Polarization and Modal Cotnrol of GaN Nanowire Lasers

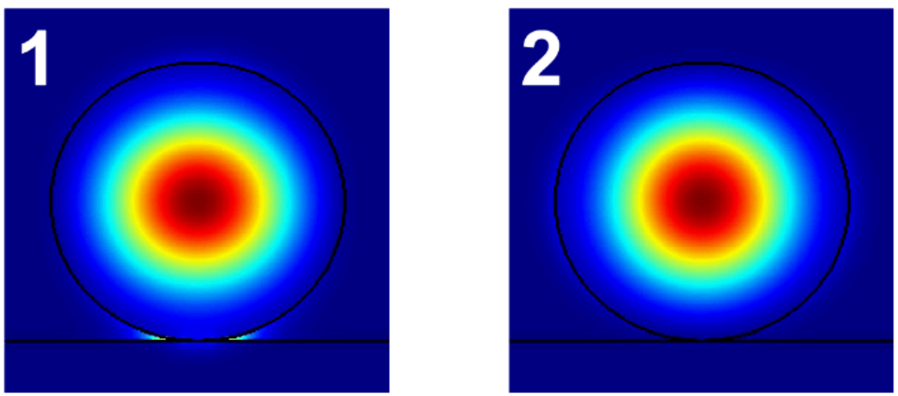
SAND2013-7054C

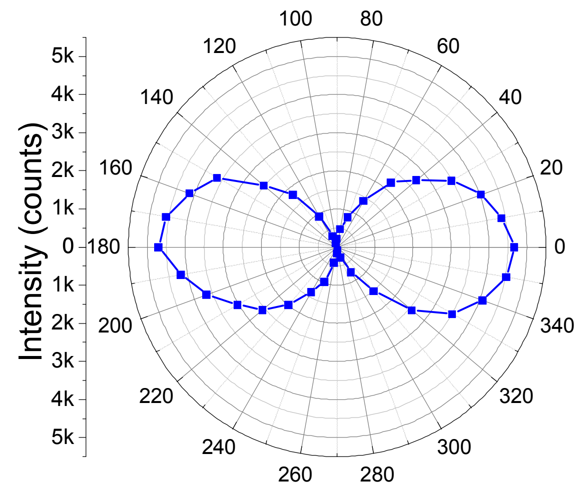
Huiwen Xu, Antonio Hurtado, Ganesh Balakrishnan, and Luke Lester

Center for High Technology Materials, University of New Mexico, Albuquerque

<u>Jeremy Wright,</u> Qiming Li, George Wang, Ting-Shan Luk, Igal Brener, Jeffrey Figiel, and Karen Cross

Sandia National Laboratories, Albuquerque, NM





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

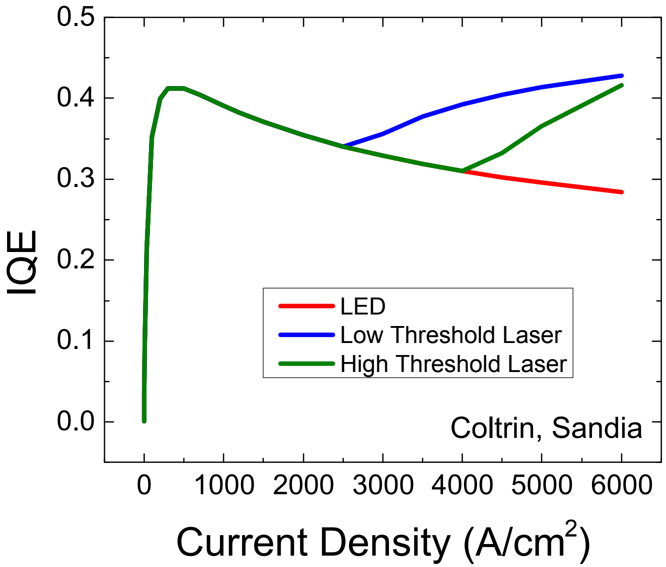
CHTM | Center for High Technology Materials

THE UNIVERSITY of NEW MEXICO

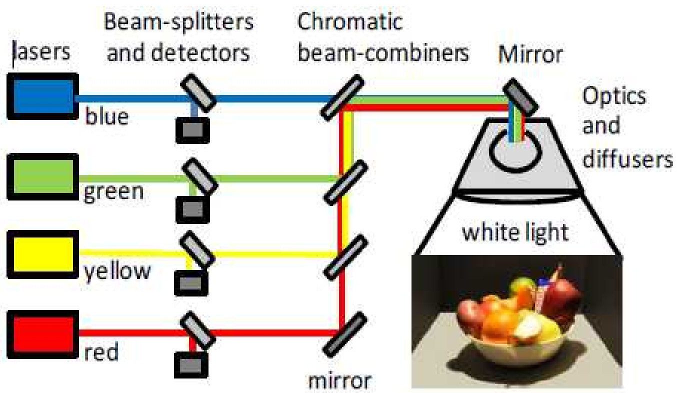
Sandia National Laboratories

Why lasers in solid state lighting?

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



4-Color Laser Illuminant



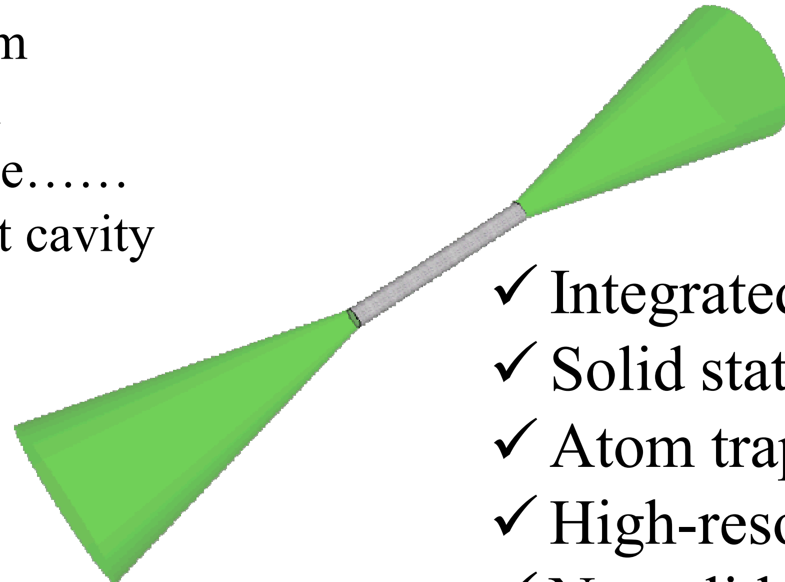
A. Neumann et al., "Four-color laser white illuminant demonstrating high color-rendering quality," Opt. Express, vol. 19, pp. A982-A990, 2011.

Outline

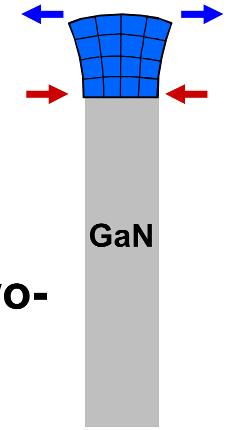
- Introduction
- Nanowire fabrication and characterization
- Typical lasing from GaN nanowires
- Controlled Single-mode Lasing
- Polarization control
- Summary

Nanowire lasers

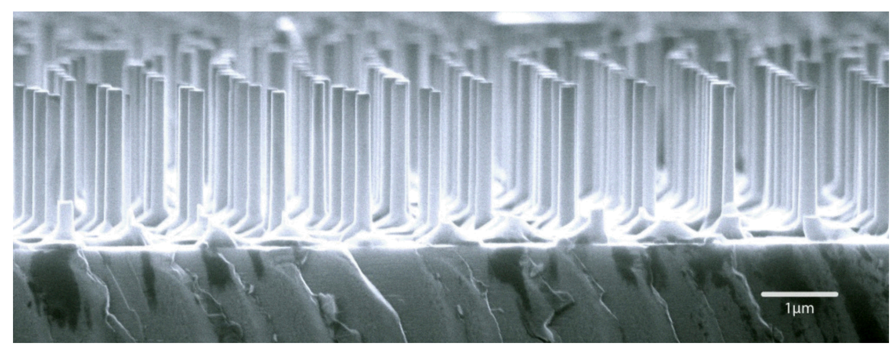
- ✓ Diameter: 100~800nm
- ✓ Length: 2μm~100μm
- ✓ GaN, ZnO, GaP, CdSe……
- ✓ Typically Febry-Perot cavity
- ✓ End-facet emission



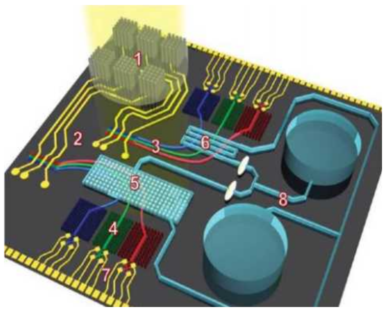
- ✓ Integrated nanophotonics
- ✓ Solid state lighting
- ✓ Atom trapping
- ✓ High-resolution microdisplay
- ✓ Nano lithography
- ✓ Bio-sensing



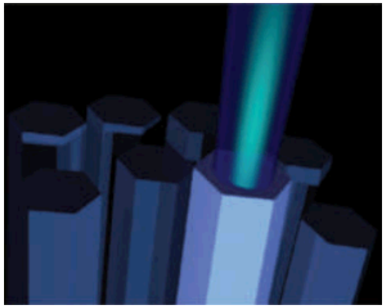
- **Reduced strain**
  - **Greater range of alloy compositions**
- **Easily integrated into two-dimensional arrays**



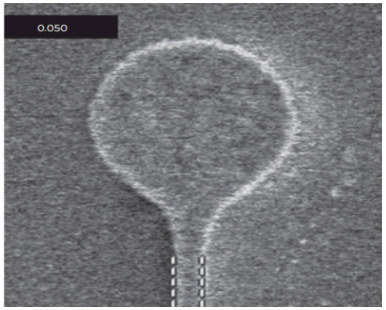
Why Single-mode GaN Nanowire Lasers?



