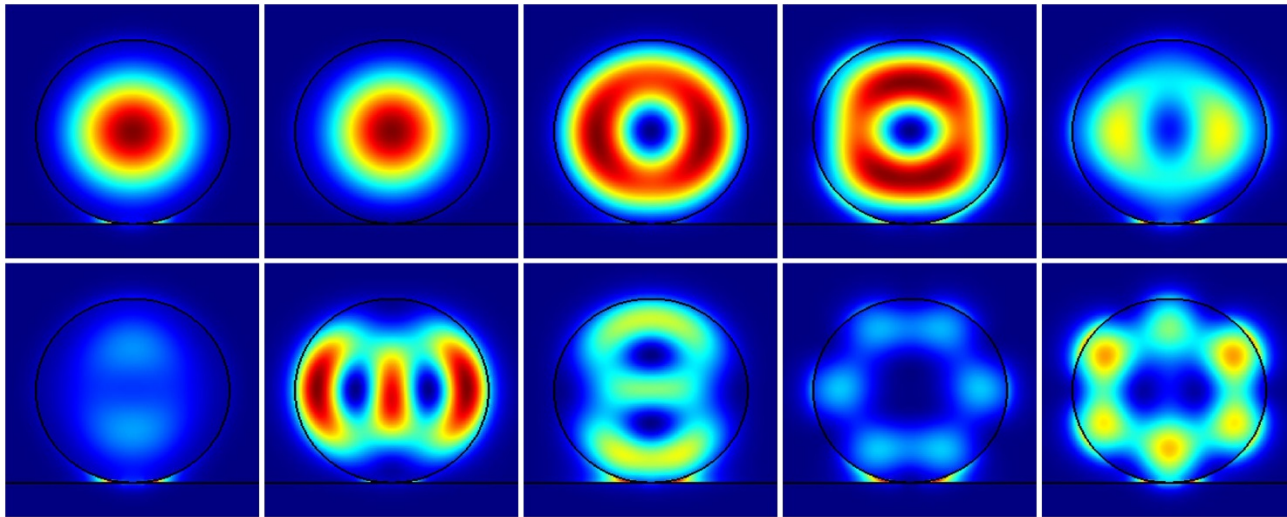
Multi-wavelength lasing

Nanowire lasers generally exhibit *multiple modes*



- *Single mode* behavior desired for highest **resolution** and **beam quality**; may also reduce **lasing threshold** due to reduced mode competition

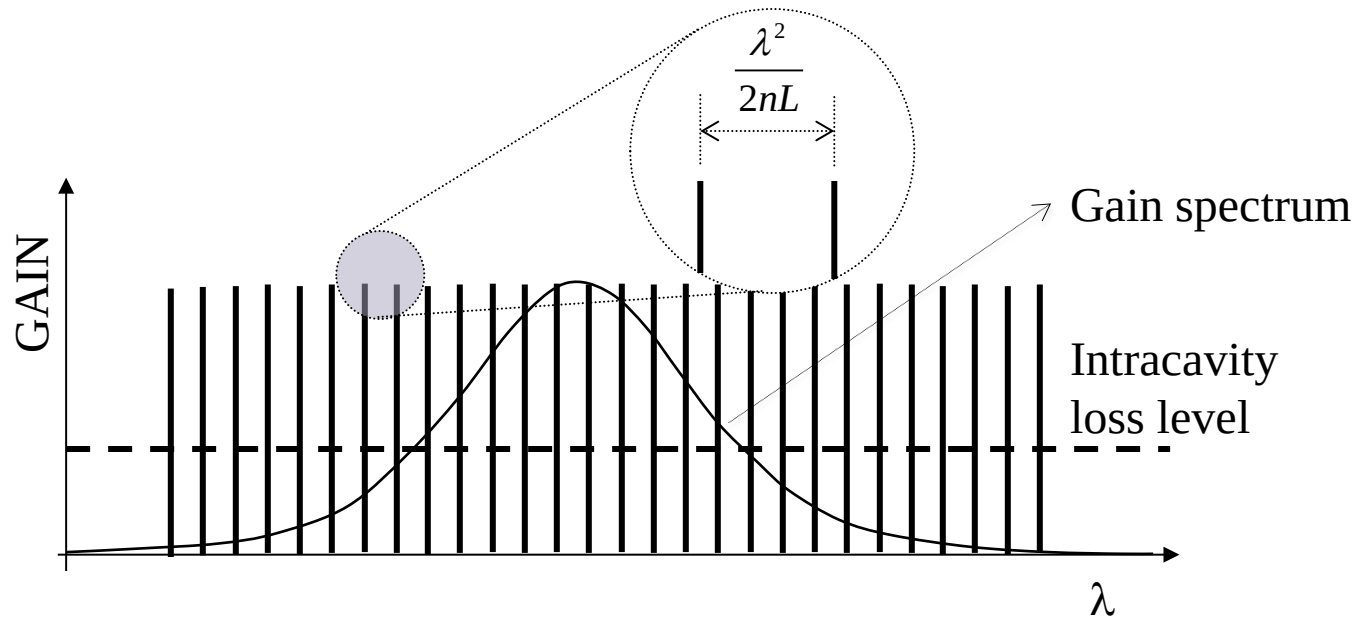
Why Multimode Lasing Occurs



Calculated transverse modes supported by a 300 nm diameter GaN nanowire.

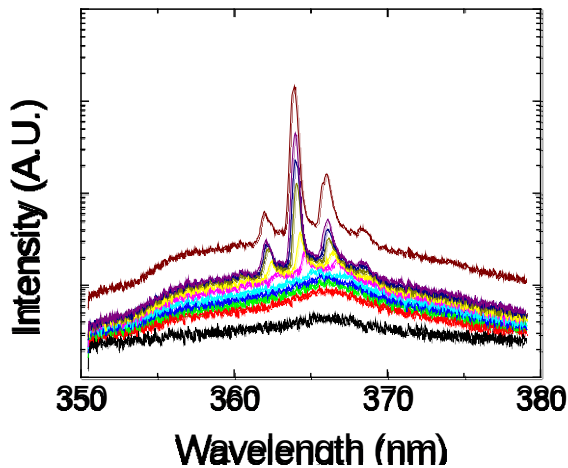
- ✓ Multiple transverse mode waveguide;
- ✓ Single-mode cutoff diameter ~ 120 nm;
- ✓ Lasing in multiple transverse mode operation
- ✓ Polarization is mode-dependent

Why Multimode Lasing Occurs

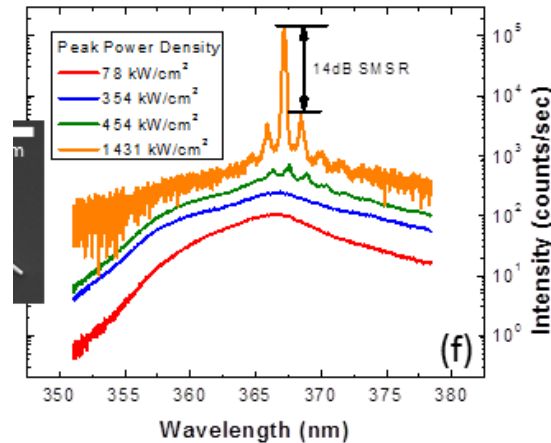


- ✓ Gain bandwidth ~ 7 nm;
- ✓ Longitudinal mode spacing ~ 1 nm;
- ✓ Several modes located in the gain spectrum;
- ✓ Multiple longitudinal mode oscillation

Method 1: Single-mode NW laser via geometry control

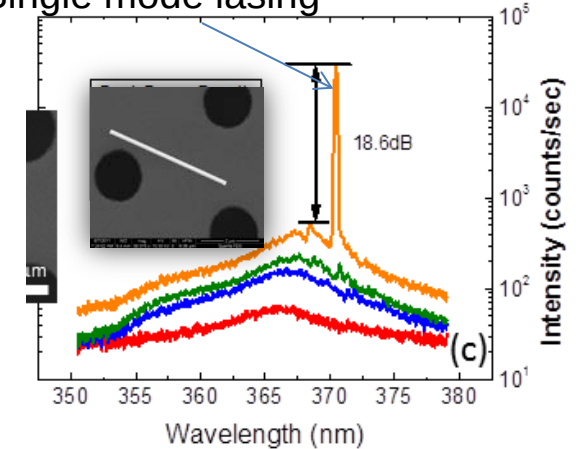


~500 nm x 4.7 μm (short)



145 nm x 7.2 μm (skinny)

Single mode lasing



~130 nm x 4.7 μm (short & skinny)

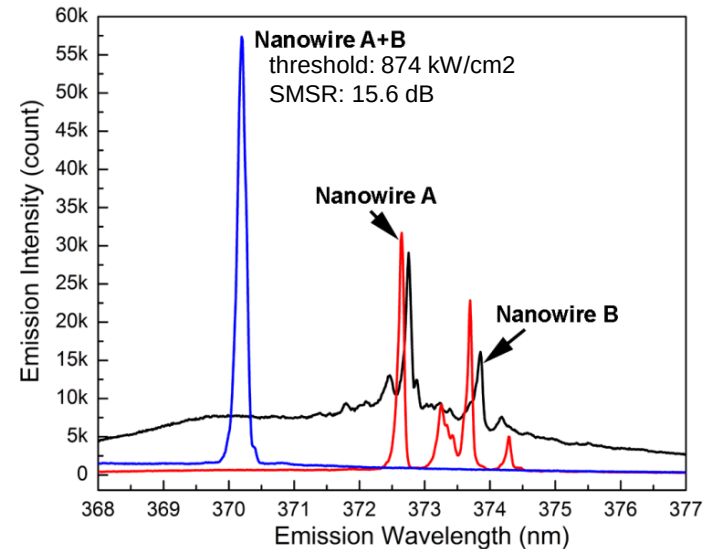
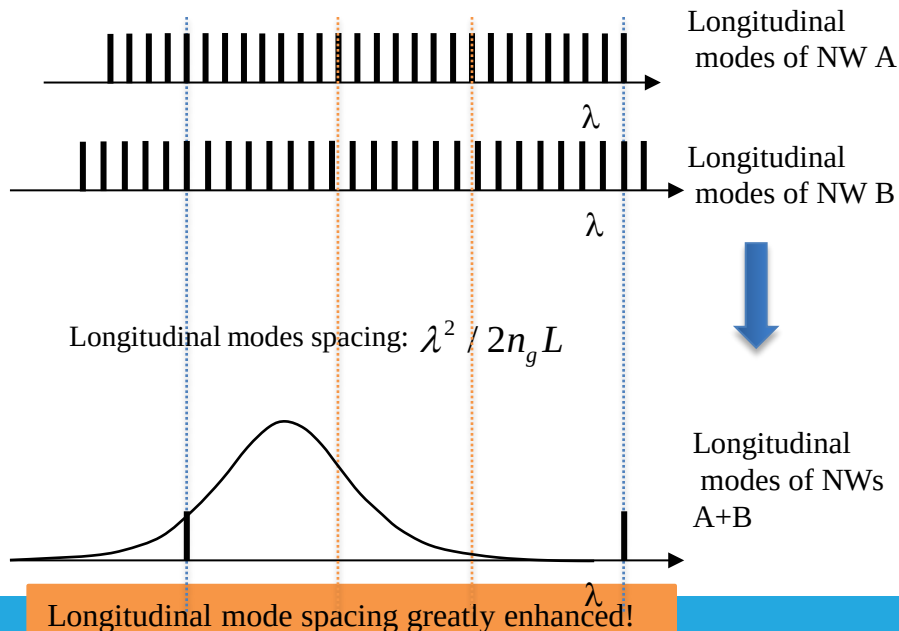
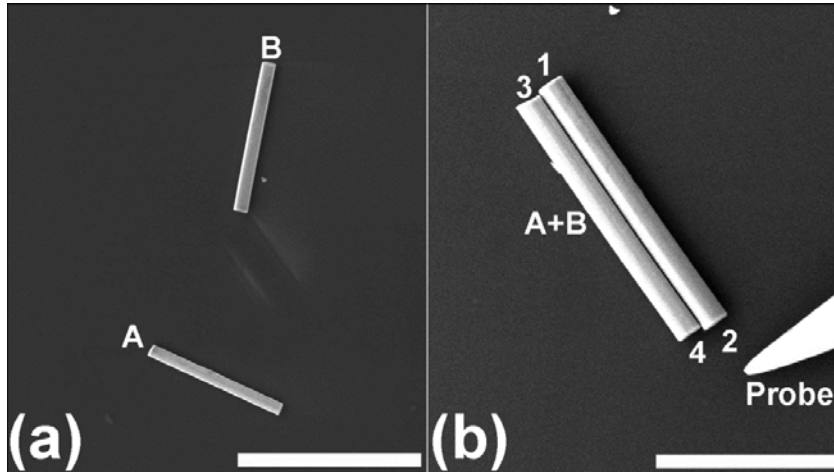
NW diameter x length

Q. Li et al., *Opt. Exp.* **20** 17873 (2012)

Single-mode: Narrow-Linewidth (<0.1 nm), 18.6 dB Side Mode Suppression Ratio

- Reduction of diameter (<~130 nm): reduction of transverse modes
- Reduction of length: (<~6 μm length): reduction of longitudinal modes
- **Reduced dimensionality leads to single mode lasing**

Method 2: Single-mode lasing via coupled nanowire cavities

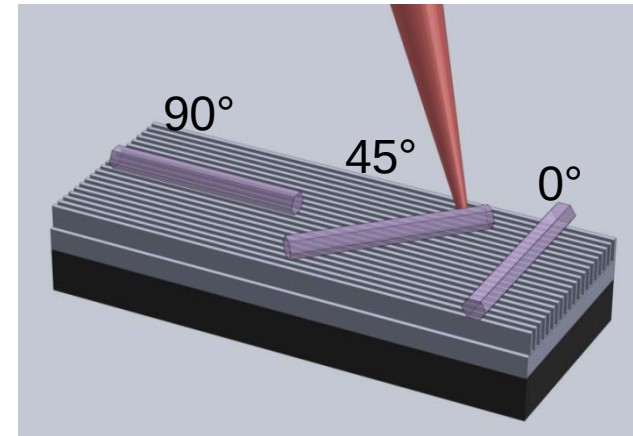


- Individual large NWs shows multiple modes.
- Coupled nanowires show single mode!
- Vernier effect – only resonant modes survive

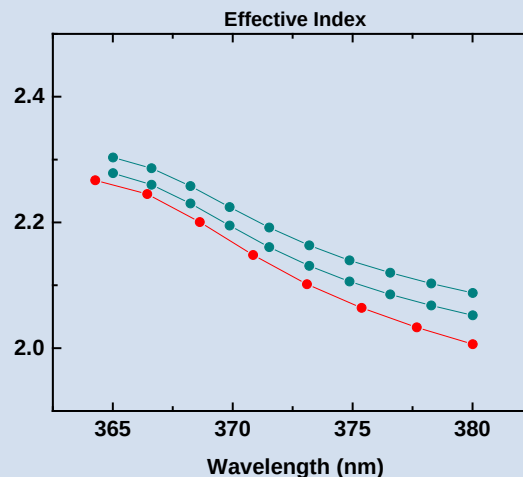
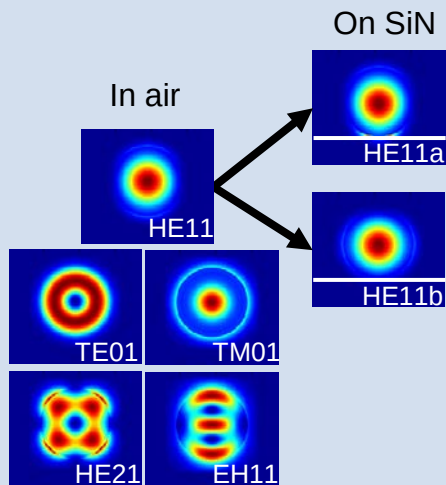
H. Xu et al., *Appl. Phys. Lett.* **101** 113106 (2012)

