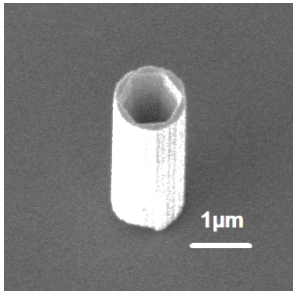
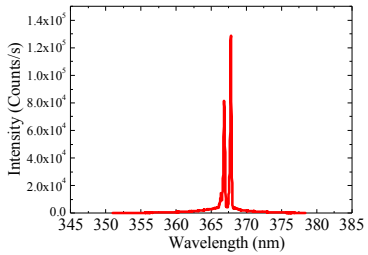
SAND2014-15250PE

Z4. Top-Down III-Nitride Nanotube Lasers

Changyi Li[1]; Antonio Hurtado[2]; Jeremy Wright[1,3]; Huiwen Xu[1]; Sheng Liu[3,4]; Ting Luk[3,4]; Igal Brener[3,4]; Steven R. J. Brueck[1]; George Wang[3]

1. Center for High Technology Materials, University of New Mexico, 1313 Goddard St. SE, Albuquerque, NM, 87106, USA.
2. School of Computer Science and Electronic Engineering, University of Essex, Wivenhoe Park, Colchester, CO4 3SQ, United Kingdom.
3. Sandia National Laboratories, Albuquerque, New Mexico 87185, USA.
4. Center for Integrated Nanotechnology, Sandia National Laboratories, Albuquerque, New Mexico 87185, USA





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

Outline

- Why nanowire and nanotube laser?
- GaN nanotube lasers fabrication
  - Top-down two-step etch process
- Experimental demonstration of lasing by optical pumping
  - Light-light curve
  - Lasing spectra
  - Image of end-facet emission
- Rectangular cross-sectional GaN nanowire laser
- Summary

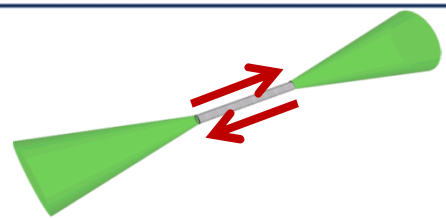
Nanowire lasers – potential light sources for on-chip applications

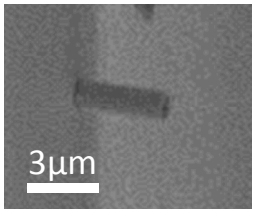
- Nanowire lasers

  Optically or electrically pumped

  Semiconductor material – gain medium

  Cleaved facet – Fabry-perot cavity





- Advantages

  Compact size

  – Desired for on-chip application

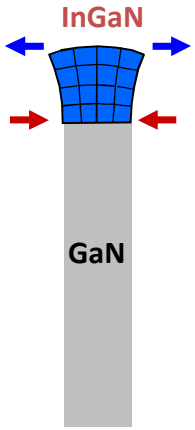
  – Low power requirement

  Coherent emission

  – High spectral purity

  Strain relaxation

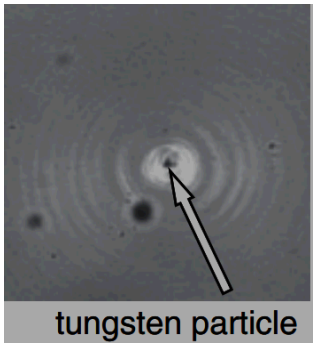
  – Reduce defect

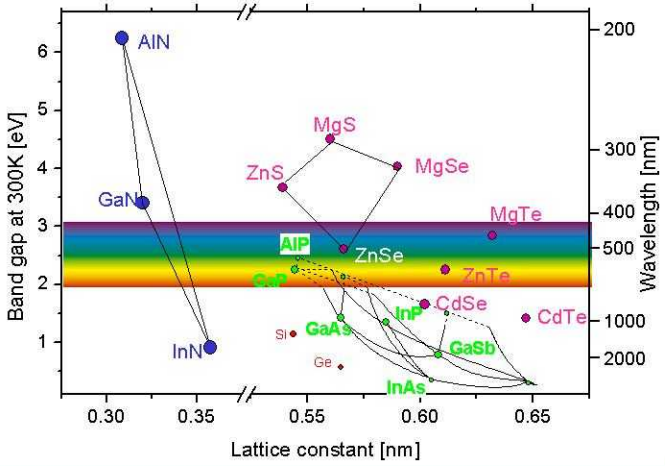


Nanotube lasers

- Nanotubes: hollow geometry
  - Optofluidic
  - Bio sensing
- Nanotube lasers: engineering the lasing emission:

  Annular emission
  - Atom trapping
  - Stimulated emission depletion (STED) microscopy
- Why GaN?
  - III-Nitride materials cover the entire visible and partial near-IR range