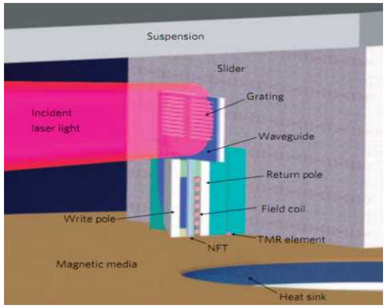
Integrated nanocommunicatio
n



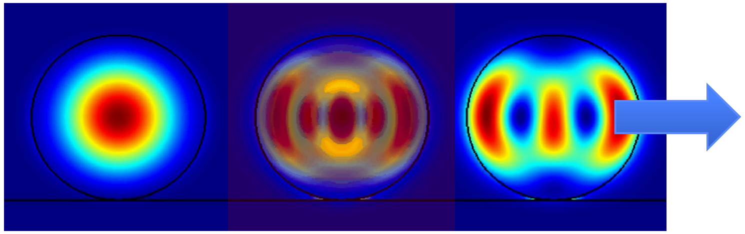
High-
resolution
microdisplay



Nano
lithography



Ultra-high density
data storage



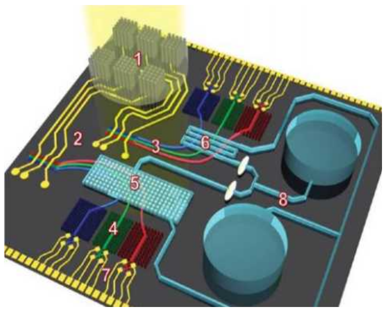
Multiple transverse modes

Low beam quality

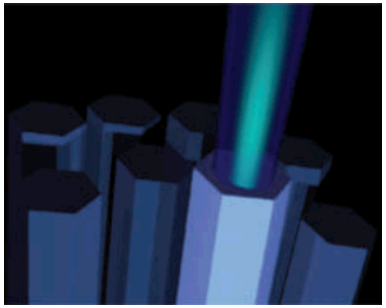
P. J. Pauzauskie, et al. Mat. Today 9(10), 36 (2006)
W. A. Challener, et al. Nat. Photonics 3(220), (2009)

Sandia National Laboratories

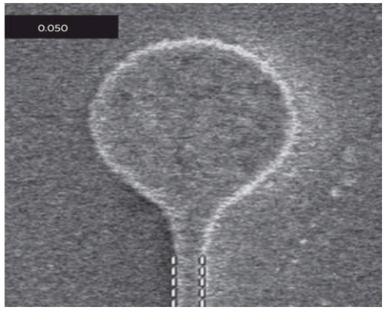
Why Single-mode GaN Nanowire Lasers?



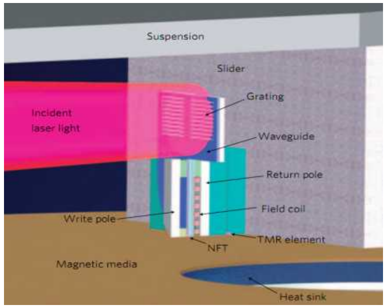
Integrated nanocommunication



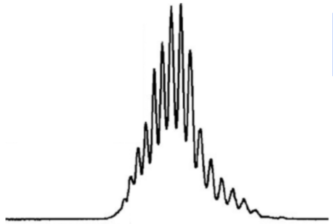
High-resolution microdisplay



Nano lithography



Ultra-high density data storage



Multiple longitudinal modes

SINGLE MODE LASING

Low spectral purity

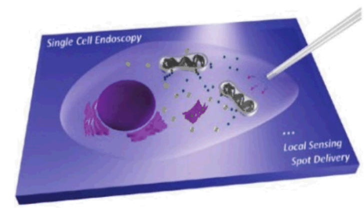
HIGH BEAM QUALITY + SINGLE WAVELENGTH OPERATION

P. J. Pauzauskie, et al. Mat. Today 9(10), 36 (2006)

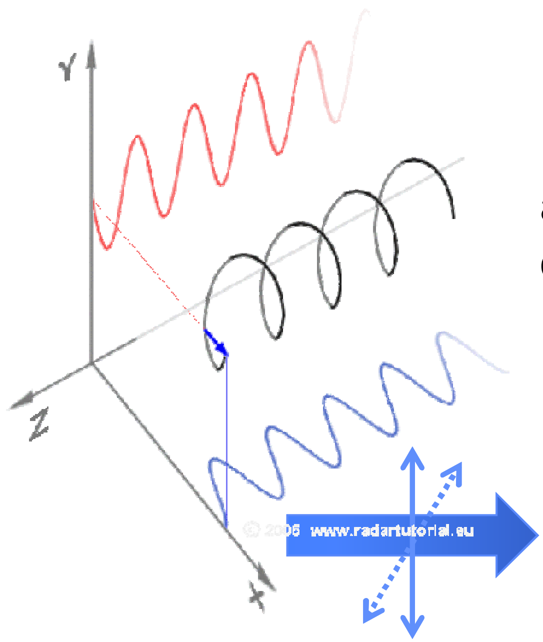
W. A. Challener, et al. Nat. Photonics 3(220), (2009)

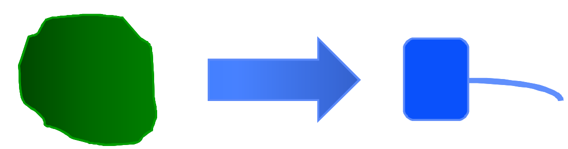
Sandia National Laboratories

Why Polarization Control?



anisotropic testing
of biocells



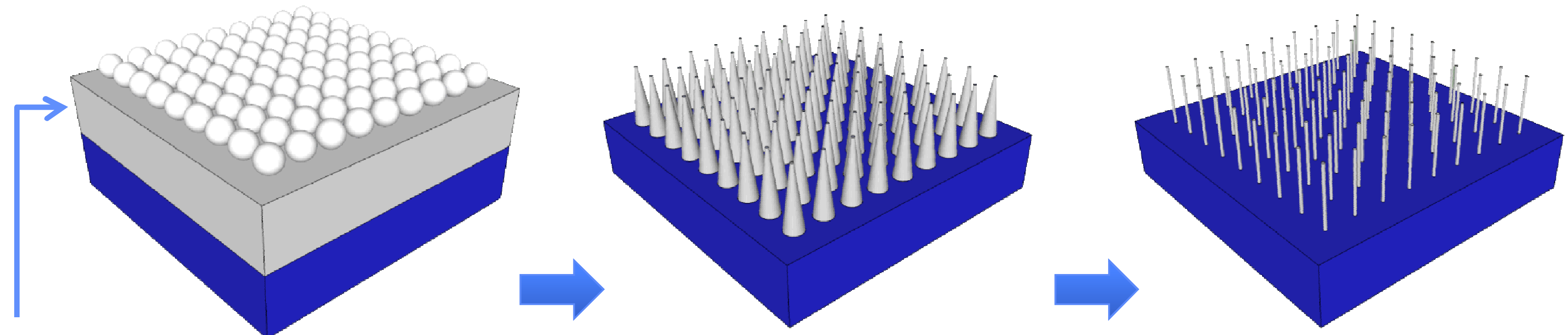


incident   biocells   detector

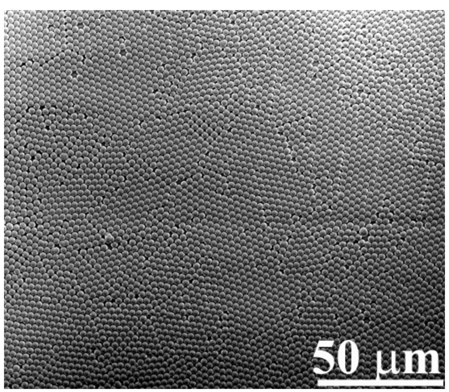
- ✓ Interferometers,
- ✓ Modulators,
- ✓ Sensors,
- ✓ Nanolithography,
- ✓ Anisotropic properties of biocell testing

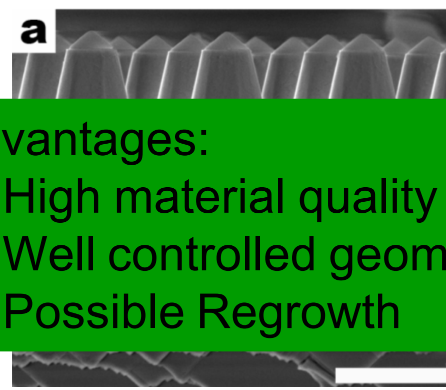
Advanced Nanowire Fabrication Technique

Two-step top-down etch = dry etch + wet etch

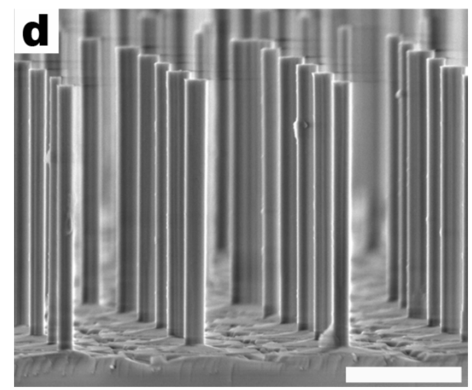


GaN epilayer ICP etch wet etch (AZ-400K developer)



