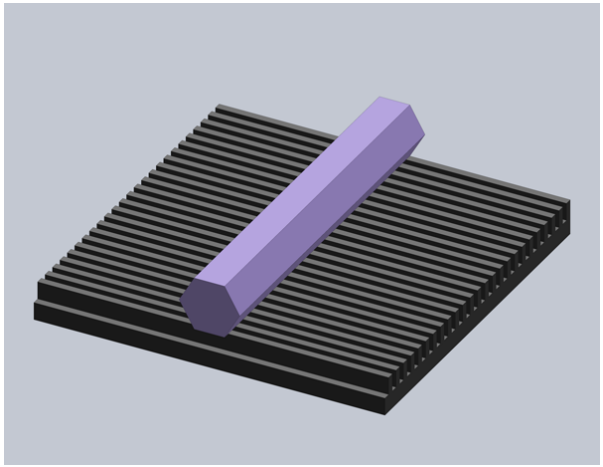
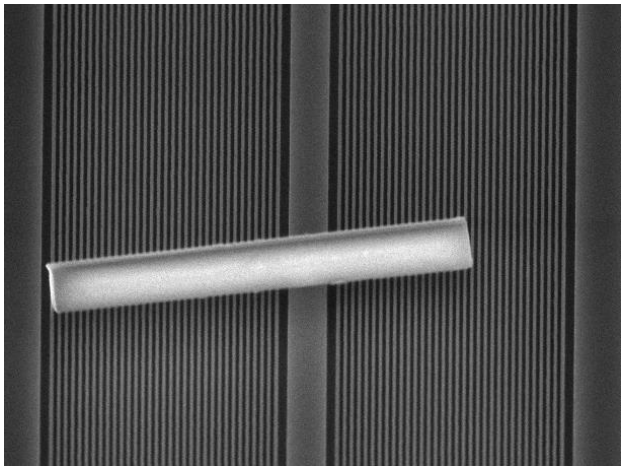
Gallium Nitride Nanowire Distributed Feedback Lasers

SAND2014-4849C

Jeremy B. Wright, Salvatore Campione, Sheng Liu, Julio A. Martinez, Huiwen Xu, Ting S. Luk, Qiming Li, George T. Wang, Brian S. Swartzentruber, Luke F. Lester, and Igal Brener



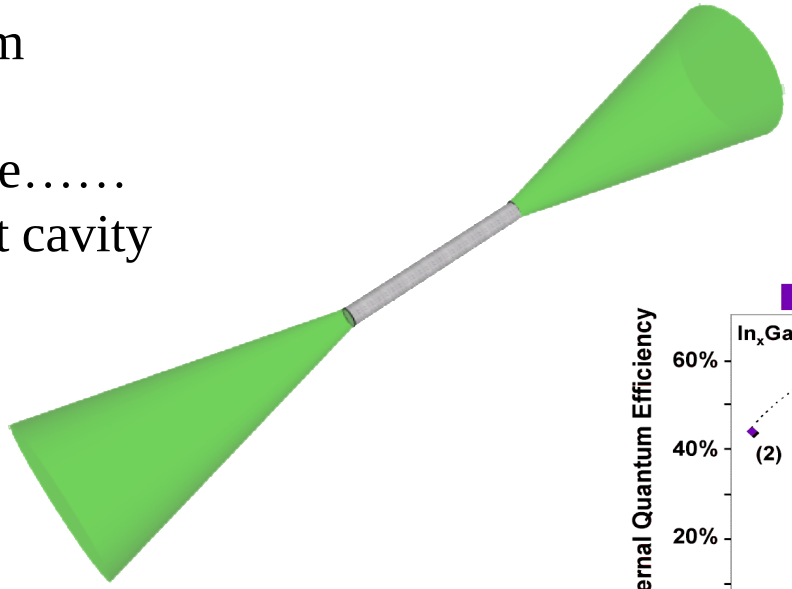


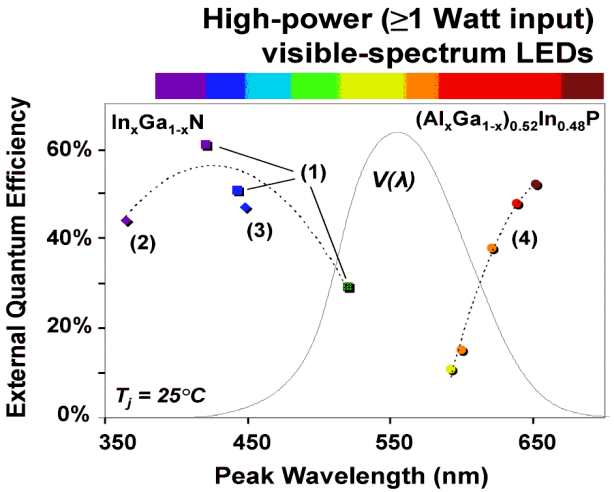
This work was supported by Sandia's Solid-State Lighting Science Energy Frontier Research Center, sponsored by the Department of Energy Office of Science. This work was performed, in part, at the Center for Integrated Nanotechnologies, a U.S. Department of Energy, Office of Basic Energy Sciences user 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 | CINT | THE UNIVERSITY of NEW MEXICO | Sandia National Laboratories

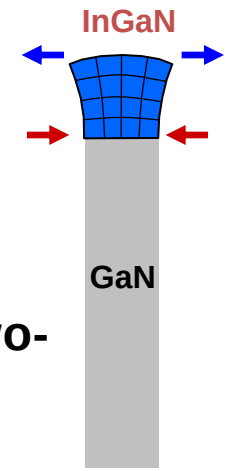
Nanowire lasers

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

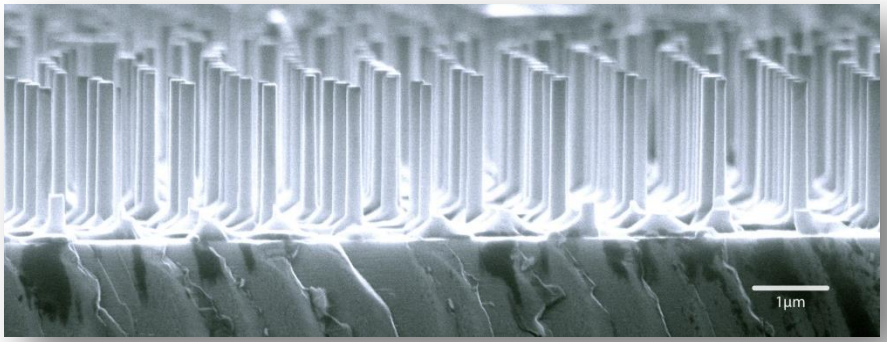




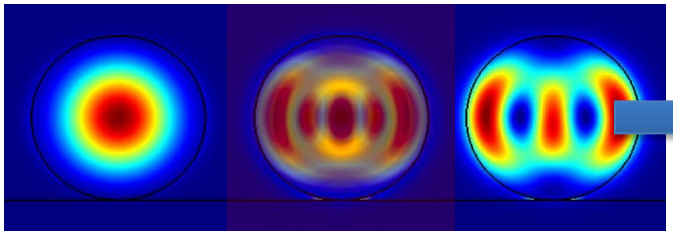
M. Krames, Philips Lumileds



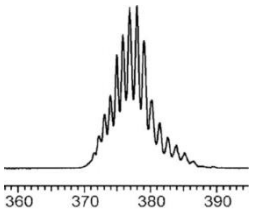
- **Reduced strain**
  - **Greater range of alloy compositions**
- **Easily integrated into two-dimensional arrays**



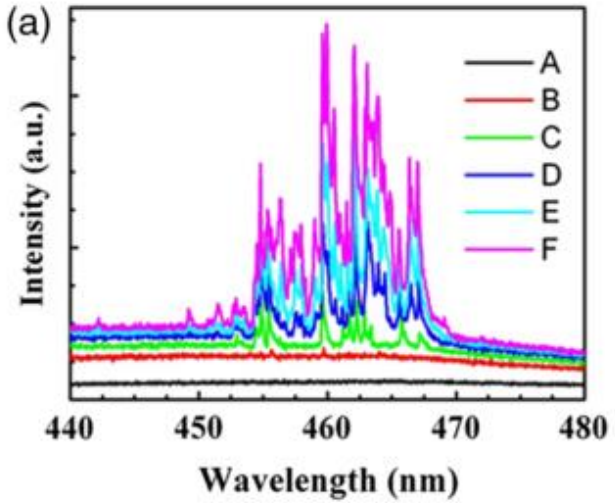
Motivation | Why single-mode nanowire lasers?