Method 3: Distributed Feedback (DFB) Nanowire Laser

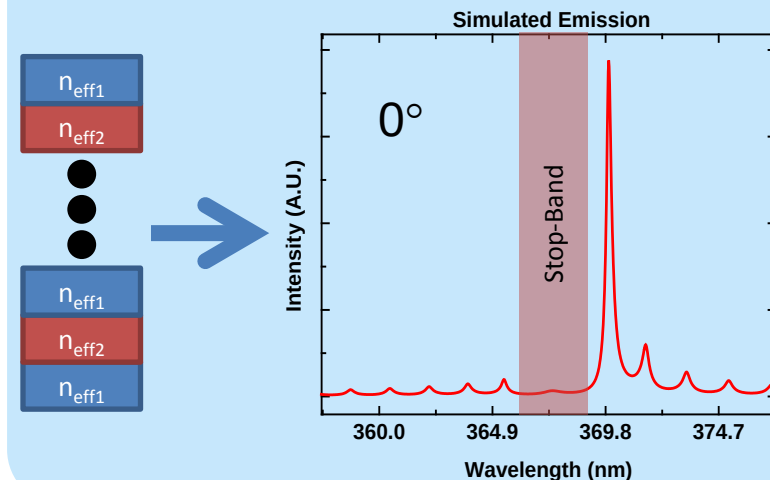
- Standard method for mode control in semiconductor lasers
- Here, single nanowires are coupled to grating substrate to achieve distributed feedback
- Stop-band position and width tuning via nanomanipulation of the angular alignment



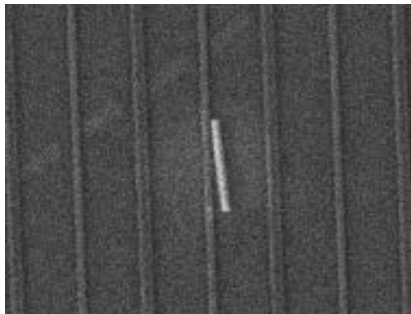
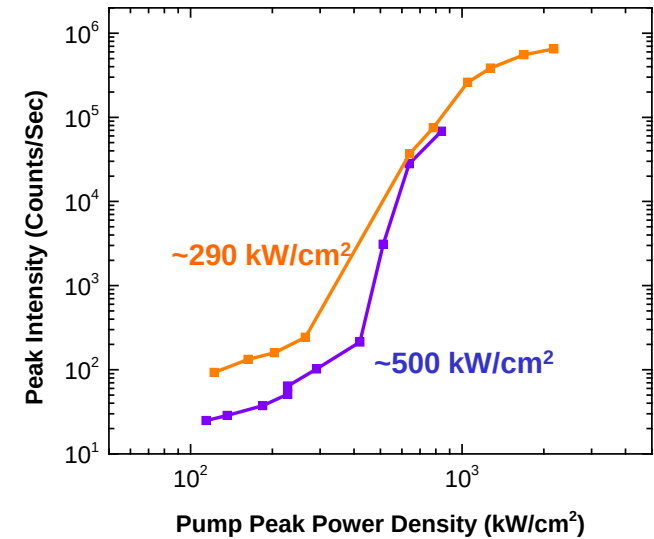
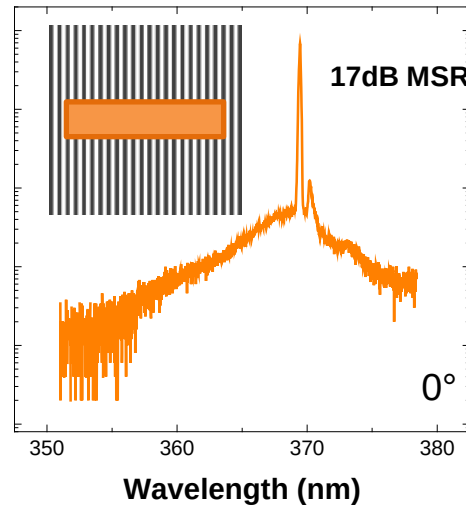
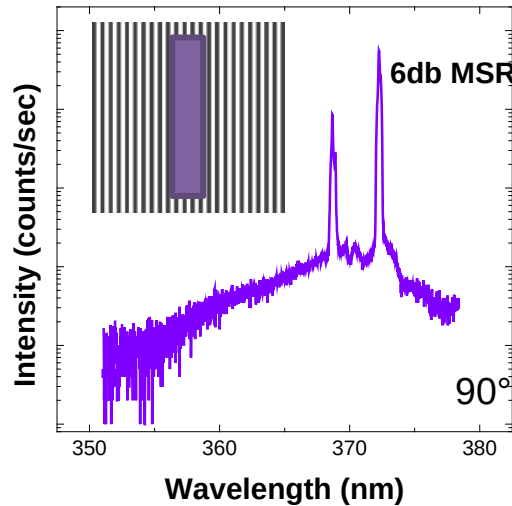
Mode Calculations



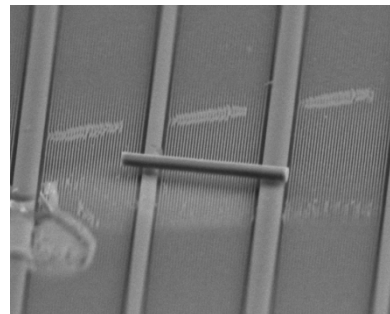
Transfer Matrix Method



Method 3: DFB Nanowire - Optical Results



NW diameter $\sim 180 \text{ nm}$

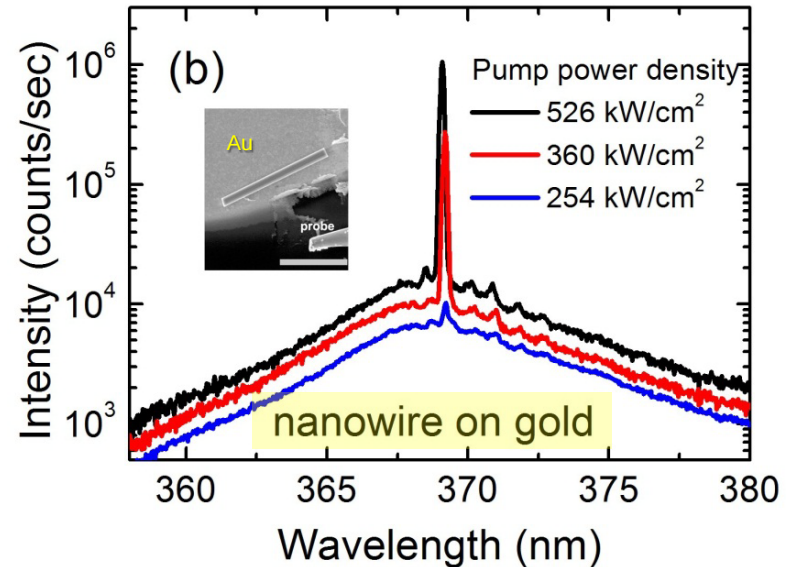
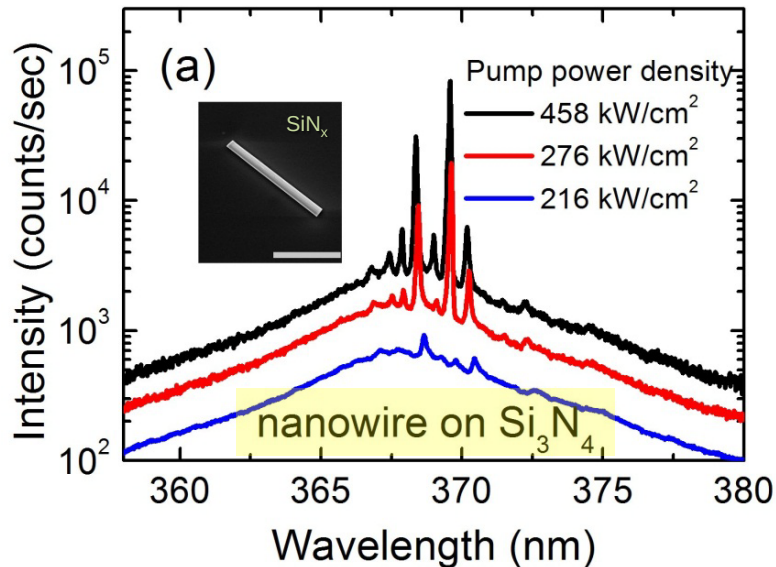


- At the designed alignment single-mode lasing was achieved with a 17dB mode suppression ratio.
- Observed reduction in the lasing threshold

J.B. Wright, S. Campione, S. Liu, J.A. Martinez, H Xu, T.S. Luk, Q. Li, G.T. Wang, B.S. Swartzentruber, L.F. Lester, and I. Brener, APL 104 (4), 041107 2014.

Method 4: Metal substrate induced single-mode nanowire lasing

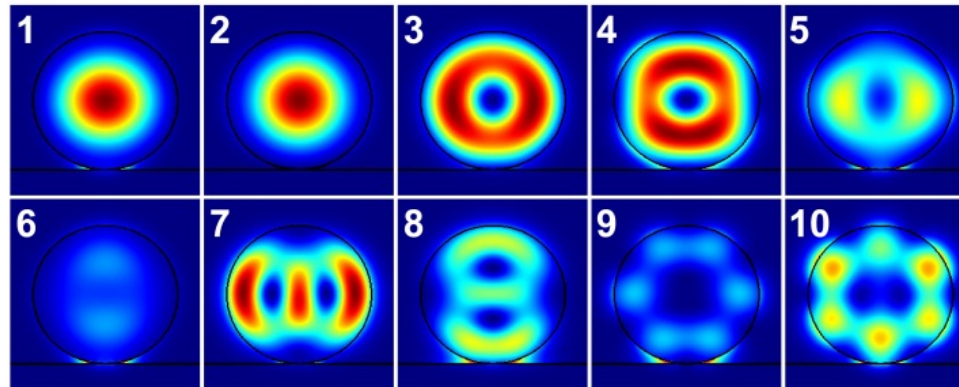
diameter ~350 nm, length ~5.3 μm



- NWs on Si_3N_4 show multi-mode lasing
- **Same NWs moved onto gold-coated spot show single-mode lasing**
- Increase in lasing threshold of only ~13%

H. Xu et al., *Appl. Phys. Lett.* **101** 221114 (2012)

Gold-substrate induced single-mode lasing



H. Xu et al., *Appl. Phys. Lett.* **101** 221114 (2012)

Transverse modes supported by a 300nm diameter nanowire on gold substrate.

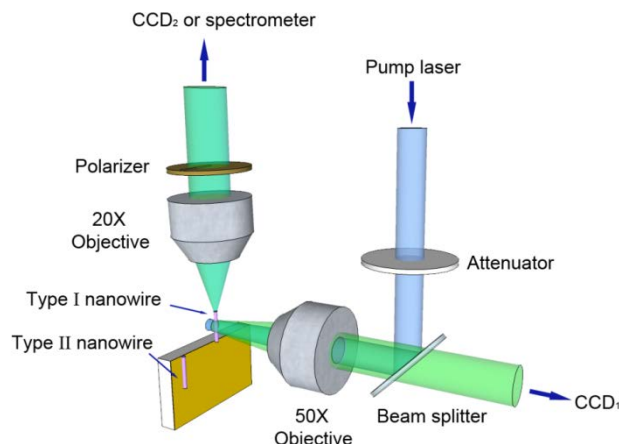
Only surviving mode

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Loss (dB/cm)	8151	1730	4806	7109	16041
	Mode 6	Mode 7	Mode 8	Mode 9	Mode 10
Loss (dB/cm)	34858	7551	22205	29175	28706

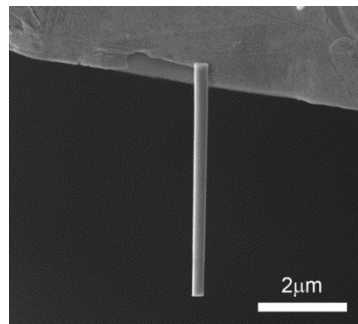
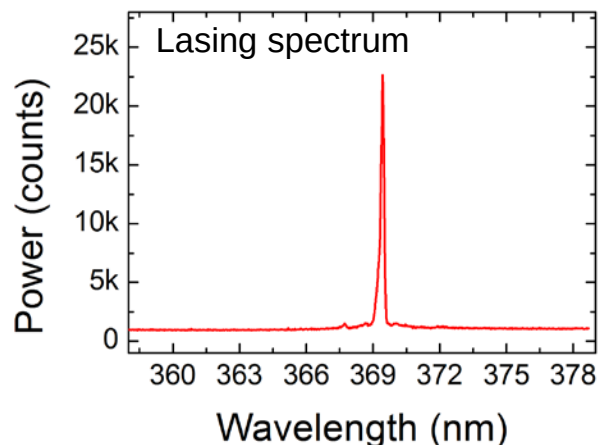
Propagation loss of different transverse modes.

Metal substrate generates a mode-dependent propagation loss

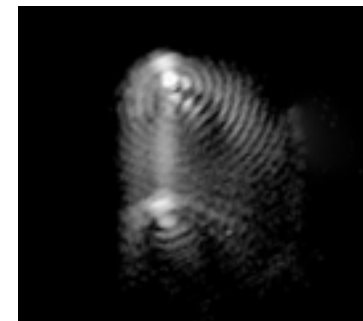
Lasing Polarization Properties of Freestanding GaN NWs



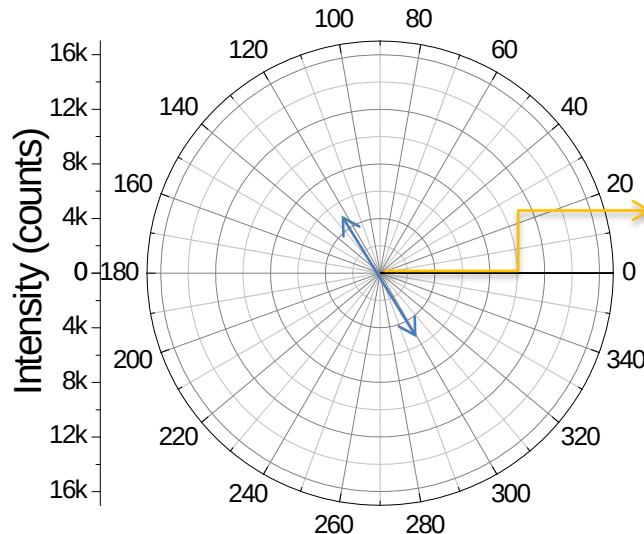
End-facet optical characterization setup