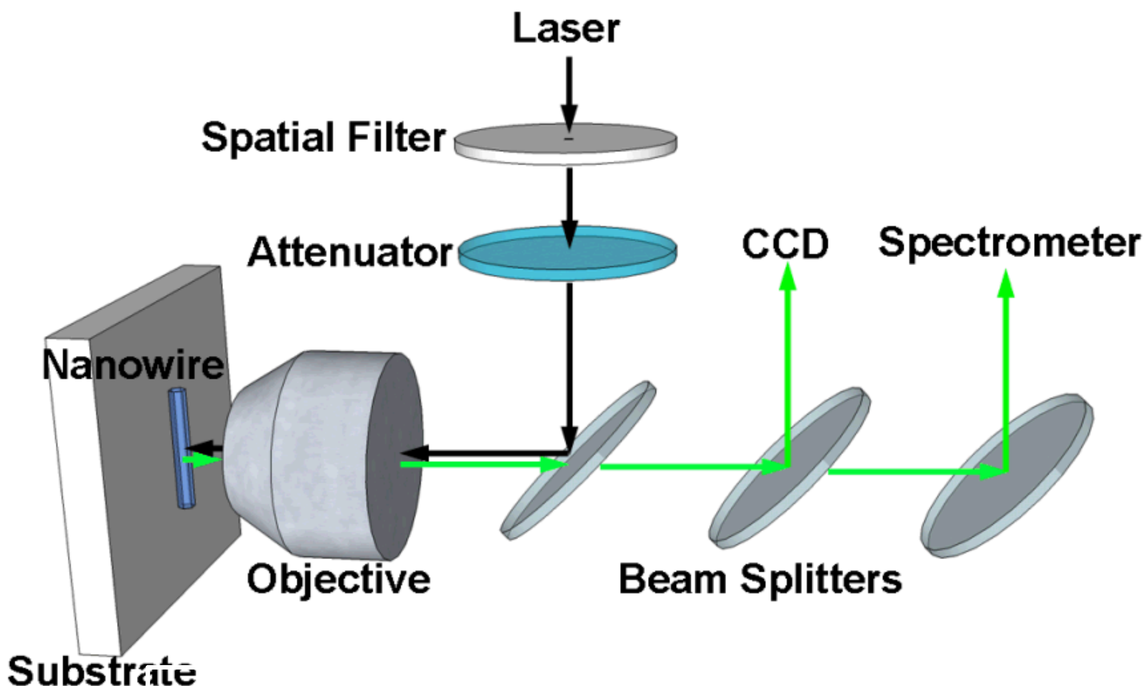


Advantages:
- ✓ High material quality
- ✓ Well controlled geometry
- ✓ Possible Regrowth



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

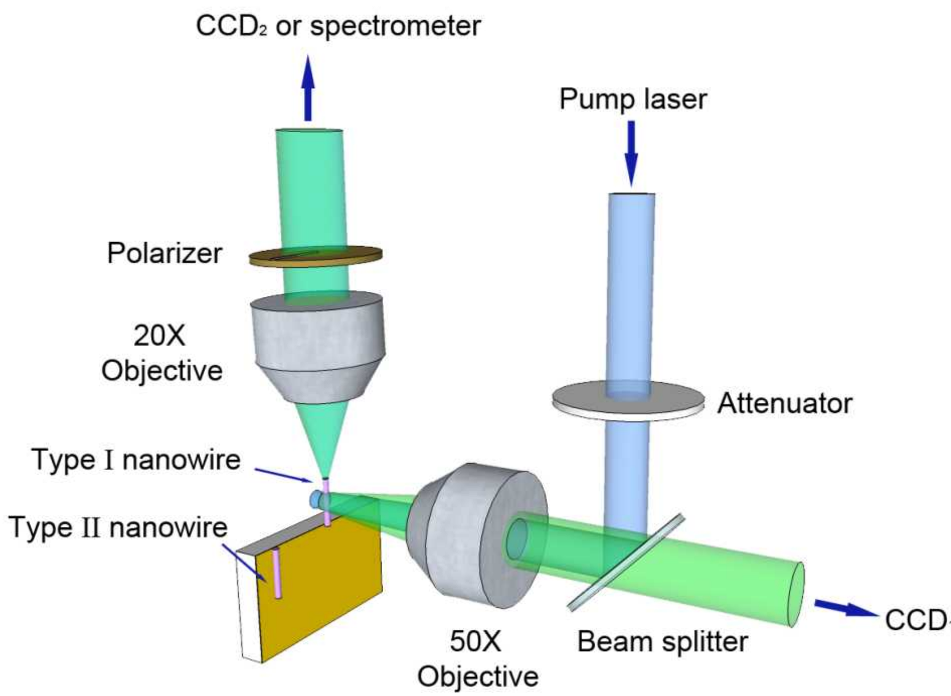
Nanowire Optical Characterization



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

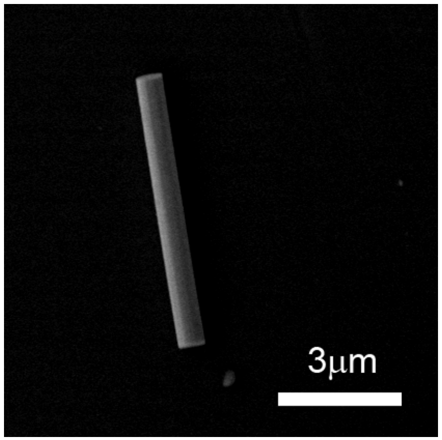
Q. Li, et al. Opt. Express 20, 17873 (2012)

Nanowire Optical Characterization

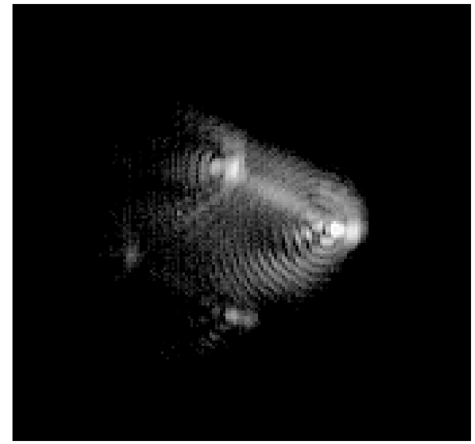


- ✓ Pump: pulsed quadrupled Nd:YAG laser
- ✓ 266nm, 400ps, 10kHz, 5.2mW, ~5μm pump Spot size
- ✓ Separation of the pumping and collecting arms
- ✓ Analysis of light emission directly from the end-facet

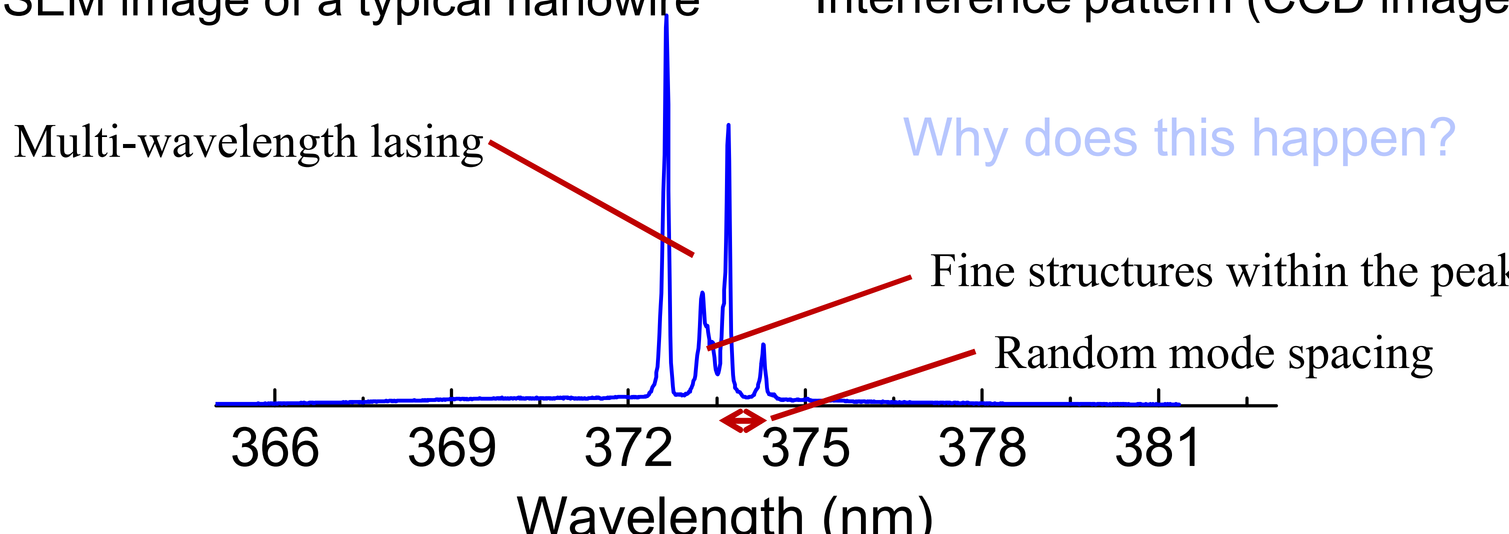
Typical GaN Nanowire Lasing: Multimode Operation



SEM image of a typical nanowire

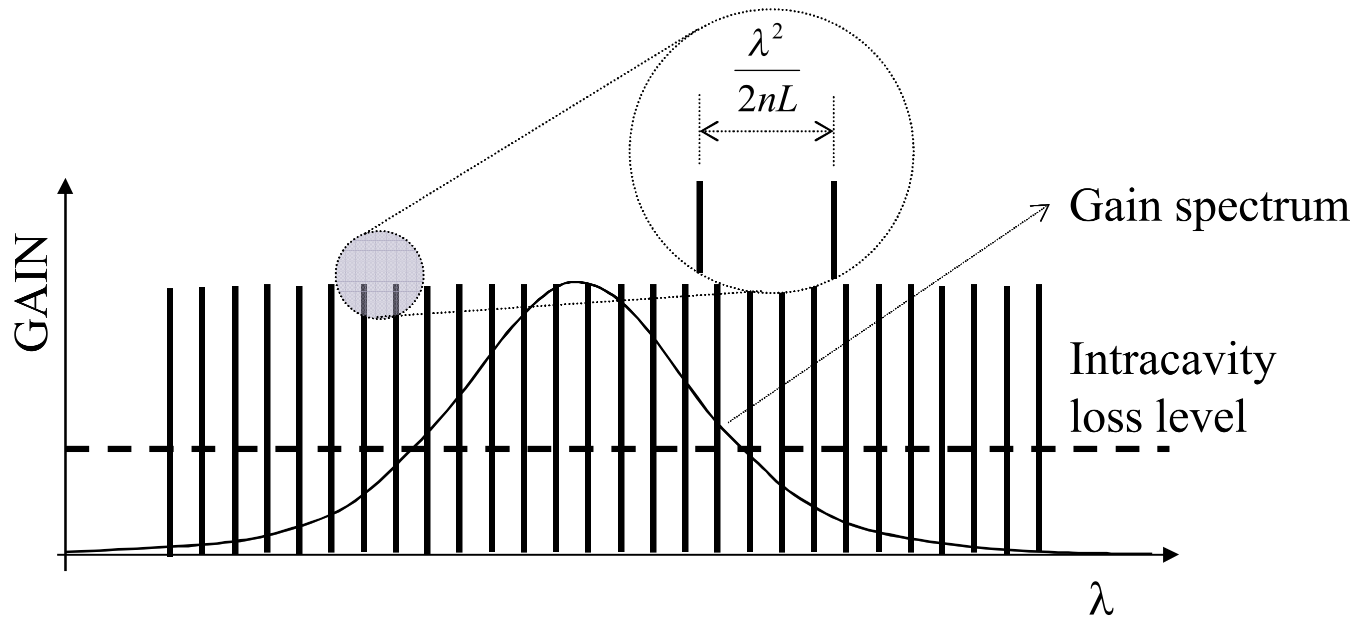


Interference pattern (CCD image)