Multiple transverse modes

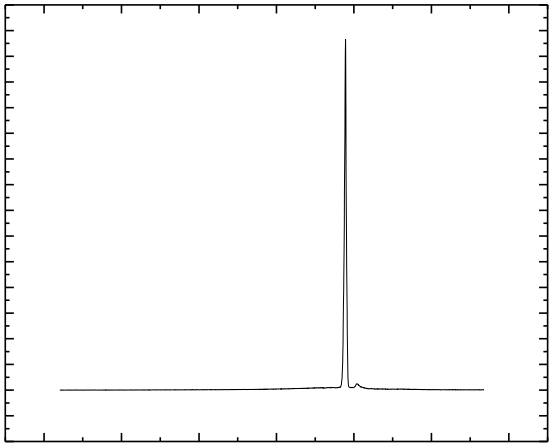


Multiple longitudinal modes



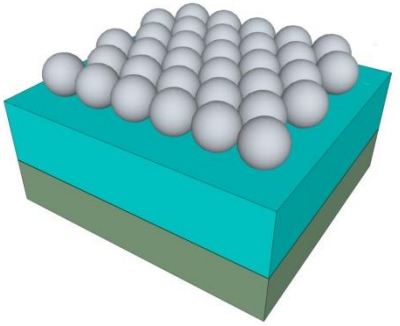
Single-Mode Lasing
(Transverse and Longitudinal)

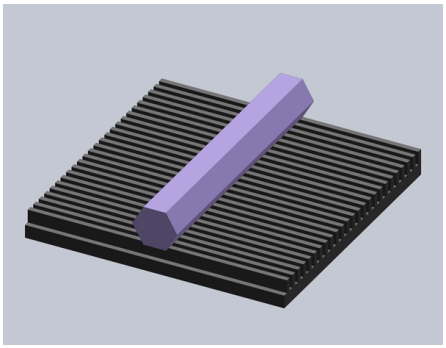
High Beam Quality + Single Frequency Operation

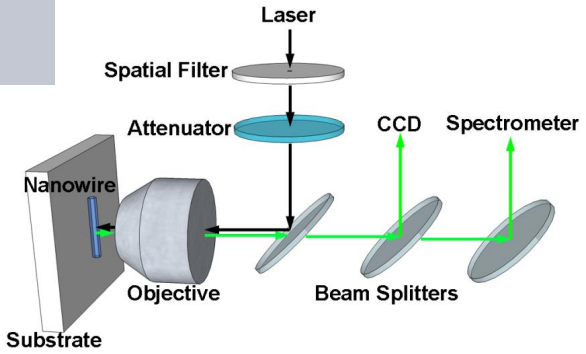


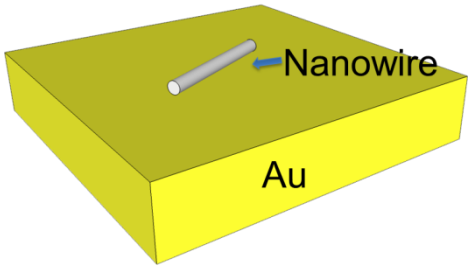
Outline

- Top-Down two-step nanowire fabrication
- Single Nanowire with Distributed Feedback – Modeling and Simulation
- Characterization and results
  - Grating Substrate
  - Lossy Substrate



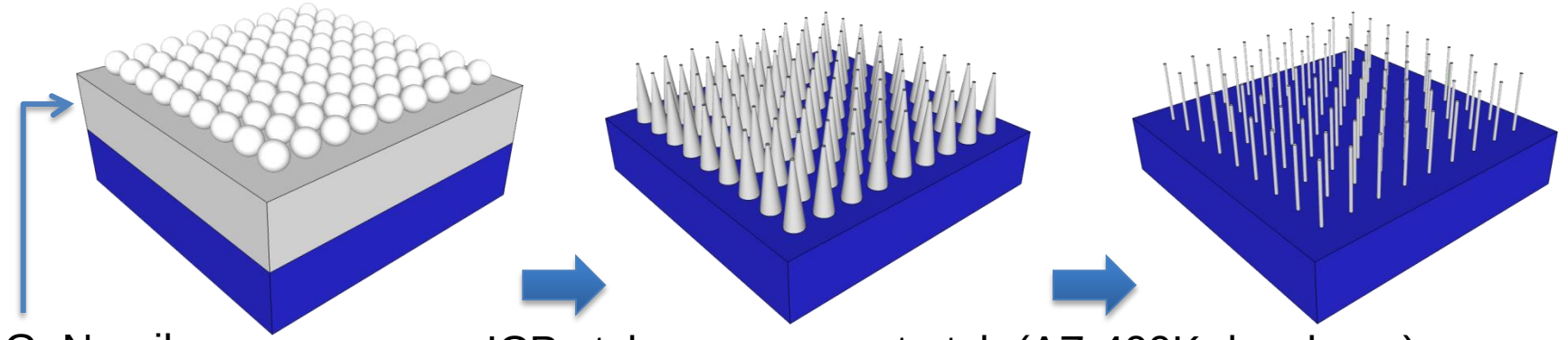


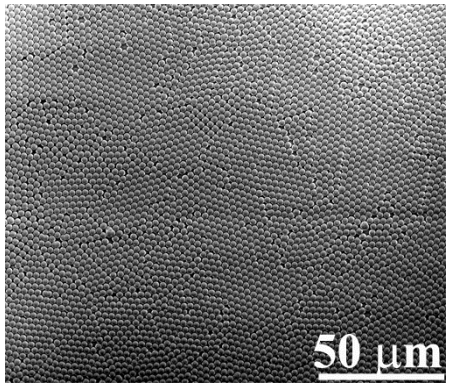


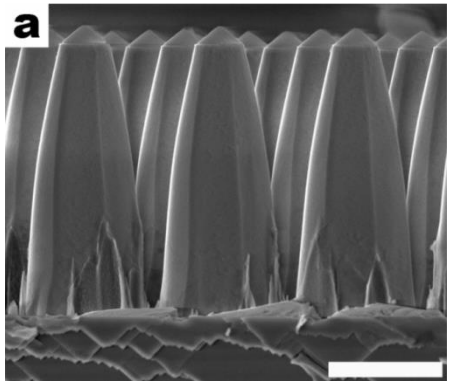


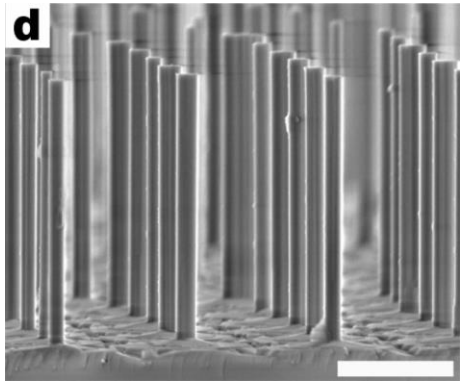
Top-down Nanowire Fabrication Technique

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





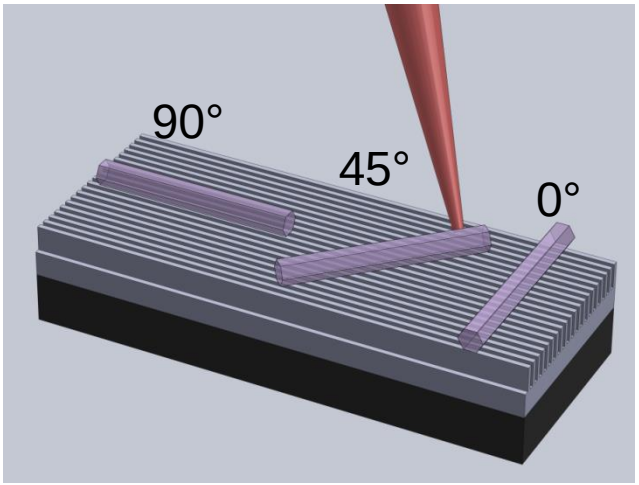




Q. Li, et al. *Opt. Express* 20.16 (2012)
Q. Li, et al. *Opt. express* 19.25 (2011):

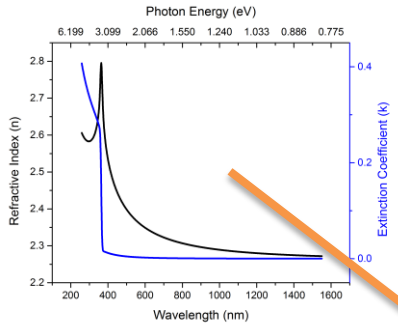
Single nanowire with distributed feedback