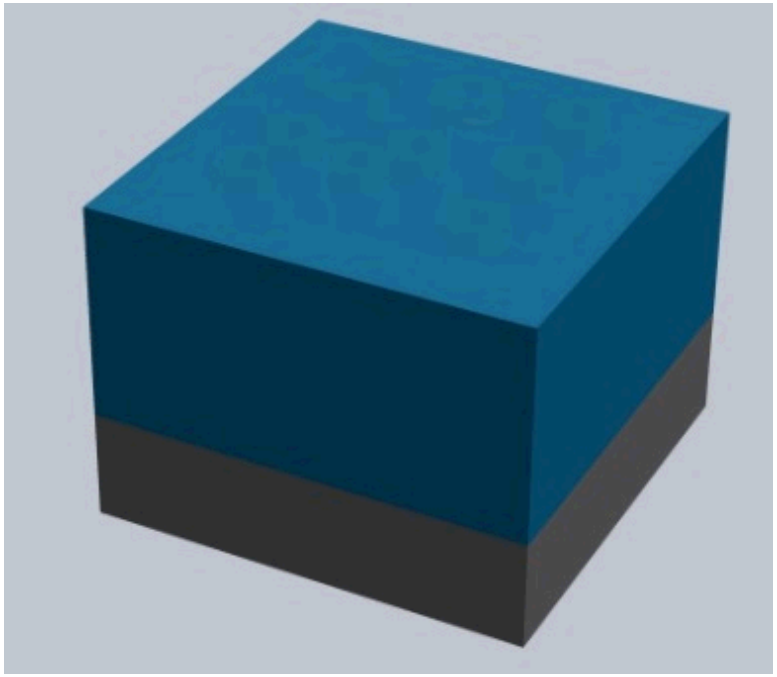


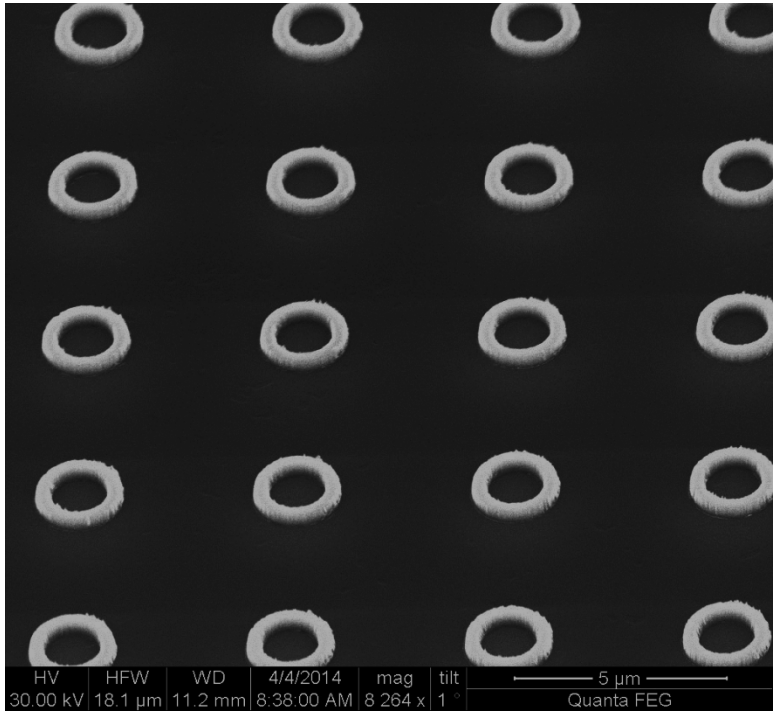
No GaN nanotube laser has been reported.

Prof. Ya-Hong Xie's group website. http://www.seas.ucla.edu/smrl/GaN.html

GaN Nanotube Lasers Fabrication – Top-down two-step etch process

EBL Patterning AZ400K dry etch Annealing dry etch PMMA Lift-off





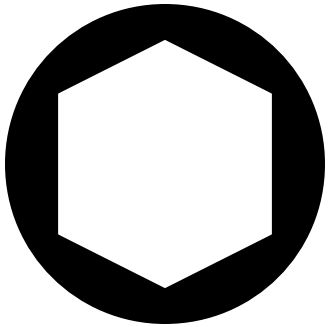
Details of the process, see

Li, Qiming, et al. *Optics express* 19.25 (2011): 25528-25534.

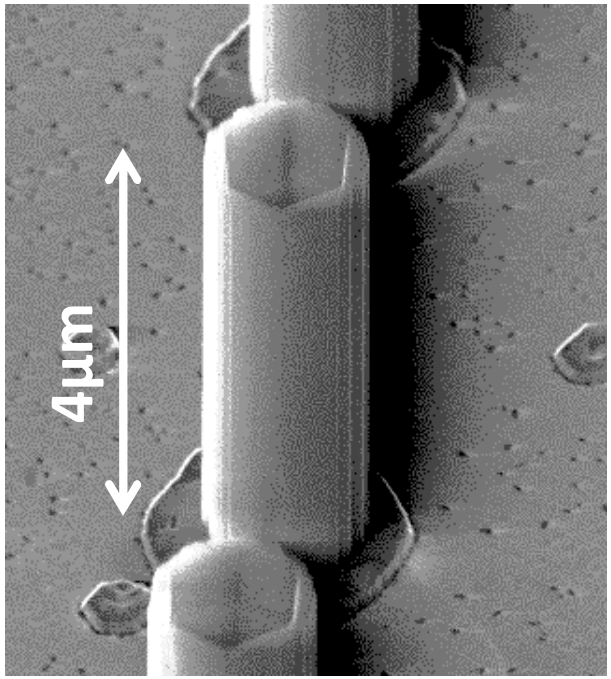
Li, Qiming, et al. *Optics express* 20.16 (2012): 17873-17879.