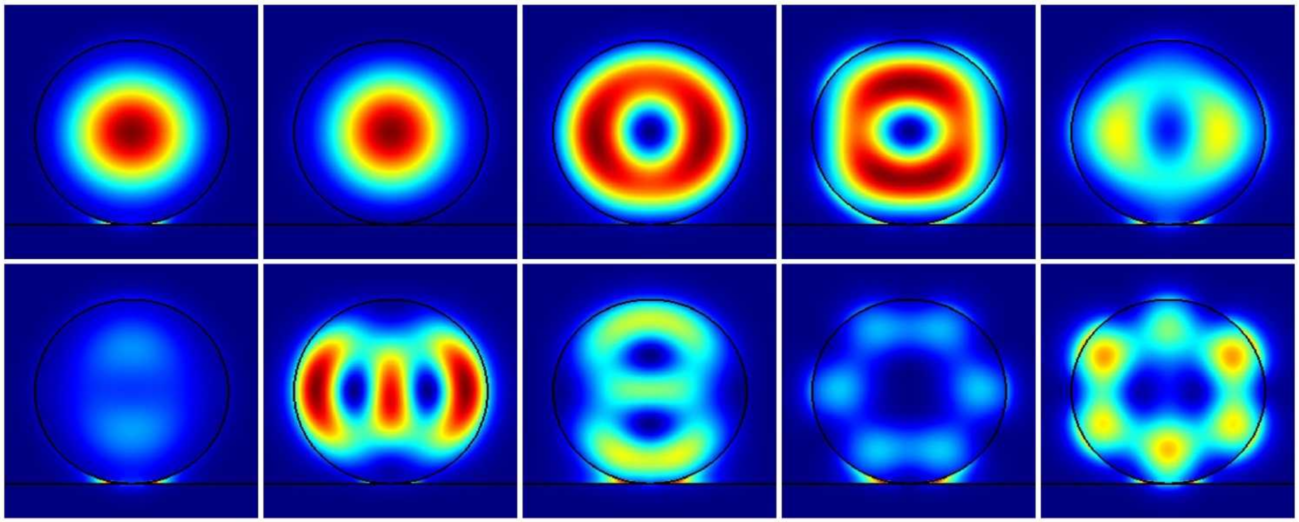
Why does this happen?

Why Multimode Lasing Occurs



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

Why Multimode Lasing Occurs (2)

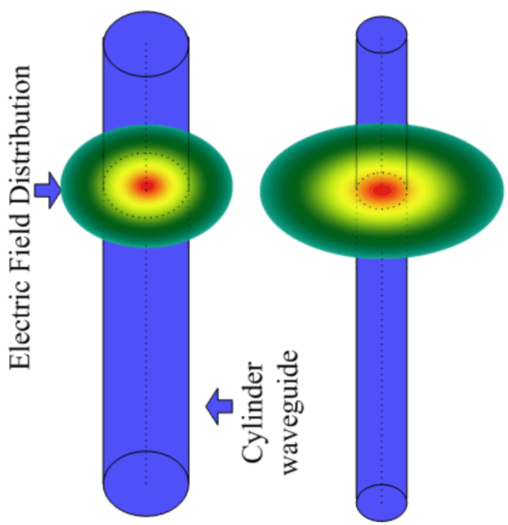


Transverse modes supported by a 300 nm diameter GaN nanowire.

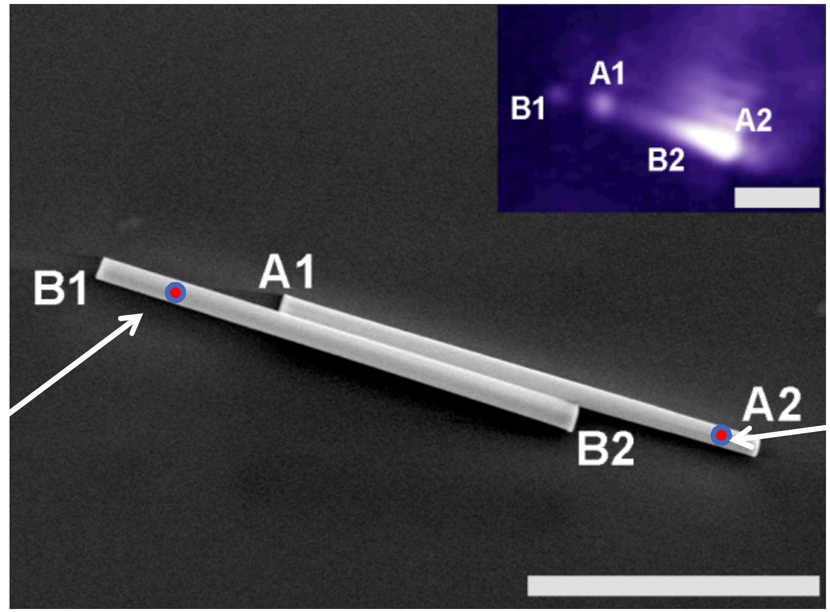
- ✓ Multiple transverse mode waveguide;
- ✓ Single-mode cutoff diameter ~120 nm;
- ✓ Lasing in multiple transverse mode operation

Sandia National Laboratories

Method 1: Mode coupling effect



Light emissio
n



Pumping spot

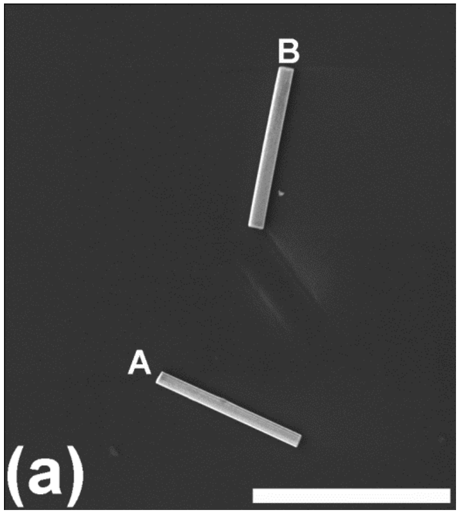
Nanowire mode distribution

Mode coupling between nanowires

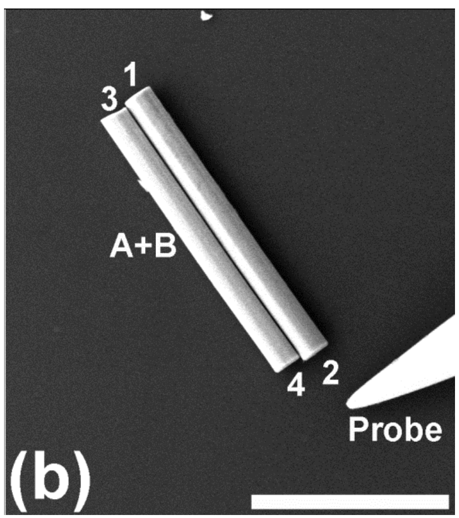
The evanescent field coupling forms two closely spaced nanowires a coupled cavity

Sandia National Laboratories

Vernier Effect From a Coupled Cavity



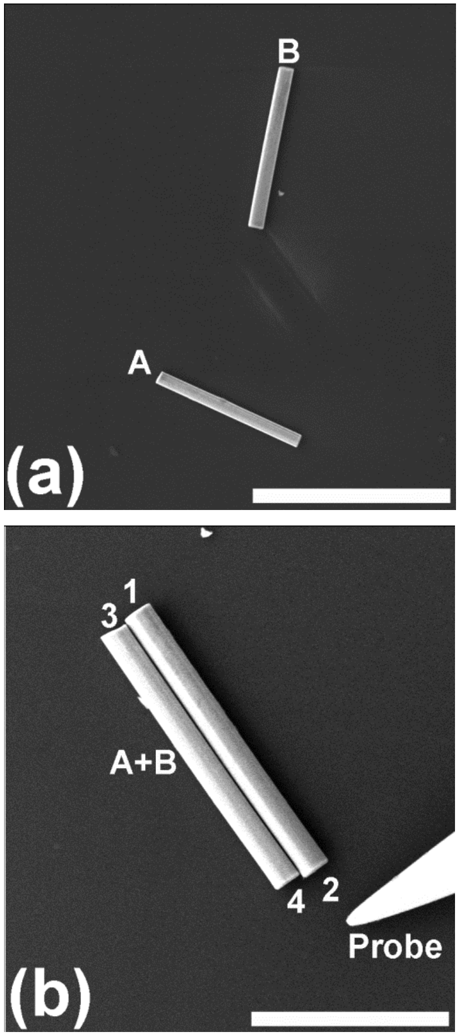
✓ Individual nanowire: individual cavity;