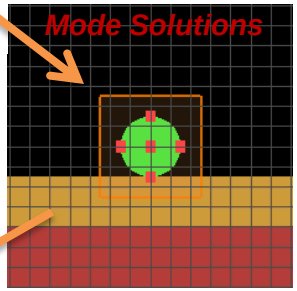
- **Single nanowires are coupled to a silicon nitride grating substrate to achieve distributed feedback**
- **Stop-band tuned via nanomanipulation of the angular alignment**
- **Modeling using mode solver and TMM**

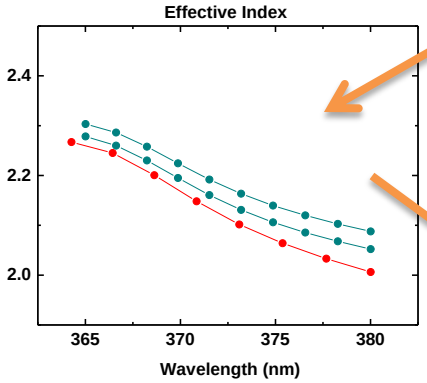


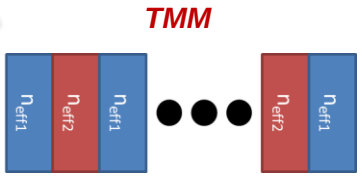
Model Development of DFB Nanowire

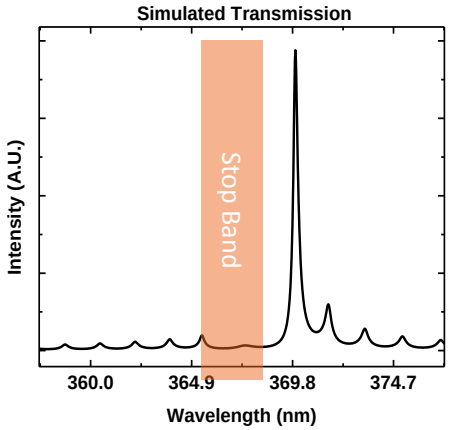
1. **Ellipsometry**
   1. retrieve optical constants
2. **Mode solutions**
   1. effective indices
3. **Transfer Matrix Method (TMM)**
   1. Stop band vs angle





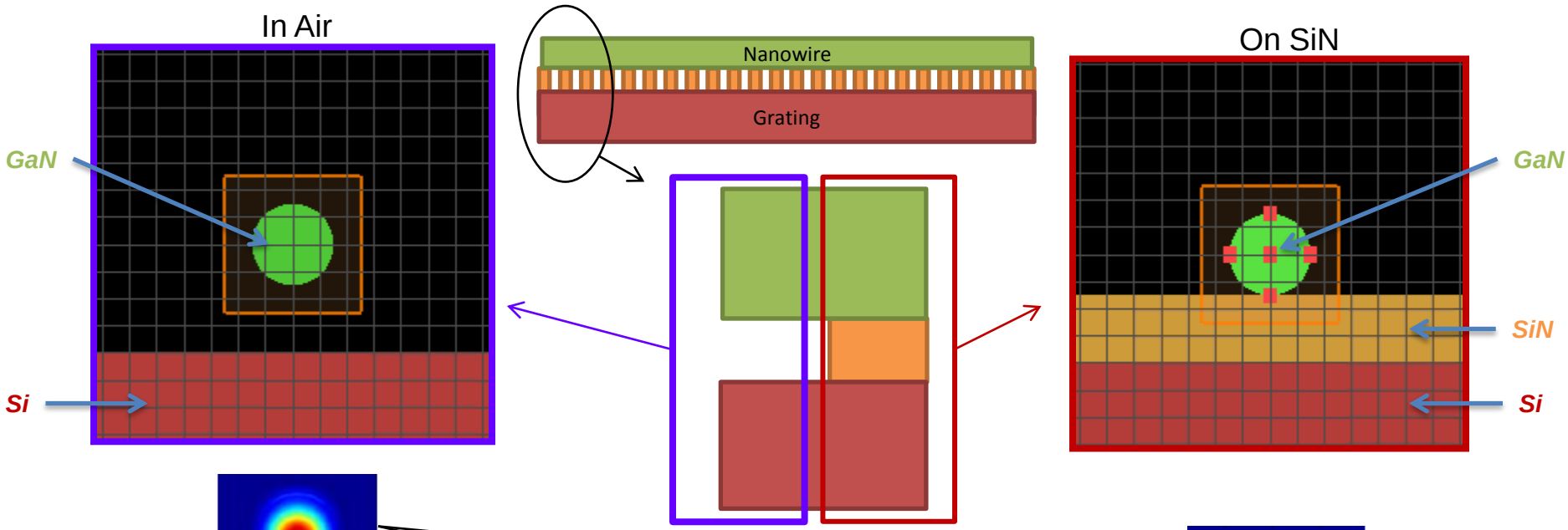


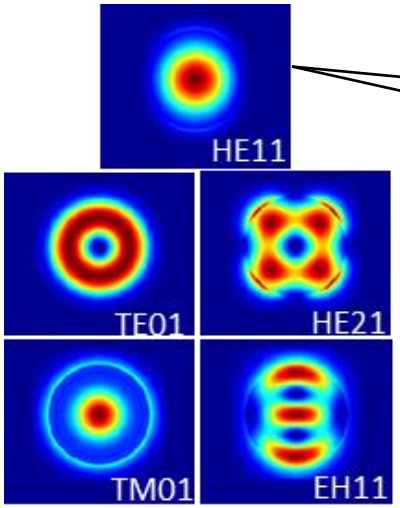


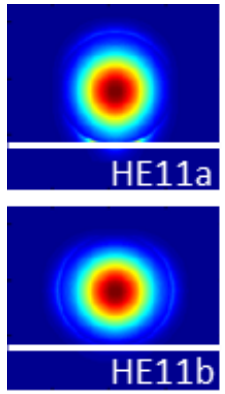


Sandia National Laboratories

DFB Nanowire Simulations – Mode Theory



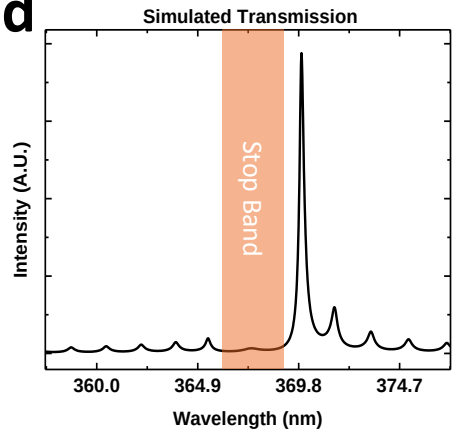


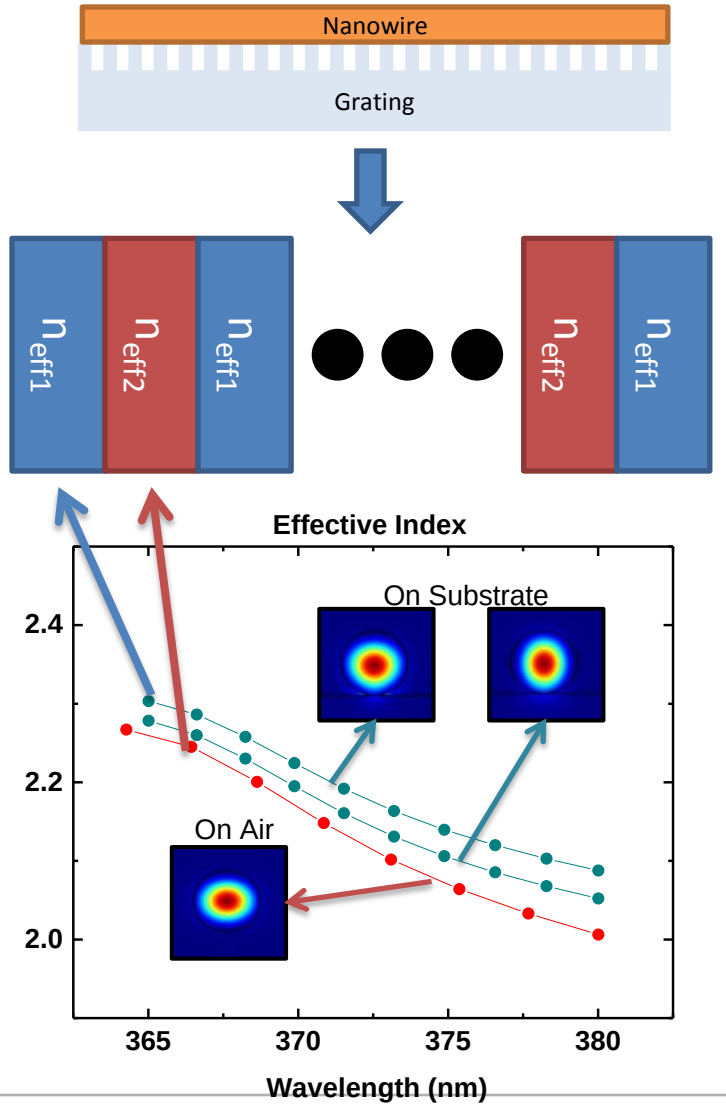


- The higher order modes are suppressed by the SiN layer
- The addition of the SiN in contact breaks the degeneracy of HE11