Fabricated GaN nanotube

- Length: 4µm
- Outer Diameter: 1.3µm
- Thickness: 150nm

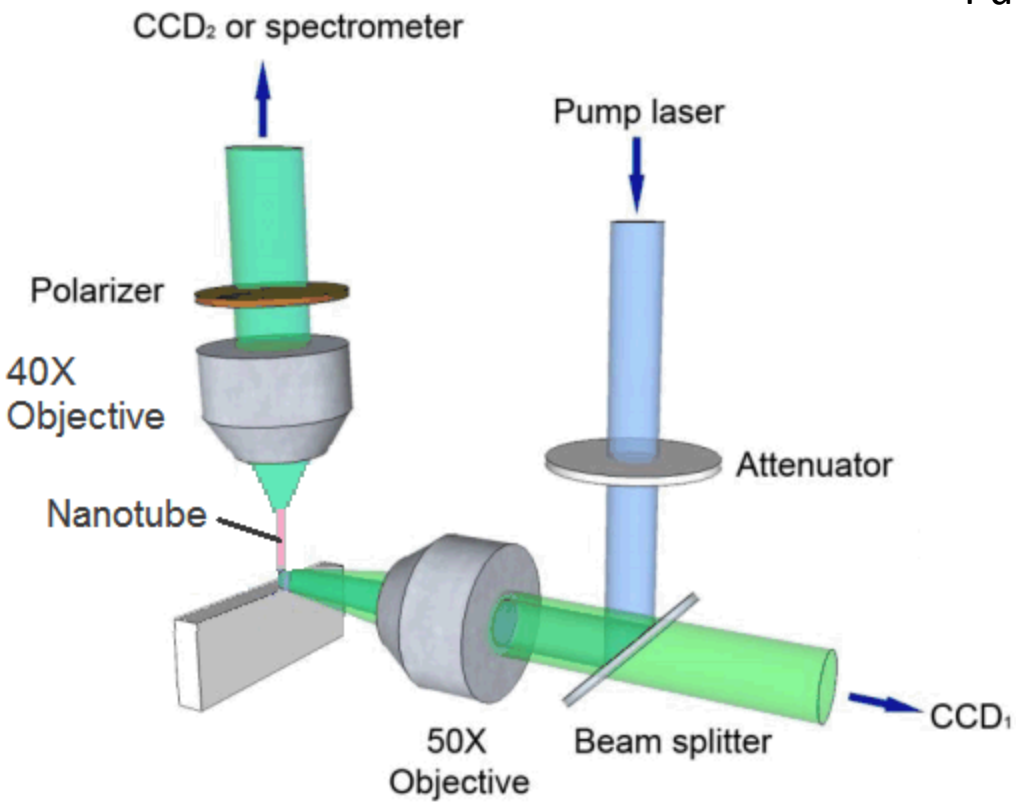


Hexagonal opening



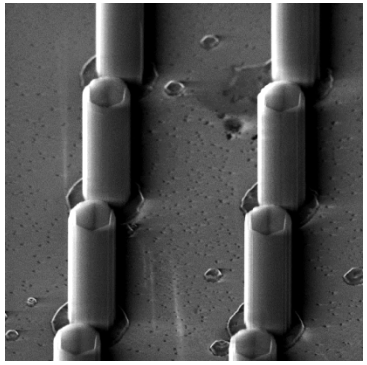
Can we get lasing?

Experimental Setup



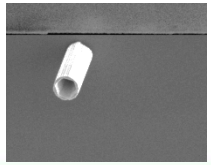
Pump laser:

Nd:YAG laser	@266nm
Pulse duration:	400 ps
Rep rate:	10 kHz
Tunable spot size:	>1µm



As fabricated on Sapphire

Far-field microscopic CCD images



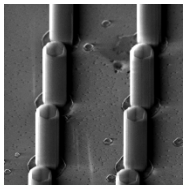
Lower peak pump power density (1800kW/cm^2)

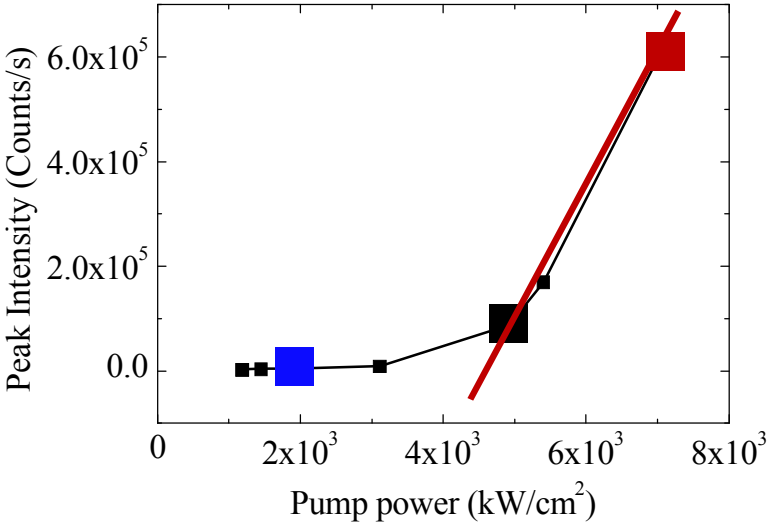
- Uniform intensity over the entire tube
  - Spontaneous emission
- No interference fringe
  - Incoherent emission

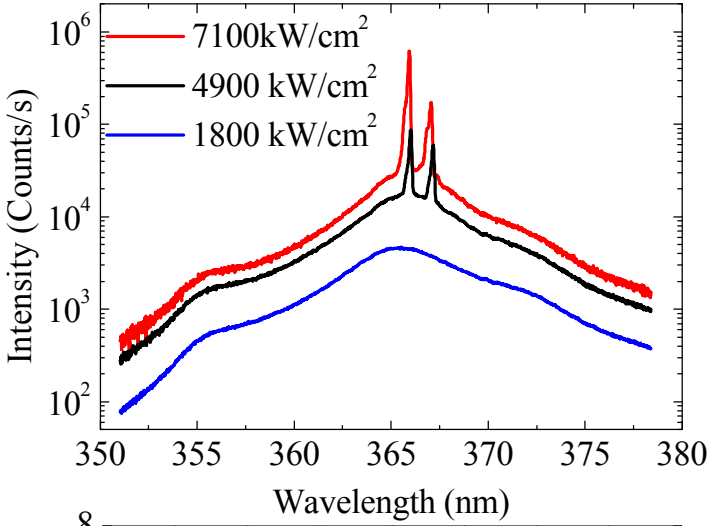
Higher peak pump power density (4900kW/cm^2)

- High intensity at both ends
  - Strongly guided emission
- Interference fringe
  - Spatially coherent emission