SEM image of a nanowire hanging off substrate



CCD image of lasing nanowire hanging off substrate



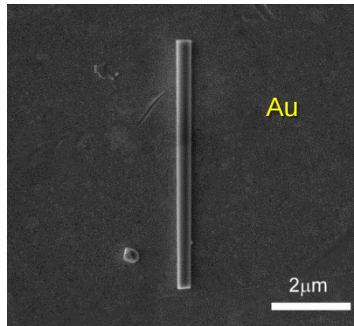
Indicative of elliptical polarization

Polarization angle random wrt surface

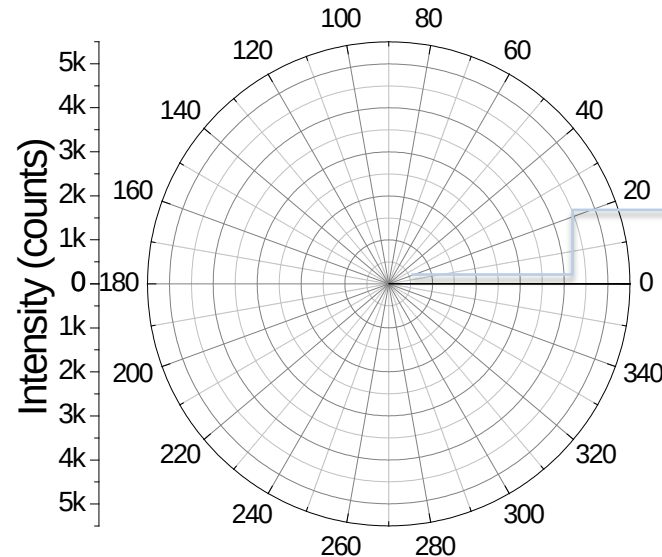
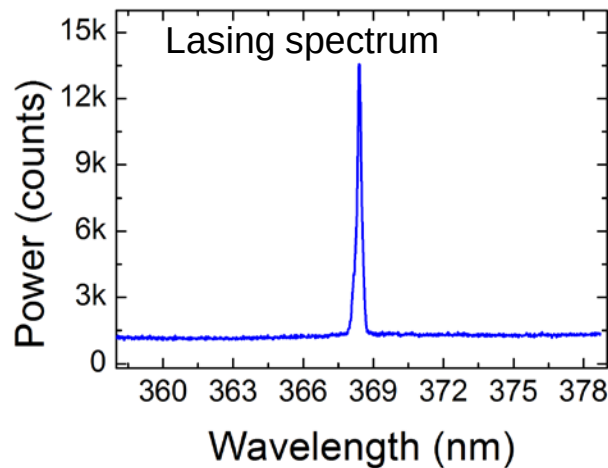
Intensity vs. the rotation of the polarizer

Polarization Control: Nanowire on Gold Substrate

Polarization control (linear polarization) desired for many applications



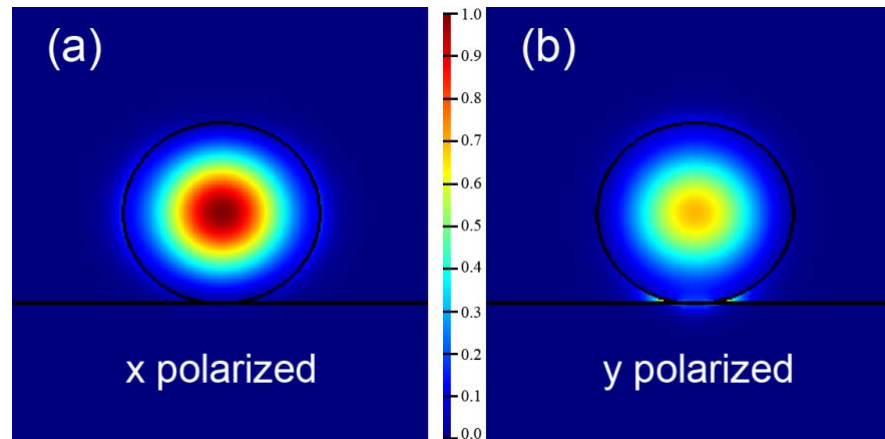
nanowire on **gold**



Intensity vs. the rotation of the polarizer

- ✓ Single-wavelength lasing
- ✓ Linear polarization
- ✓ Large cross-polarization suppression ratio (CPSR): 21:1
- ✓ 0° polarization angle

Why Does Linear Polarization Happen on Gold?



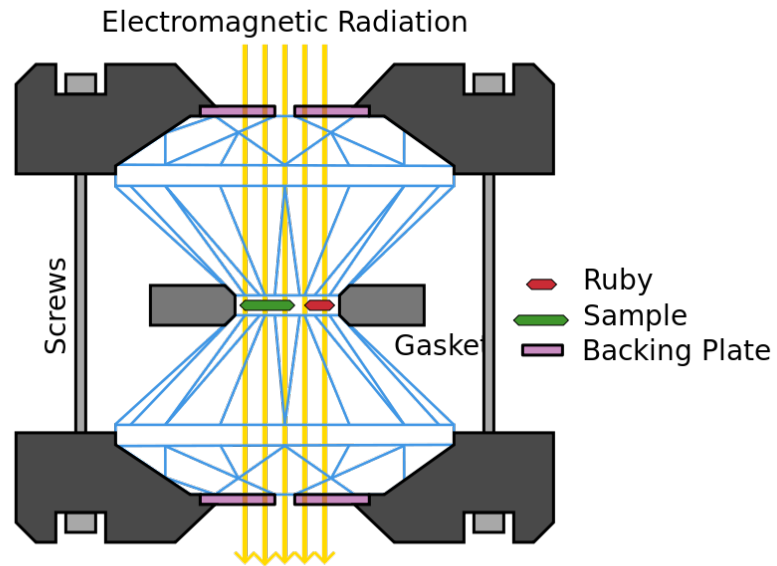
Fundamental modes supported by the nanowire-gold geometry

- ✓ Differently polarized modes experience different cavity losses
- ✓ Loss for x-polarized mode: 0.36 dB/mm
- ✓ Loss for y-polarized mode: 2.11 dB/mm

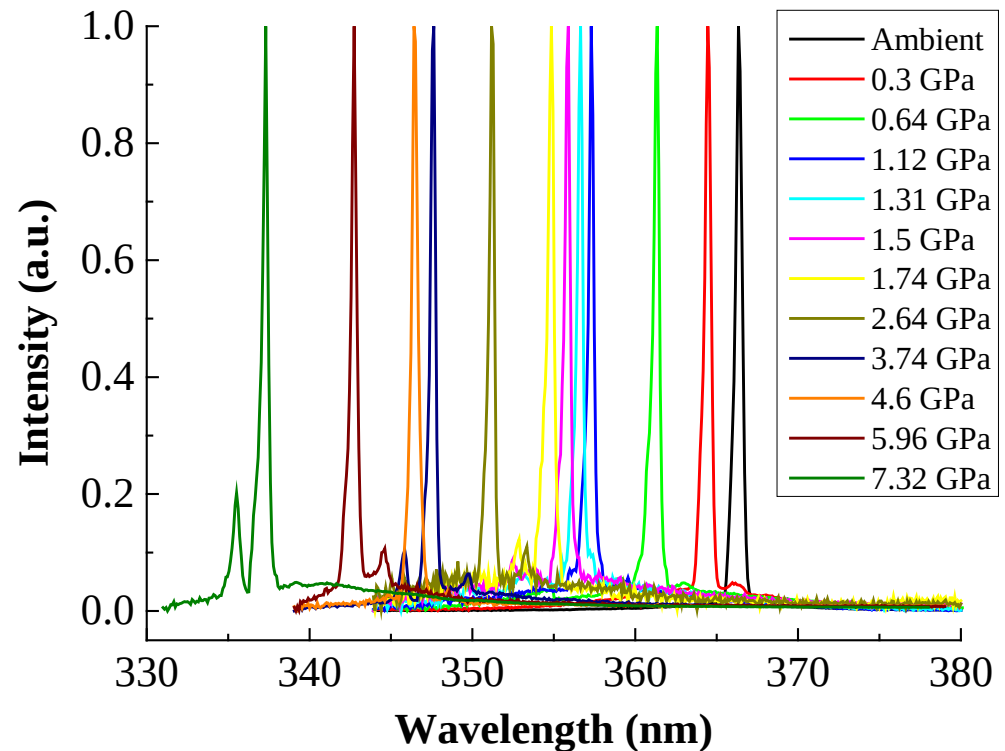
A nanowire on gold substrate experiences a larger cavity loss for the perpendicularly polarized mode, leading to linear polarization with a fixed polarization parallel to the substrate

Continuous & dynamic bandgap/wavelength tuning in GaN NW lasers via hydrostatic pressure

Hydrostatic pressure medium (silicone oil) transmits pressure isotropically



http://en.wikipedia.org/wiki/Diamond_anvil_cell

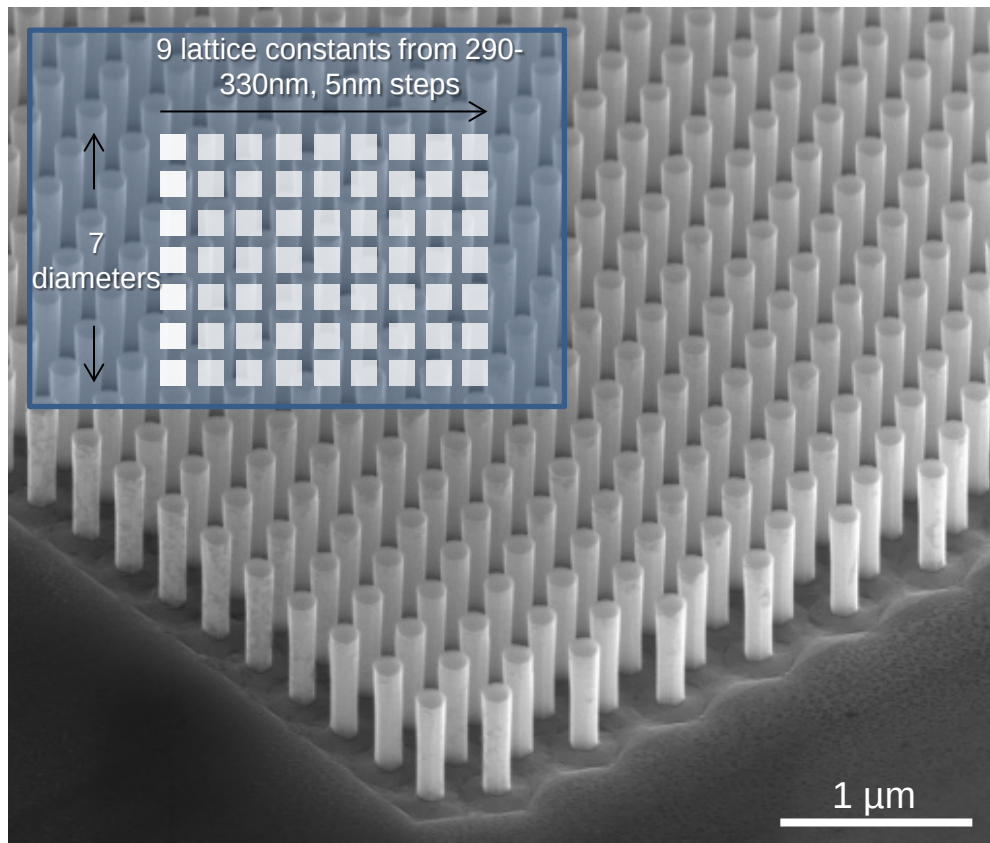


- Applied pressure induces bandgap increase
- ~30nm lasing tuning demonstrated over ~7.3 GPa
- Continuous and reversible tuning possible
- Well defined fine tuning (<0.1nm) possible with current setup

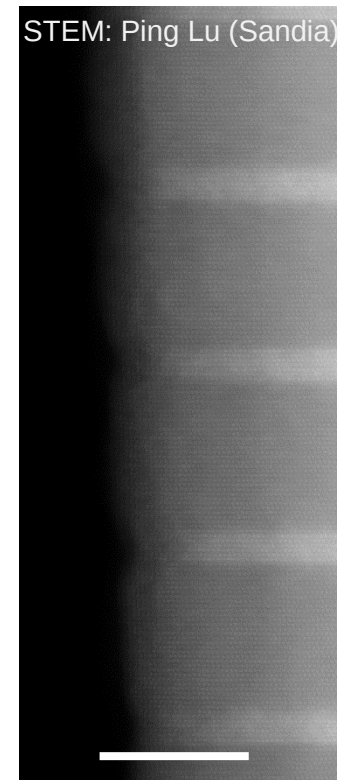
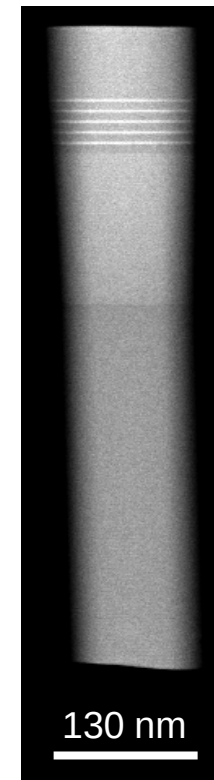


III-N Nanowire Photonic Crystal (PC) Lasers

Motivation: Achieve single-mode, tunable lasing on same chip. Applications in optical information processing, biology, solid state lighting, displays, etc.



Nanowire PCs fabricated by top-down method using e-beam lithographic mask



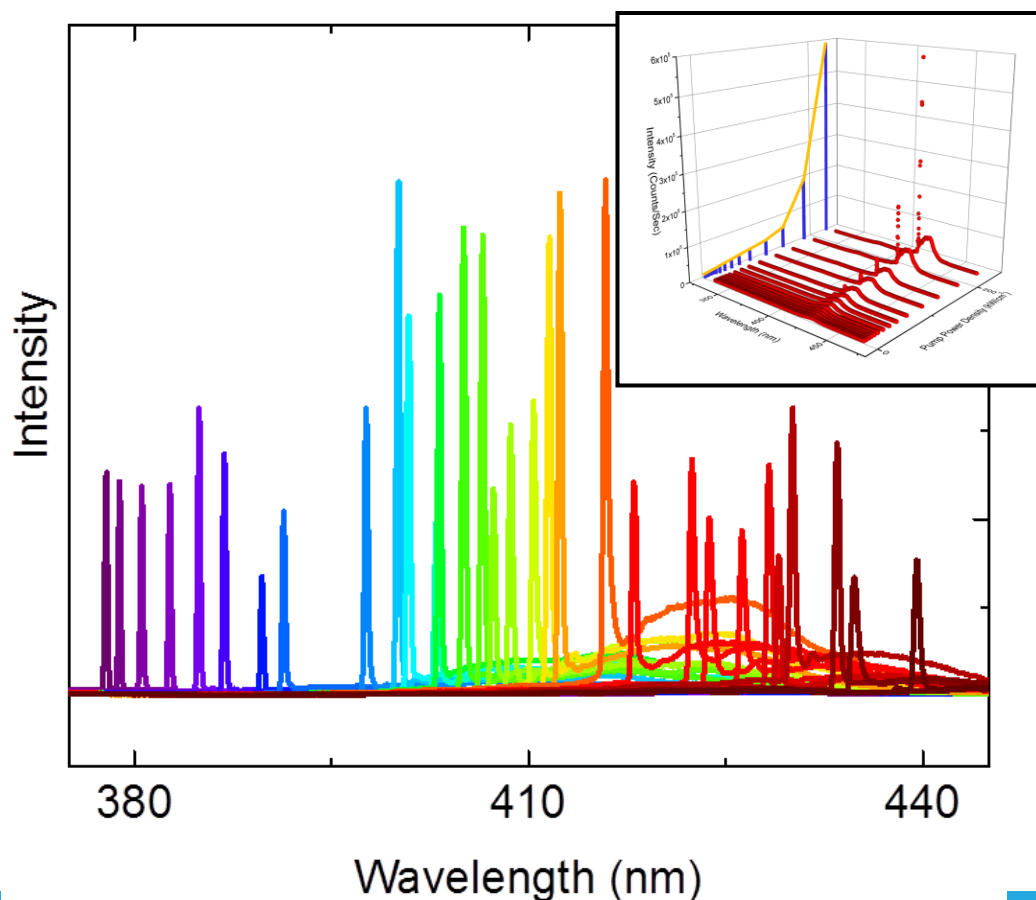
NW STEM images: 5x MQW InGaN emission centered at 420nm, In_{0.02}GaN underlayer