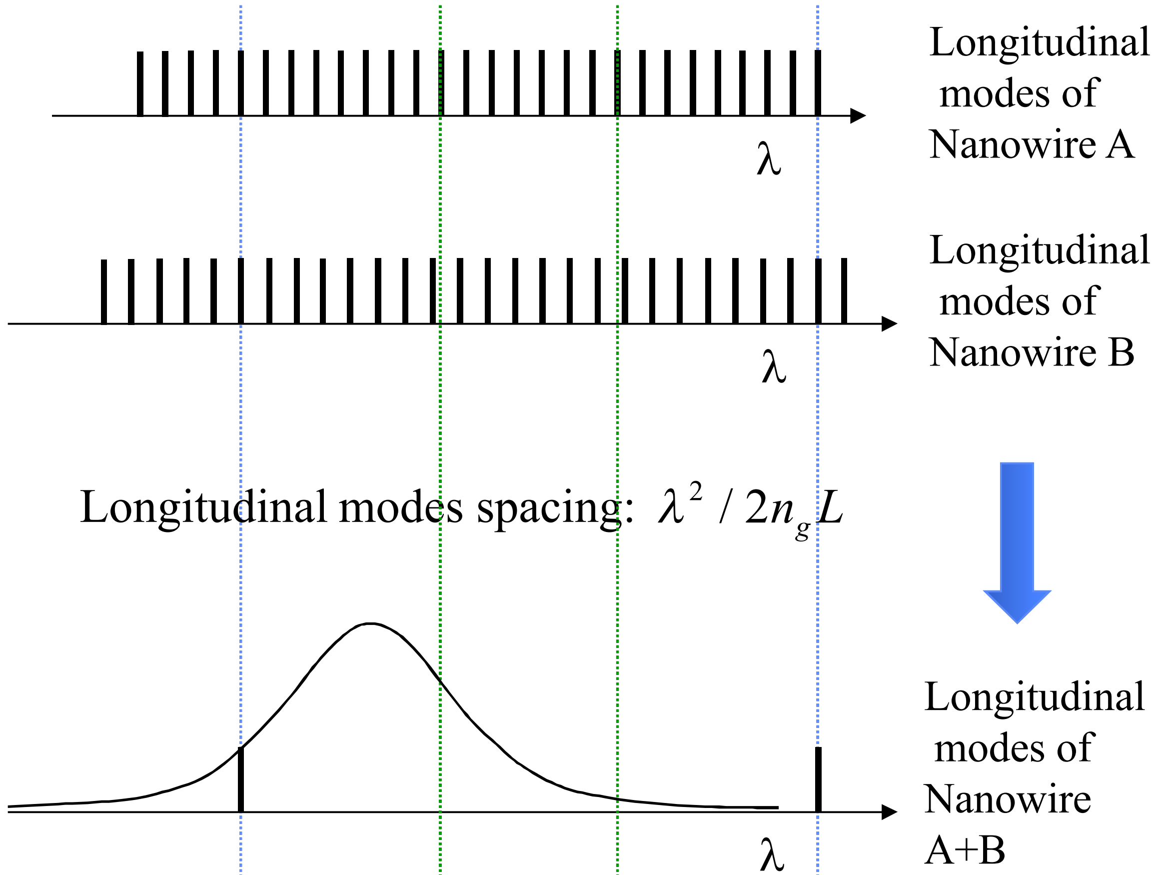


✓ A nanowire pair: coupled cavity;
✓ Four subcavities: 12, 14, 23, 34;
✓ Resonance condition: 4 subcavities resonant simultaneously

Sandia National Laboratories

Vernier Effect From a Coupled Cavity





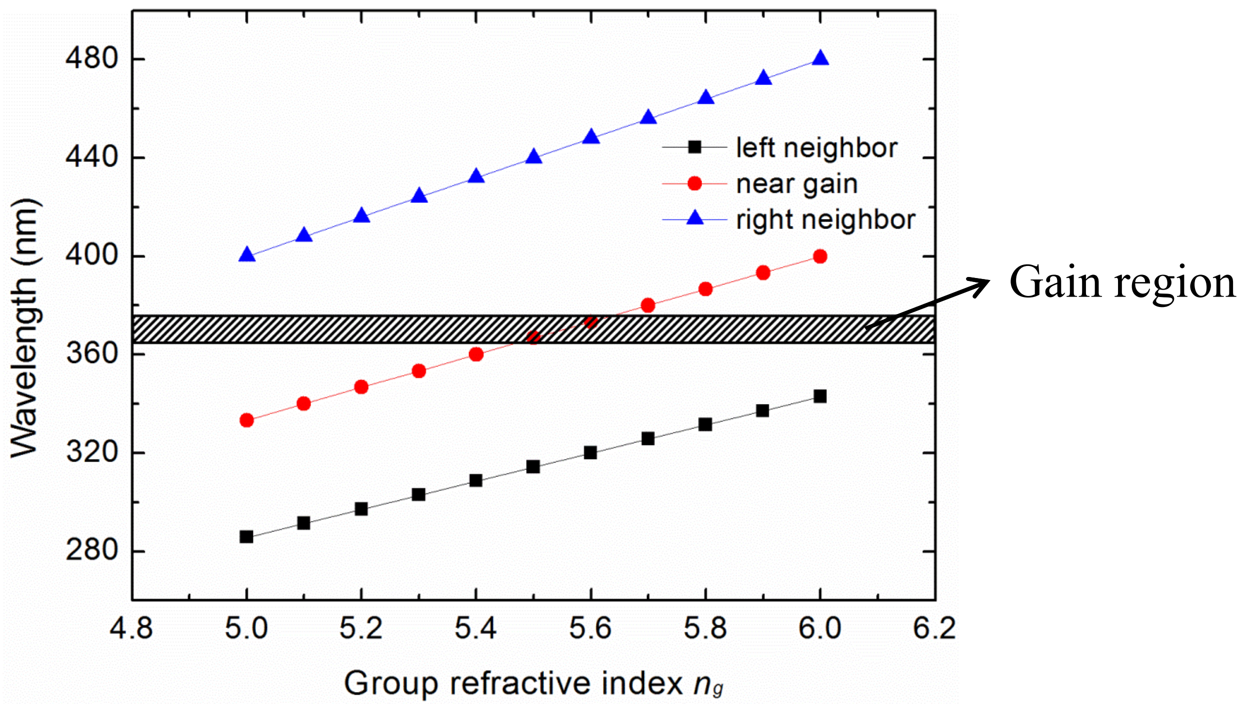
Longitudinal mode spacing greatly enhanced!
(10s of nanometers in this coupled cavity)

Sandia National Laboratories

Transverse mode selection

Mode location calculated by :

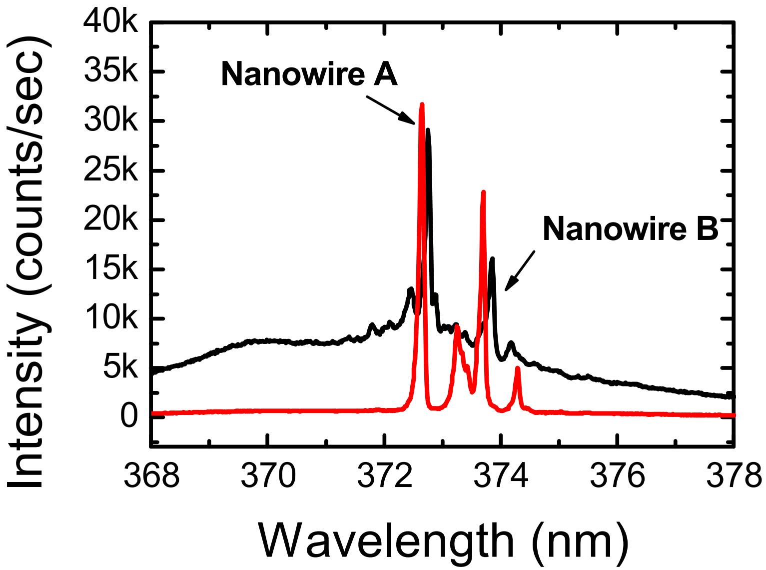
$$T(\lambda) = (1-R)^2 / [(1-R)^2 + 4R\sin^2(2\pi L n_g/\lambda)]$$

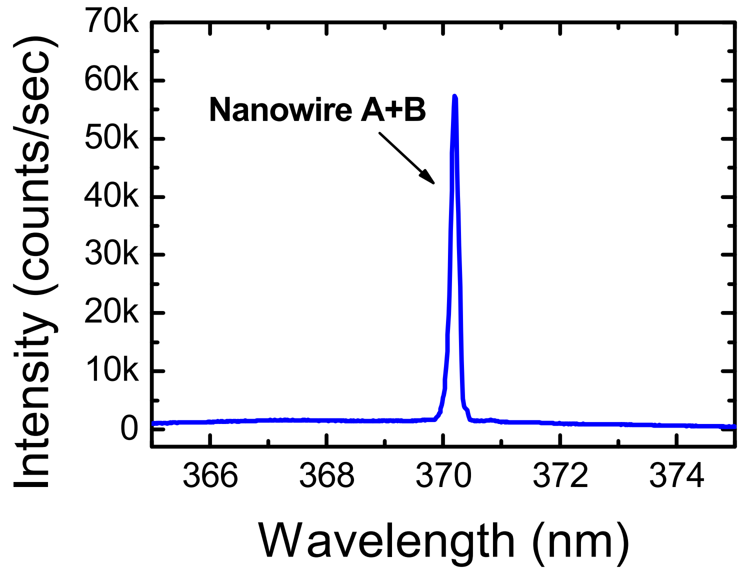


Only transverse mode with n_g within 5.47-5.64 can oscillate in the nanowire-pair!