Lasing Spectra and L-L Curve



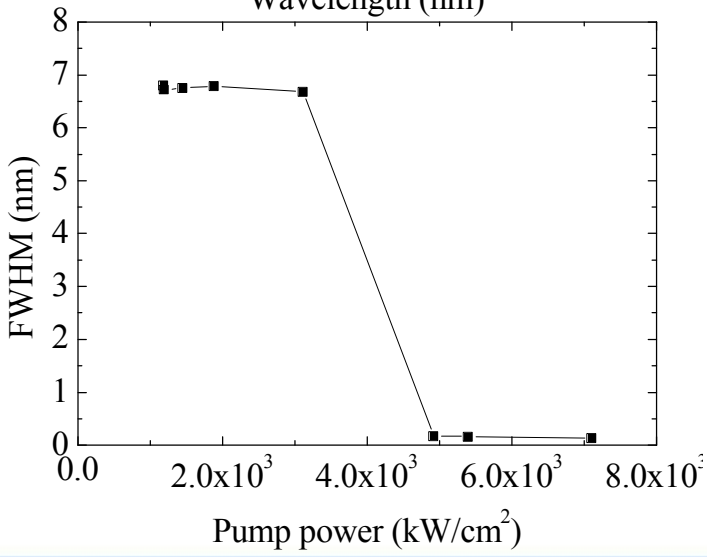




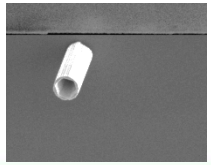
Threshold pump density = 4600kW/cm²

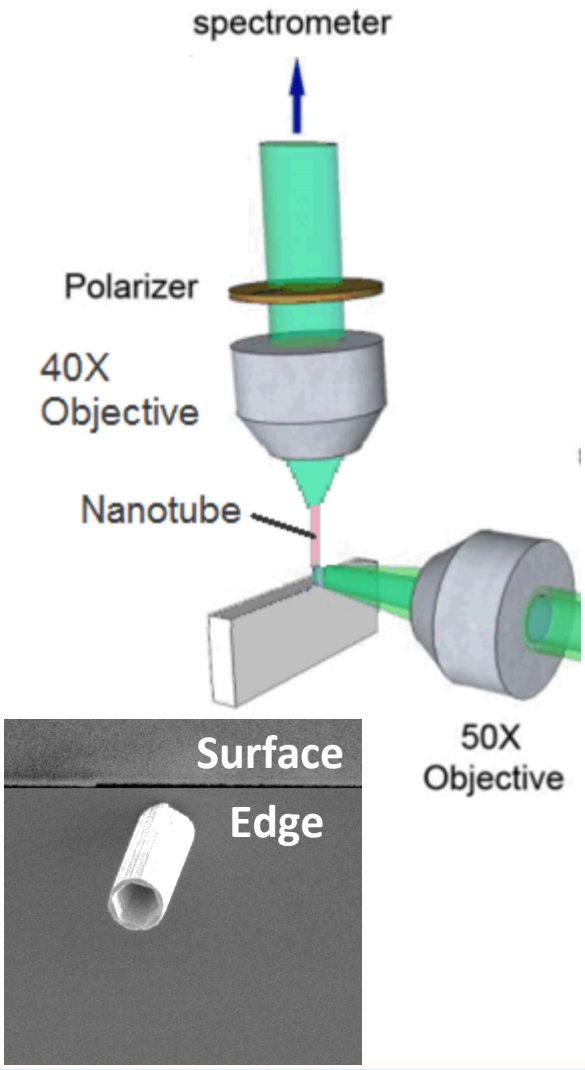
FWHM decreases to 0.13nm as the nanotube laser is pumped above threshold

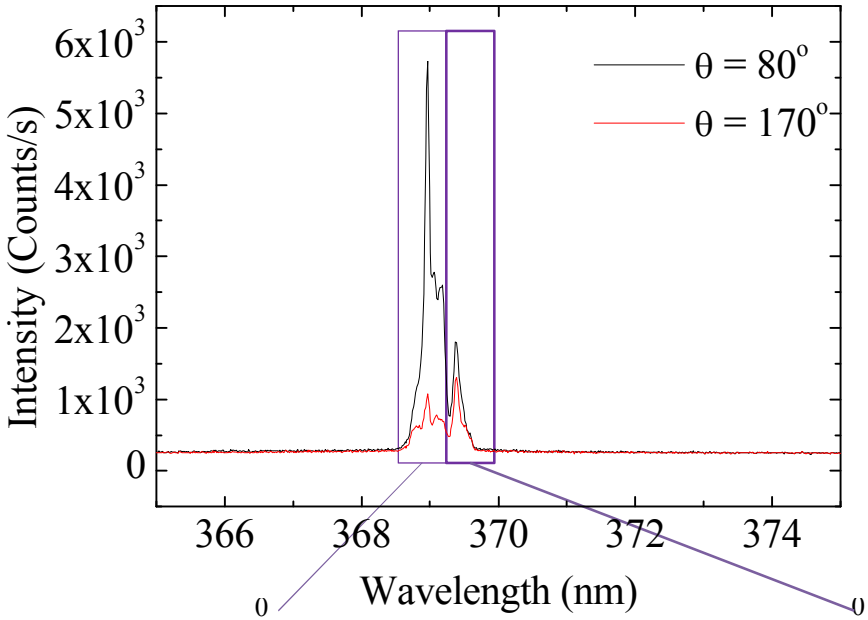
FWHM is limited by the resolution of the spectrometer

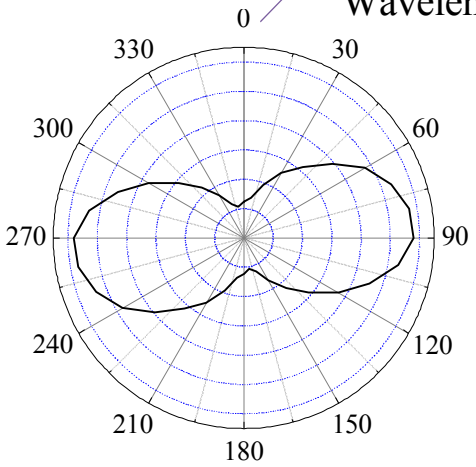


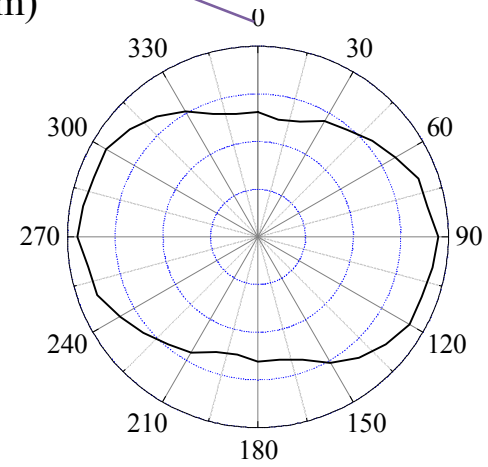
Polarization of the lasing emission



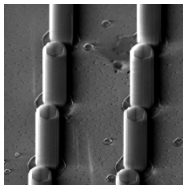


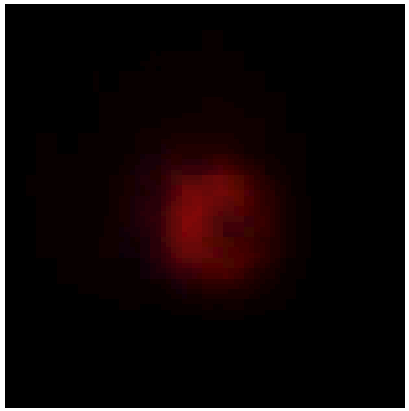






CCD images of the lasing emission





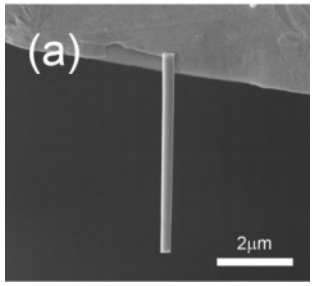
CCD image shows an annular shape emission.