III-N Nanowire Photonic Crystal Lasers

Broad gain width of InGaN MQWs with PC design allows for tunable single mode lasing over large range on same chip

61 color nanowire laser array

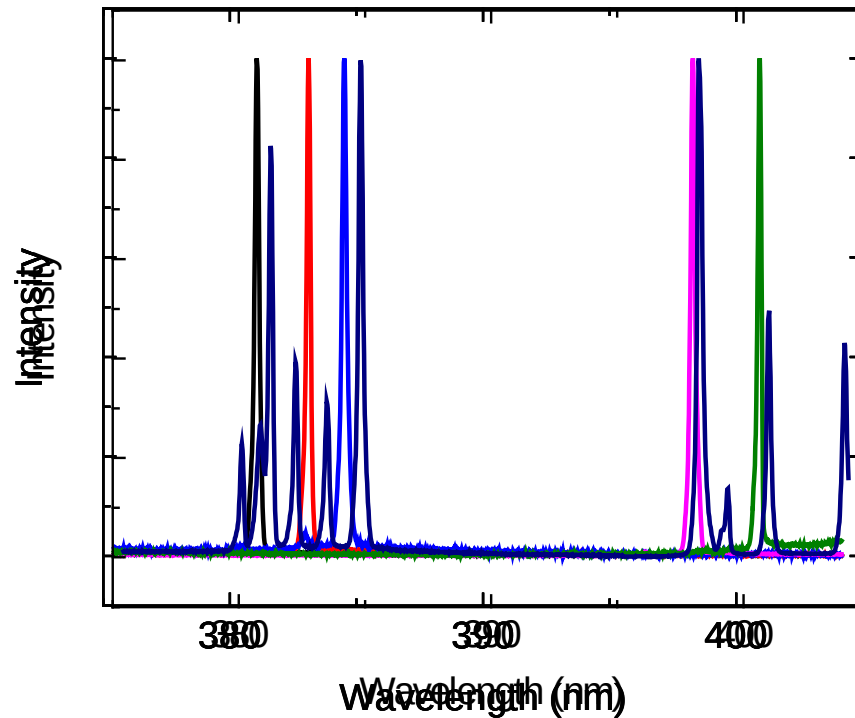


- High-yield >95% (2 of the PCLs were accidentally removed during sample handling.)
- Spectral Coverage from 380-440nm.
- Emission wavelength increases with the diameter and the lattice constant
- Thresholds are reasonable compared to other optically pumped III-N nanowire devices. (<500kW/cm² for all devices)

J.B. Wright et al., Scientific Reports 3, Article number: 2982 (2013) doi:10.1038/srep02982

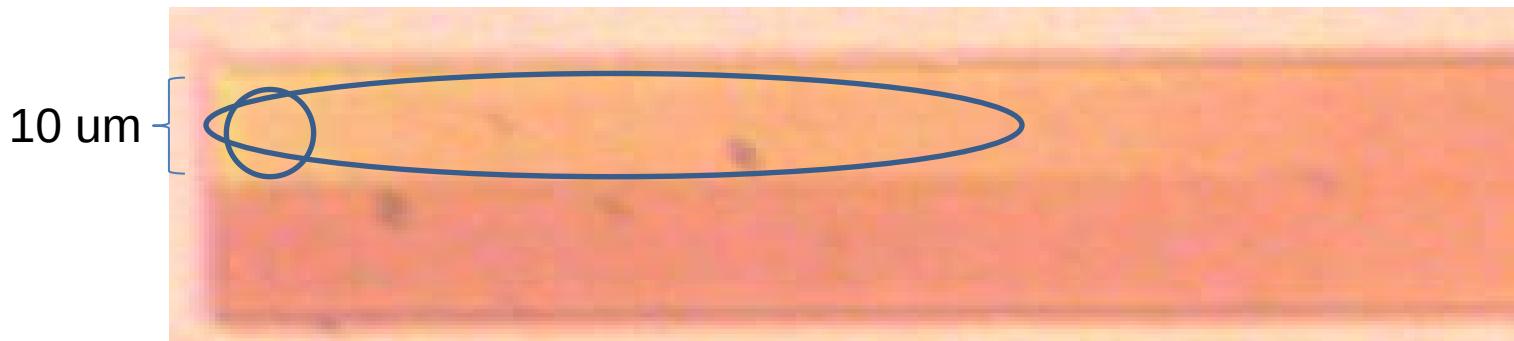


III-N Nanowire Photonic Crystal Lasers



J.B. Wright et al., Scientific Reports 3, Article number: 2982 (2013) doi:10.1038/srep02982

pitch: 320 nm
diameter: 130-140nm

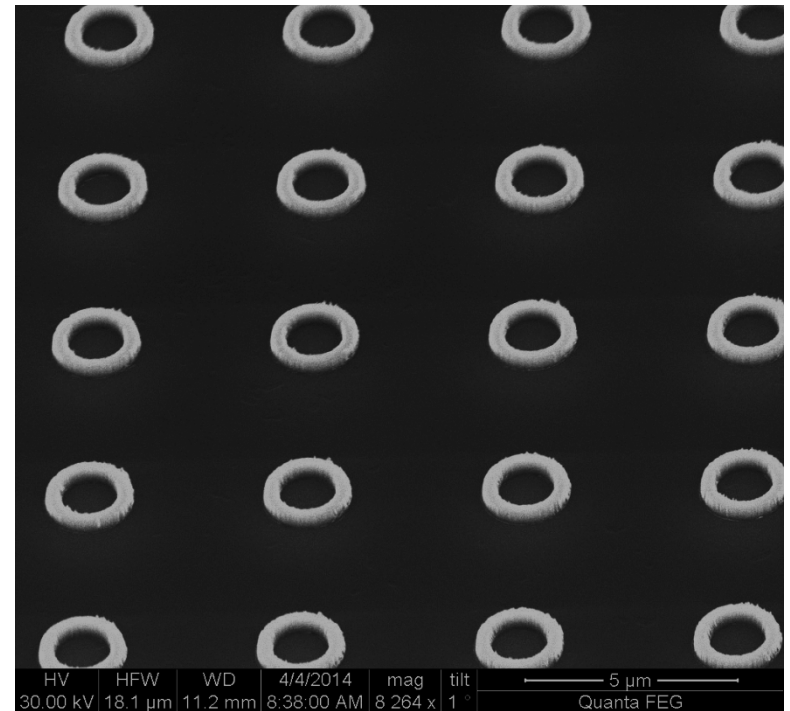
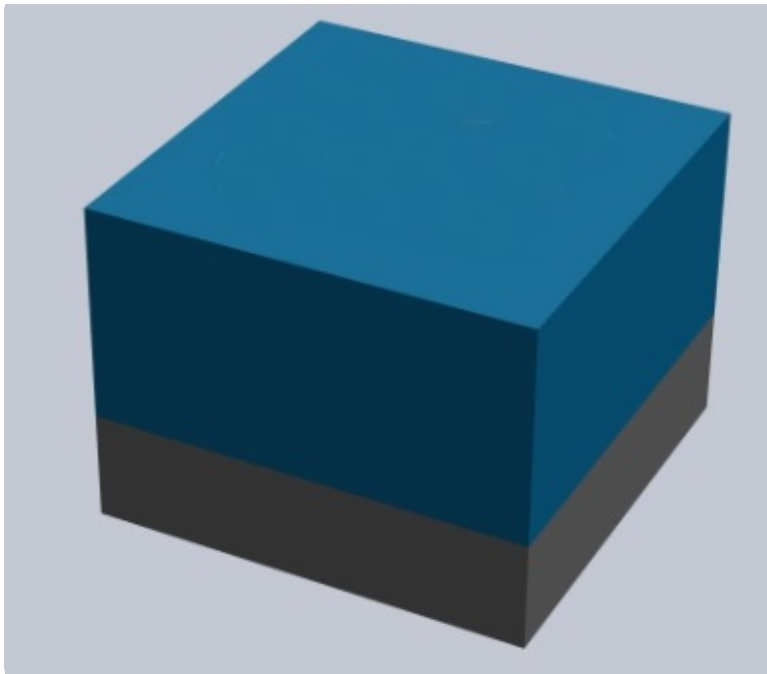




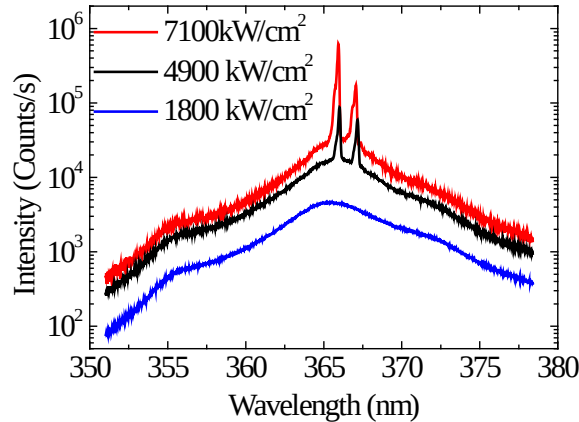
Top-down cross-sectional shape control: GaN nanotubes

Nanowire cross-sectional shape control may allow for manipulation of optical and electronic properties

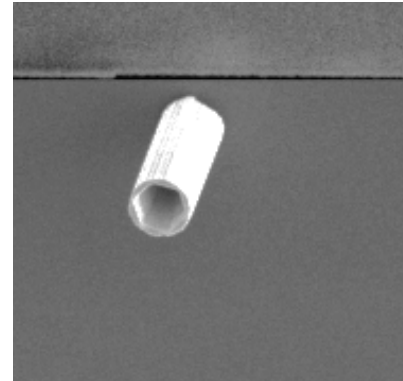
EBL Patterning growth AZ4561 Polymer MMA Lift-off



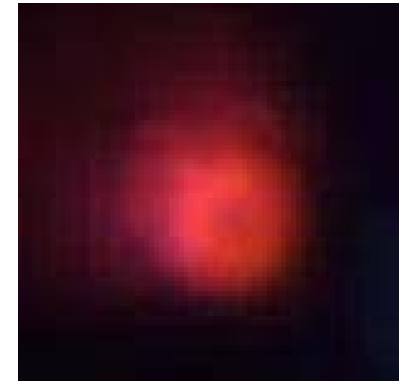
GaN nanotube lasers



Threshold pump density = 4600kW/cm²



Nanotube pointing off edge of substrate for end-on collection



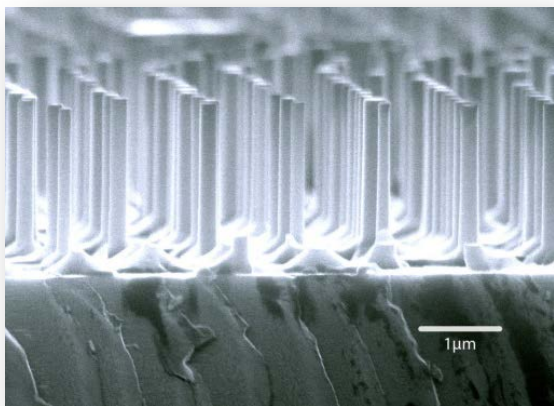
CCD image far field lasing emission

- Hollow nanotube geometry potentially useful for optofluidic/biosensing applications
- Observed annular shaped emission may have potential applications for atom trapping, stimulated emission depletion (STED) microscopy, etc.



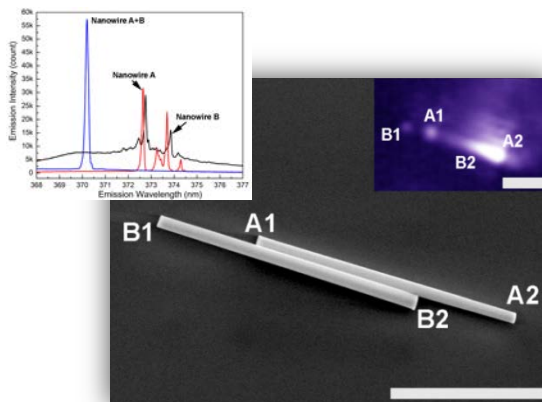
Summary – Mode & Polarization Control

Top-down fabrication



Q. Li et al., *Optics Express* **19**, 25528 (2011)

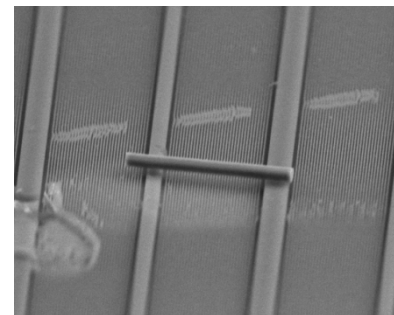
Mode Control



H. Xu et al., *Appl. Phys. Lett.* **101** 113106 (2012)

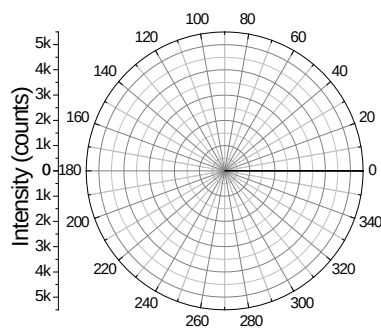
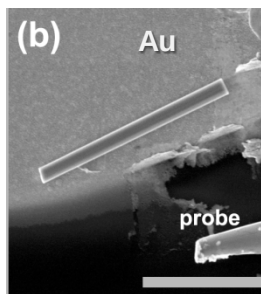
Q. Li et al., *Optics Express* **20** 17874 (2012)

Distributed feedback NW lasers



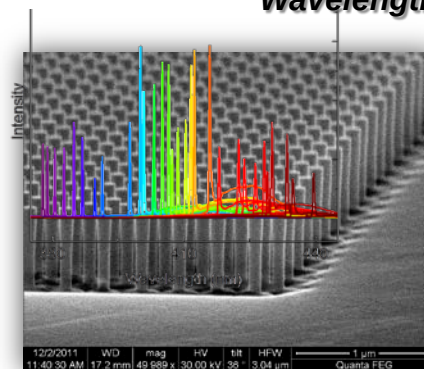
J.B. Wright et al., *App. Phys. Lett.* **104** 041107 (2014)

Polarization Control

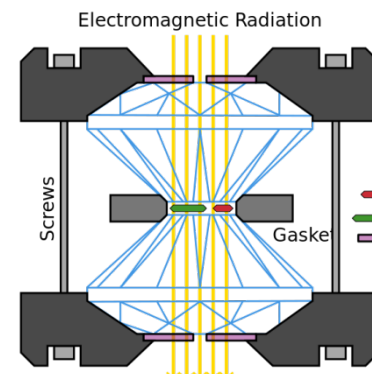


H. Xu et al., *Appl. Phys. Lett.* **101** 221114 (2012); H. Xu et al, *Opt. Exp.* (2014)

Wavelength Tuning Control



J.B. Wright et al., *Scientific Reports* 3, Article number: 2982 (2013) doi:10.1038/srep02982