Sandia National Laboratories

Single-mode Lasing From a Nanowire-pair





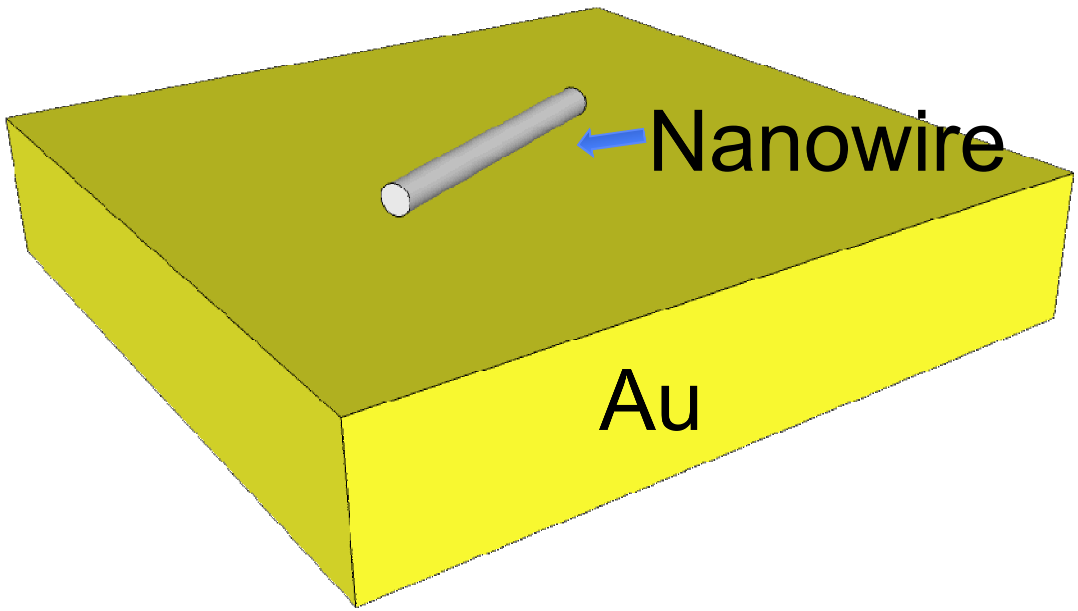
- ✓ Each individual nanowire shows multimode lasing;
- ✓ The nanowire-pair shows single-mode operation;
- ✓ 18 dB side mode suppression ratio (SMSR);
- ✓ 0.12 nm lasing bandwidth;
- ✓ Wavelength shifting;
- ✓ First demonstration of Vernier effect on transverse mode selection

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

Sandia National Laboratories

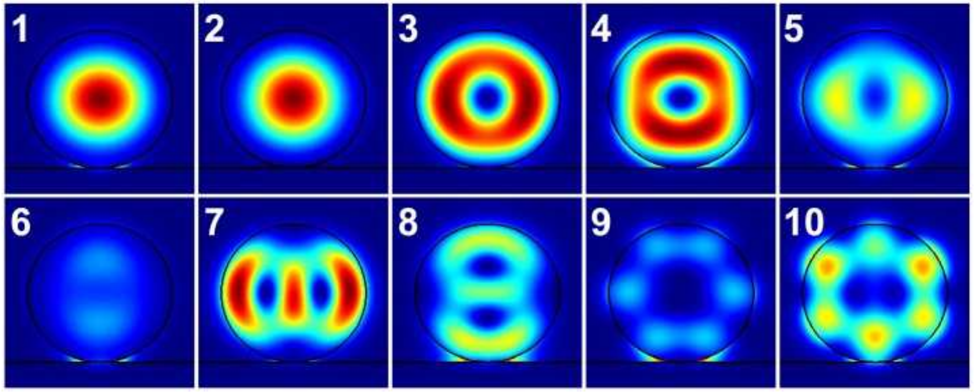
Method 2 : mode-dependent attenuation

What happens when a nanowire is surrounded by a lossy material?



A nanowire on a gold substrate

Substrate Induced Mode-dependent Loss



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

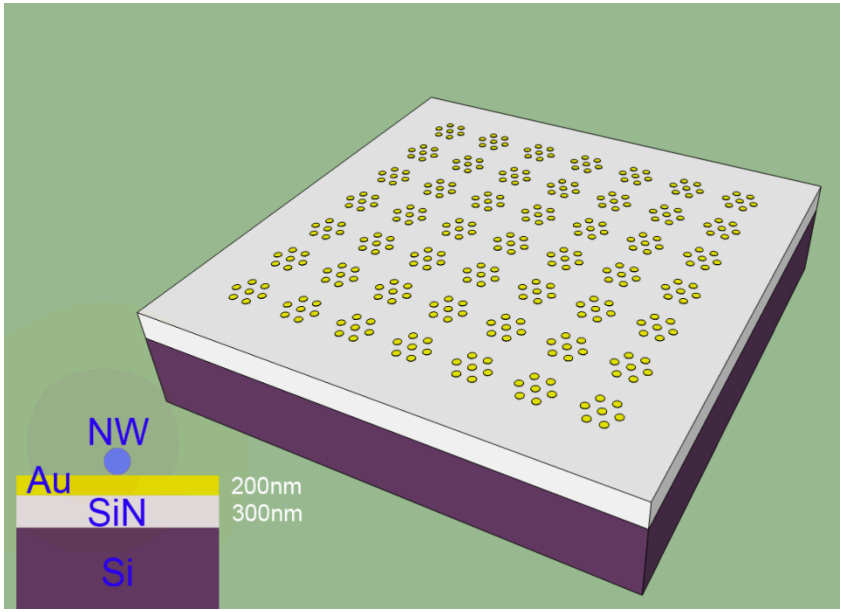
Only surviving mode

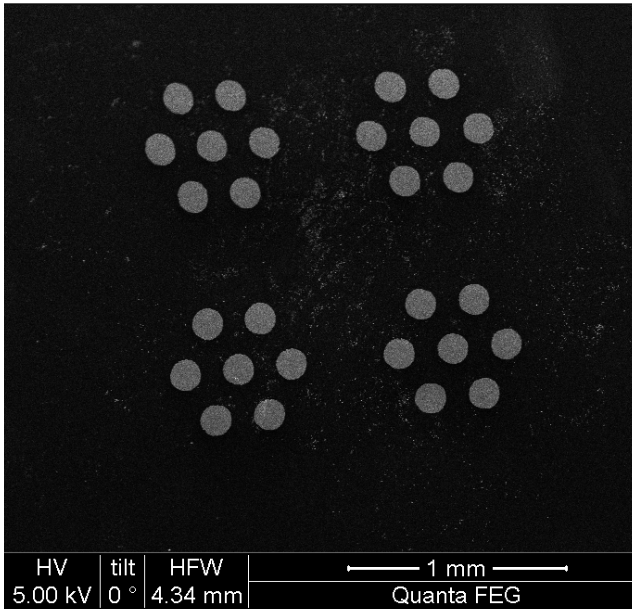
	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Loss (dB/cm)	8151	1730	4806	7109	16041
	Mode 6	Mode 7	Mode 8	Mode 9	Mode 10
Loss (dB/cm)	34858	7551	22205	29175	28706

Propagation loss of different transverse modes.

Metal substrate generates a mode-dependent propagation loss.