Distributed feedback transfer matrix method

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



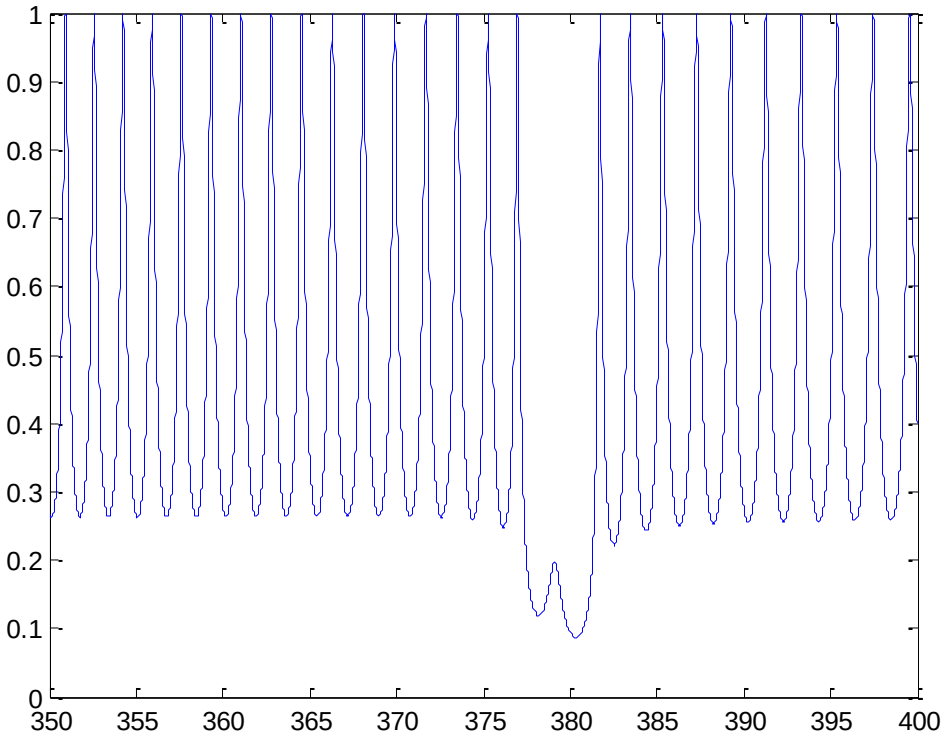


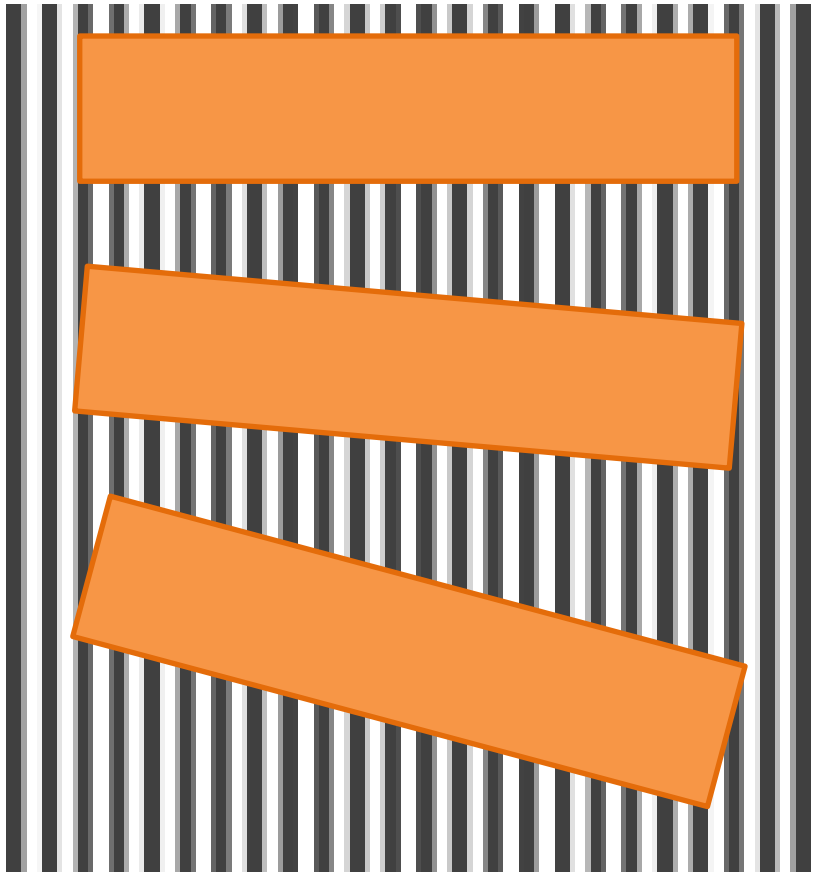
- **The coupled system is treated as a stack of dielectric layers**
- **The index of each layer is extracted from the modal model**

Stop-band vs. Alignment Angle

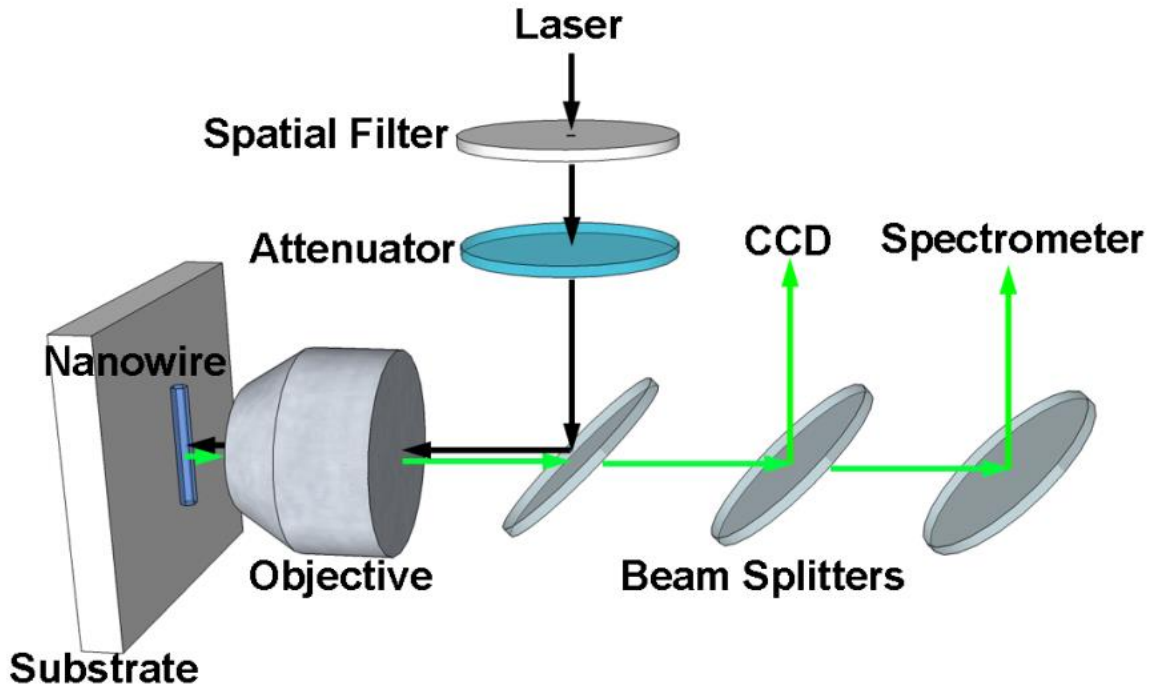
The alignment angle is varied in the model by changing the layer thicknesses.

0° ➡ 5° ➡ 15°





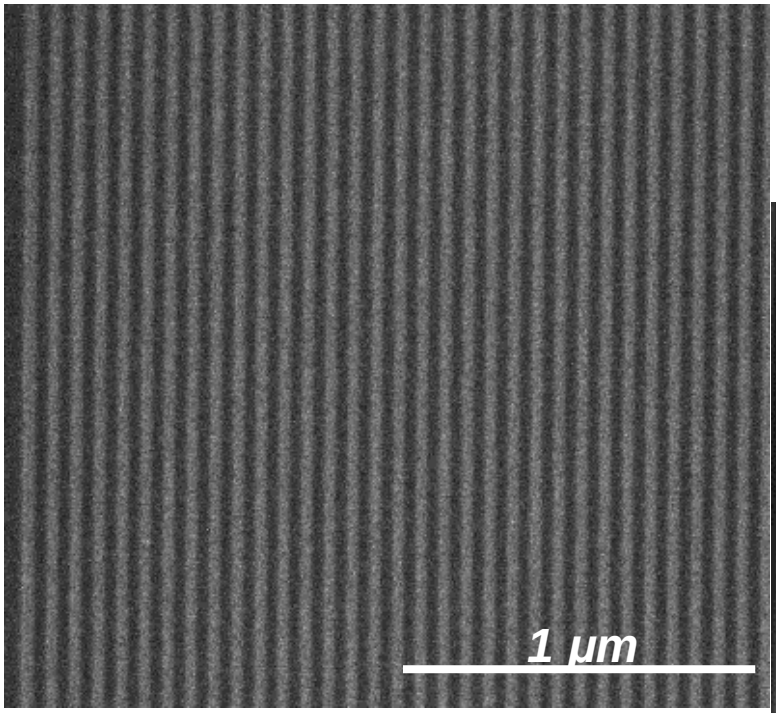
Nanowire Optical Characterization



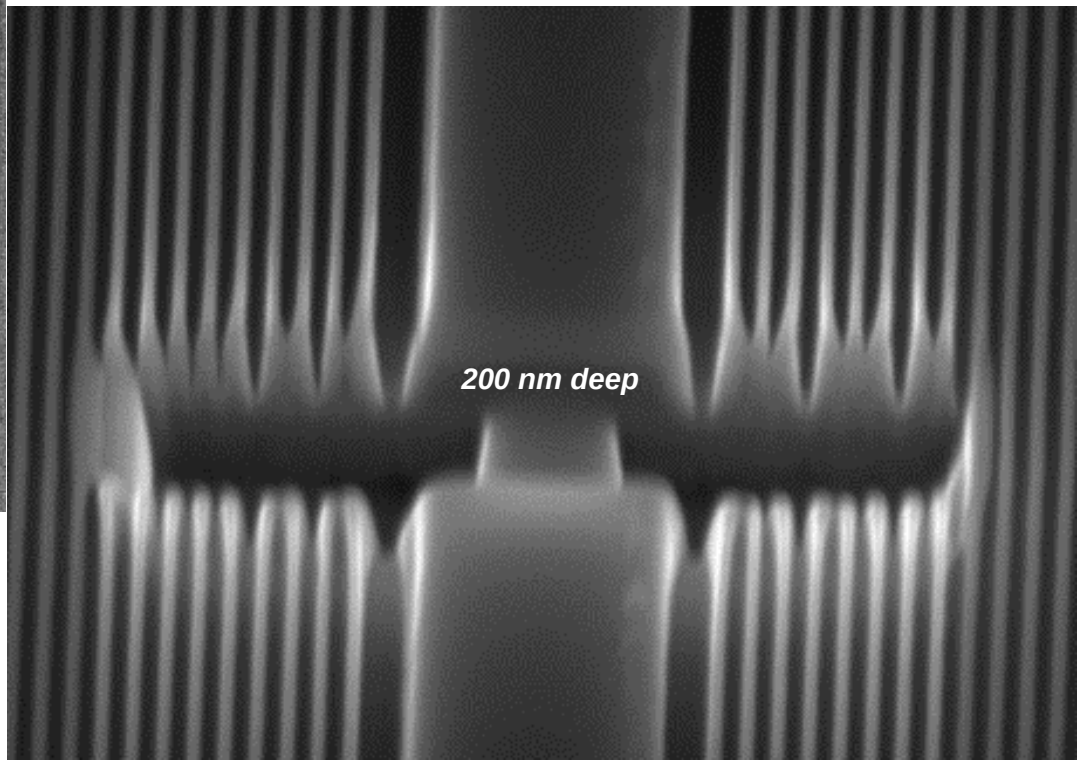
- ✓ Pump: pulsed quadrupled Nd:YAG laser
- ✓ 266nm, 400ps, 10kHz, 5.2mW
- ✓ Spot size: 1~5 μm
- ✓ Room temperature operation

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

Silicon Nitride Grating Substrate



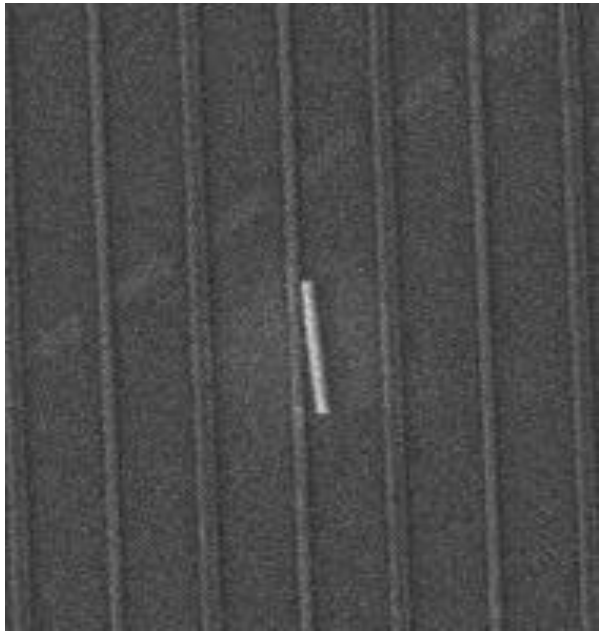
FIB Cross Section

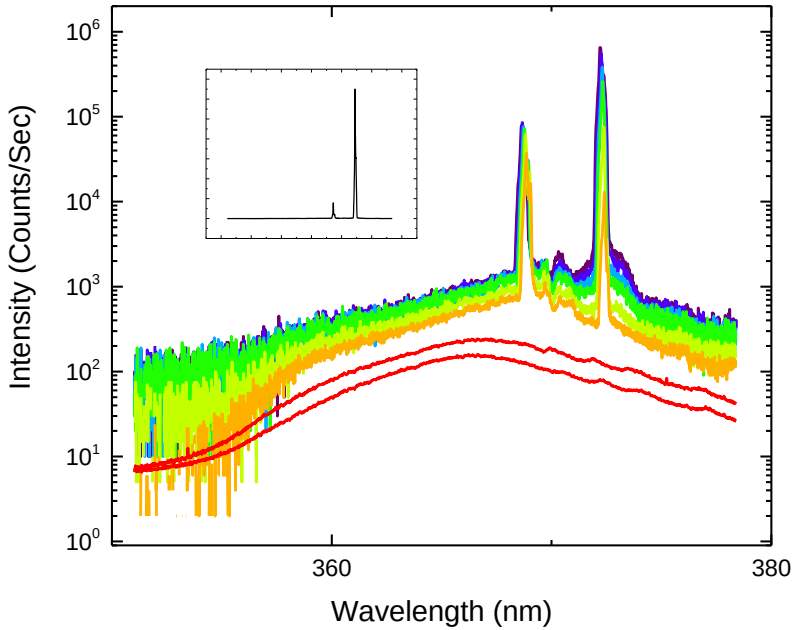


90nm period
~50% duty cycle

Out of Alignment – Multimode Operation

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

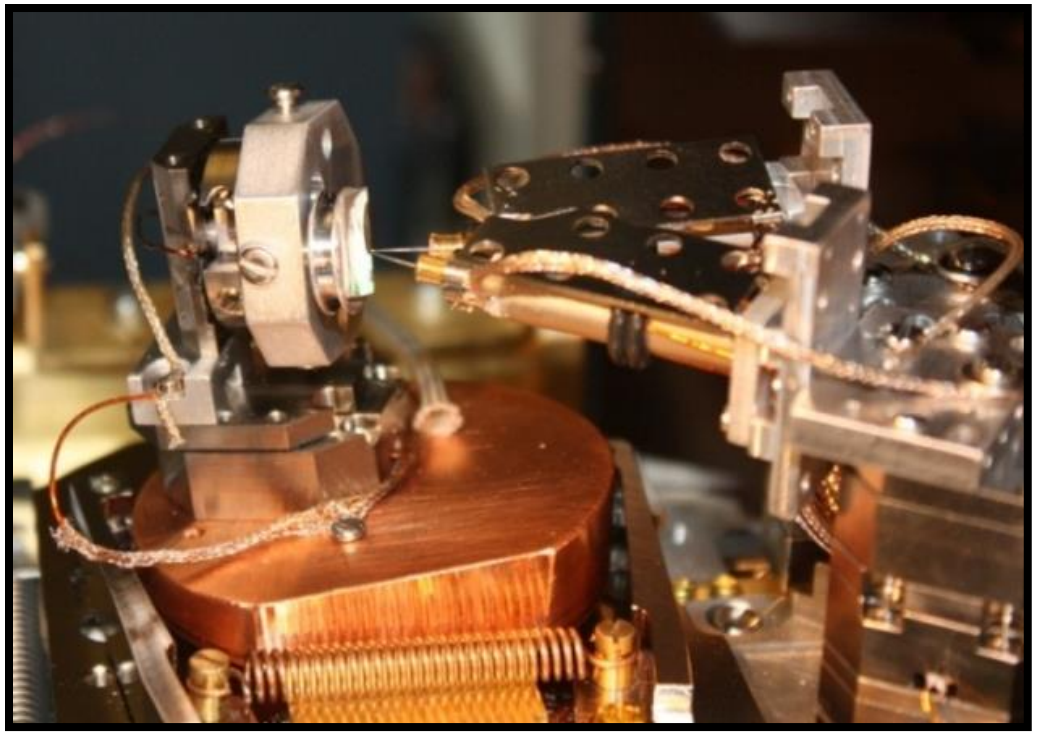


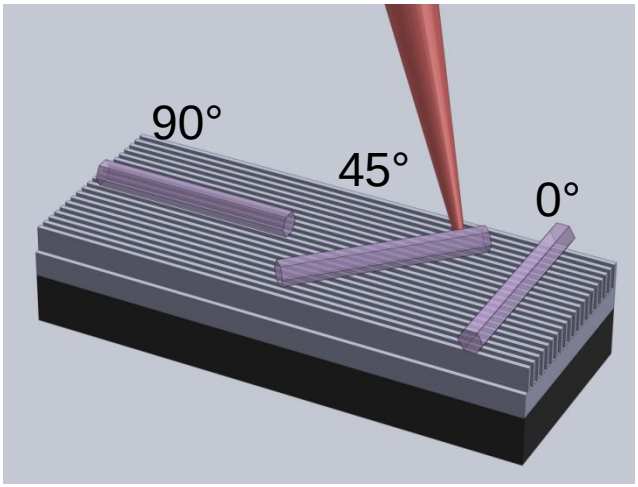


5dB Mode Suppression Ratio

SEM Manipulator Tool

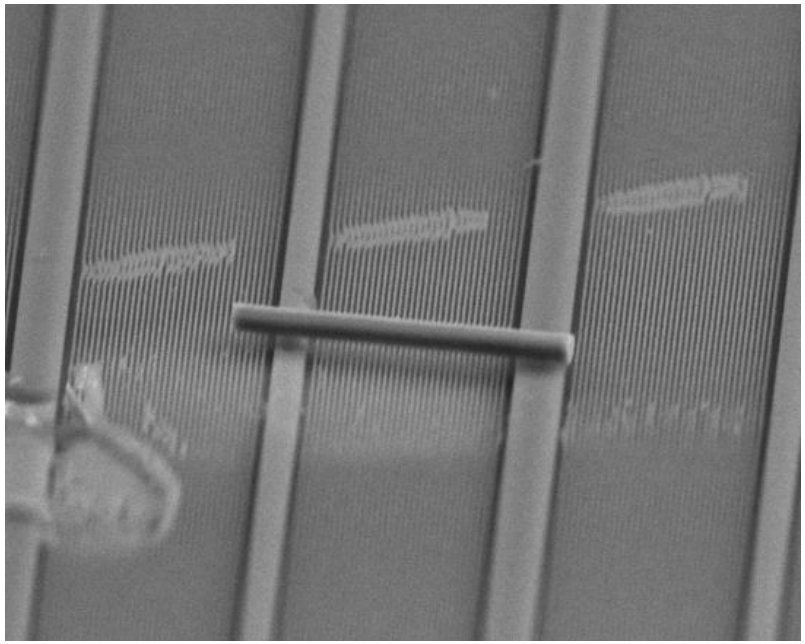
- Inside of an SEM
- Two piezo actuated 3-axis stages
- Two probes used simultaneously

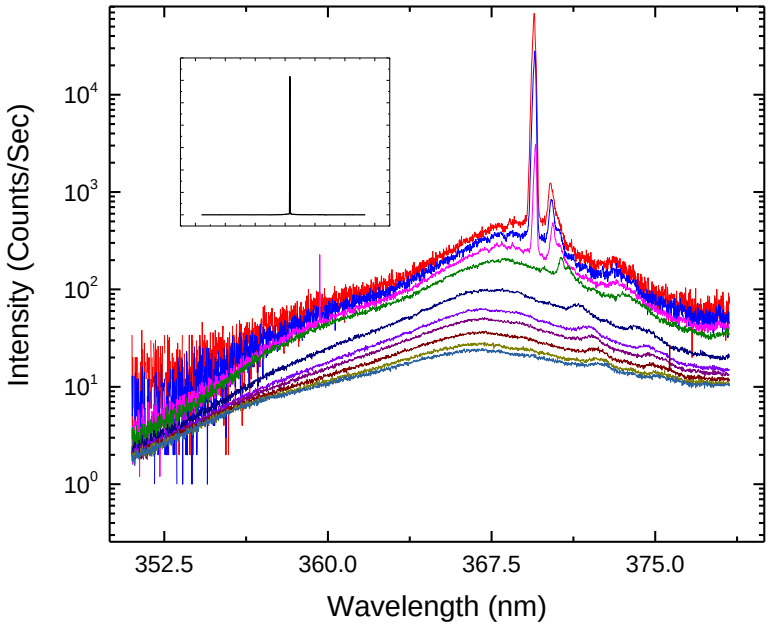




Single-mode Operation

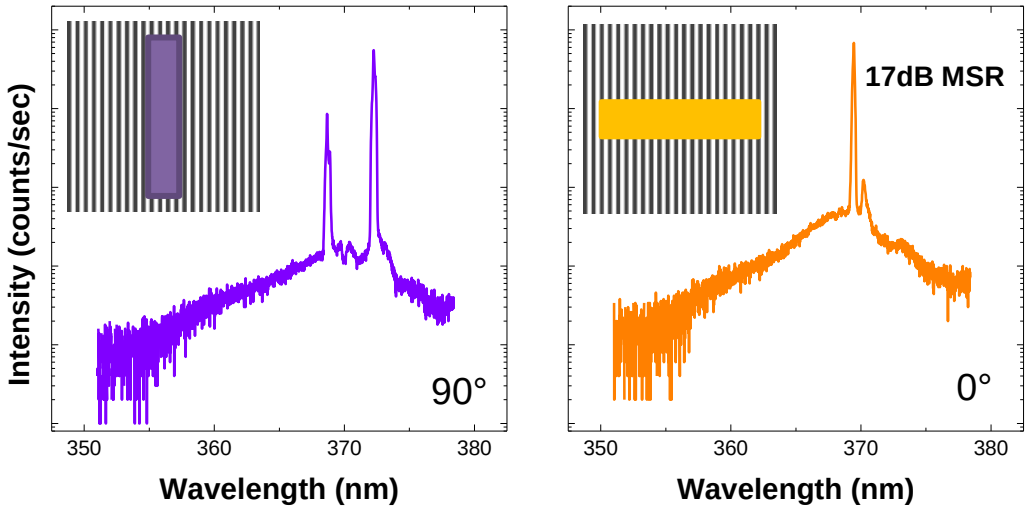
- **After Rotation – the nanowire is rotated so that the designed periodicity of the grating is used.**

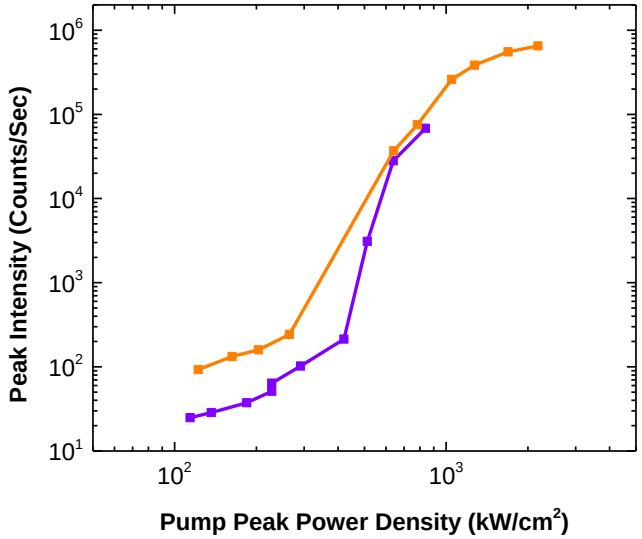


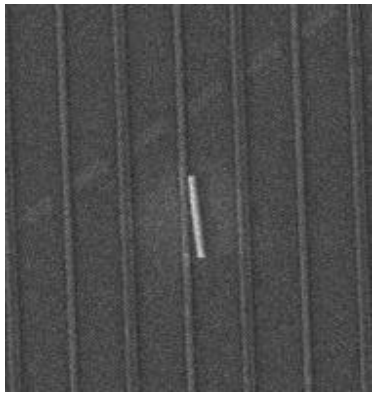


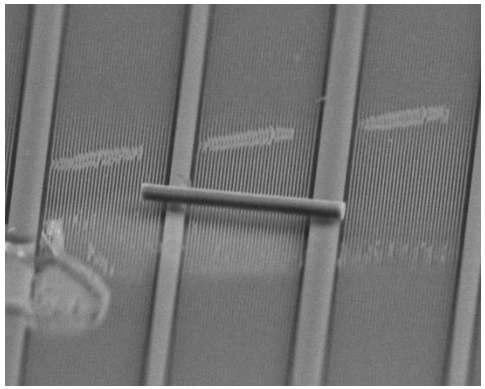
17dB Mode Suppression Ratio

Distributed feedback nanowire laser | Summary







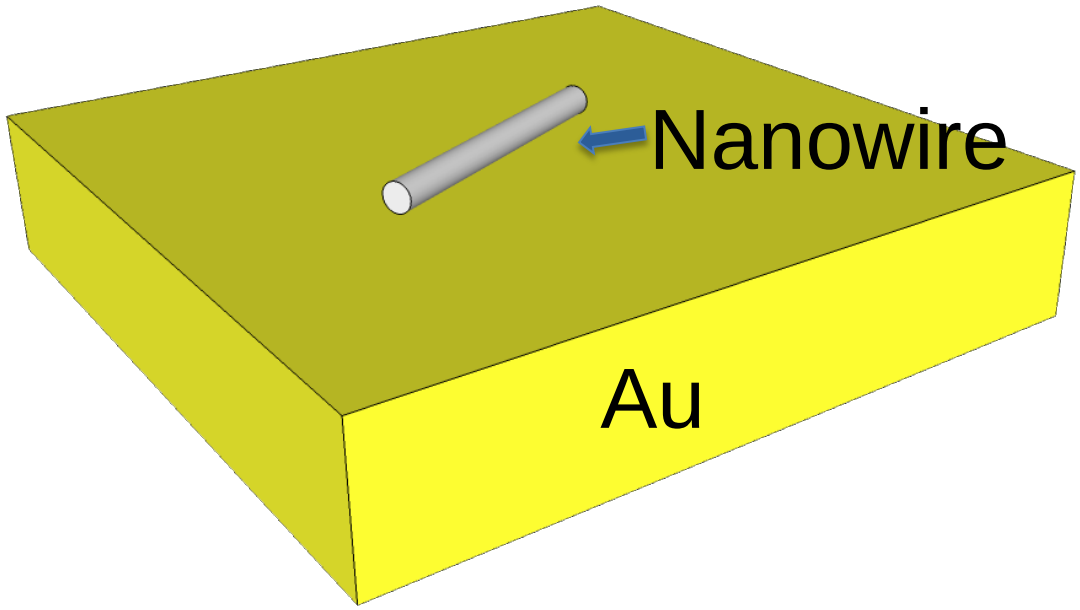


- Single-mode lasing with 17dB mode suppression ratio.
- Slight reduction in the lasing threshold
- Model development of nanowires with external gratings

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

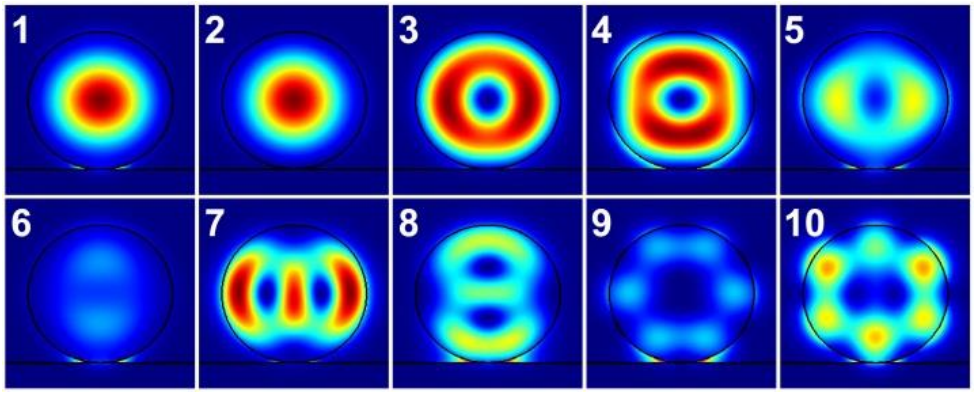
Method 2 : mode-dependent attenuation

What happens when a nanowire is in contact with a lossy substrate?



A nanowire on a gold substrate

Substrate Induced Mode-dependent Loss



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

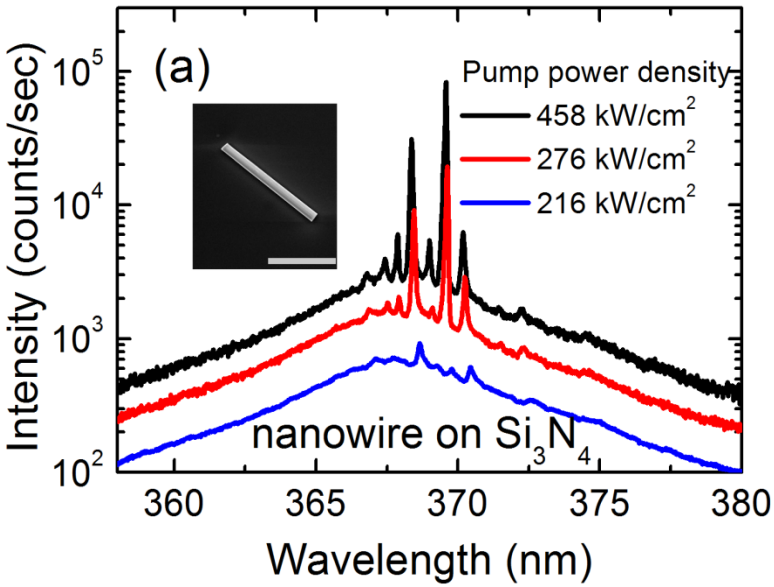
Only surviving mode

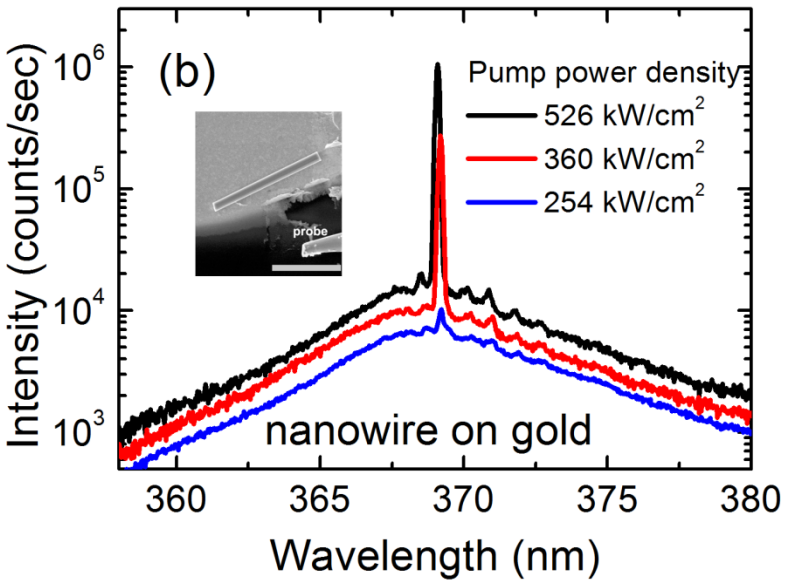
	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Loss (dB/cm)	8151	1730	4806	7109	16041
	Mode 6	Mode 7	Mode 8	Mode 9	Mode 10
Loss (dB/cm)	34858	7551	22205	29175	28706

Propagation loss of different transverse modes.

Metal substrate generates a mode-dependent propagation loss.

Lasing Behavior Transition from Multimode to Single-mode



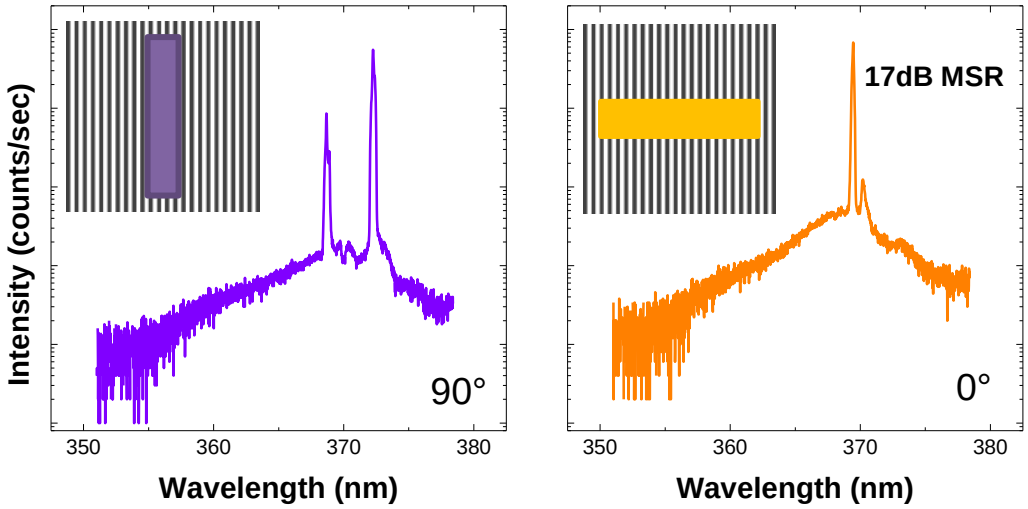


- ✓ Wavelength: 369nm; bandwidth: 0.12nm; SMSR: 17.4 dB;
- ✓ Threshold increased by 13%;
- ✓ Offering guidance to metal contacted nanowire lasing (electrically-injected)

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

Summary

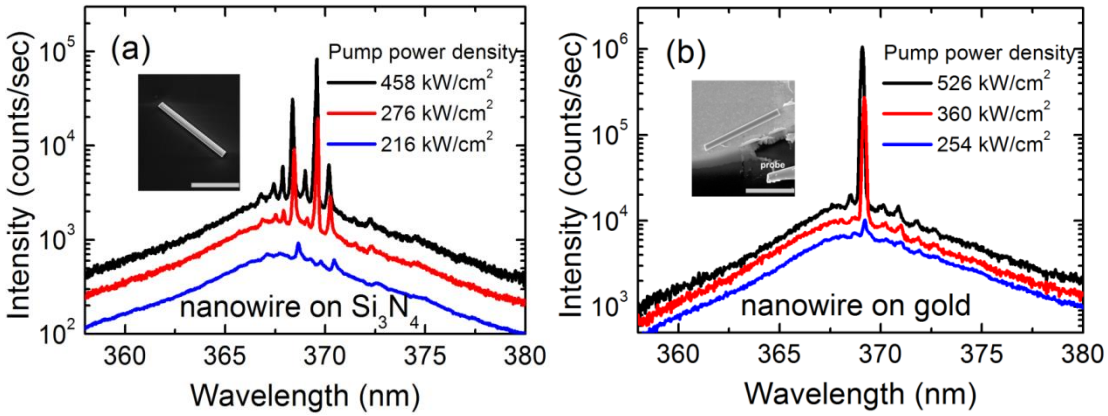
Grating Substrate



- Single-mode lasing with 17dB mode suppression ratio.
- Slight reduction in the lasing threshold

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

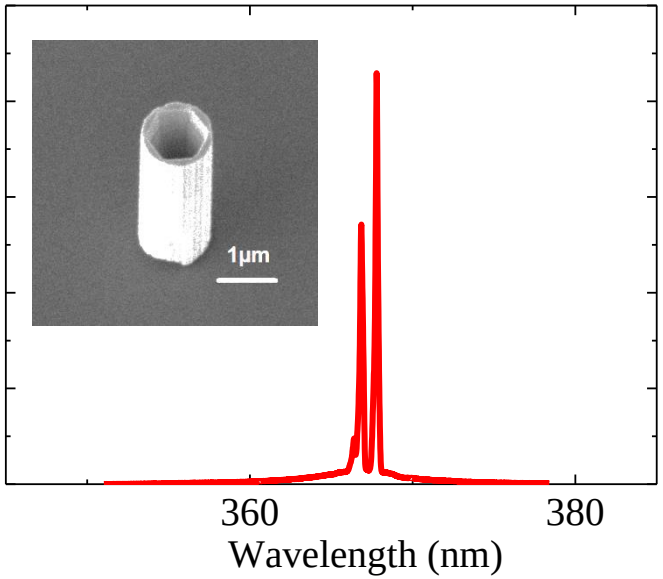
Gold Substrate



- MSR: 17.4 dB
- Threshold increased by 13%

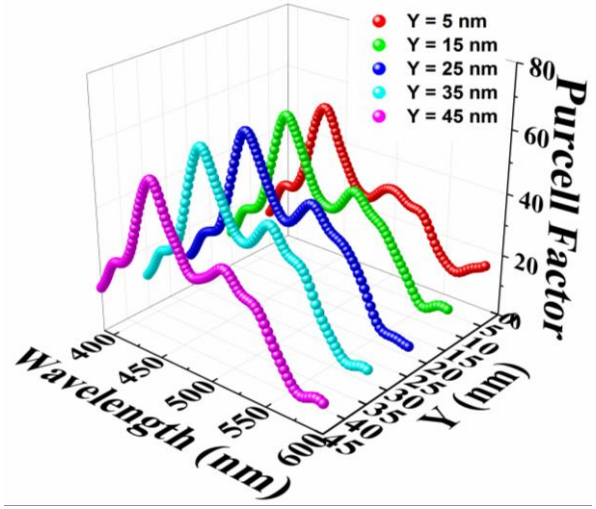
H. Xu, et al. APL 101, 221114 (2012)

GaN Nanotube Lasers



SW1G.3 - 210G Wed 11:15-11:30

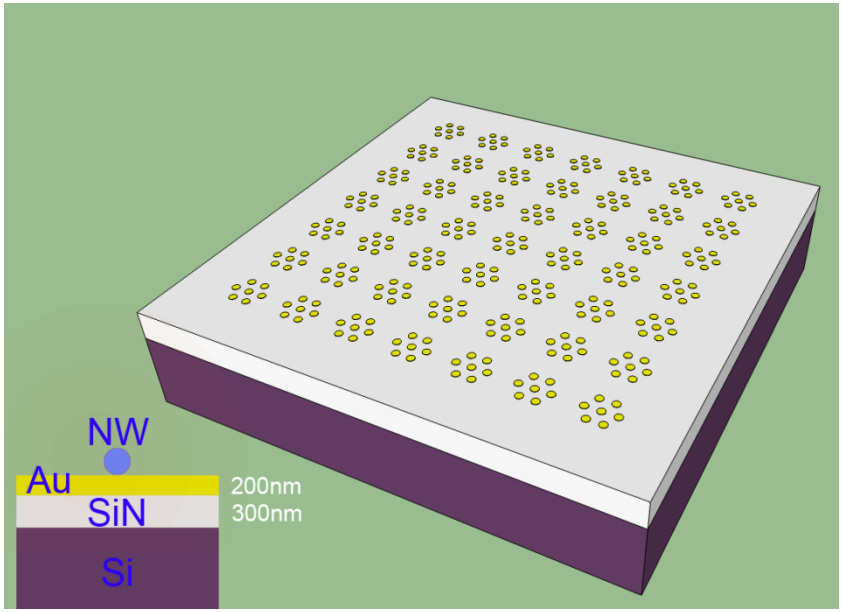
Ag-Coated In/GaN Core-Shell Nanowires



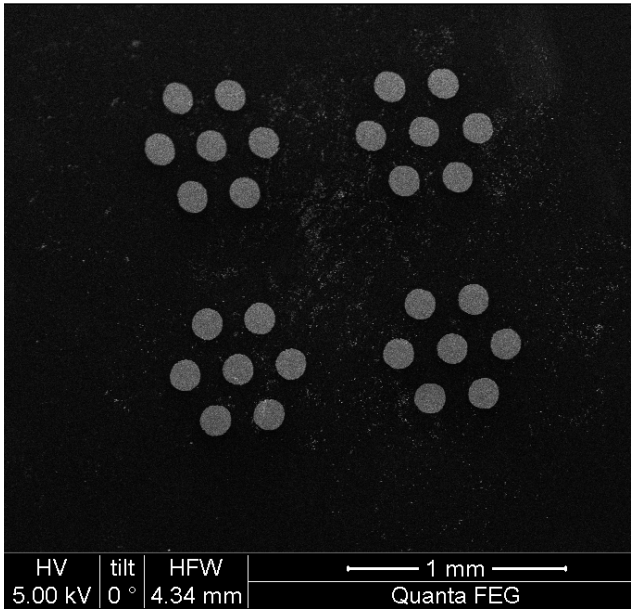
SM2J.4 – 212A/C Mon 11:15-11:30

Thank you for your attention!

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