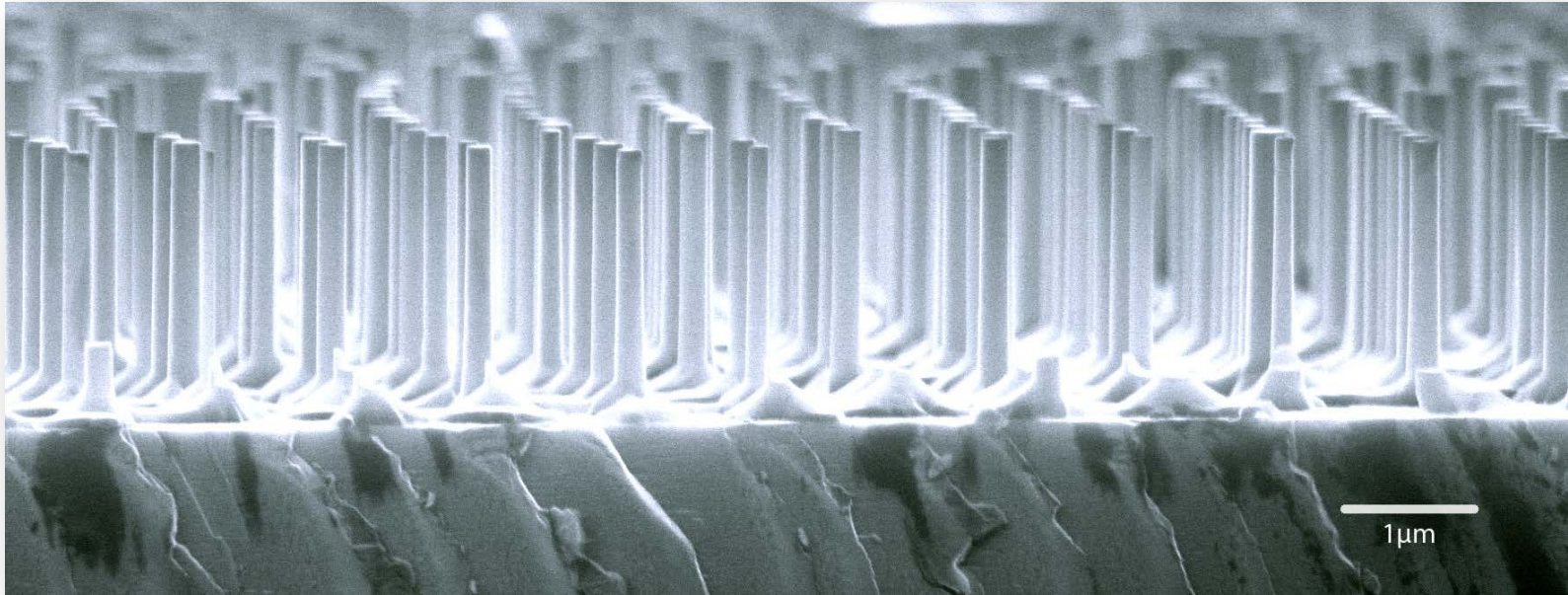


Backup/Extra Slides

Mode control (i.e. How to make a single-mode GaN nanowire laser)

- Nanowire lasers generally exhibit *multiple modes*
- *Single mode* behavior desired for highest resolution and beam quality

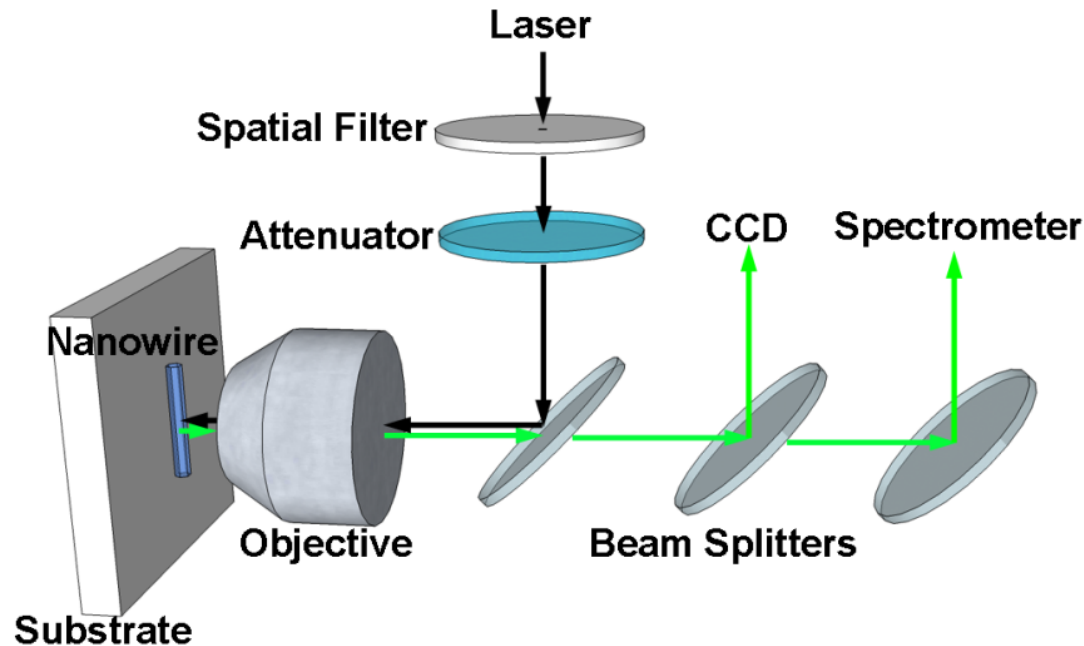
Advantages of new top-down nanowire fabrication method



- Wider range of growth conditions, material tunability (1D growth cndns not needed)
- Lower point defect densities (higher growth temperature)
- Ordered/periodic arrays (difficult with catalyst/VLS-based methods)
- Axial III-nitride nanowire heterostructures possible by MOCVD
- Better control of geometry (independent control over height, width, & pitch)
- Improved uniformity
- Easier vertical device integration (height uniformity, base GaN-layer)



Nanowire Optical Characterization

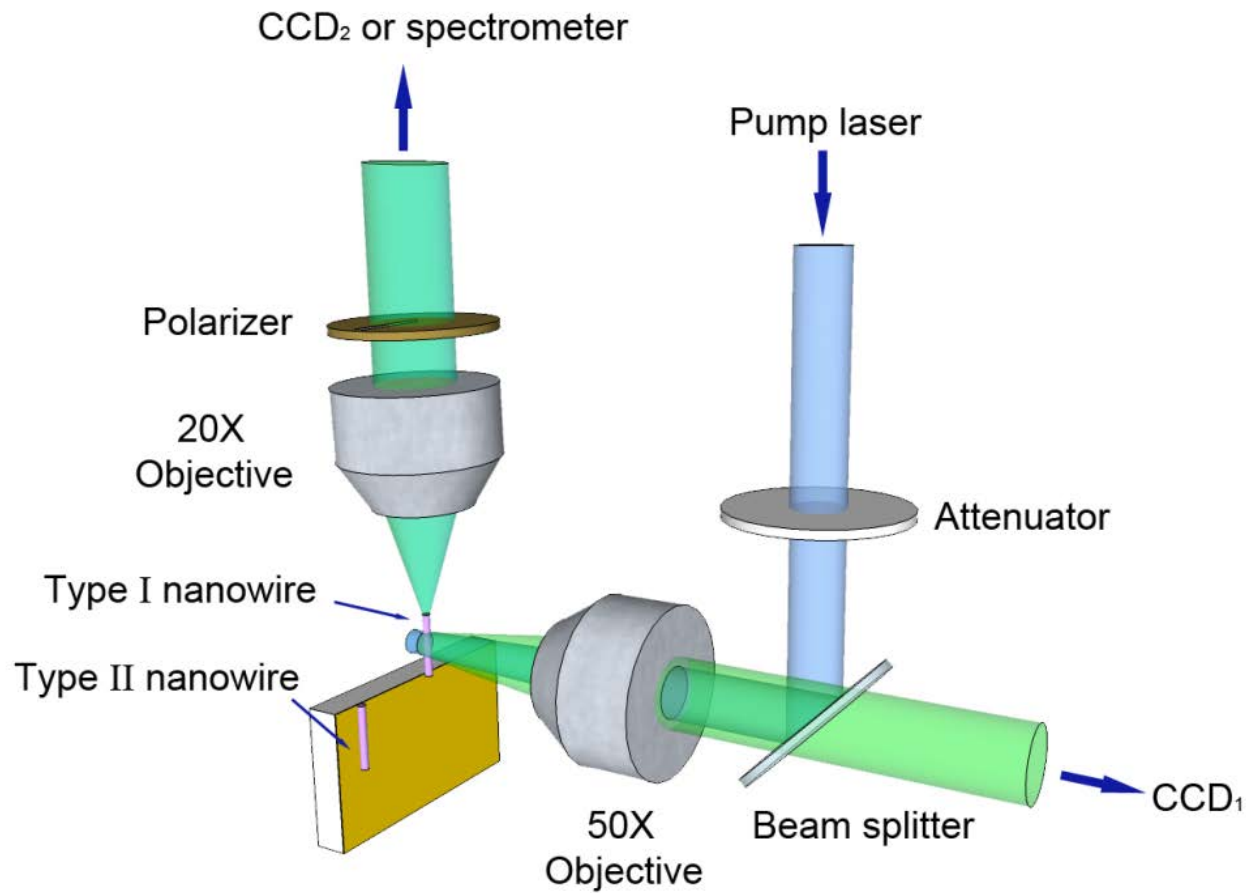


- ✓ Pump: pulsed quadrupled Nd:YAG laser
- ✓ 266nm, 400ps, 10kHz, 5.2mW
- ✓ Spot size: 1~5 μm
- ✓ Room temperature operation

Q. Li, et al. Opt. Express 20, 17873 (2012)

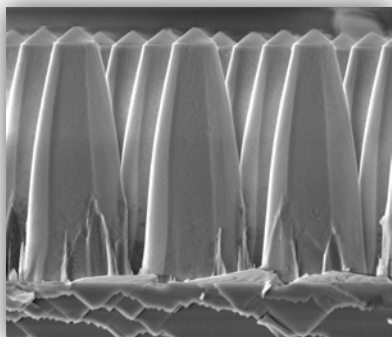


End-Facet Optical Characterization

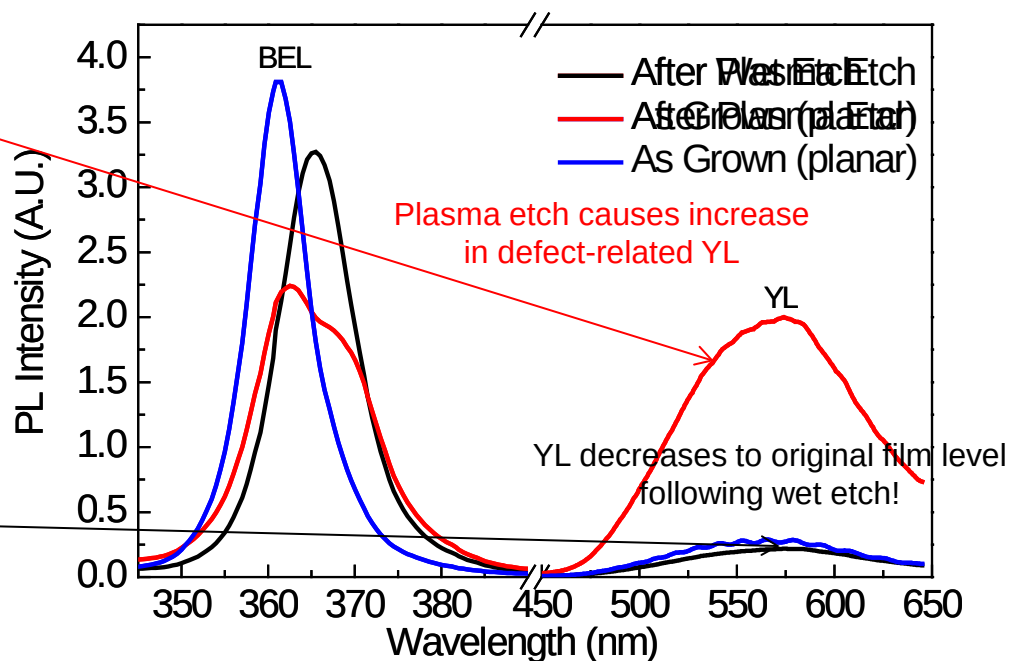
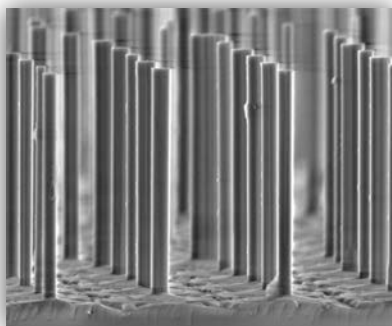


Wet etch step removes plasma etch damage

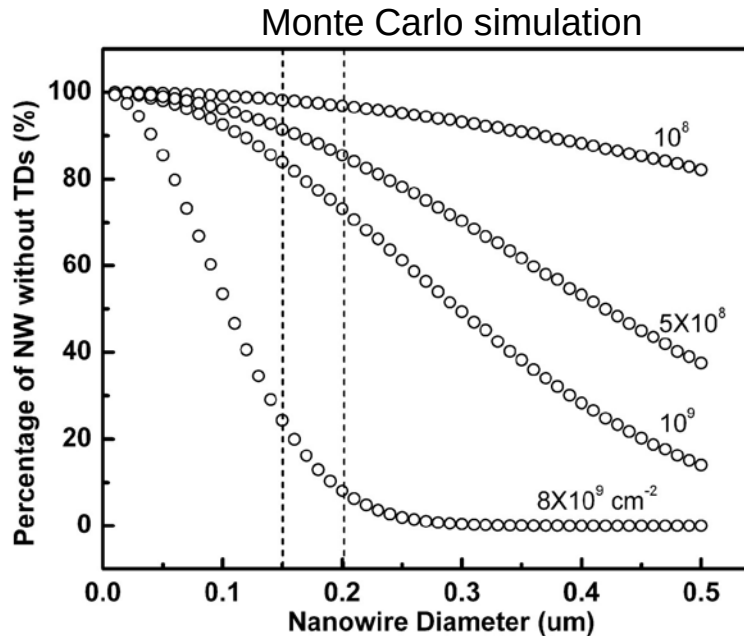
Plasma etch only



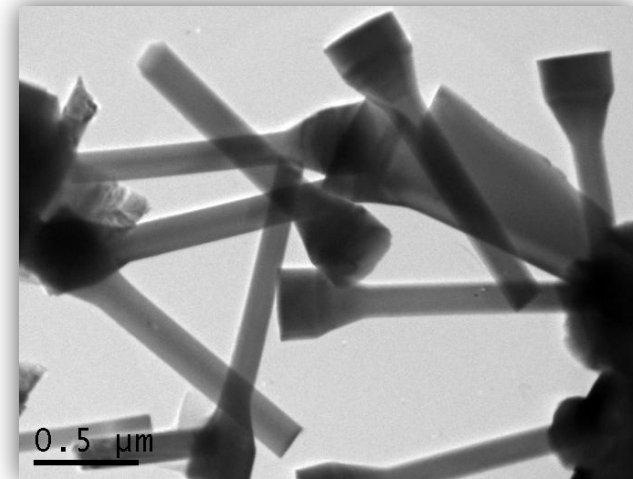
After wet etch



Top-down nanowire threading dislocations



Bright-field TEM



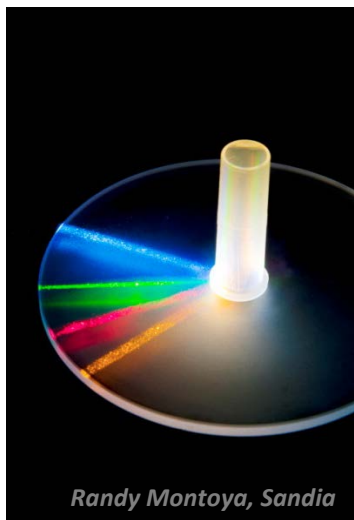
Nanowires etched from $\sim 5 \times 10^8 \text{ cm}^{-2}$ planar LED

- Etched nanowires inherit the dislocation density of the parent film
- However, as the diameter approaches zero, the *fraction* of nanowires with one or more dislocations also approaches zero! [$\# \text{ TDs per rod} \sim (\text{TDD}) \times (A_{\text{cross-section}})$]
- $\sim 94\%$ of nanowires $\sim 150 \text{ nm}$ in diameter from $\text{TDD} \sim 5 \times 10^8 \text{ cm}^{-2}$ film dislocation free!
- *Thus, nanowire LEDs can function as arrays of largely dislocation-free individual lighting elements*

Lasers for Solid State Lighting

Advantages of lasers for lighting:

- Lasers show very high efficiency at high power
- LED and LD current densities are converging
- Carrier density is clamped at threshold
 - Circumvent the droop problem in LEDs
 - Need to reduce threshold to avoid losses
- After threshold slope efficiency is one
- Directionality, polarized emission, modulation

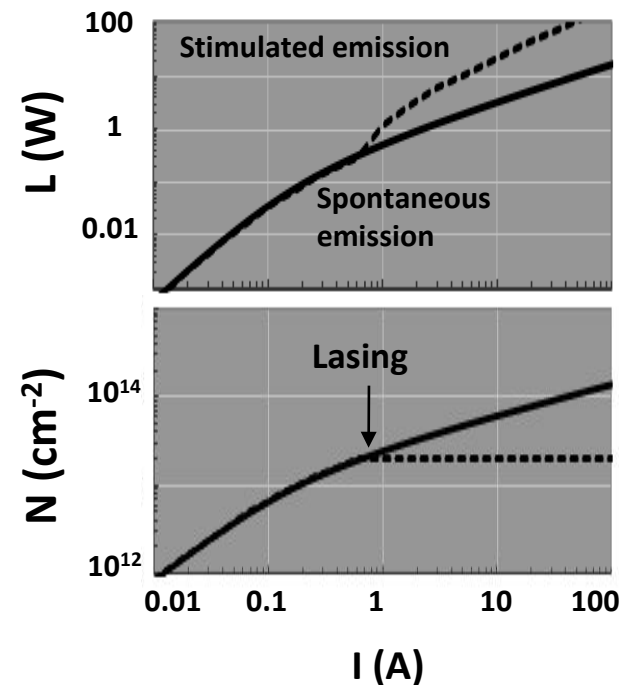


Randy Montoya, Sandia

Laser Sources For SSL:

- High efficiency
- Low threshold
- Focus on III-nitrides
- **Nanowire lasers**
 - Low threshold
- **Polariton lasers**
 - Ultralow threshold
 - New physics

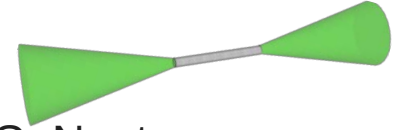
Clamped carrier density



Are narrow linewidth sources acceptable?

Nanowire Lasers

- Nanowire forms a freestanding, low loss optical cavity
- Optically pumped nanowire lasers: ZnO, CdS, GaAs, GaSb, GaP, GaN, etc.
- Most commonly Fabry-Perot type lasing from end facets
- Compact and low power due to small mode volume
- Strain accommodation in GaN nanowires opens up possibility of high efficiency lasers over a wide spectral range (incl. green and yellow) through facile In incorporation

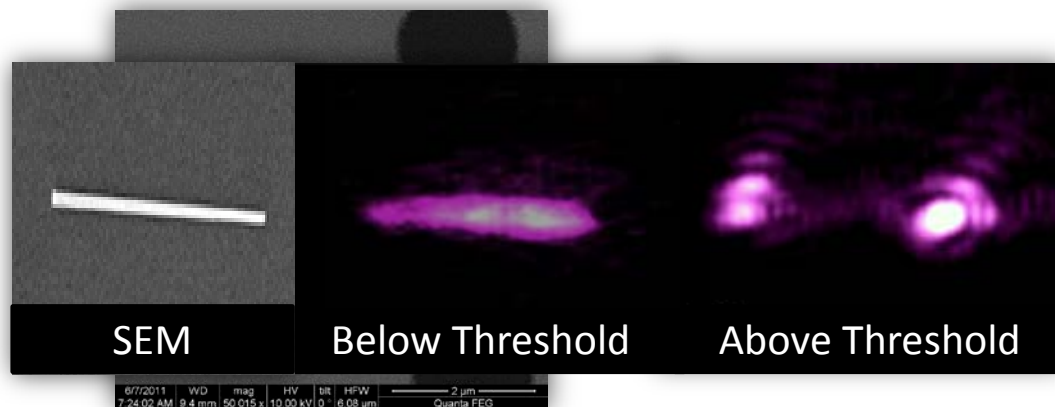
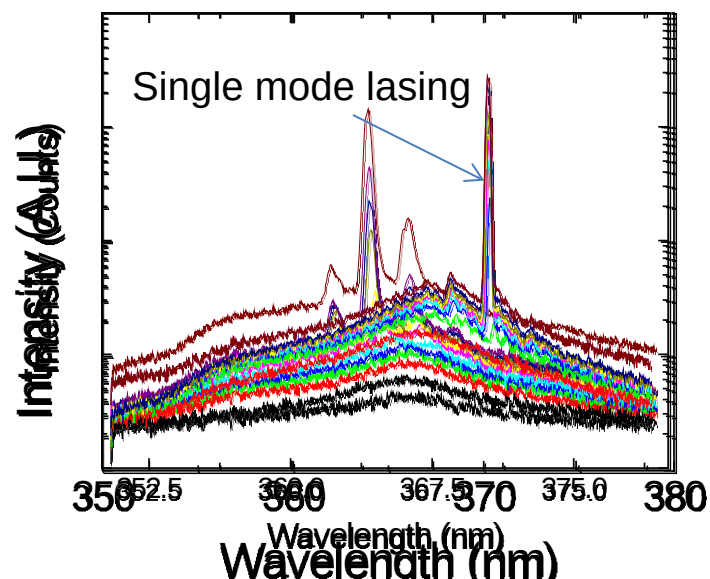


Nanowire lasers: *need to understand & control optical properties*

- **Mode control** – single vs. multi-mode behavior
- **Polarization control** – linear vs. elliptical
- **Wavelength tuning**
- **Beam shaping**
- **Beam steering**

See also: S. Arafin, X. Liu, Z. Mi, "Review of recent progress of III-nitride nanowire lasers," *J. Nanophotonics* **7**, 074599-1 (2013)

Method 1: Single-mode NW laser via geometry control



Nanowire dimensions: $\sim 130\text{nm} \times 4.7\mu\text{m}$
 Nanowire dimensions: $\sim 500\text{ nm} \times 4.7\mu\text{m}$

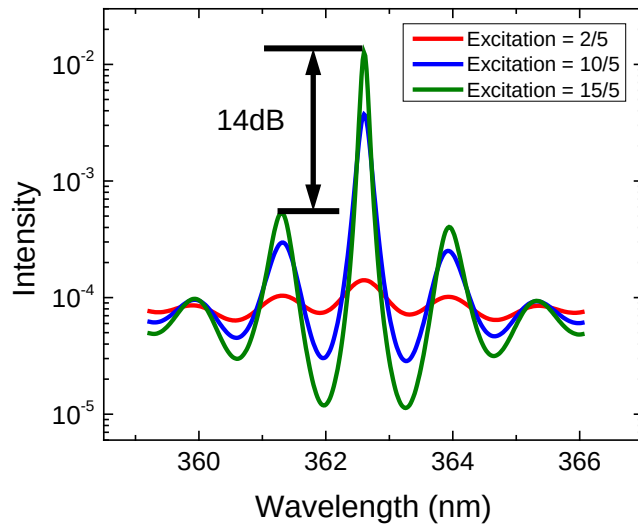
Q. Li et al., *Opt. Exp.* **20** 17873 (2012)

Single-mode: Narrow linewidth ($<0.1\text{ nm}$), $>150\text{ dB}$ Side Mode Suppression Ratio, and **Low Threshold** ($\sim 250\text{ kW/cm}^2$)

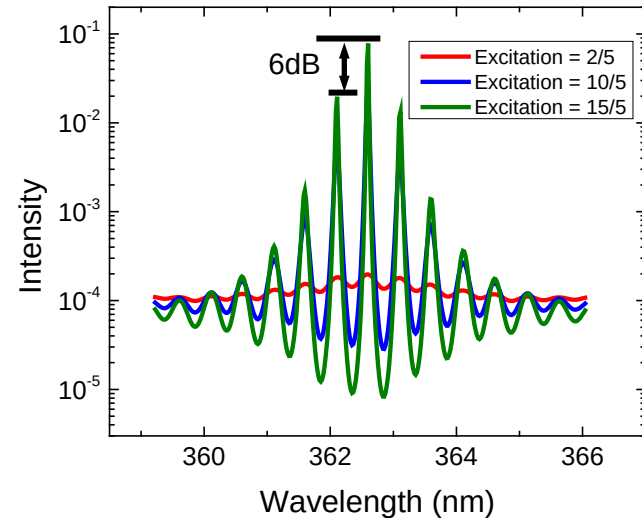
- Reduction of diameter ($<\sim 130\text{ nm}$): reduction of transverse modes
- Reduction of length: ($<\sim 6\text{ }\mu\text{m}$ length): reduction of longitudinal modes
- **Reduced dimensionality leads to single mode lasing**

Single mode GaN nanowire laser

4 μm long, 140 nm dia. nanowire

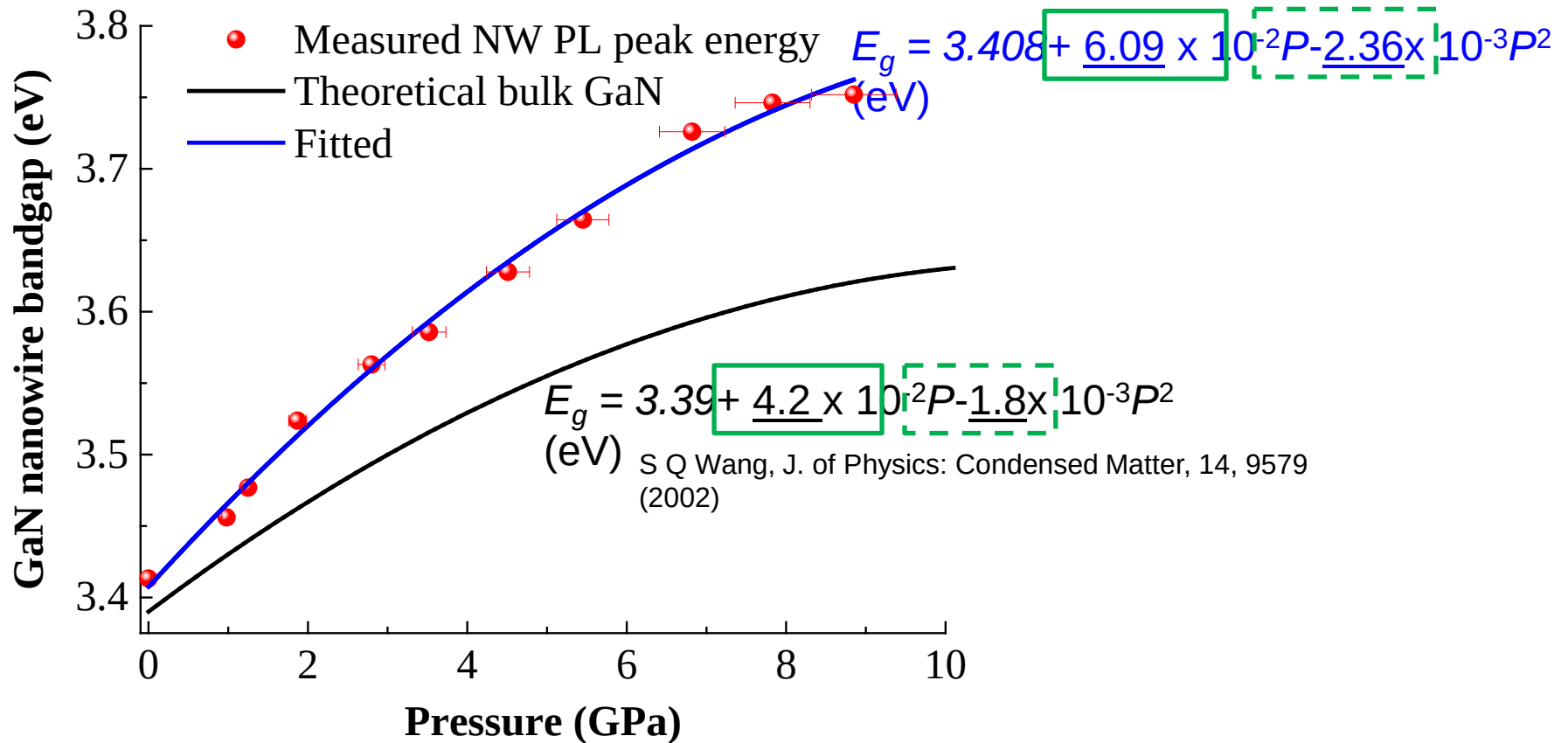


12 μm long, 140 nm dia. wire



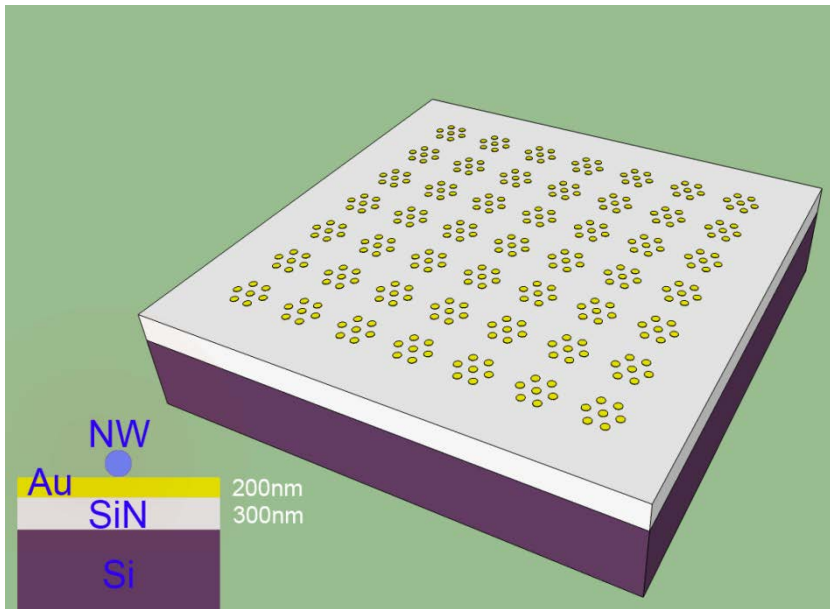
- Multimode laser theory calculations to determine which of the passive-cavity eigenmodes will be above lasing threshold for given experimental conditions.
- Modeling shows that by reducing the dimensionality of the wire we can reduce the number of competing modes, leading to single-mode lasing.

Pressure coefficients of single GaN nanowire

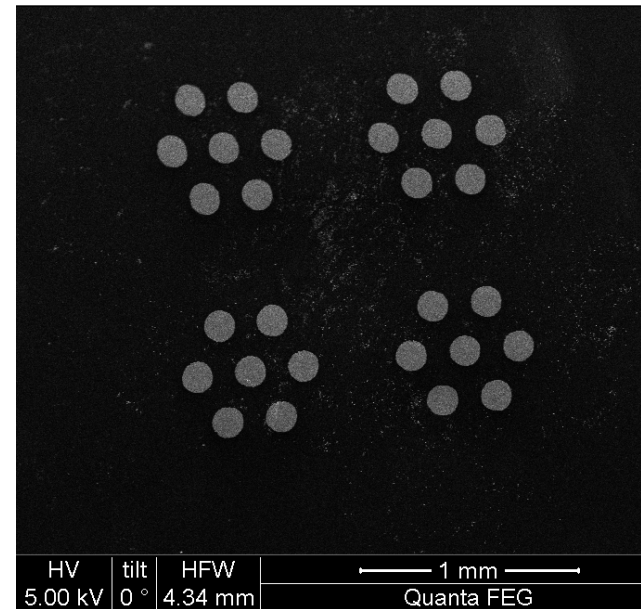


- Larger pressure coefficients of GaN nanowires

Gold substrate preparation



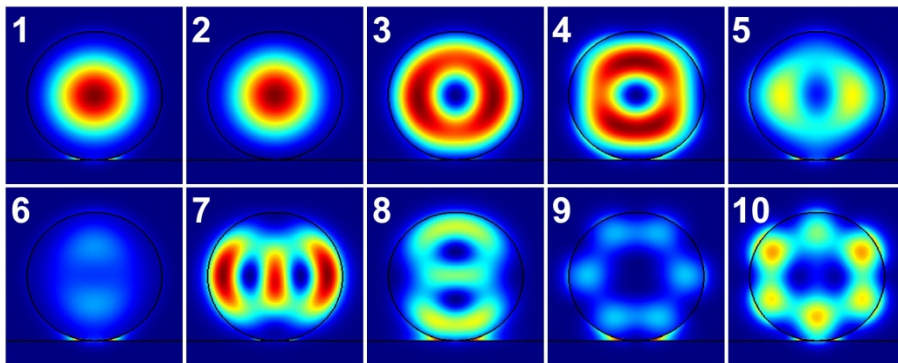
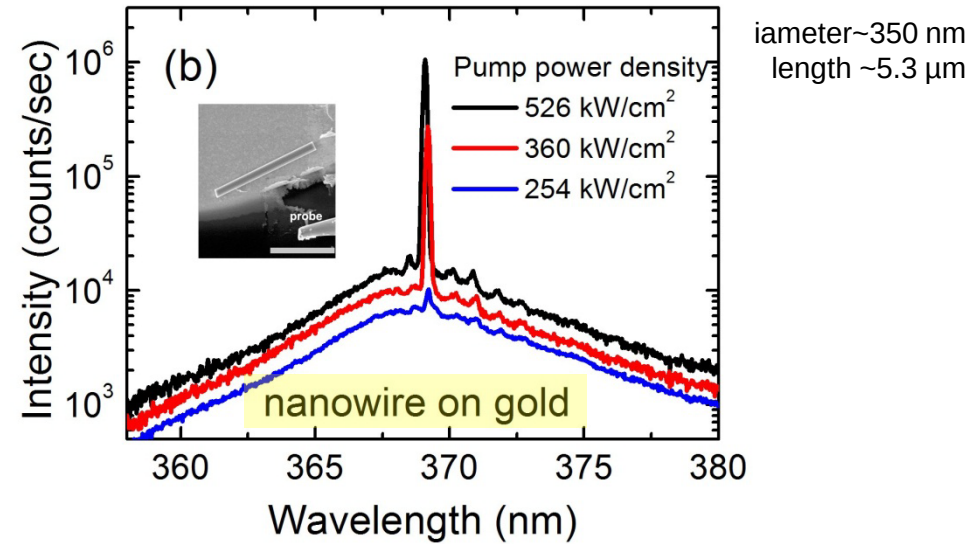
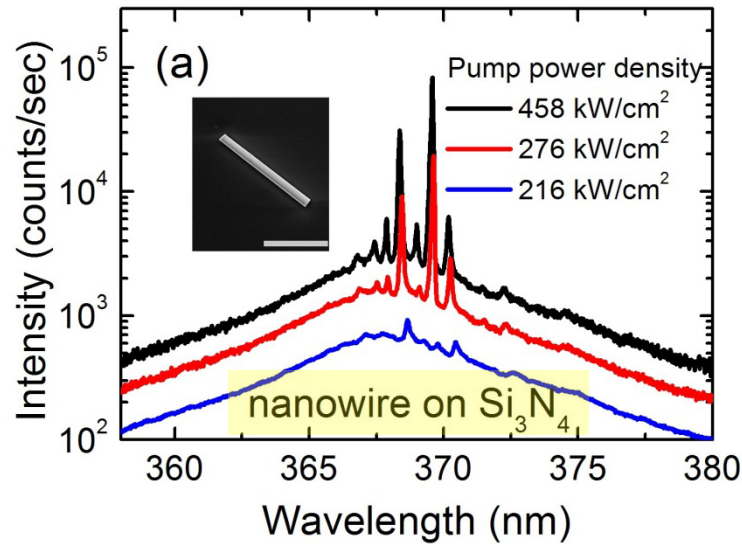
Schematic of the substrate design



SEM image of prepared Au on SiN substrate

Nanowires can be transferred between SiN and Au regions for lasing behavior comparison

Method 4: Metal substrate induced single-mode nanowire lasing

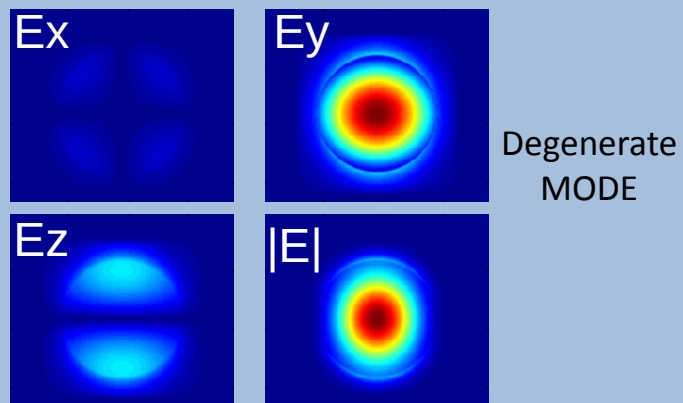


Calculated mode profiles

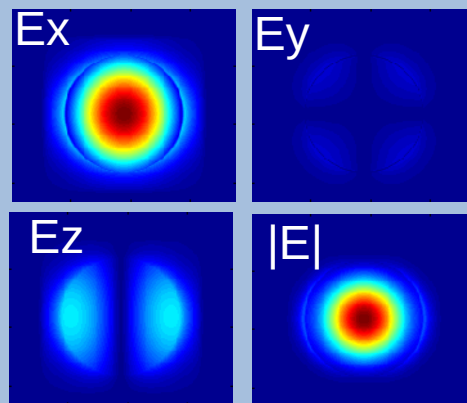
- NWs on Si_3N_4 show multi-mode lasing
- Same NWs moved onto gold-coated spot show single-mode lasing!
- Metal substrate induces mode-dependent loss mechanism

H. Xu et al., *Appl. Phys. Lett.* **101** 221114 (2012)

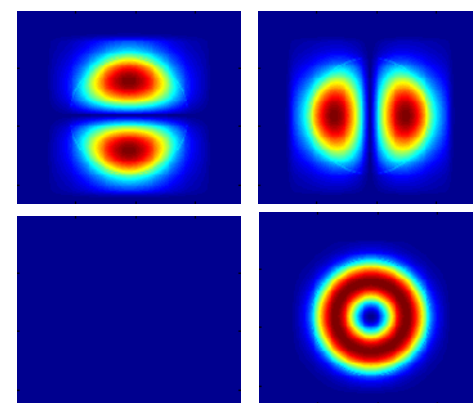
Mode 1 HE₁₁_a - $n_{\text{eff}}=2.148$



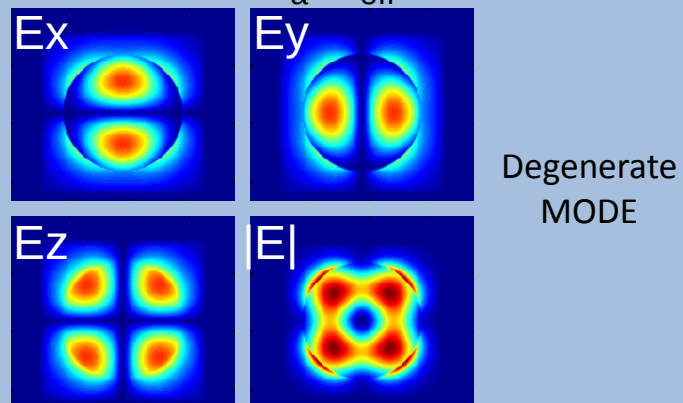
Mode 2 HE₁₁_b - $n_{\text{eff}}=2.148$



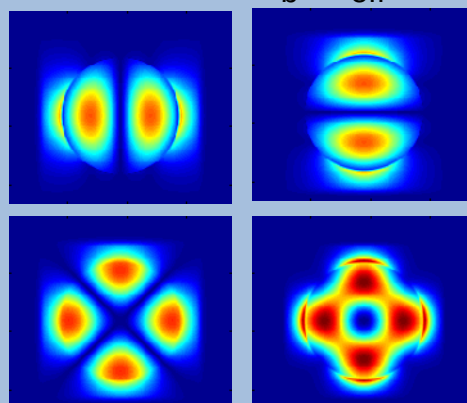
Mode 3 TE₀₁ - $n_{\text{eff}}=2.020$



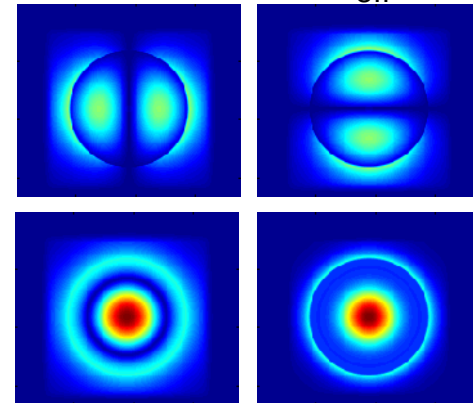
Mode 5 HE₂₁_a - $n_{\text{eff}}=1.795$



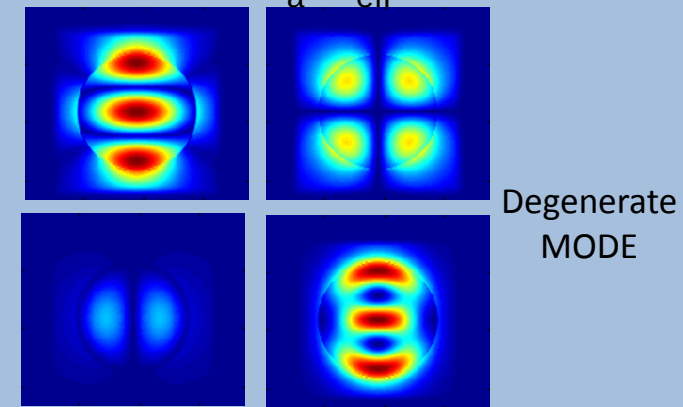
Mode 6 HE₂₁_b - $n_{\text{eff}}=1.795$



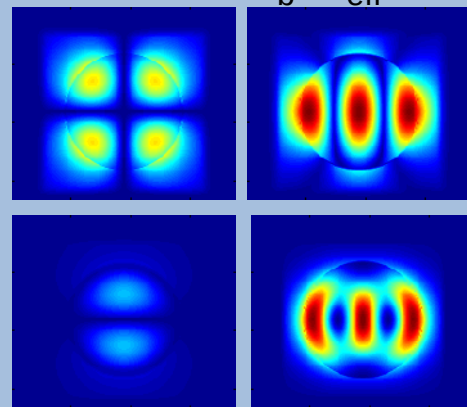
Mode 4 TM₀₁ - $n_{\text{eff}}=1.716$



Mode 7 EH₁₁_a - $n_{\text{eff}}=1.340$



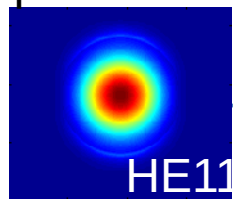
Mode 8 EH₁₁_b - $n_{\text{eff}}=1.340$



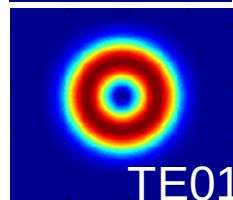
200 nm diameter NW in air

Supported Waveguide Modes

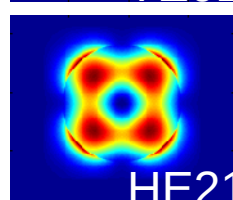
Suspended in Air



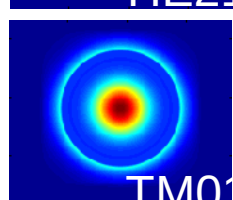
$n_{\text{eff}}=2.148$



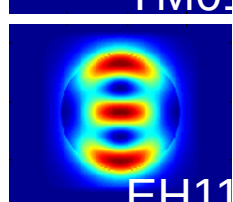
TE₀₁ $n_{\text{eff}}=2.020$



HE₂₁ $n_{\text{eff}}=1.795$

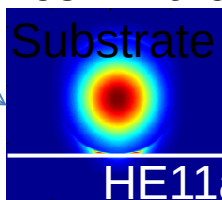


TM₀₁ $n_{\text{eff}}=1.716$

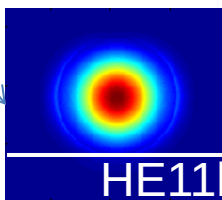


EH₁₁ $n_{\text{eff}}=1.340$

Silicon Nitride



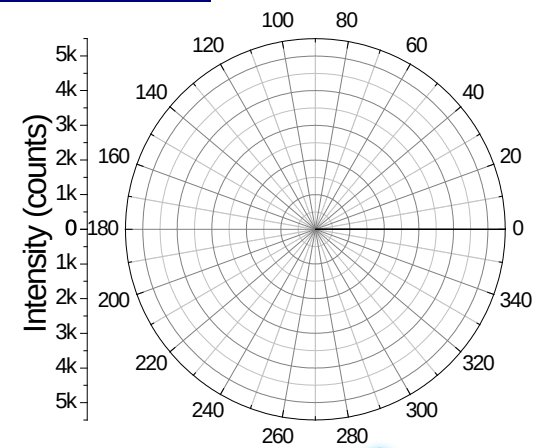
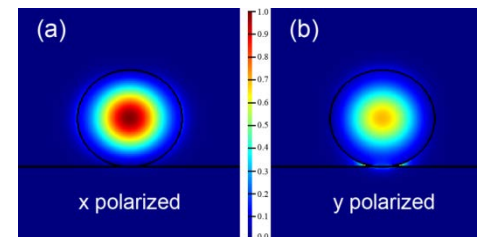
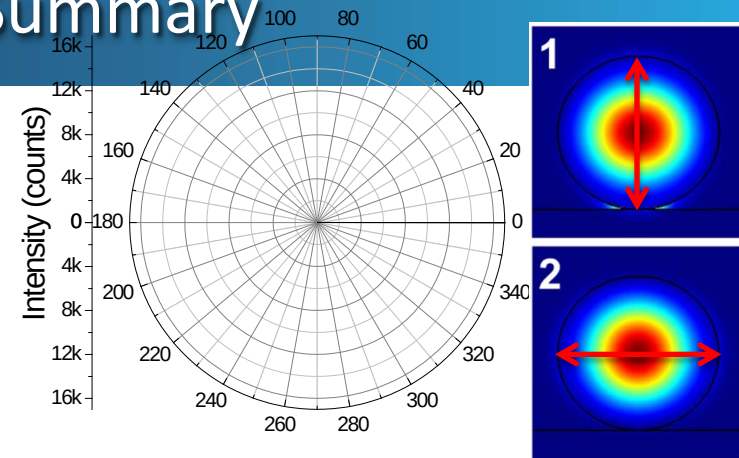
HE₁₁ $n_{\text{eff}}=2.192$



HE₁₁ $n_{\text{eff}}=2.161$

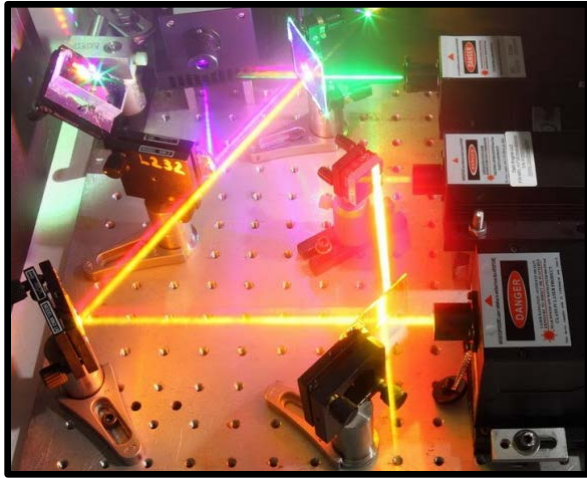
Polarization Control Summary

- A free-standing GaN nanowire laser is typically elliptically polarized with random orientation
- The elliptical polarization originates from the mode degeneracy of the nanowire
- A on-gold nanowire generates a larger cavity loss for the perpendicularly polarized mode
- Linear polarization is achieved with a fixed polarization parallel to the substrate

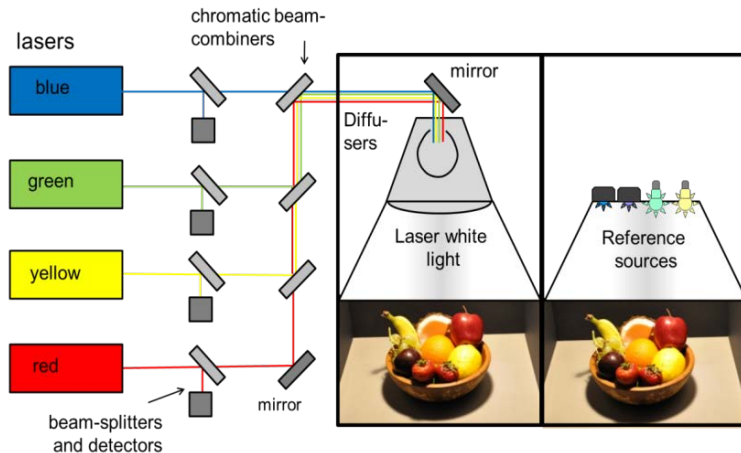


Lasers for Solid-State Lighting?

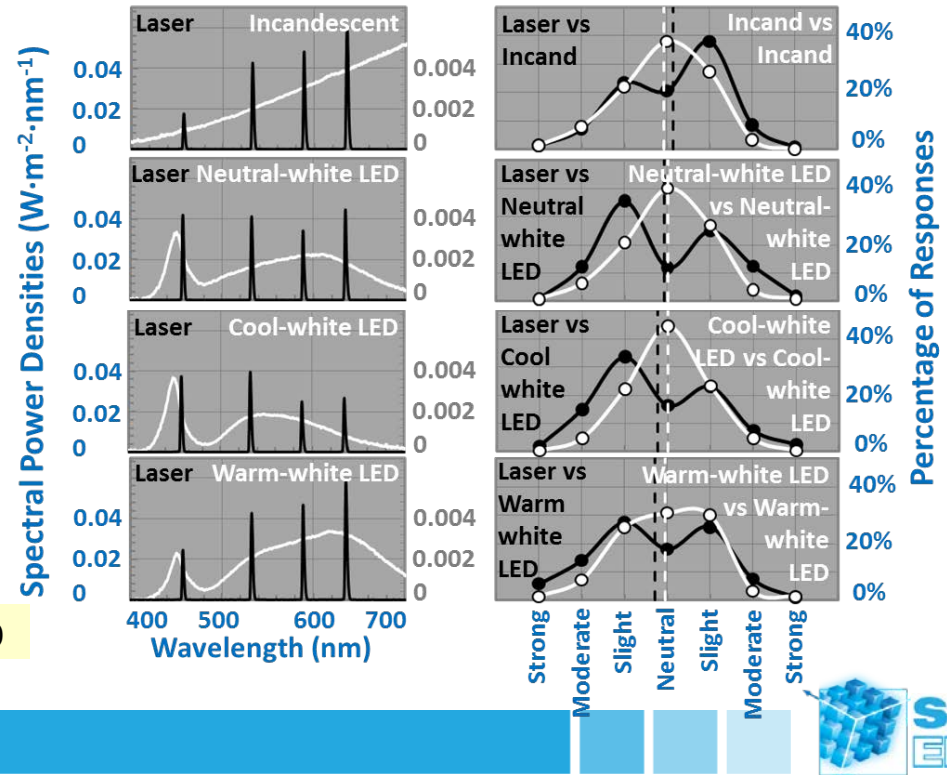
A Human Factors Study: RYGB Laser Illuminant



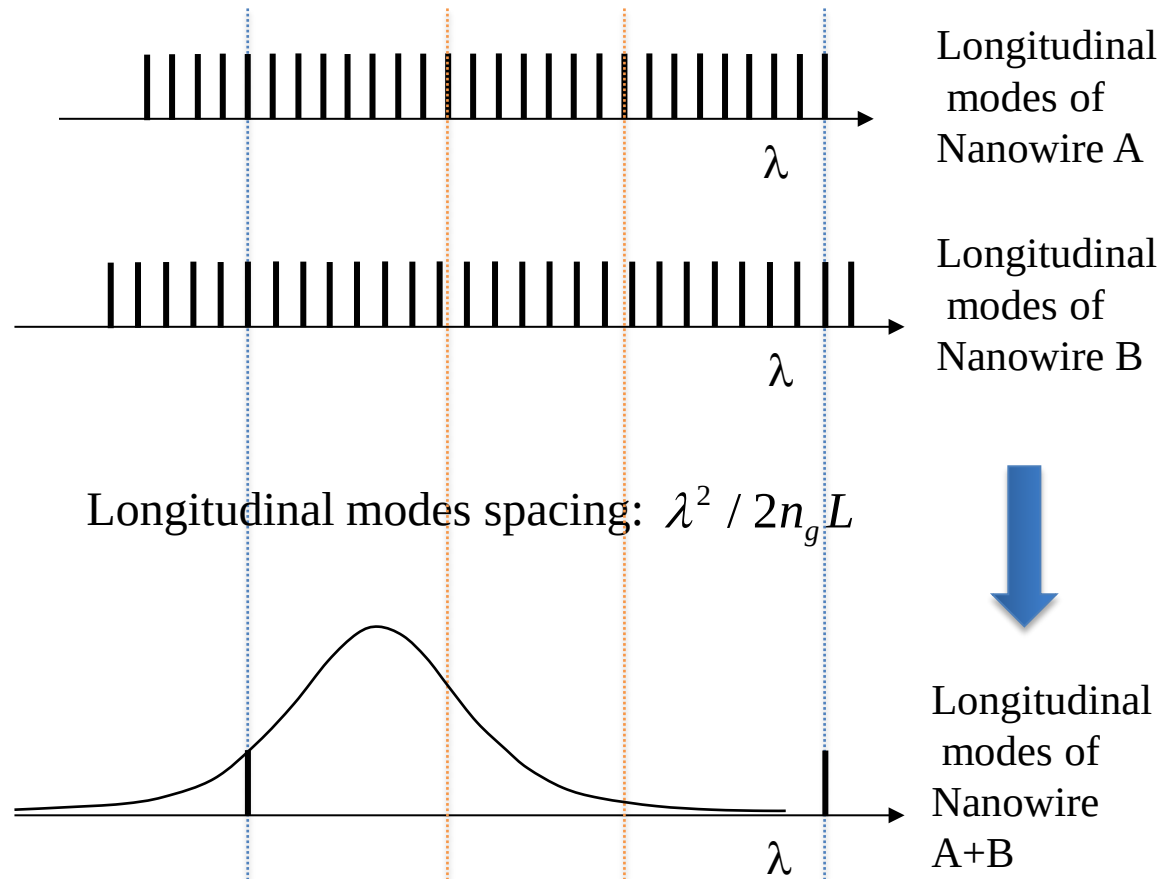
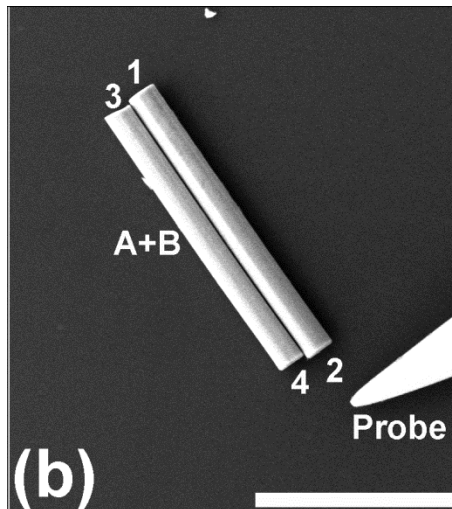
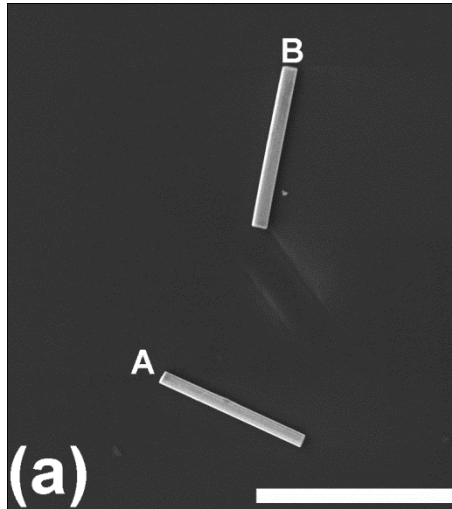
- Constructed an RYGB laser white-light source
 - Compare Laser, Incandescent, and LEDs
- Laser sources are virtually indistinguishable from broadband sources
- **Paves the way for serious consideration of lasers for SSL**



A. Neumann et al, *Optics Express*, **19**, A982-A990 (2011)



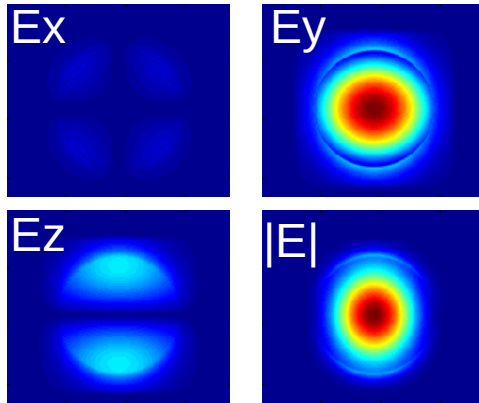
Method 2: Vernier Effect From a Coupled Cavity



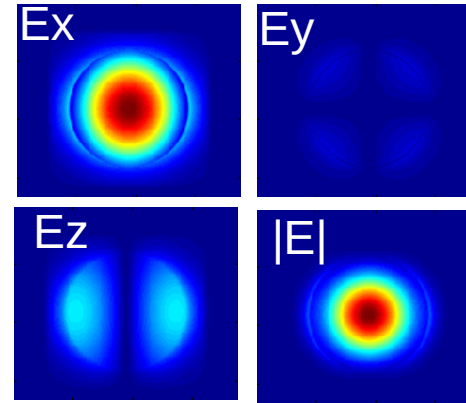
Longitudinal mode spacing greatly enhanced!
(10s of nanometers in this coupled cavity)

Why nanowire laser elliptically polarized?

Mode 1 HE_{11_a} - $n_{\text{eff}}=2.1$



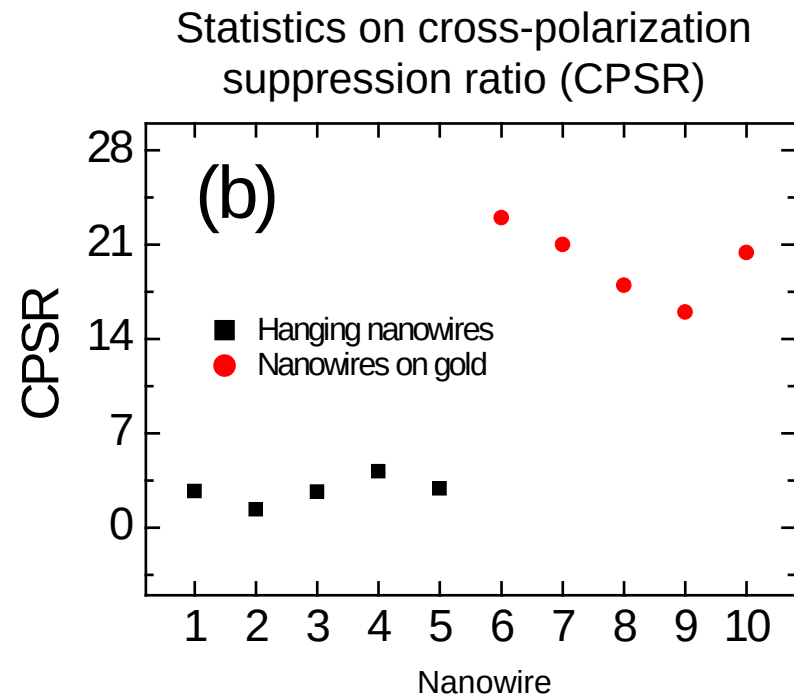
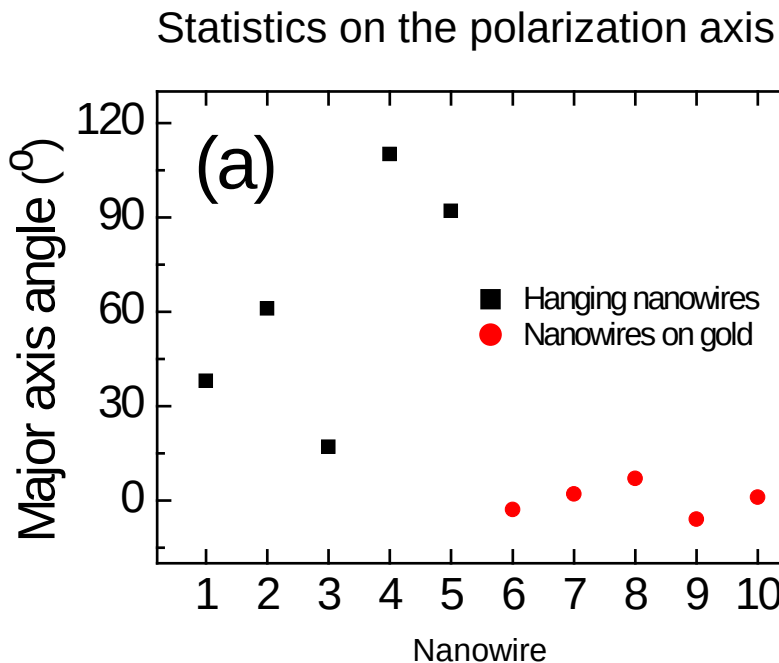
Mode 2 HE_{11_b} - $n_{\text{eff}}=2.1$



Two orthogonal polarized fundamental modes supported by a 200 nm diameter nanowire in air

- ✓ Both fundamental transverse modes
- ✓ Same electric field intensity
- ✓ **Two degenerate modes superimpose resulting in elliptical polarization**

Lasing Polarization Statistics of Free Standing and on-Gold Nanowires



- ✓ Free standing nanowires are polarized with random axes and a small CPSR
- ✓ On-gold nanowires have fixed polarization angle and large CPSR