Gold substrate preparation





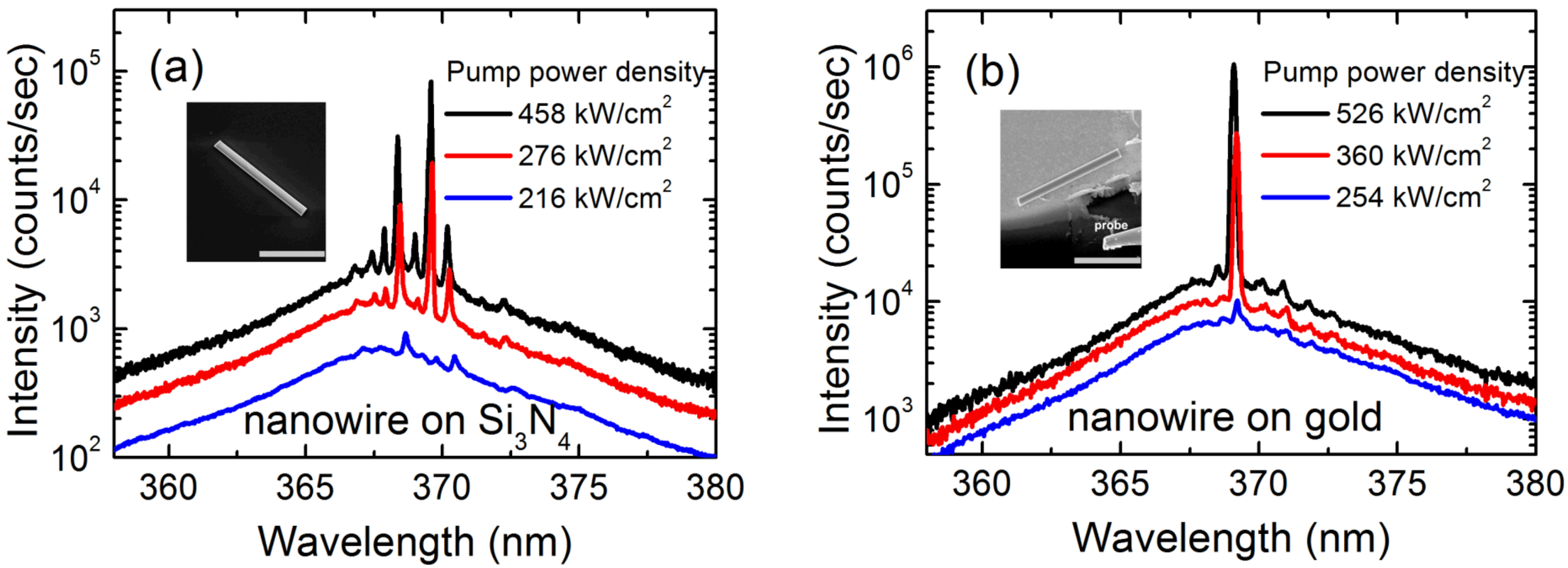
Schematic of the substrate design

SEM image of prepared Au on SiN substrate

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

Sandia National Laboratories

Lasing Behavior Transition from Multimode to Single-mode

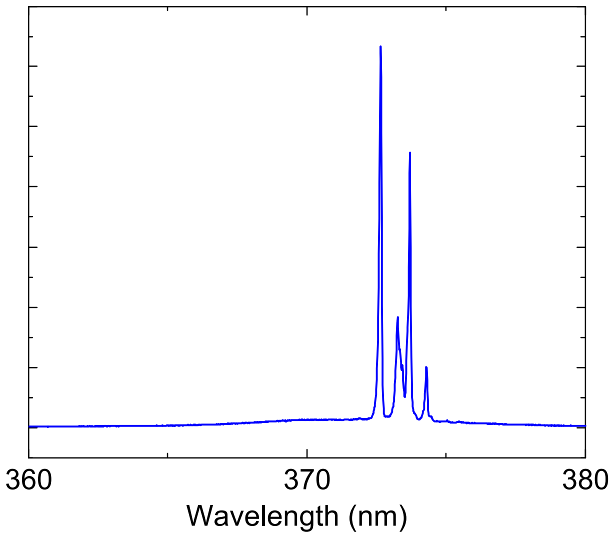


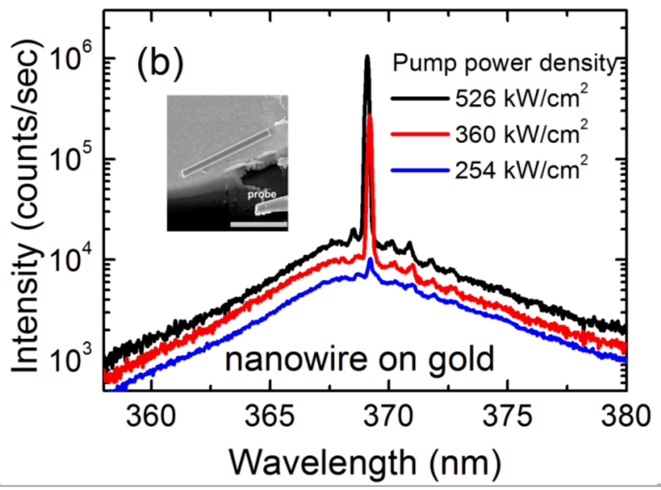
- ✓ Wavelength: 369nm; bandwidth: 0.12nm; SMSR: 17.4 dB;
- ✓ Threshold increased by 13%;
- ✓ Offering guidance to metal contacted nanowire lasing (electrically-injected)

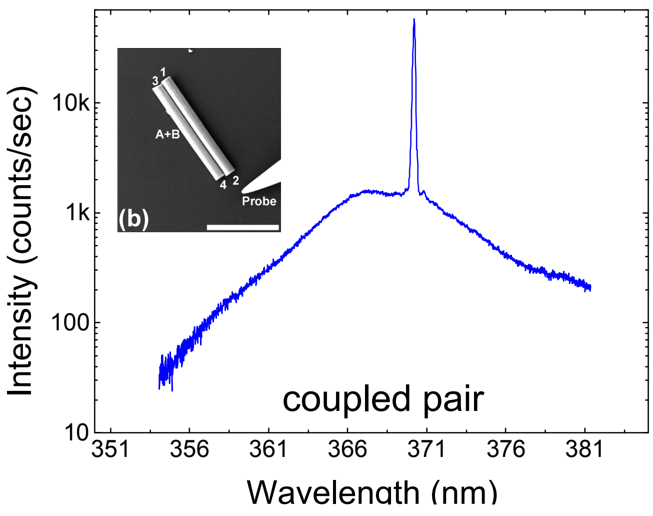
H. Xu, et al. Appl. Phys. Lett. 101, 221114 (2012)

Summary

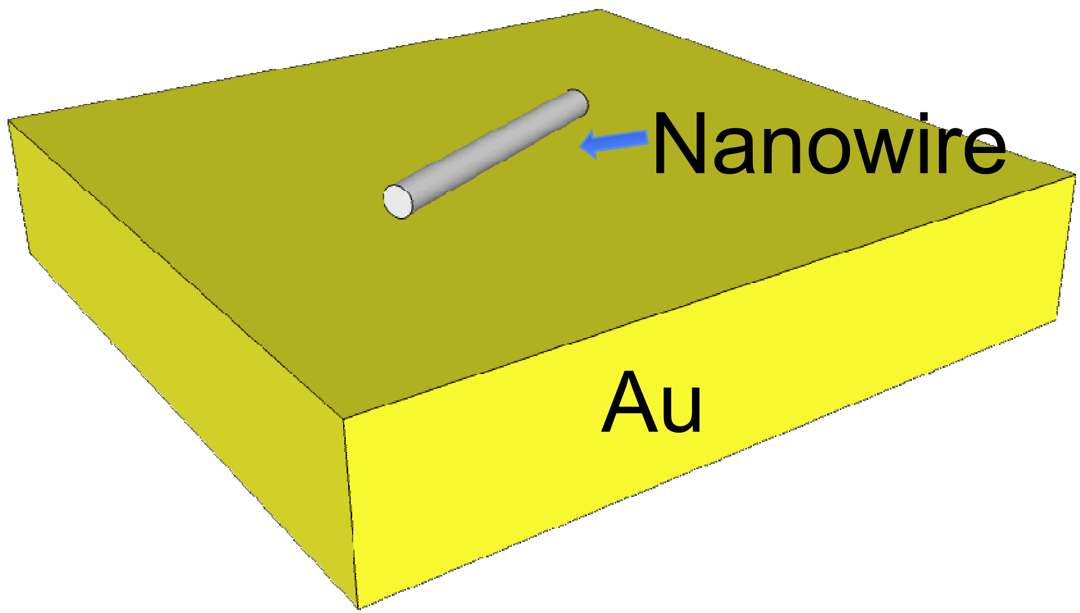
- Typical GaN nanowire lasers operate in multi-mode state
  - Single-mode is highly desirable in many applications
- Nanowire-pair and nanowire-gold geometries are proposed for high performance: >14dB SMSR, bandwidth ~0.12nm single-mode lasing





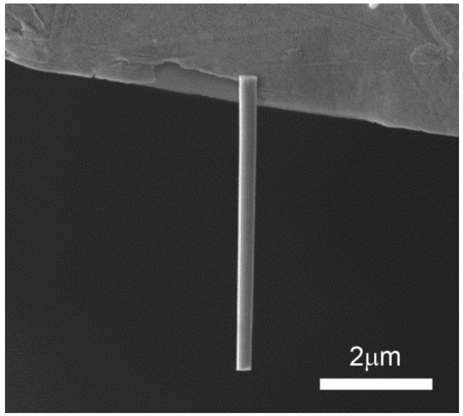


Polarization Control by Metal Substrate



Does the loss generated by the metal substrate help to select a polarization?

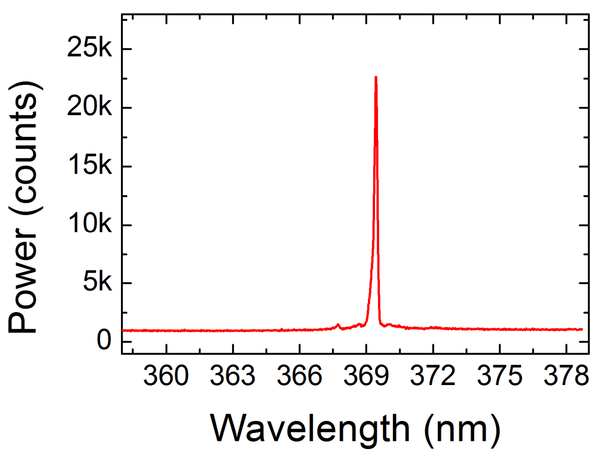
Lasing Properties of a Free Standing GaN Nanowire



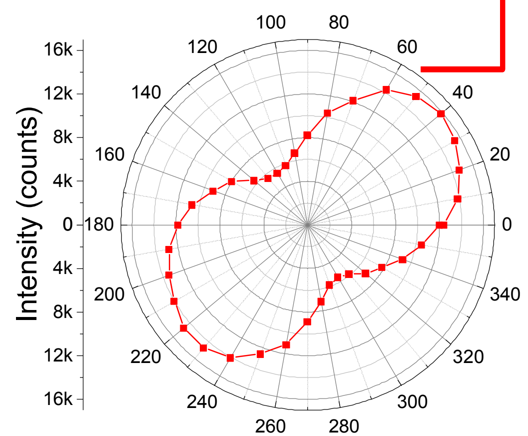
SEM image of a nanowire

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

CCD image



Lasing spectrum

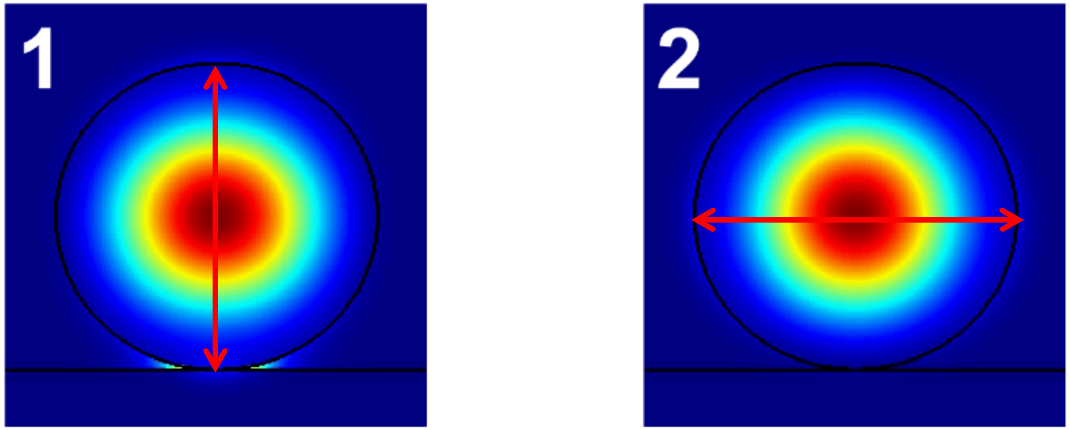


Indicative of elliptical polarization

Intensity V. S. the rotation of the polarizer

Sandia National Laboratories

Why elliptically polarized?