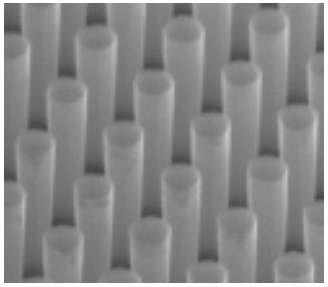
Potential applications:

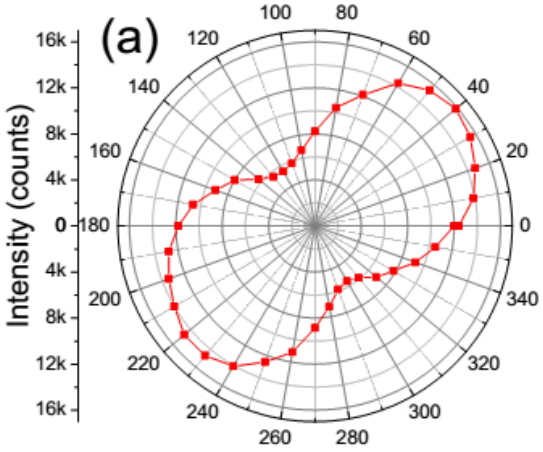
- Atom trapping
- STED microscopy

Nanowire lasers with other cross-sections?

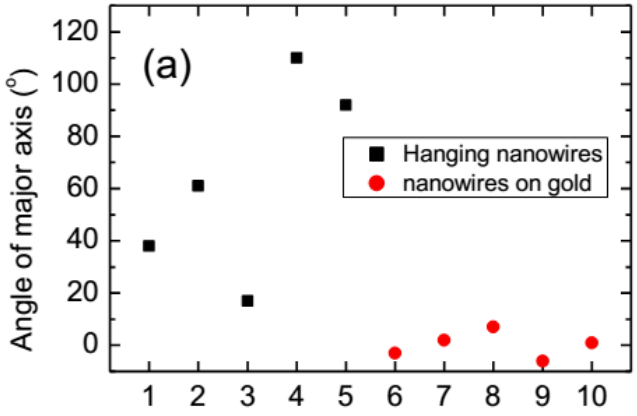
Polarization of lasing from traditional cylindrical nanowire lasers







Elliptical polarization



Random angle of major axis

Xu H. Controlled Lasing in Gallium Nitride Nanowires[D]. THE UNIVERSITY OF NEW MEXICO, 2013.

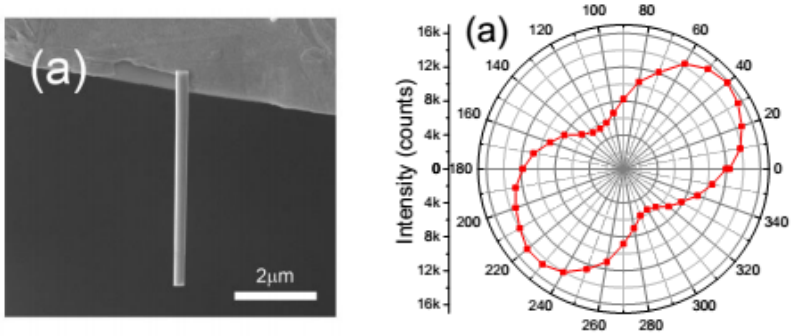
Previous work of polarization control

Polarization control

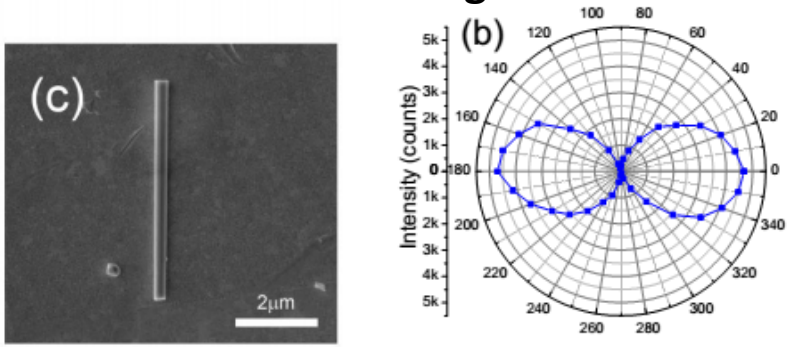
- On-chip Communication
- Backlighting for display

GaN nanwire

- Isotropy in c-plane



Free Standing Wire

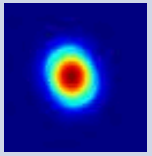
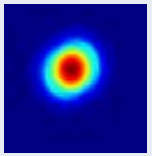
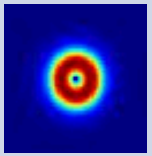
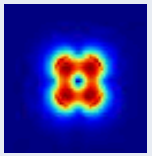


Wire on Au substrate

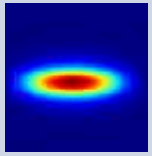
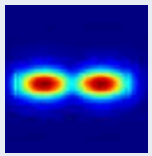
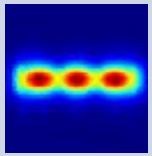
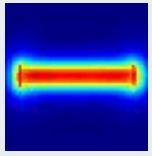
Xu H. Controlled Lasing in Gallium Nitride Nanowires[D]. THE UNIVERSITY OF NEW MEXICO, 2013.

Electric field intensity of transverse modes

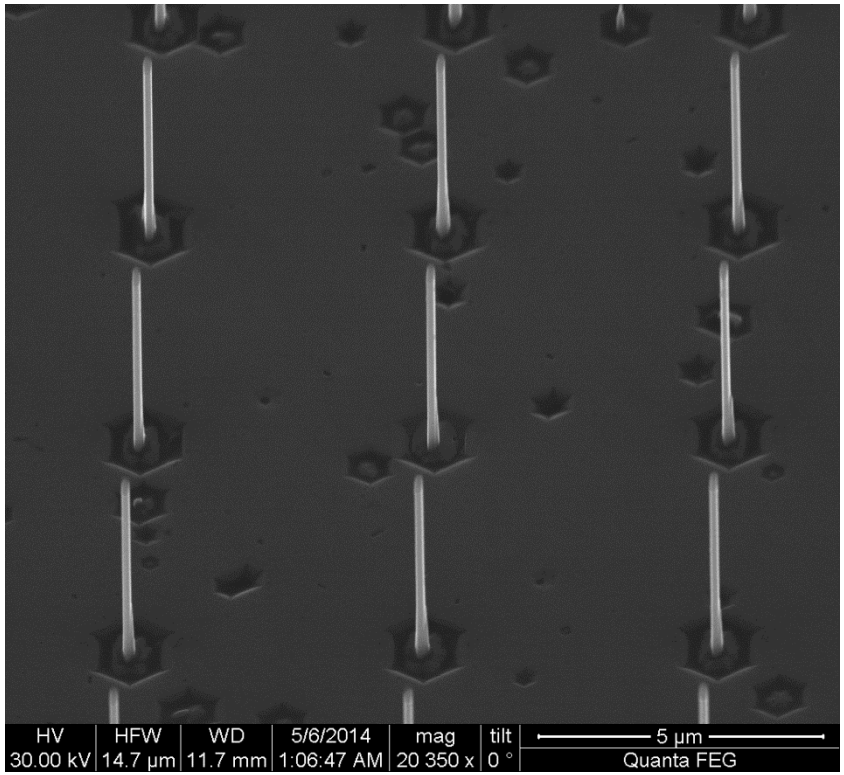
Cylindrical nanowire laser
D=300nm

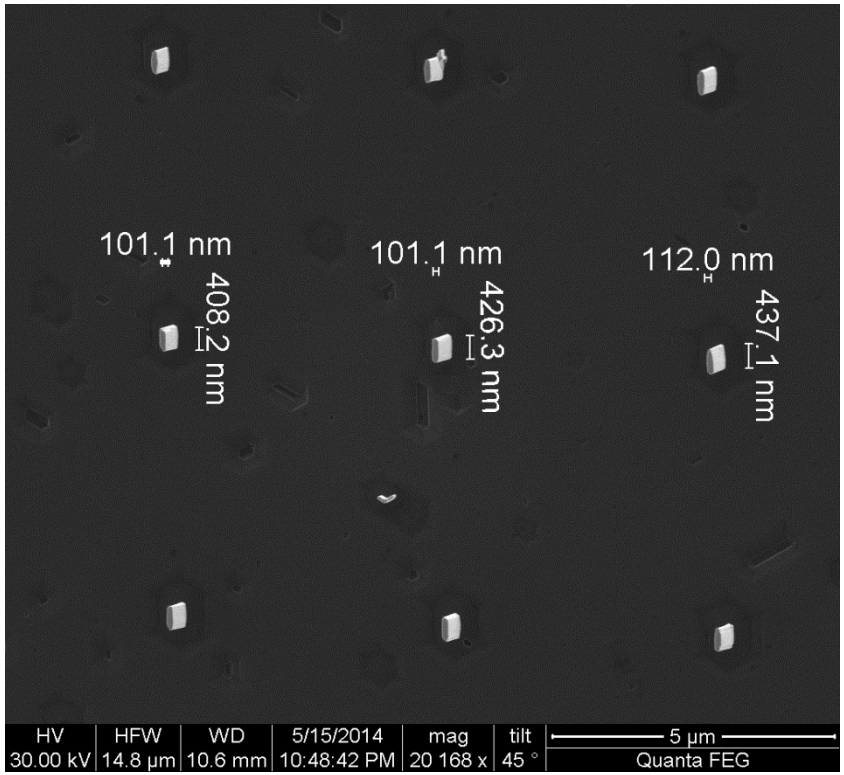
Mode Profile	$\frac{\lvert E_x \rvert}{\lvert E \rvert}$
	0
	100
	50
	50

Rectangular nanowire laser
450nm * 70nm

Mode Profile	$\frac{\lvert E_x \rvert}{\lvert E \rvert}$
	100
	100
	99
	97

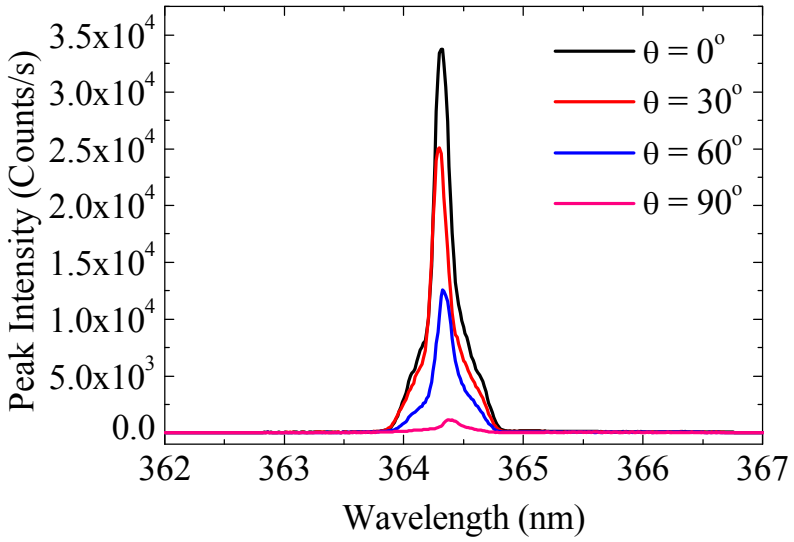
SEM images of rectangular cross-sectional GaN nanowire lasers





Length: 430 – 450nm
Width: 100 – 150nm
Height: 4µm

Polarization of lasing from rectangular cross-sectional nanowire lasers



Wire number	Extinction ratio
1	40:1
2	30:1
3	15:1
4	15:1

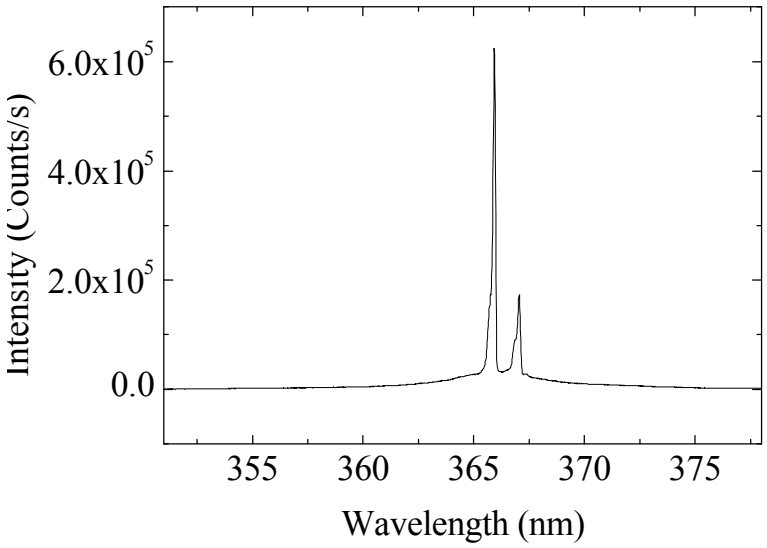
Summary

- Fabricated top-down GaN nanotube
- First experimental demonstration of lasing from GaN nanotube by optical pumping
- Optical property engineering
  - Annular shape lasing emission from GaN nanotube lasers
  - Linear polarization from rectangular cross-sectional nanowire lasers
- Future work
  - Reduce the size of the GaN nanotube lasers

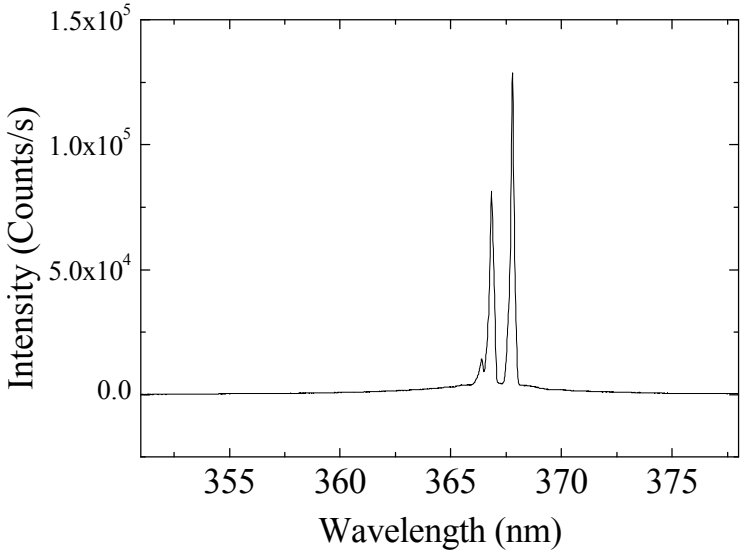
Thank you for your attention!

- Backup Materials

Mode spacing of the nanotube laser



$\Delta\lambda_{tube} = 1.1nm$

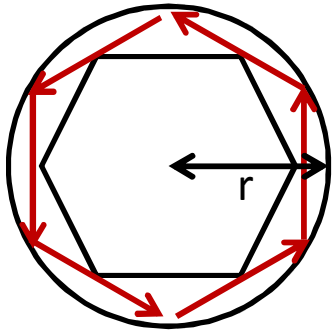


$\Delta\lambda_{tube} = 0.4 - 0.9nm$

Spectra from different nanotubelasers show $\Delta\lambda_{tube} = 0.3 \sim 1.1nm$

Mode spacing of the nanotube laser

- Whispering gallery mode



Mode spacing:

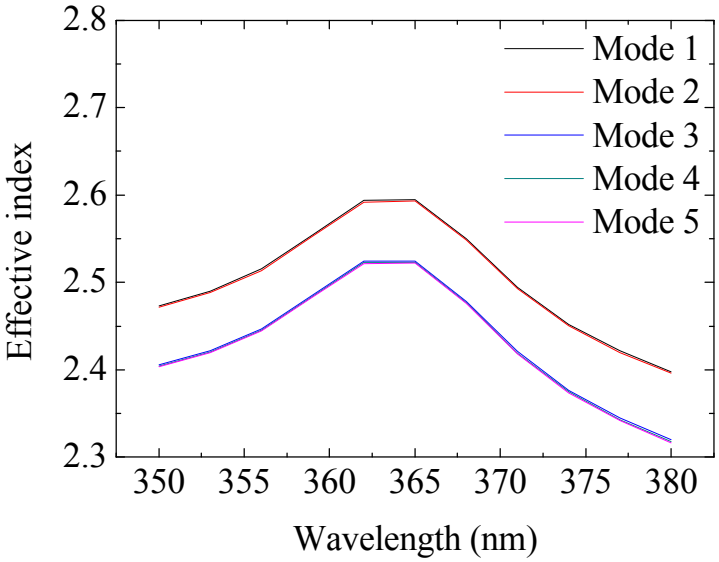
$$\Delta\lambda = \frac{\lambda^2}{2\pi r\left(n-\lambda\frac{dn}{d\lambda}\right)} = \mathbf{5.13\sim 7.83nm}$$

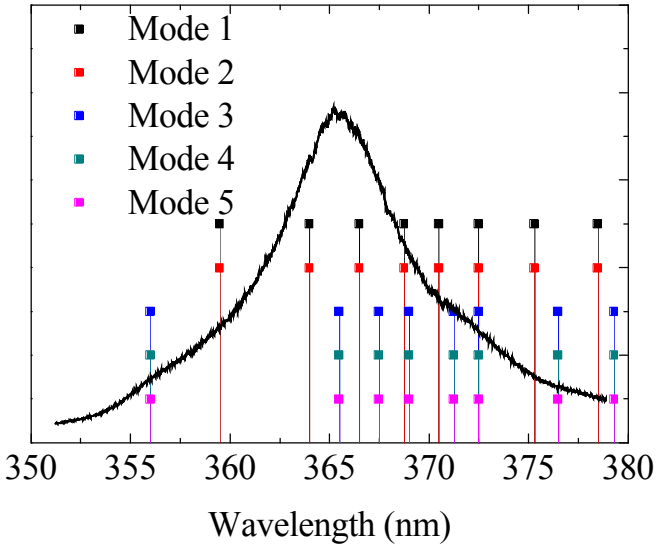
$$\lambda = 365nm \quad r = 650nm \quad n = 2.71 \quad \frac{dn}{d\lambda} = -0.004\sim -0.01$$

GaN nanotube lasers show Fabry-Perot Mode lasing.

Mode spacing of the nanotube laser

- Longitudinal Mode





$$L = \frac{m\lambda}{2n_{eff}} \qquad L = 4\mu m$$

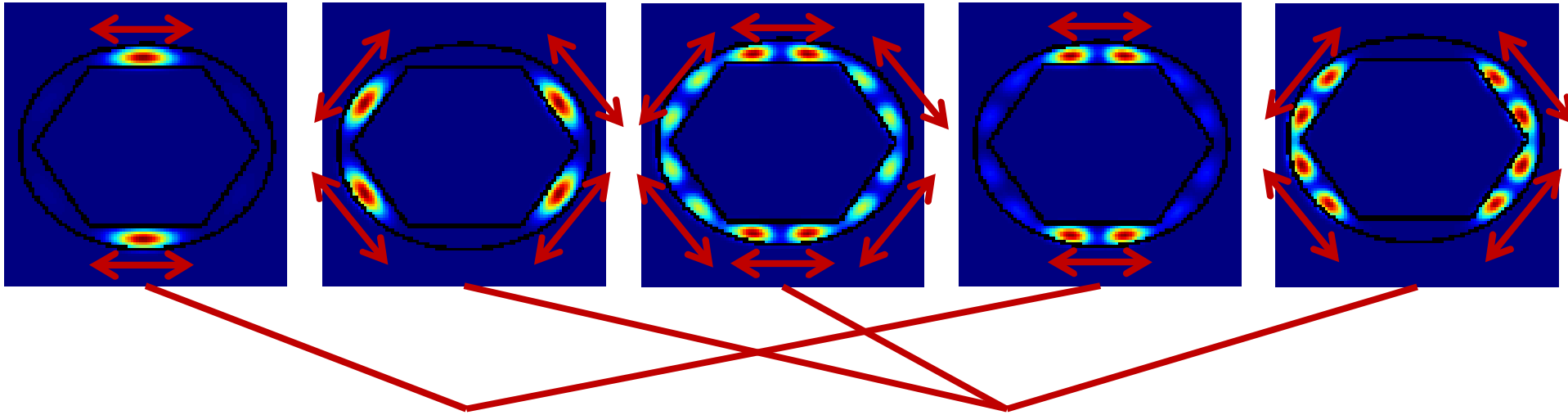
$$\Delta\lambda_{longitudinal} = 1.5\sim4.5nm$$

$$\Delta\lambda_{tube} < \Delta\lambda_{longitudinal}$$

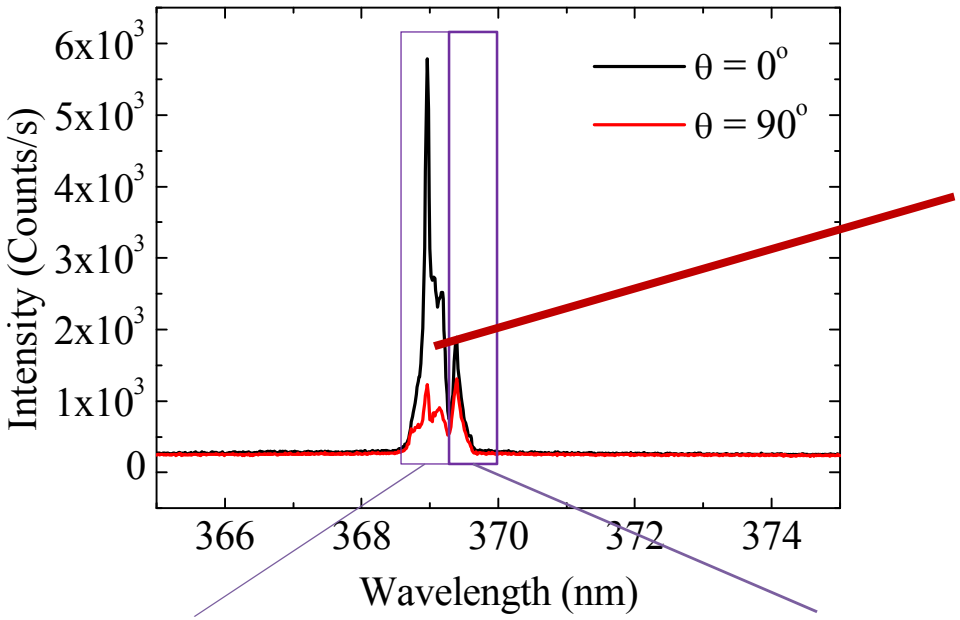
Multi-transverse mode lasing

Polarization of the lasing emission

- Electric field intensity of the 1st-5th transverse modes of the GaN nanotube laser



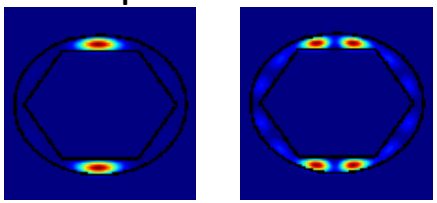
Polarization of the lasing emission



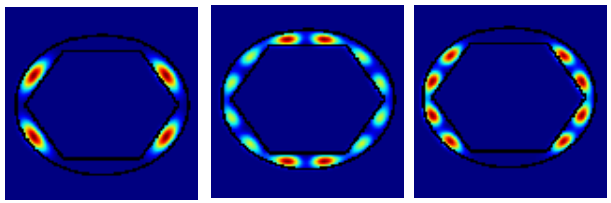
Slight n_{eff} difference between different transverse modes gives rise to the different of wavelength

Degenerate modes lead to low extinction ratio

"Linear-like" polarization



Circularly polarization



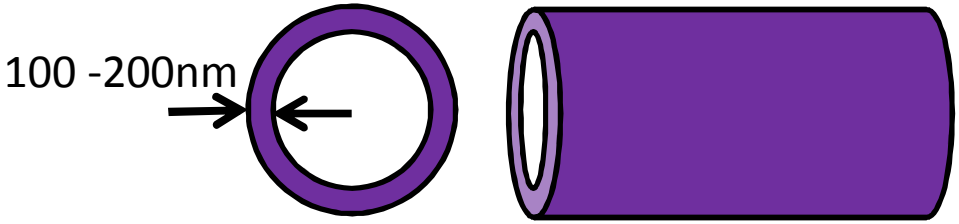
Future work

- Reduce the size of the GaN nanotube lasers
  - Reduce number of optical modes

Thank you for your attention!

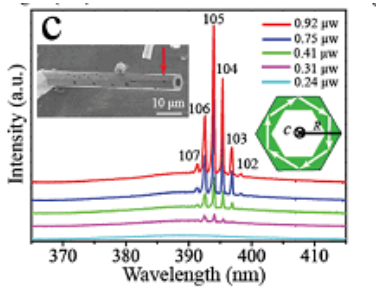
Nanotube lasers

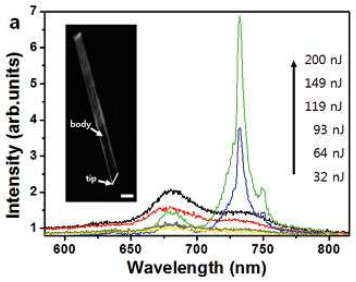
- Nanotubes: hollow geometry
  - Optofluidic
  - Bio sensing



- Nanotube lasers: engineering the far-field of the lasing emission:

  Annular far-field
  - Atom trapping
  - Stimulated emission depletion (STED) spectroscopy
- Recent work on micro/nano tube lasers





Dong, Hongxing, et al. *The Journal of Physical Chemistry C* 114.41 (2010): 17369-17373.

Yoon, Seok Min, et al. *ACS nano* 5.4 (2011): 2923-2929.

- No GaN nanotube laser has been reported.