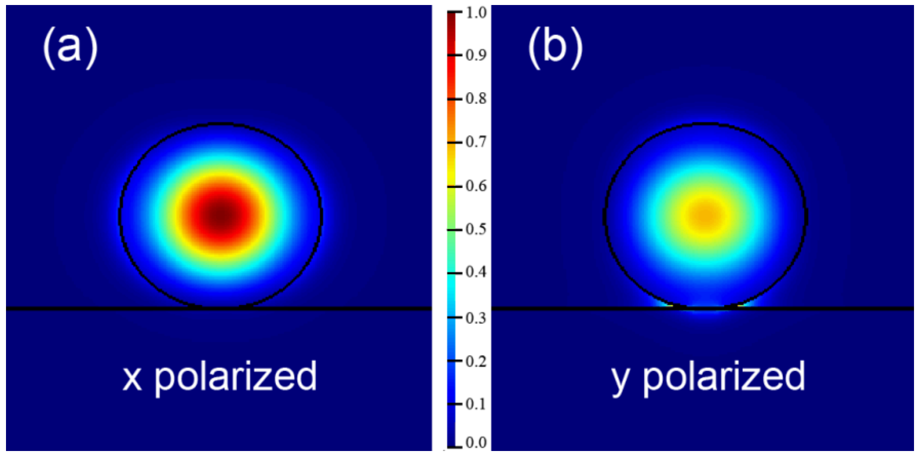


Two orthogonal polarized fundamental modes supported by a 200 nm diameter nanowire

- ✓ Both fundamental transverse modes
- ✓ Similar mode distribution
- ✓ Same lasing wavelength
- ✓ Two modes add together forming a elliptical polarization

Sandia National Laboratories

Why Polarization Control Happens?

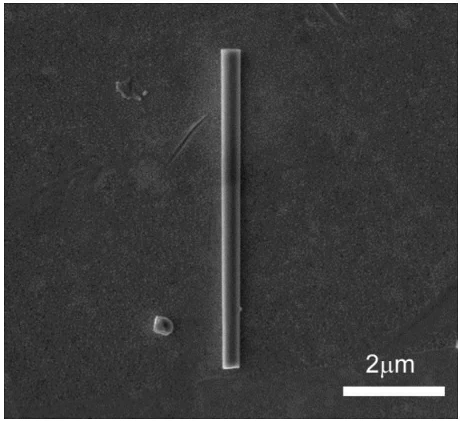


Fundamental modes supported by the nanowire-gold geometry

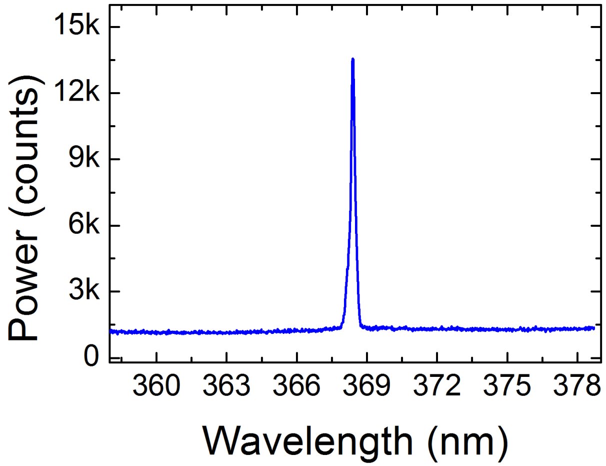
- ✓ Differently polarized modes experience different cavity losses
- ✓ Loss for x-polarized mode: 0.36 dB/mm
- ✓ Loss for x-polarized mode: 2.11 dB/mm

Sandia National Laboratories

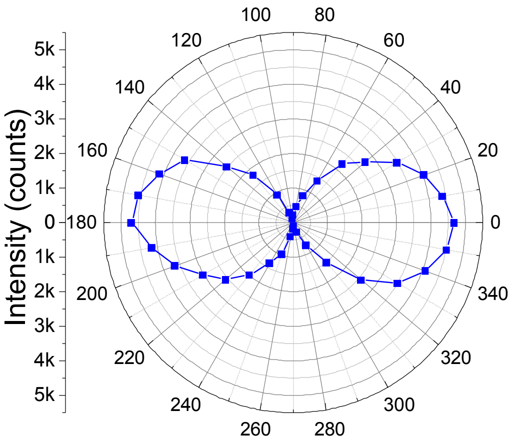
Lasing Properties of a Nanowire on Gold Substrate



nanowire on gold



Lasing spectrum

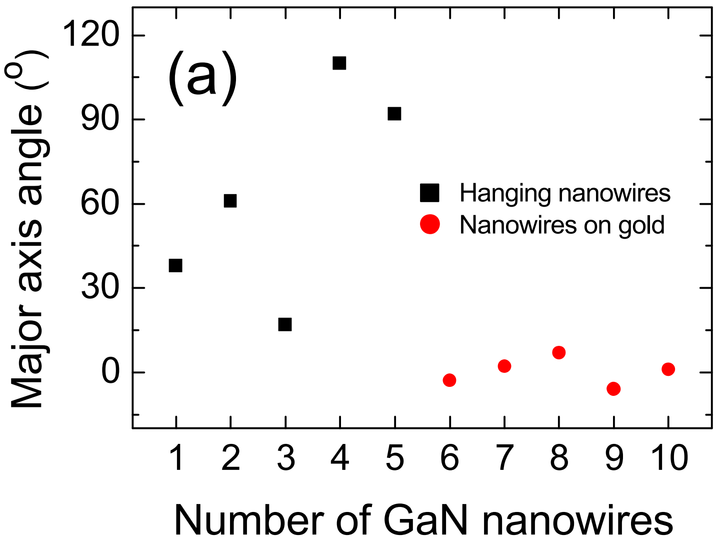


Intensity V. S. the rotation of the polarizer

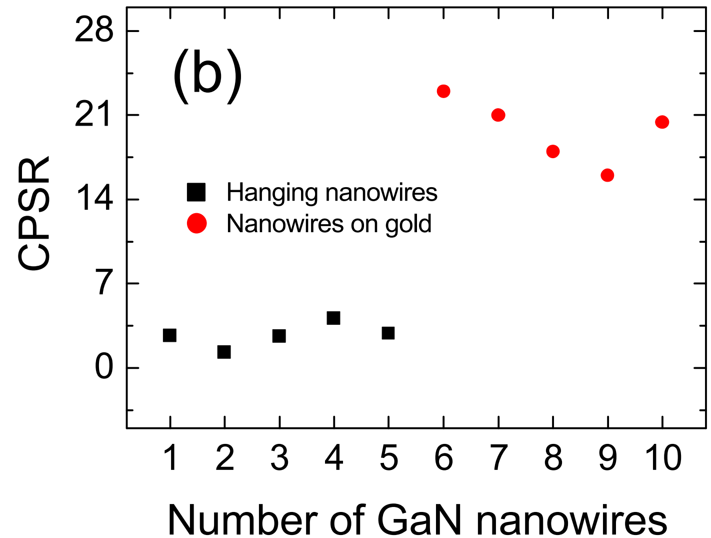
- ✓ Single-wavelength lasing
- ✓ Linear polarization
- ✓ Large extinction ratio (21:1)
- ✓ 0^{o} polarization angle

Sandia National Laboratories

Lasing Property Statistics of Free Standing and On-gold Nanowires



Statistics on the polarization axis



Statistics on cross-polarization suppression ratio(CPSR)

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

Sandia National Laboratories

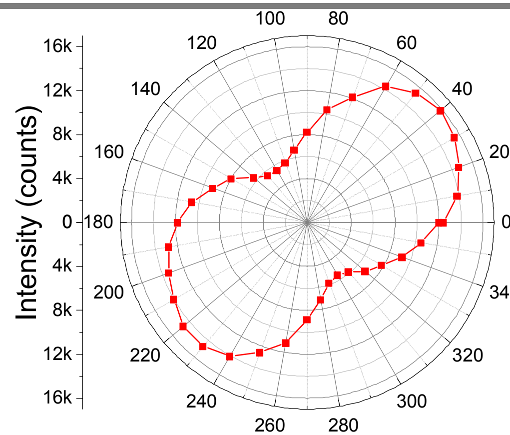
Summary

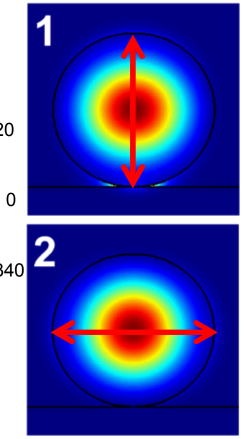
- A free-standing GaN nanowire laser is typically elliptically polarized with random orientation

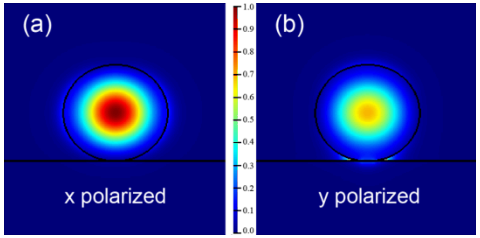
- The elliptical polarization originates from the mode degeneracy of the nanowire

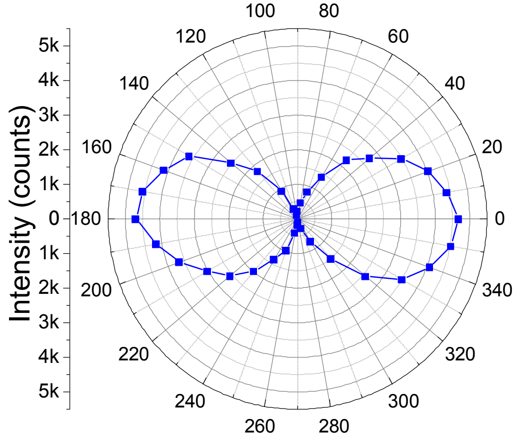
- A on-gold nanowire generates a larger cavity loss for the perpendicularly polarized mode

- Linear polarization is achieved with a fixed polarization parallel to the substrate









Thank you!

POSTER: