Integration of III-V Quantum Dot Lasers and Their Advanced Applications

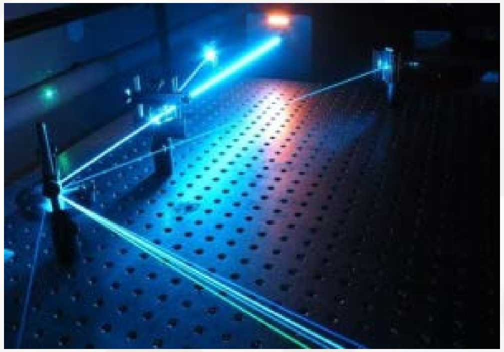
Dr. Wei Guo

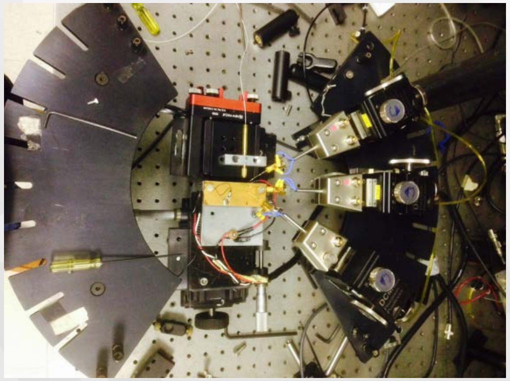
Photonics Research Laboratory
Department of Physics and Applied Physics
University of Massachusetts Lowell, Lowell, MA

Photonics Research Lab

Epitaxy tool

Fabrication facility





Characterization

Outline

- InAs quantum dot laser integration for optical interconnections
- Quantum Dot broadband SLEDs for optical coherent tomography
- QD PT symmetry and topological laser
- Summary

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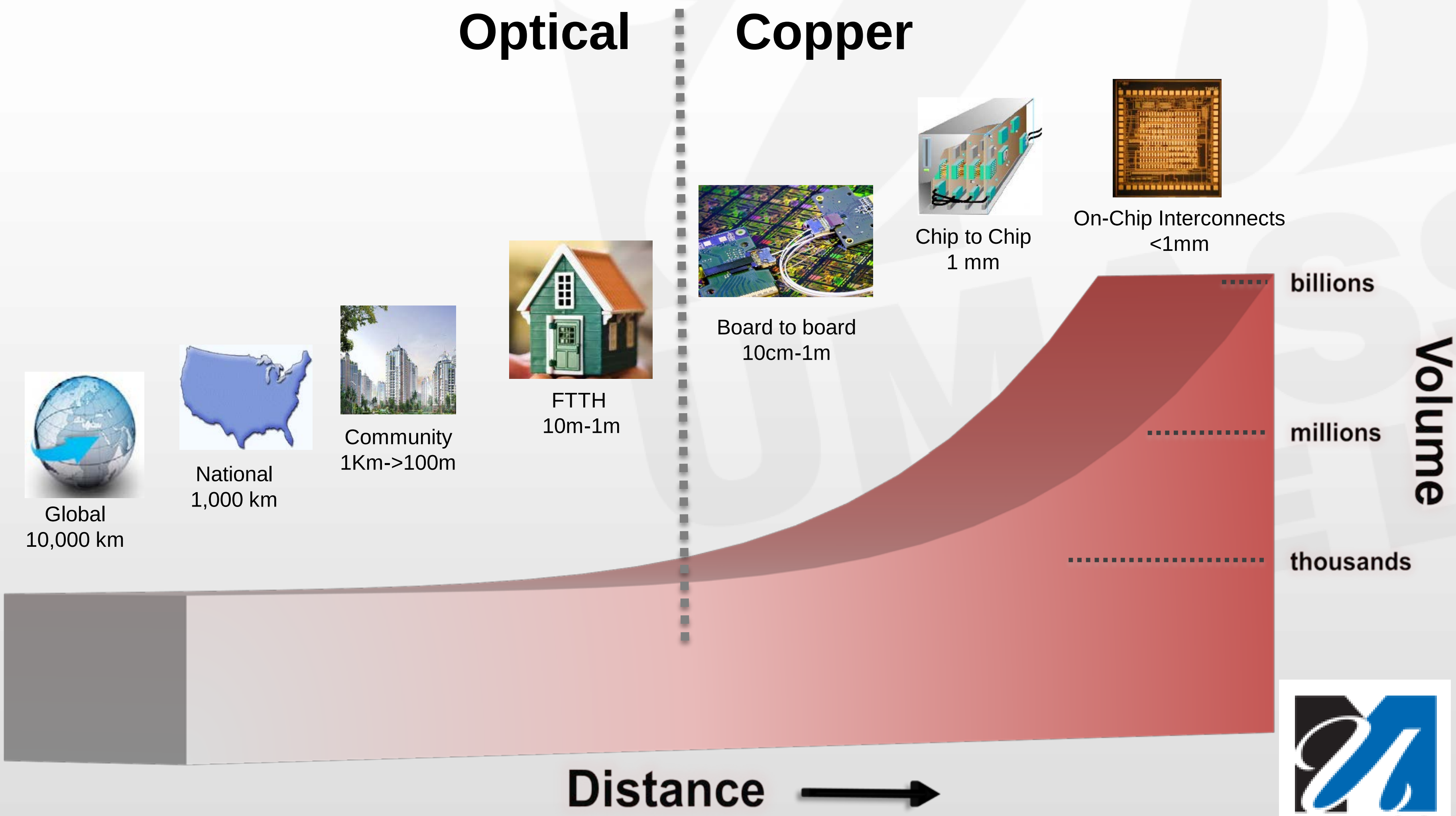
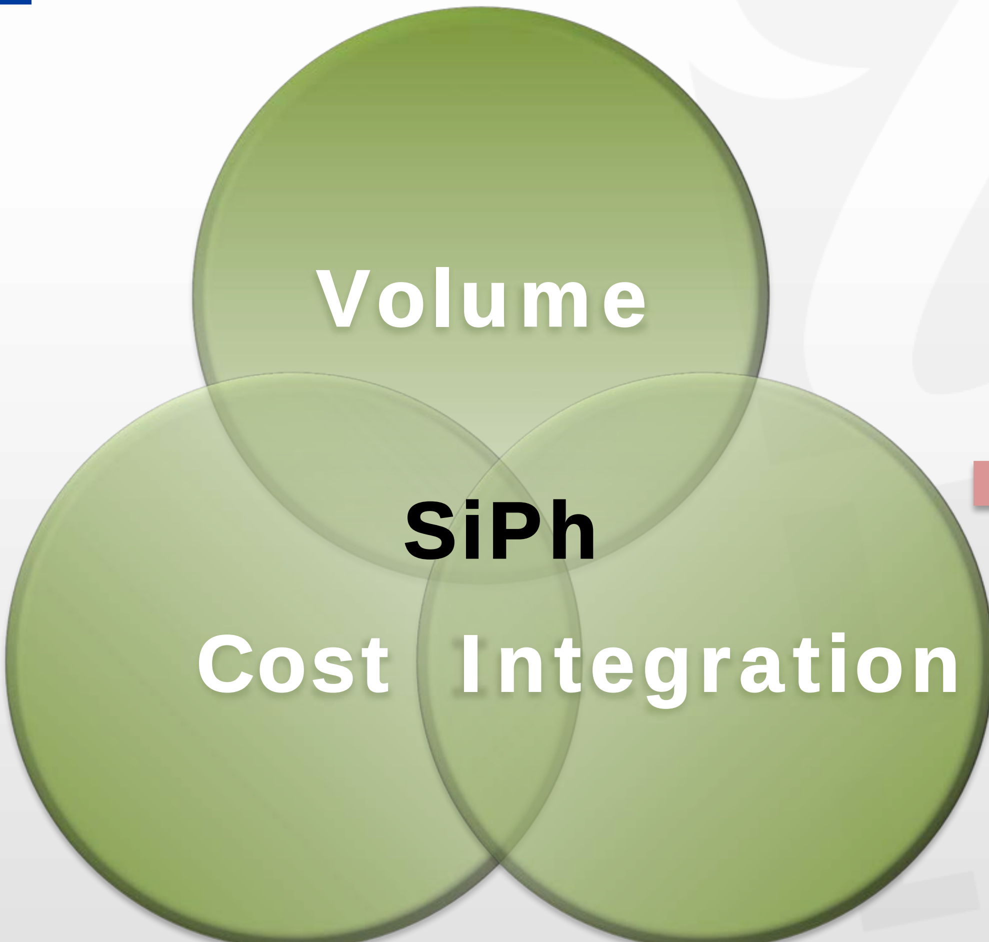
Optical Interconnection

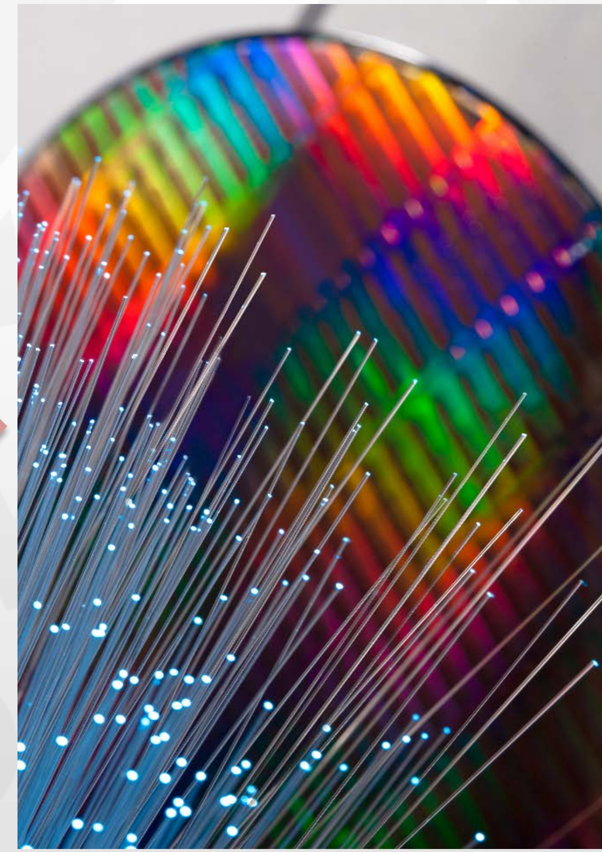


Optical Interconnection

Goal: Drive optical interconnection cheaper and faster!

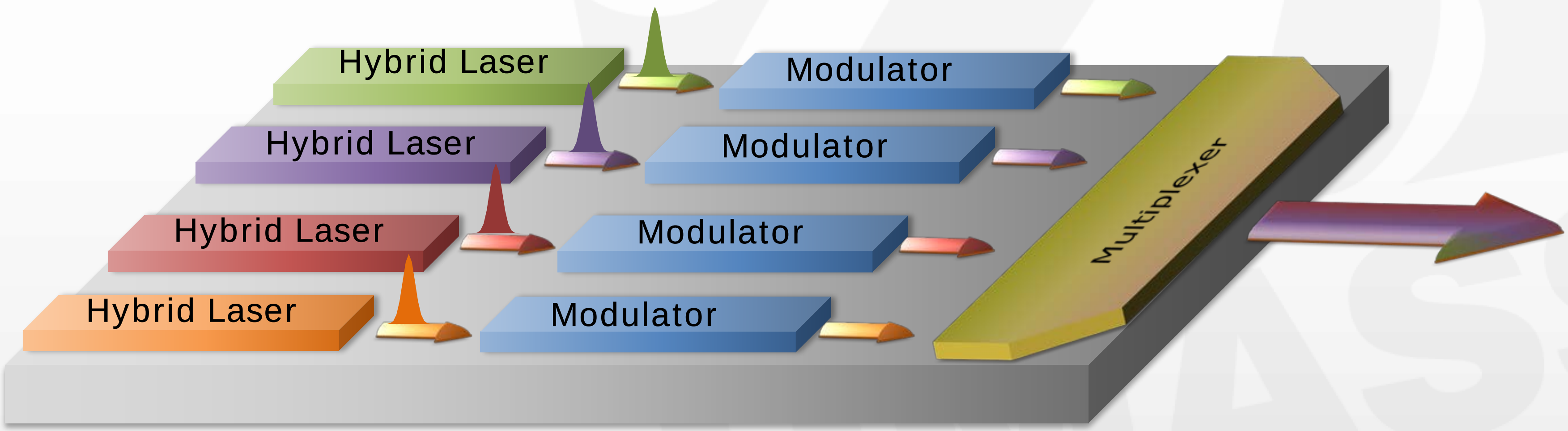
Integrated Optical Transceiver





- Silicon photonics is an ideal candidate for optical interconnections

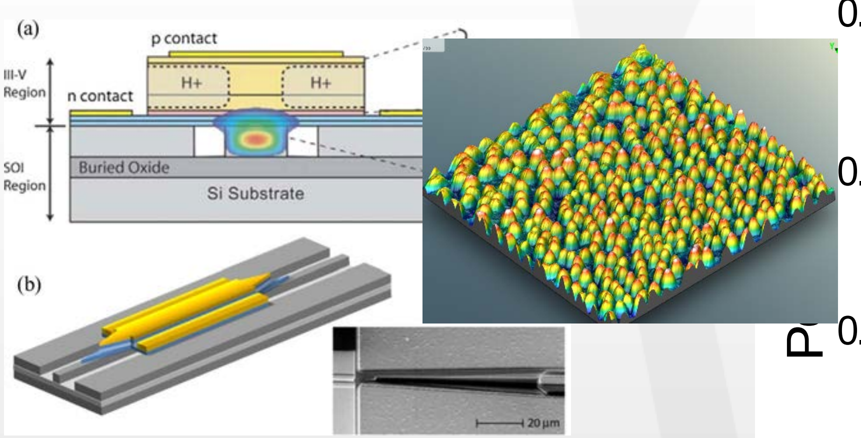
Integrated Optical Transceiver



- Parallel channels are key to scaling bandwidth at low cost
- Silicon photonics passive components have been intensively studied
- Hybrid III-V lasers are still the challenges

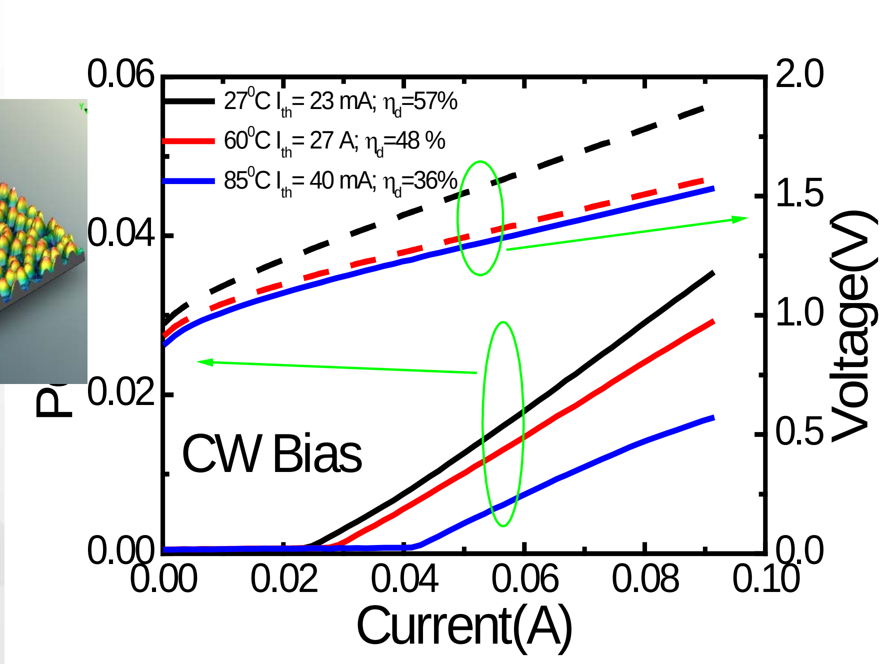
QD Lasers on Silicon

Hybrid InP quantum well laser



Bowers et. al., Selected Topics in Quantum Electronics, IEEE Journal of 17.2 (2011): 333-346.

InAs QD Lasers

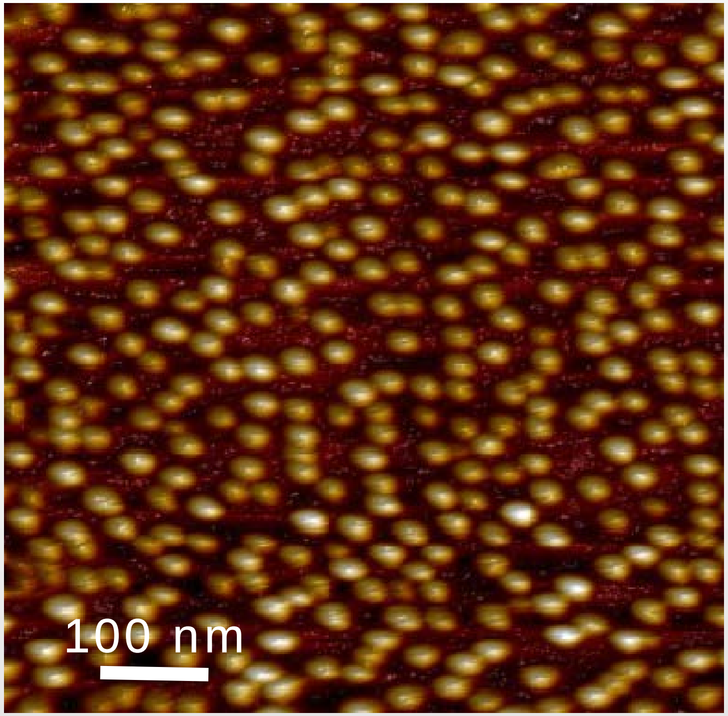


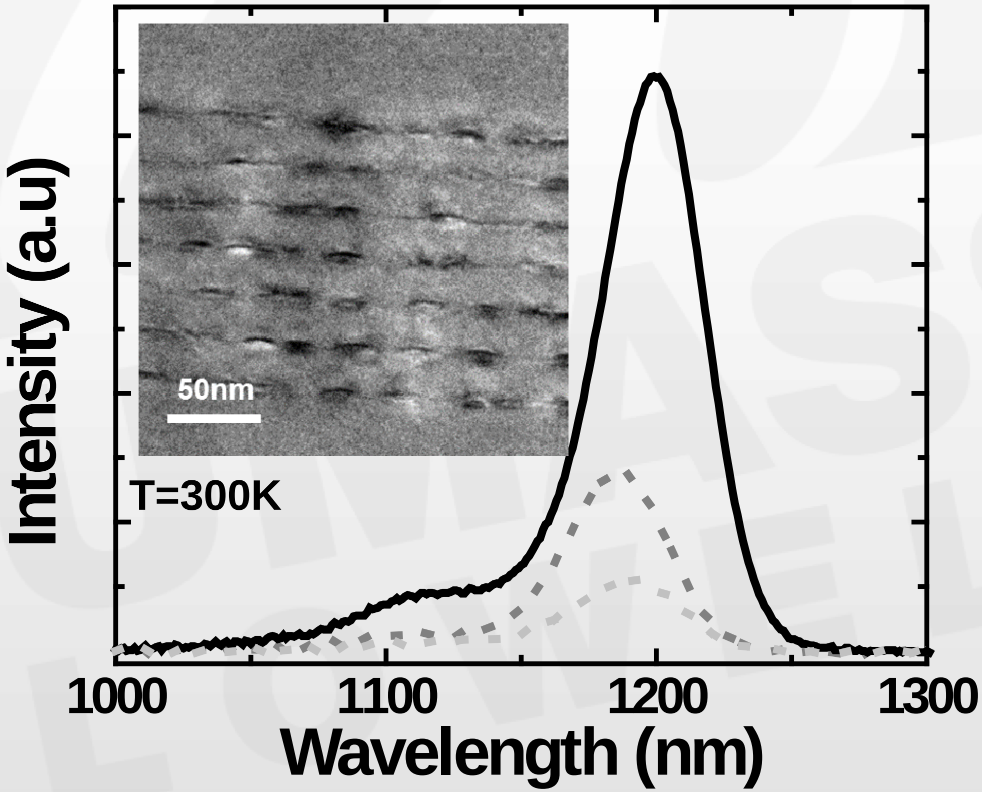
- Integration of InP based QW lasers on Si was the focus
- Quantum dot lasers are advantages with the high temperature stability and have drawn large attentions recently

MBE Growth of InAs QD

As pressure = 8×10^{-6} Torr
T_{Growth} (GaAs) = 600° C
T_{Growth} (InAs) = 500° C
InAs QDs ~ 2.6 ML
III:V Ratio = 1:15
Growth rate (InAs) = 0.1ML/s
Growth rate (GaAs) = 1ML/s

MBE Growth of InAs QD

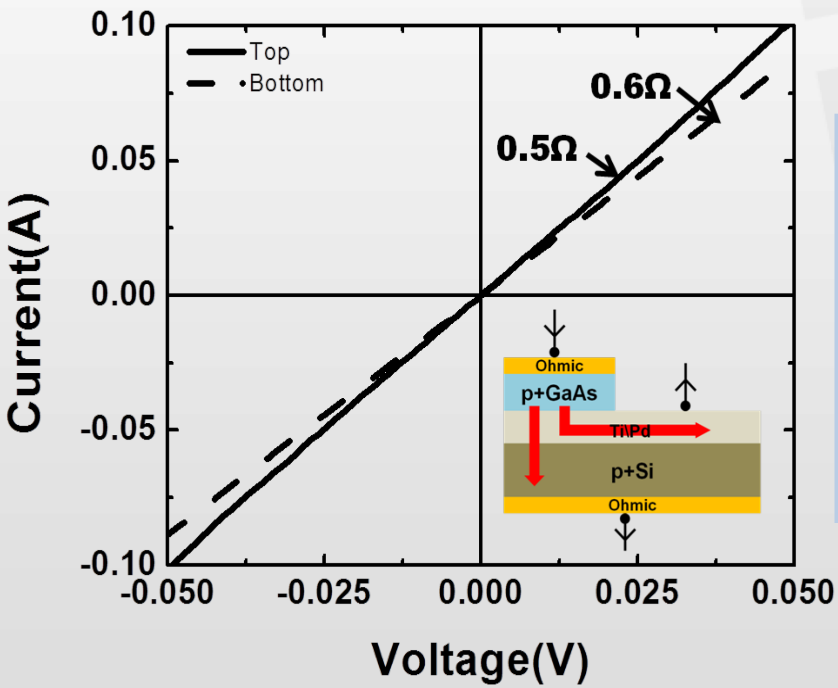




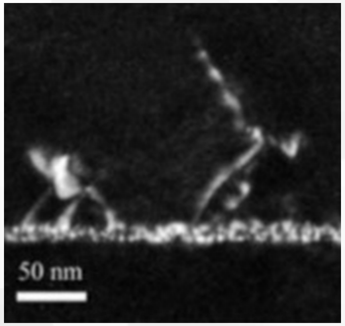
- Optimized InAs QDs with density of 8×10^{10} cm^{-2} is achieved
- PL measurements are employed during the QD optimization

Wafer Bonding

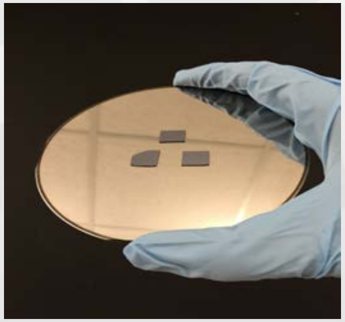
- Alignment Free
- No Dislocation and Threading Defaults
- Lower Cost
- Compatible with Si CMOS Integration



- Low resistivity
- $0.1\Omega/cm^2$
- Low Bonding Temperature 250 ℃
- Excellent thermal contact

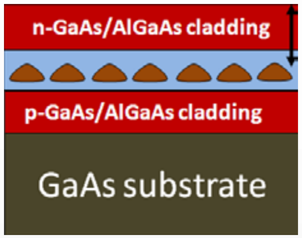


Dislocation in Si\GaAs interface



GaAs die bonded to Si

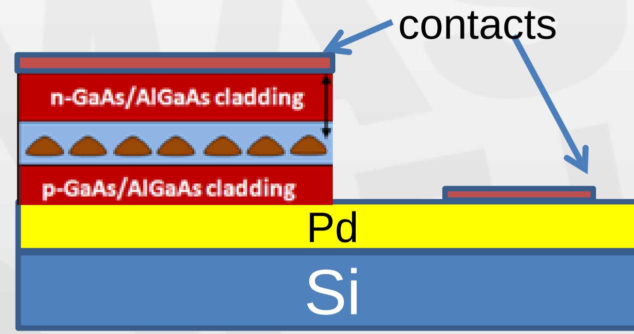
QD Laser on Si by Pd-Mediated Wafer Bonding



1) MBE growth

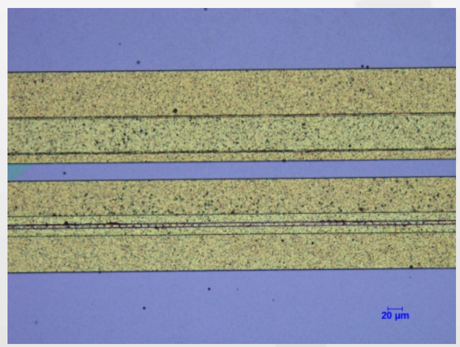
2) Deposit Pd

3) Flip-chip wafer bonding



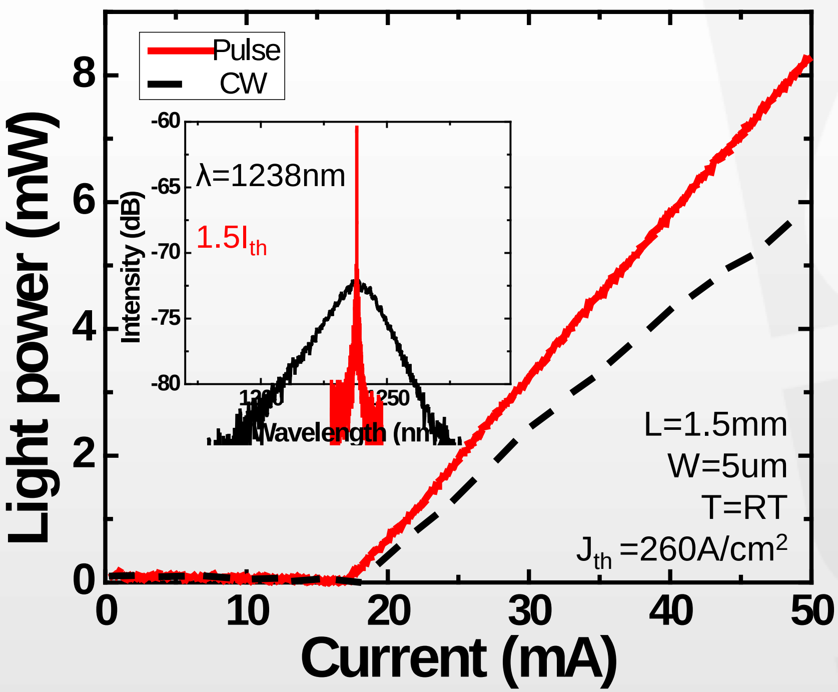
4) Laser processing

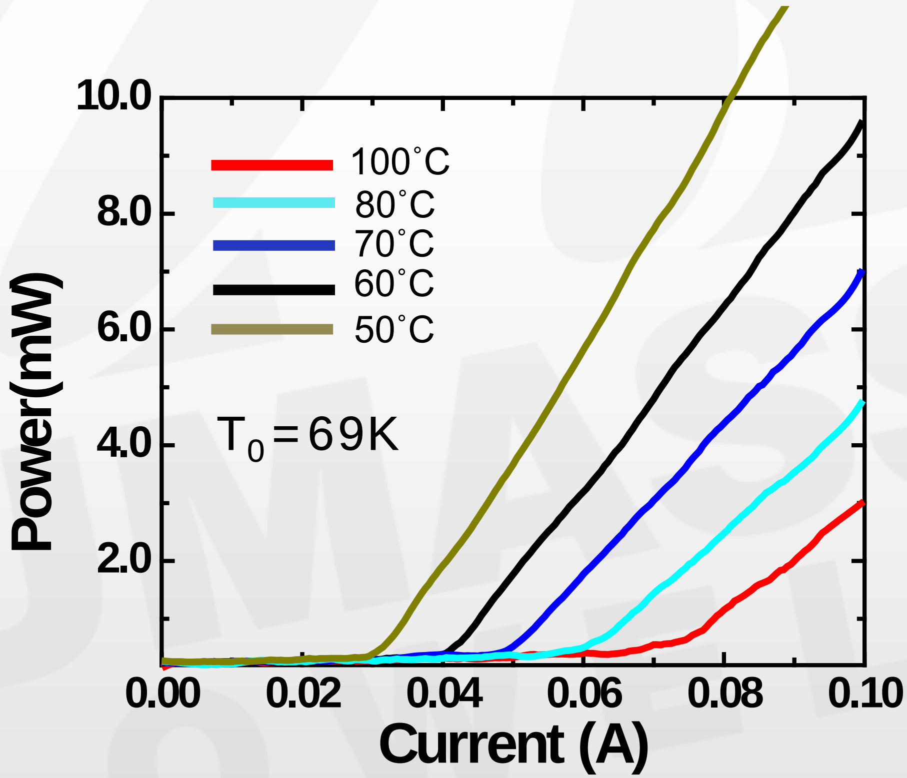
Broad Area Bonded Laser



Ridge Bonded Laser

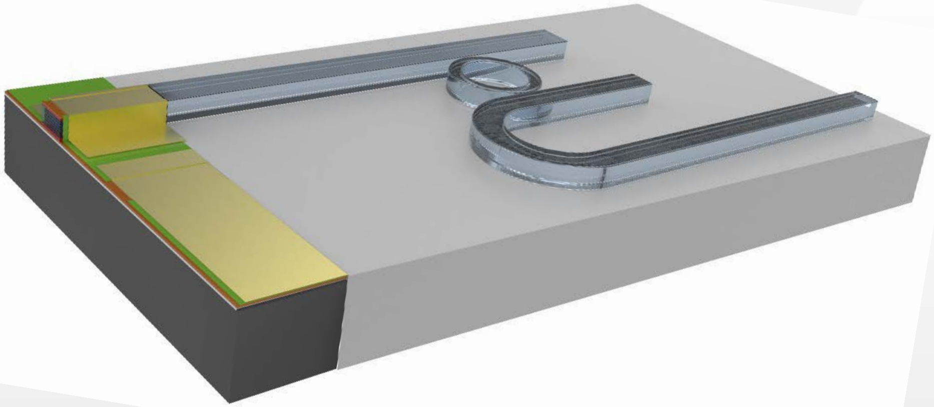
Characterizations of QD Lasers on Si

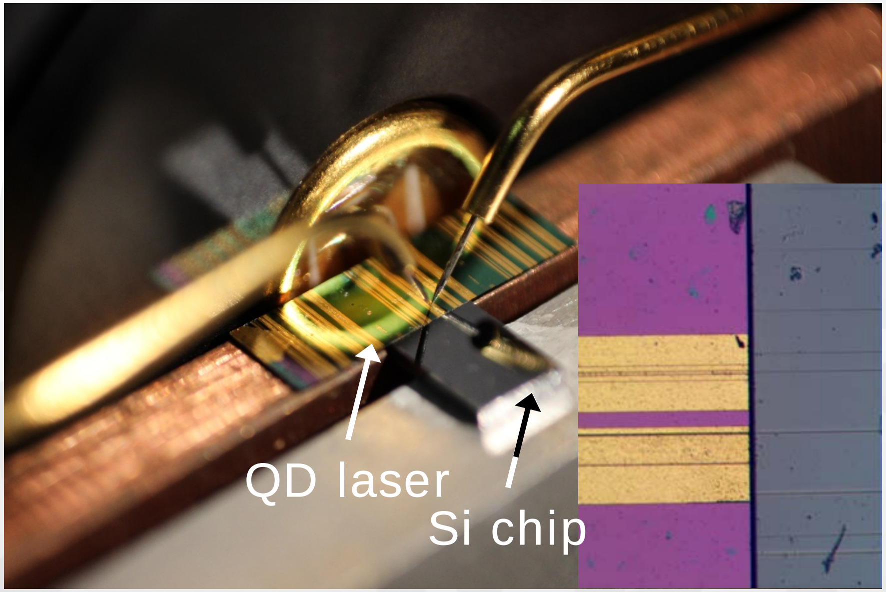




- State-of-the-art hybrid InAs QD lasers on Silicon is achieved
- Laser exhibit operation at 100˚C

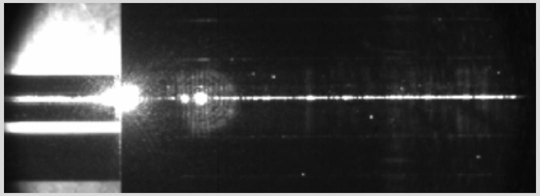
Butt-Joint Coupled Platform





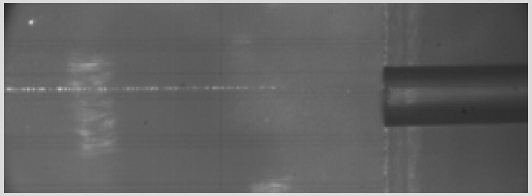
- In butt-joint coupling platform, the edge emitting laser emission is directly aligned with the silicon waveguide input port
- The laser and silicon chips were mount on translation stages
- The alignment was achieved by maximizing the output power

Butt-Joint Coupled Platform

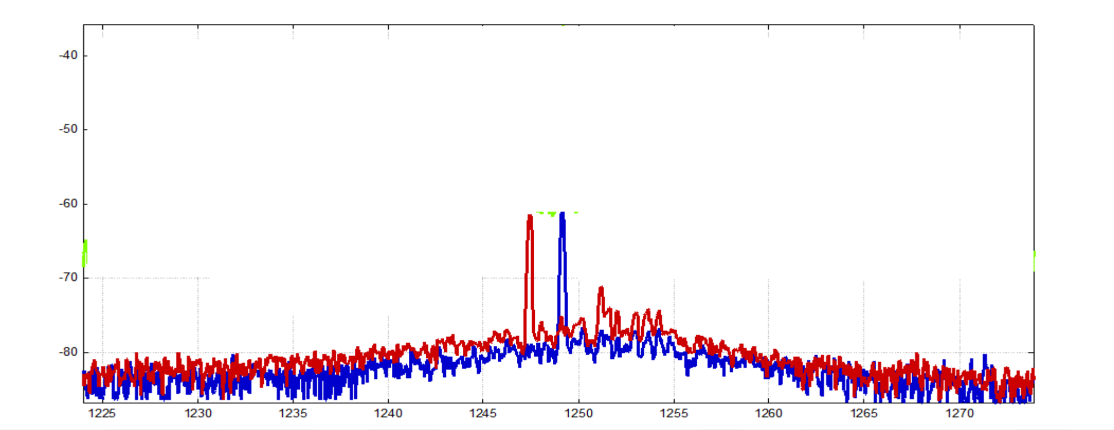


Light coupled from QDs Laser

Si ring resonator on SOI Substrate



Light coupled from SOI waveguide to Fiber



- QD laser is successfully couple in Si
- Si ring resonators can filter the comb laser emission

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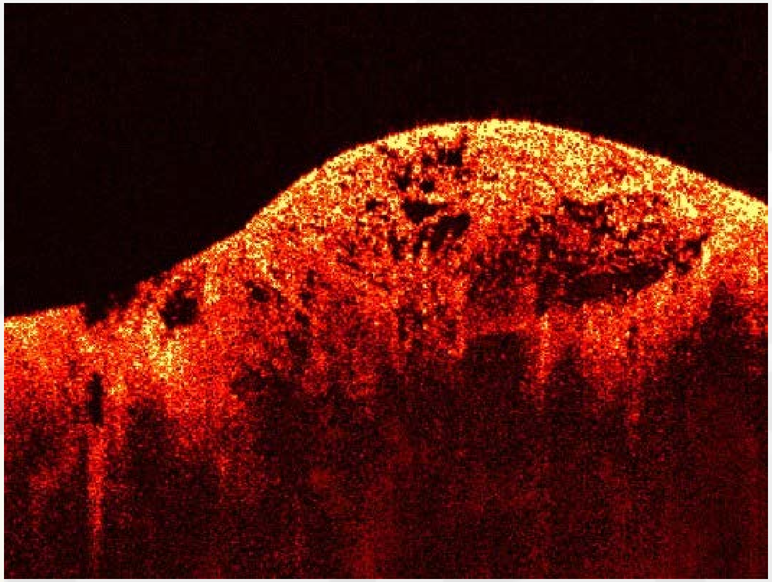
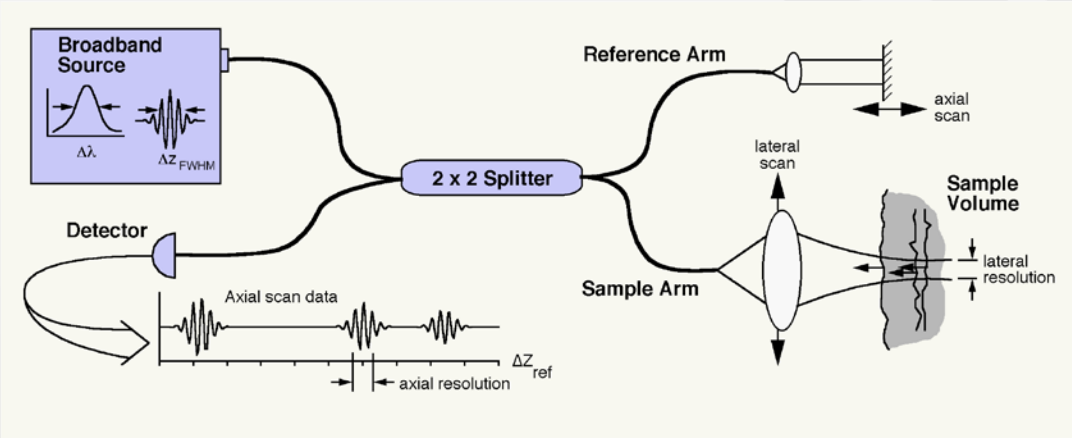
Broadband Laser

The performance of an OCT system is largely determined by the broadband source





Optical Coherence Tomography (OCT) of a sarcoma (skin cancer)

"Ss-oct" by Pumpkinegan at en.wikipedia. https://commons.wikimedia.org/wiki/File:Ss-oct.PNG#/media/File:Ss-oct.PNG

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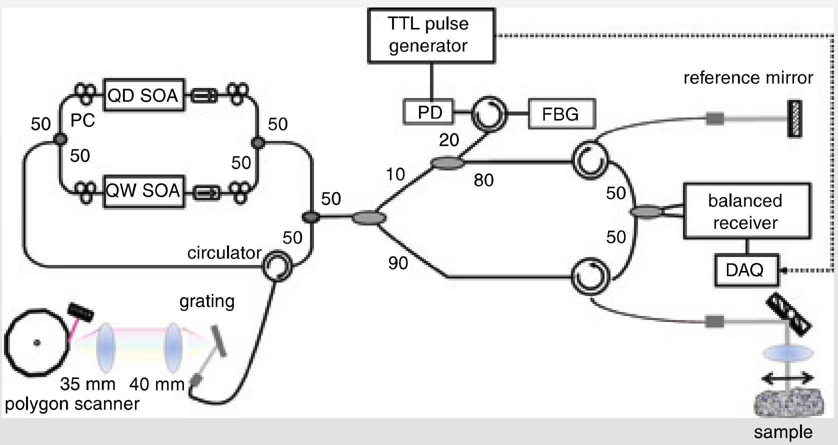
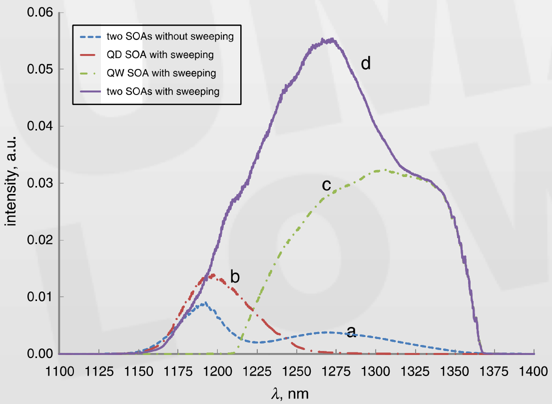
QD Gain Region

Quantum Dots are a good candidate due to having:

- **Emission from 1.0 to 1.3 μm**
- Broadband -> A-scan resolution ($\Delta Z = 0.44 \cdot \lambda_0^2 / \Delta\lambda$)
- Long Coherence length -> B-scan resolution
- Grown on GaAs substrates for DBR integration





- *Ha et. al., ELECTRONICS LETTERS Vol. 49 No. 19 pp. 1205–1206*
- *Thorlabs Inc.*

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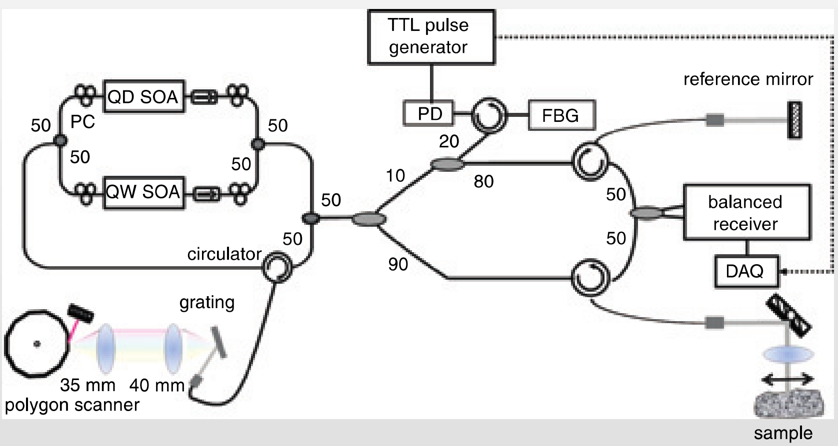

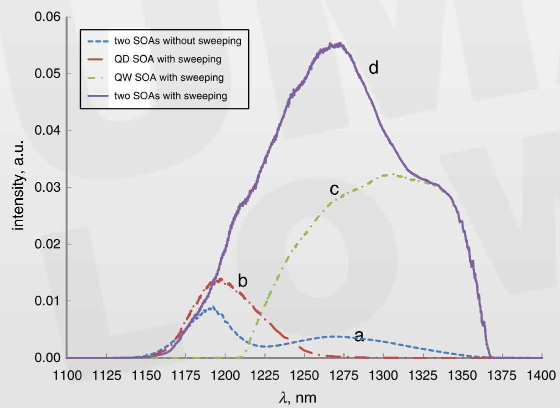

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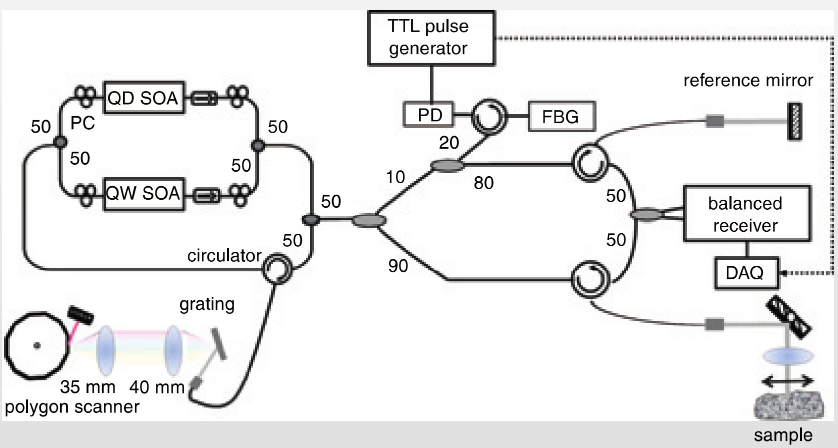

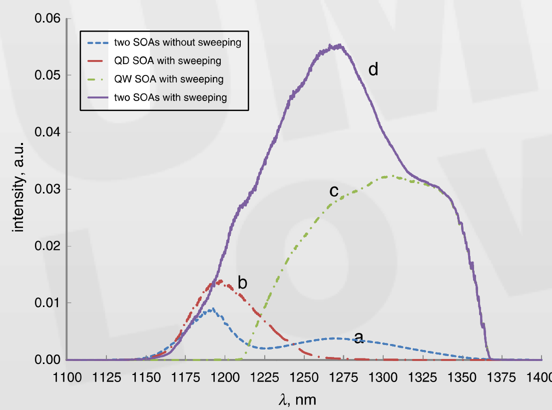

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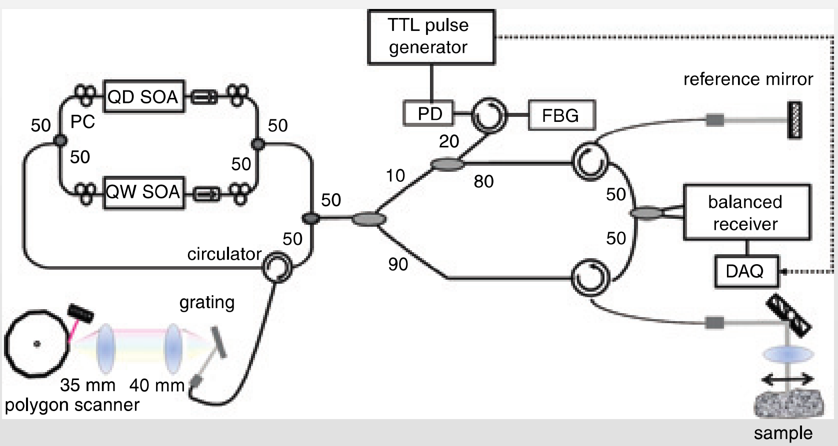

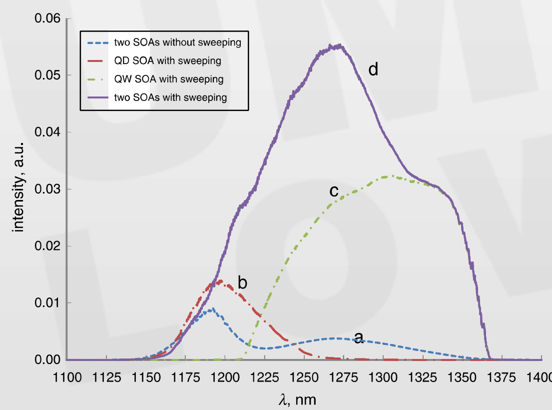

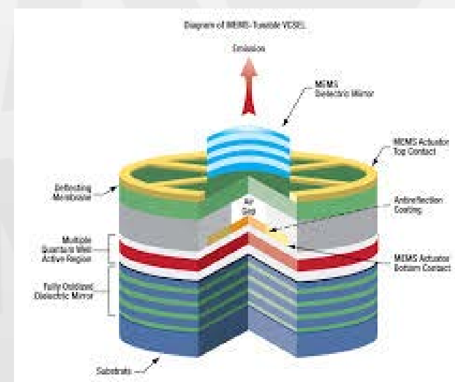

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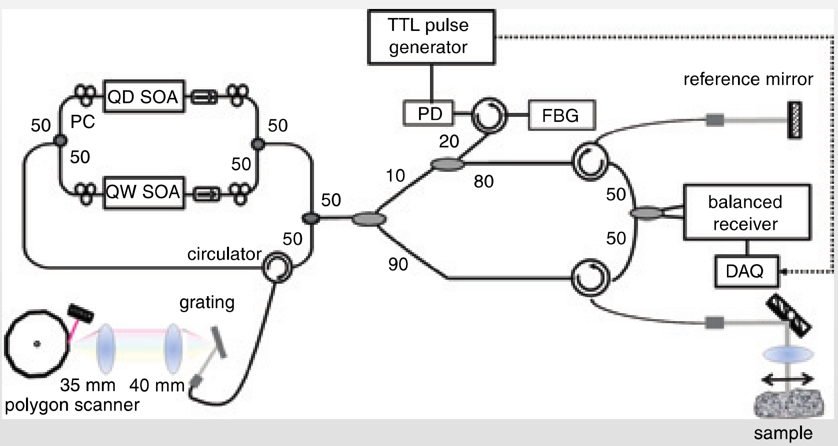

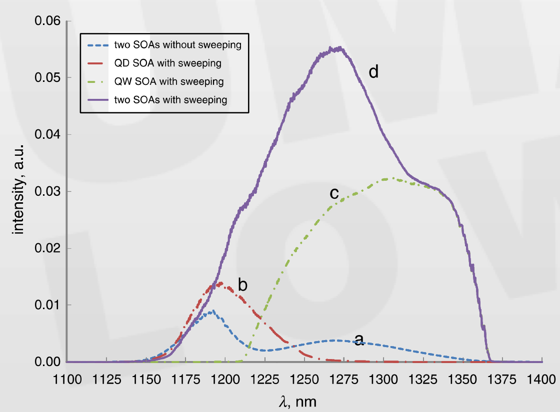

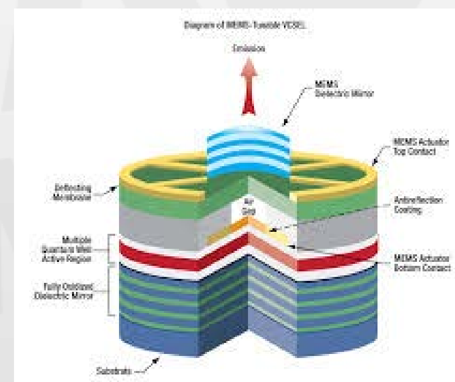

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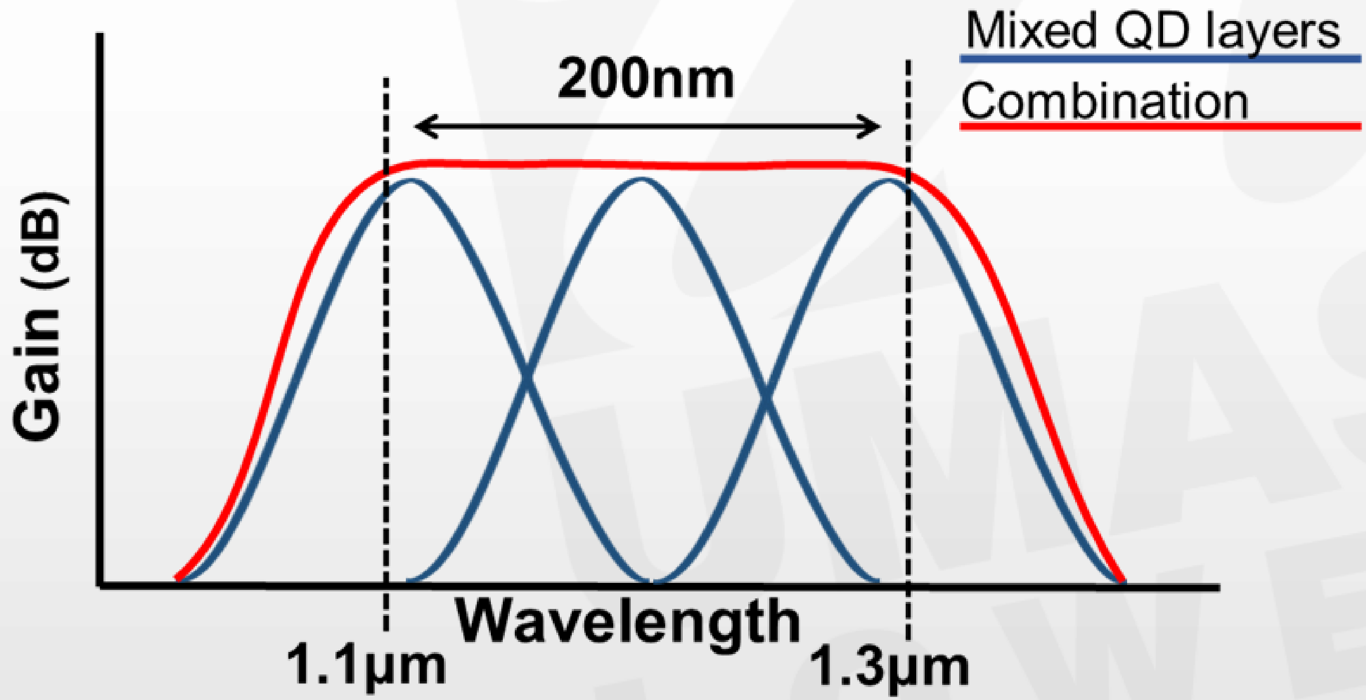
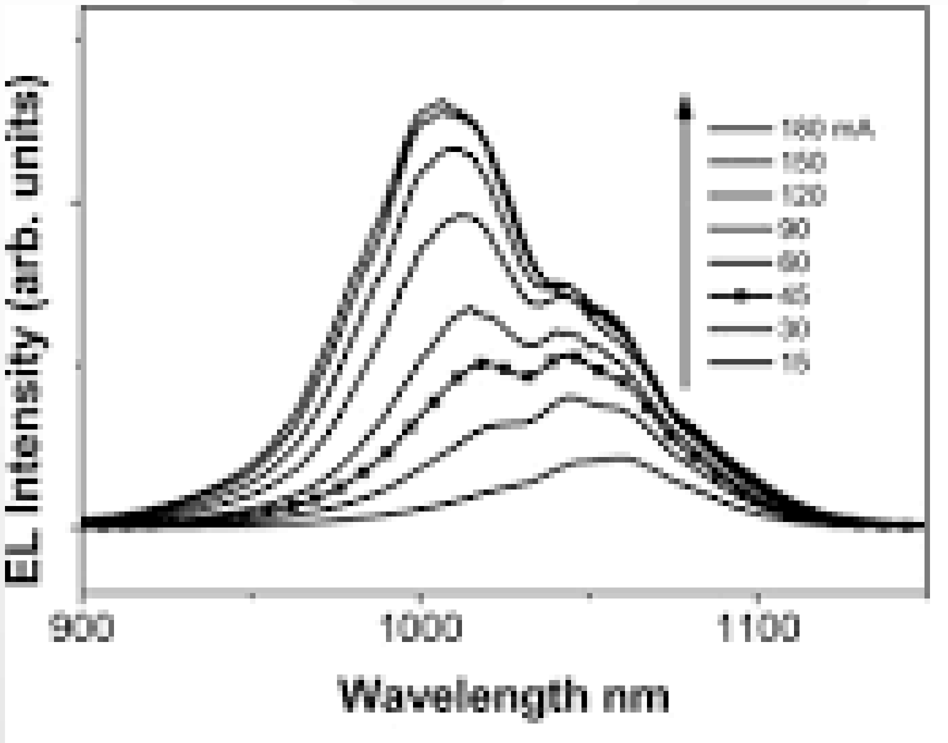
Dip-free Broadband QDs



- Different QD structures can be grown together to eliminate the spectrum dip

Dip-free Broadband QDs



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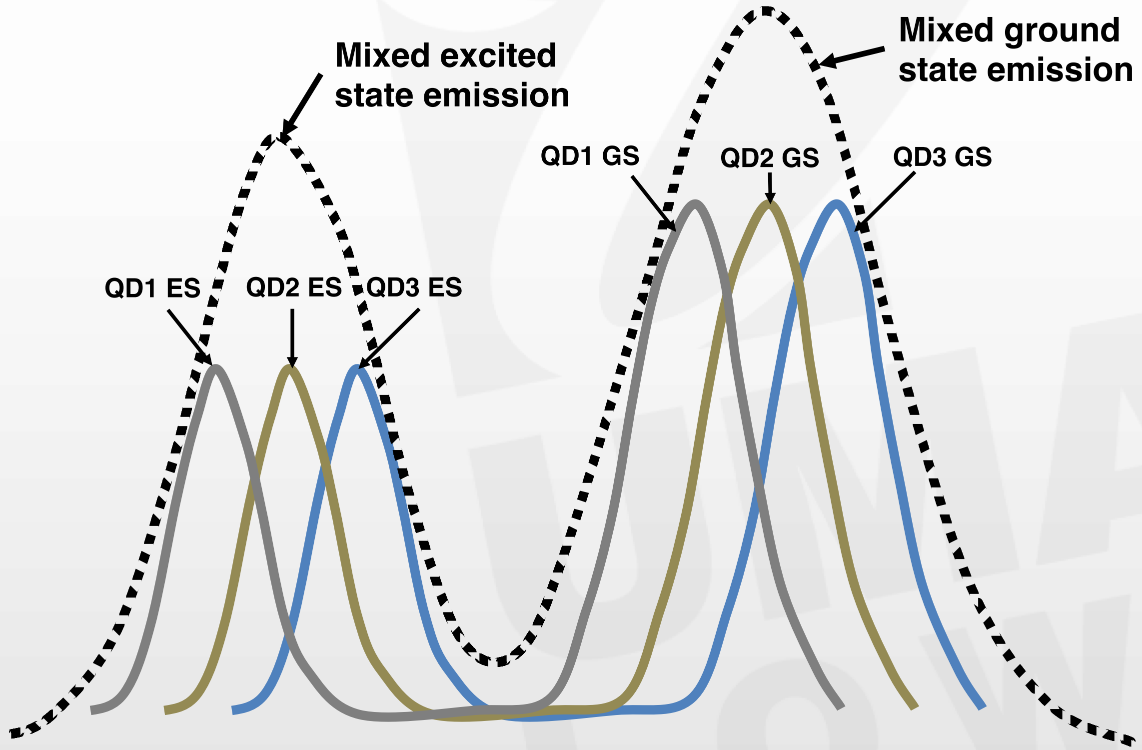
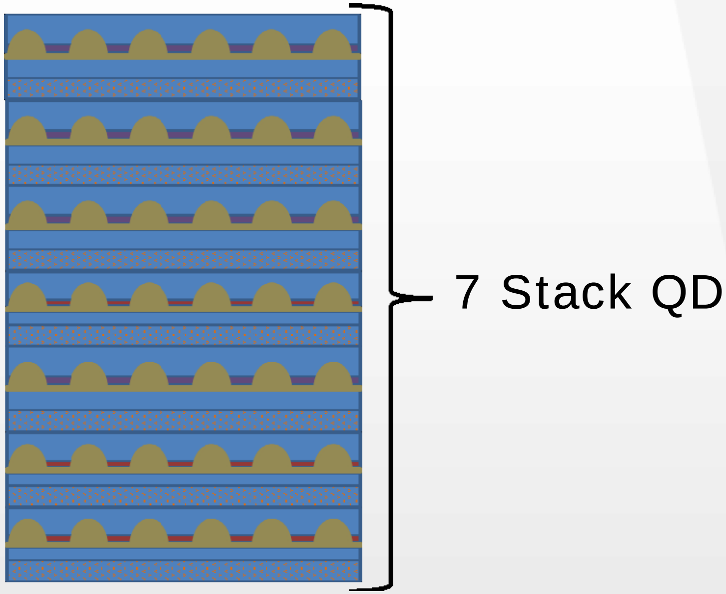
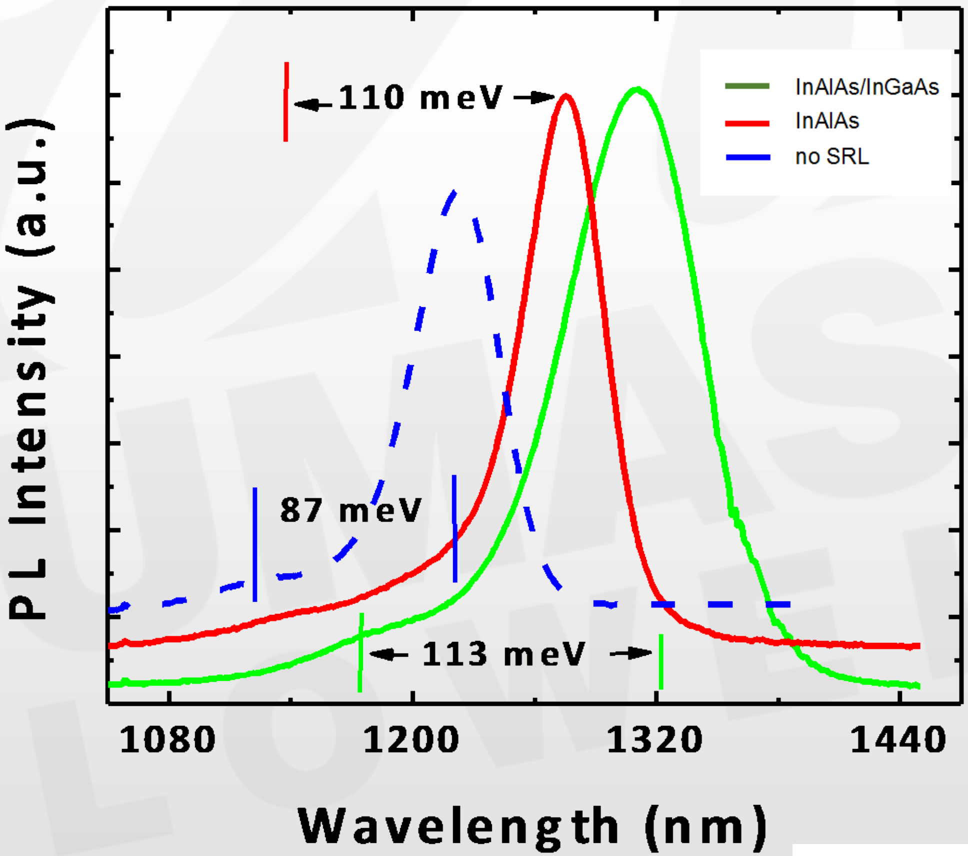
Chirped QDs with InAlAs SRLs



- By using the novel QD structures, the ground and excited state emission can be separated in the mixed QD structures

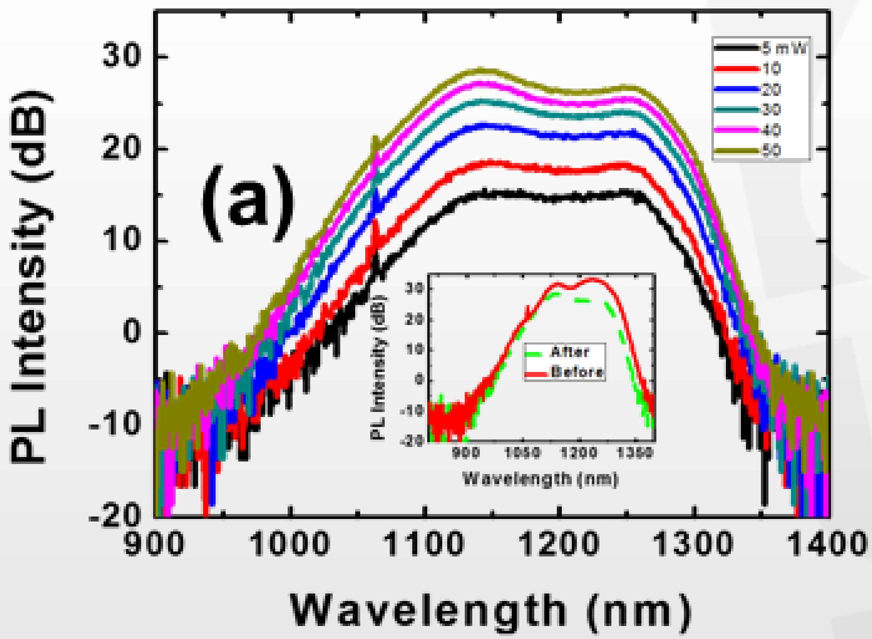
Chirped QDs with InAlAs SRLs

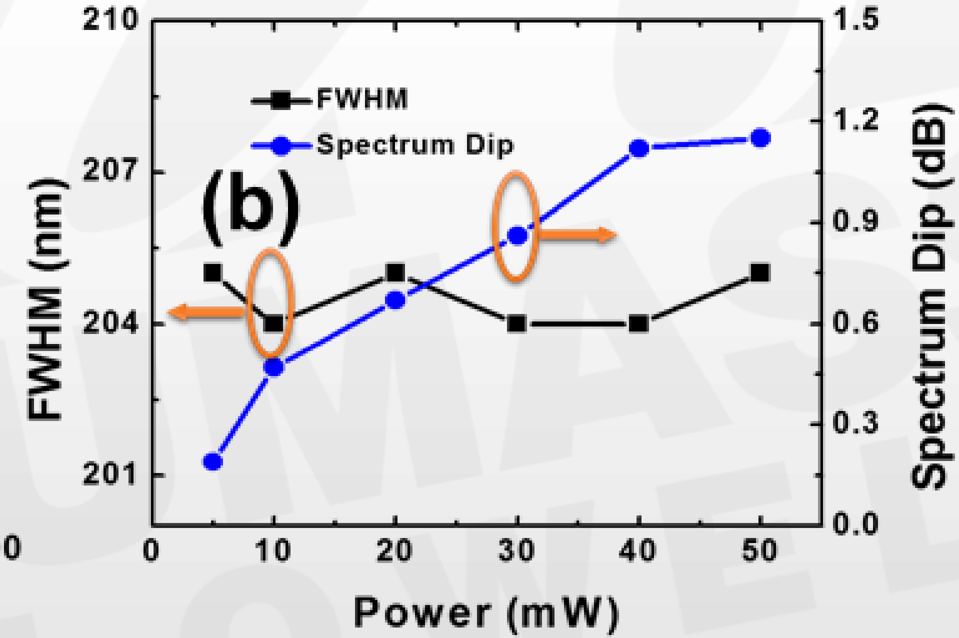




- By changing the SRL design, the GS and ES emission wavelengths can be tuned

Chirped QDs with InAlAs SRLs





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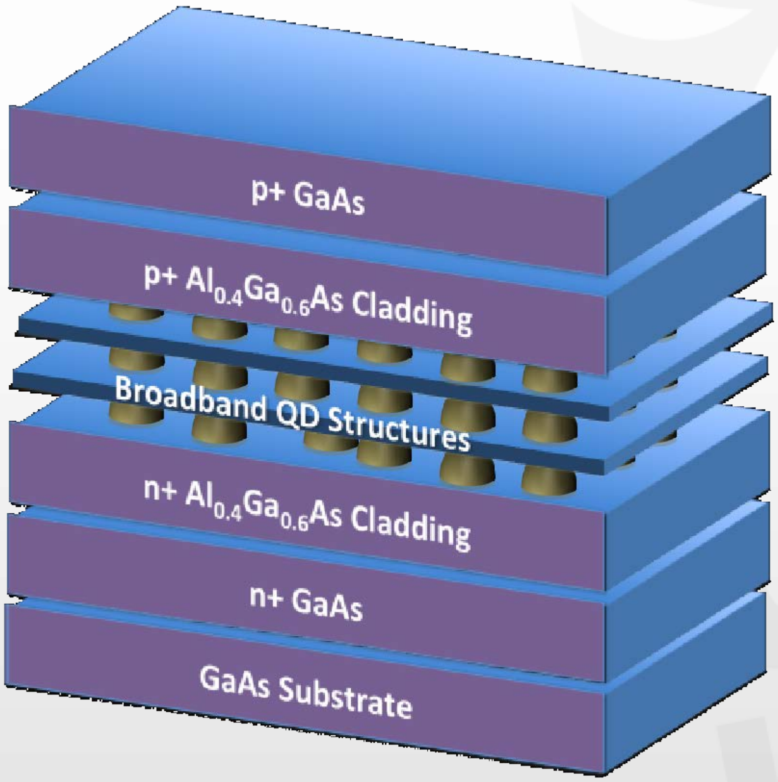
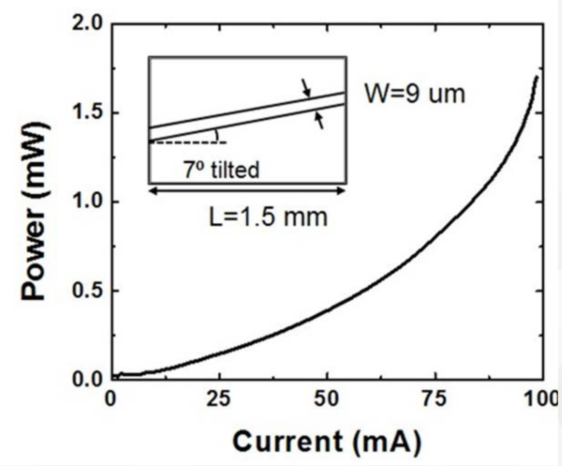
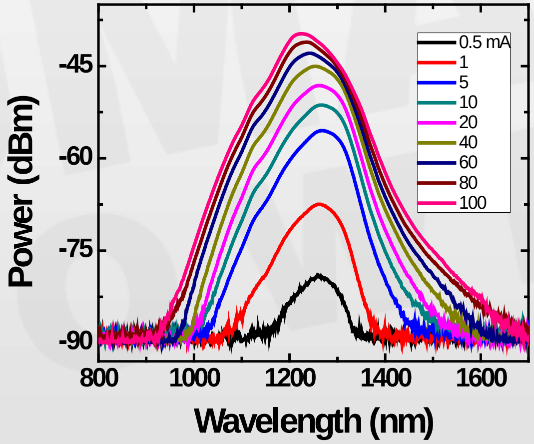
QD SLEDs / Gain Chip







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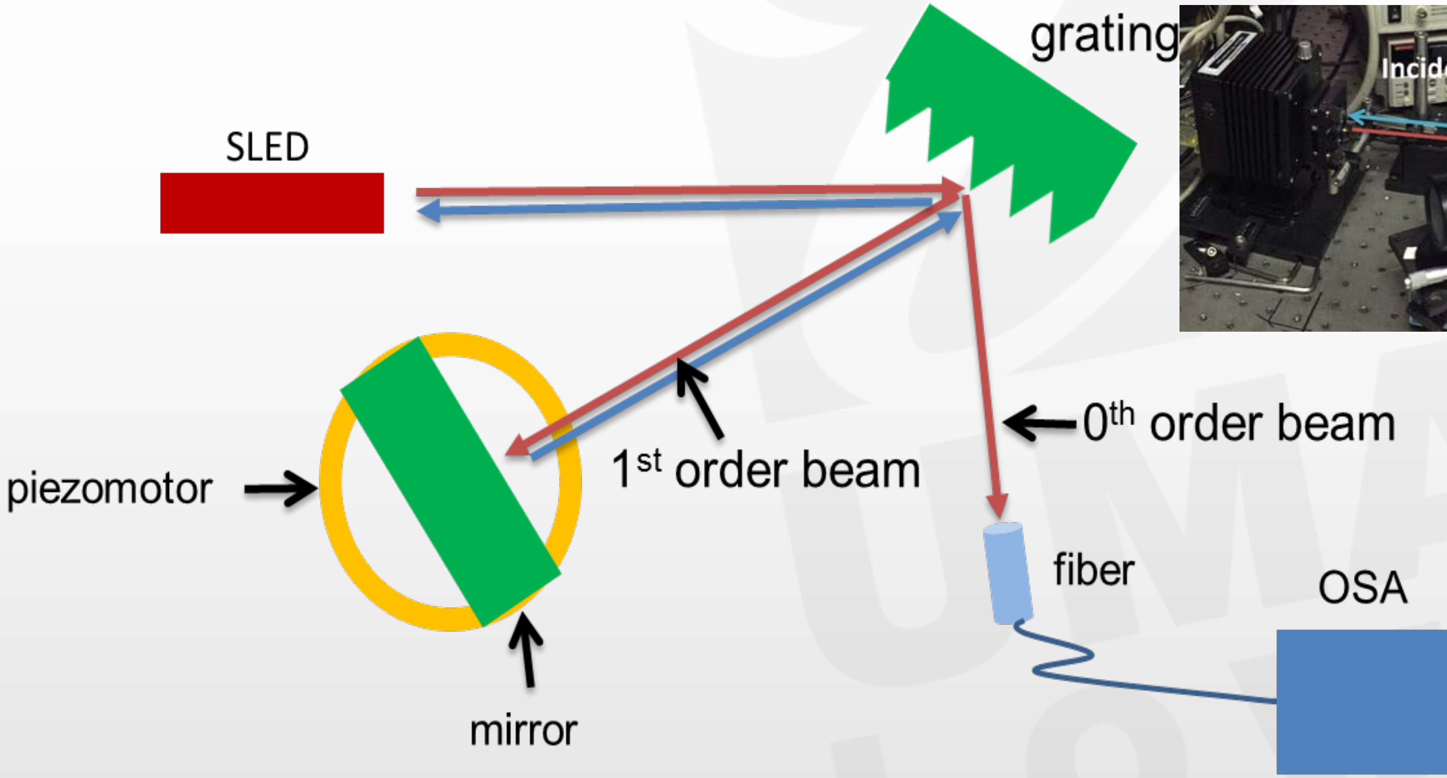
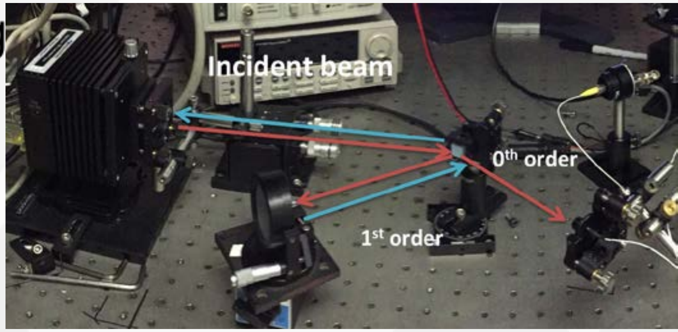
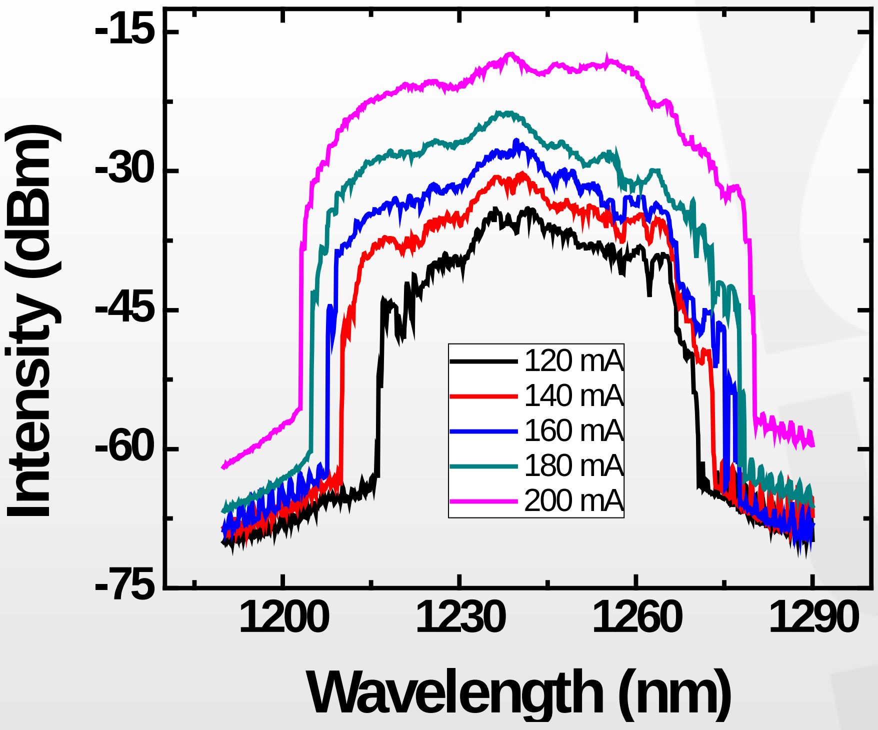
Broadband QD External Cavity Laser

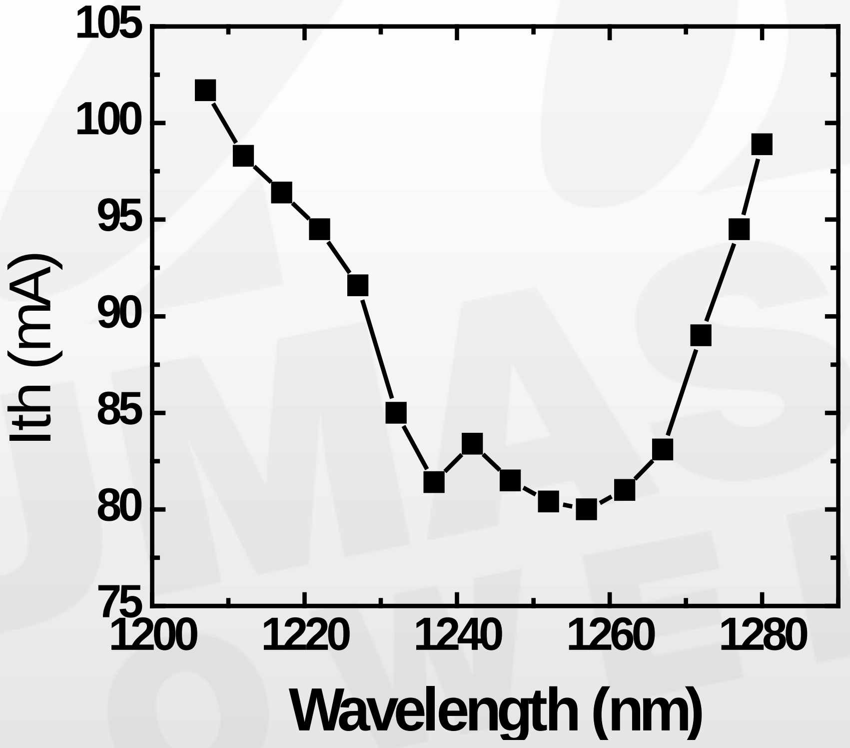




- QD external cavity laser is setup by using the wavelength selective diffraction grating

Broadband QD External Cavity Laser





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Parity-time Symmetry in Quantum Mechanics

PT Operators:

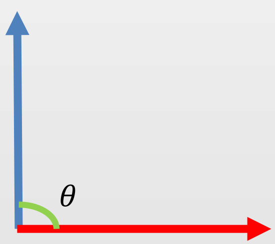
$$\hat{P} \equiv \begin{cases} \hat{p} \rightarrow -\hat{p} \\ \hat{x} \rightarrow -\hat{x} \end{cases}$$

$$\hat{T} \equiv \begin{cases} \hat{p} \rightarrow -\hat{p} \\ \hat{x} \rightarrow +\hat{x} \\ \hat{i} \rightarrow -\hat{i} \end{cases}$$

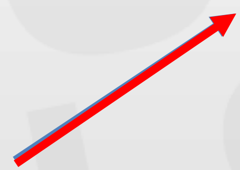
PT Symmetry satisfies:

$$[\hat{H}, \hat{P}\hat{T}] = 0$$

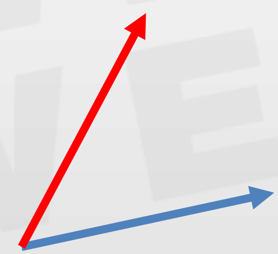
Non-broken PT phase



Exceptional Point



Broken PT phase



Condition:

$$V(x) = V^*(-x)$$

From Quantum Mechanics to Optics

Maxwell Equation in 2D waveguide

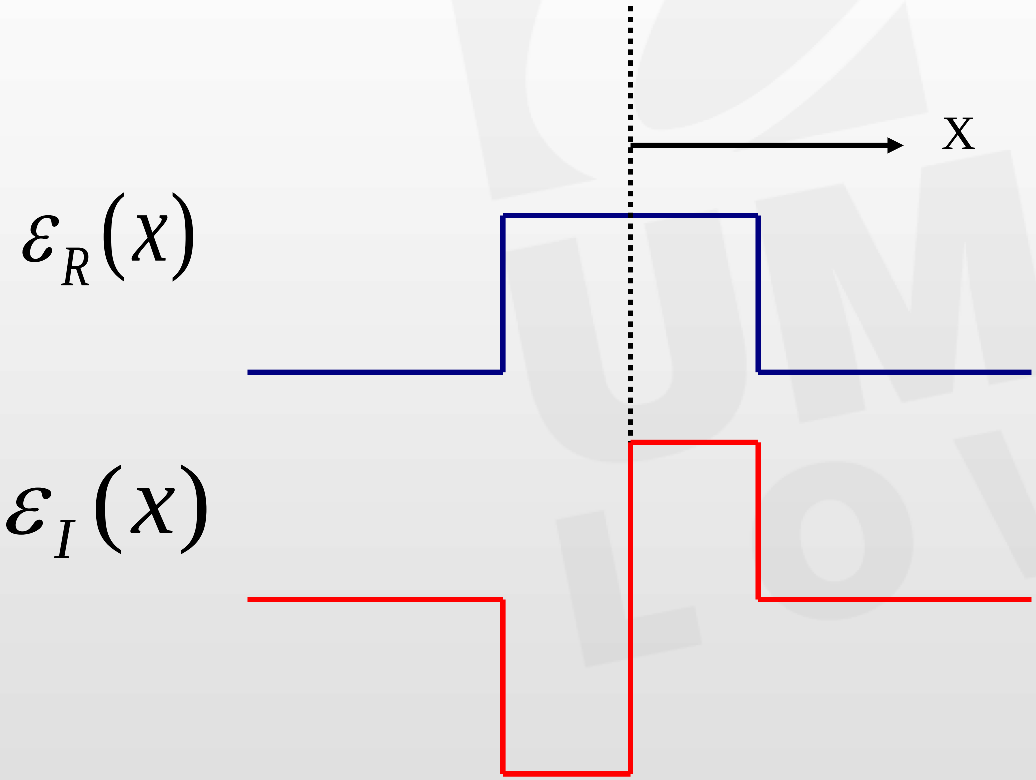
$$\nabla^2\varphi + k_0^2\varepsilon(x,y)\varphi = \beta^2\varphi$$

Schrödinger Equation

$$\nabla^2\psi - \frac{2mV(x,y)}{\hbar^2}\psi = -\frac{2mE}{\hbar^2}\psi$$

PT Symmetric Optics

$$\varepsilon(x) = \varepsilon^{*}(-x)$$

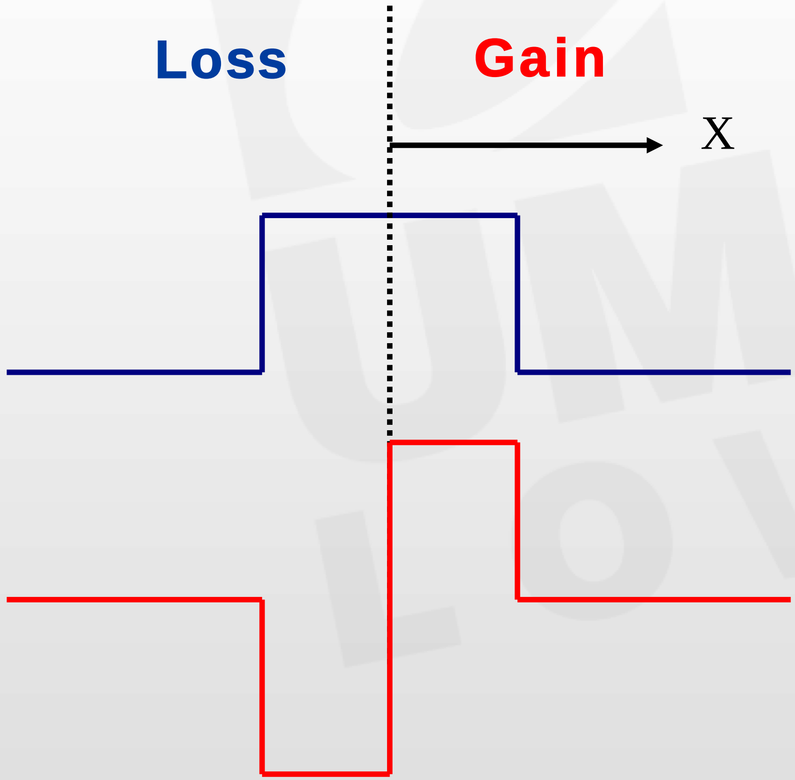


PT Symmetric Optics

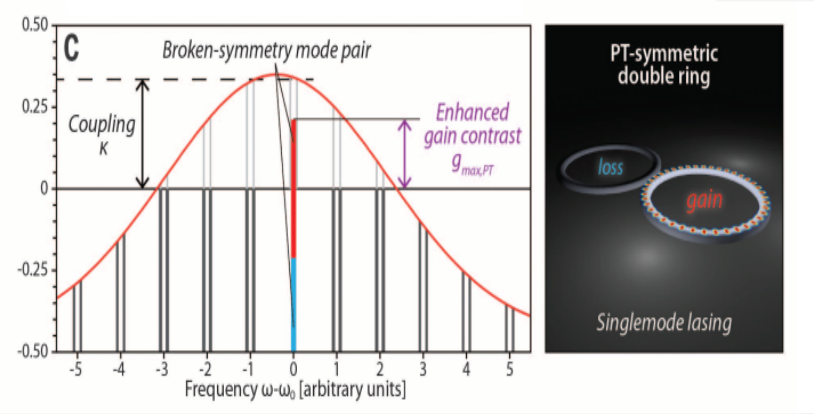
$$\varepsilon(x) = \varepsilon^{*}(-x)$$

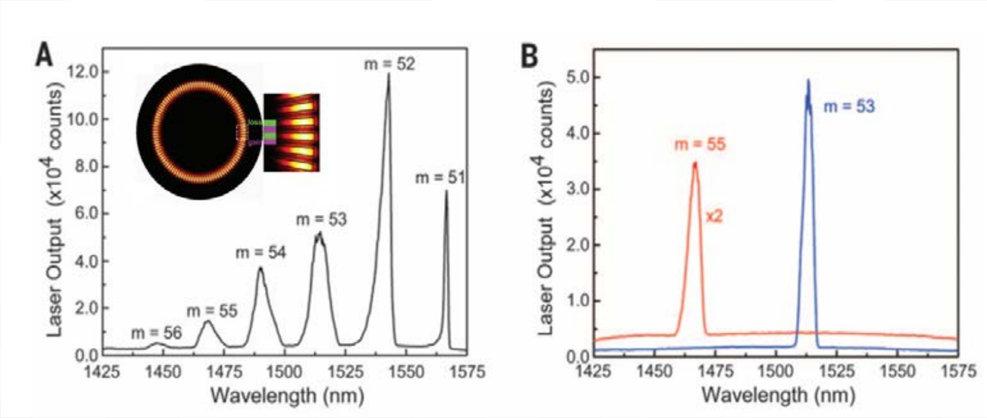
$\varepsilon_R(x)$

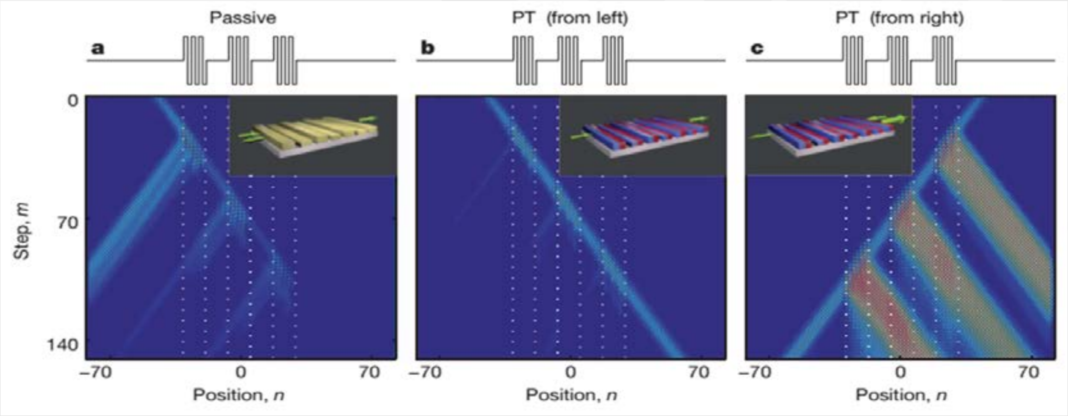
$\varepsilon_I(x)$



What Can PT Symmetric Optics Do?



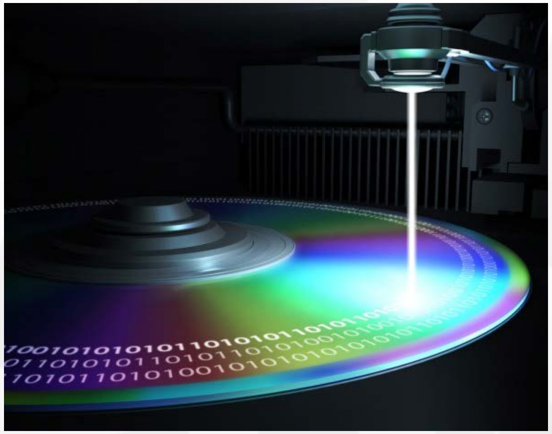




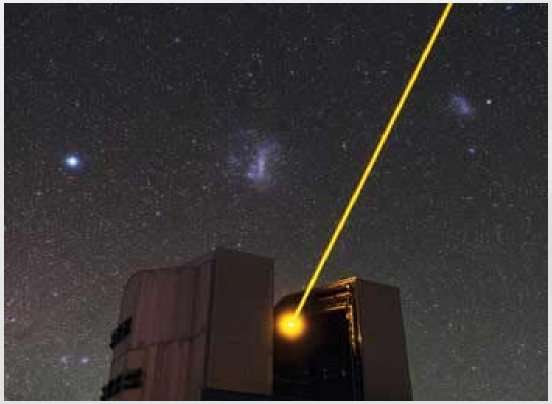
H.Hoedai, Science， Vol346 6212 (2010).
L. Feng et. al., Science, Vol 346, (2014).
A。Regensburger et. al., Nature. 488, (2012).

High Power Laser Application

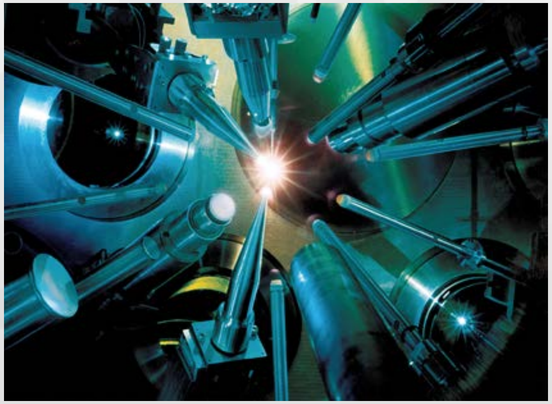
Xerographic printing



Optical data storage



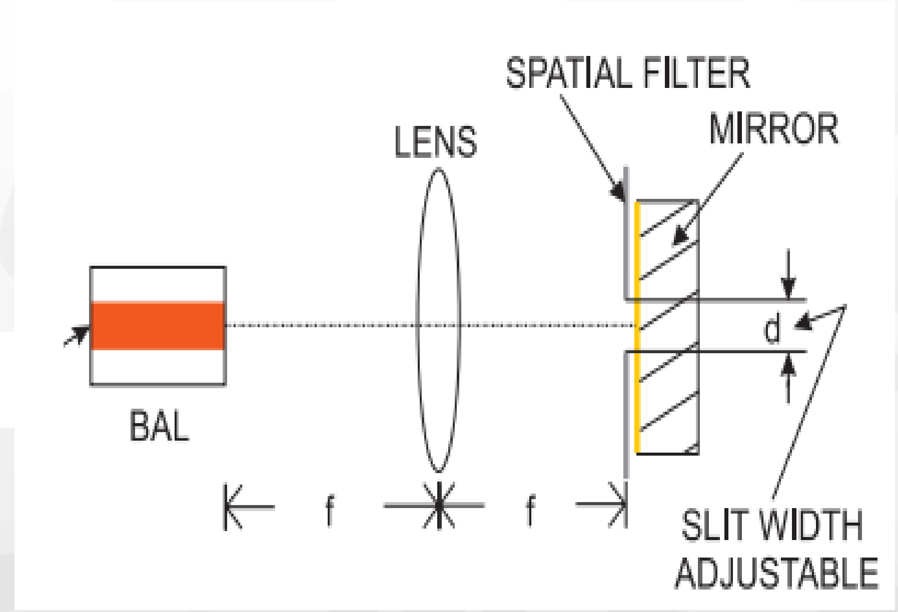
Communication



Laser-induced nuclear fusion

All images from google

Mode Filtering



- Tapered Area to amplify fundamental mode alone
- Spatial filter to increase the loss of higher order modes
- Higher order modes occur in high pumping level

https://www.photonics.com/EDU/Handbook.aspx?AID=25099
S.Wolff. Et. al., OE, Vol 5, No 3 (1999)

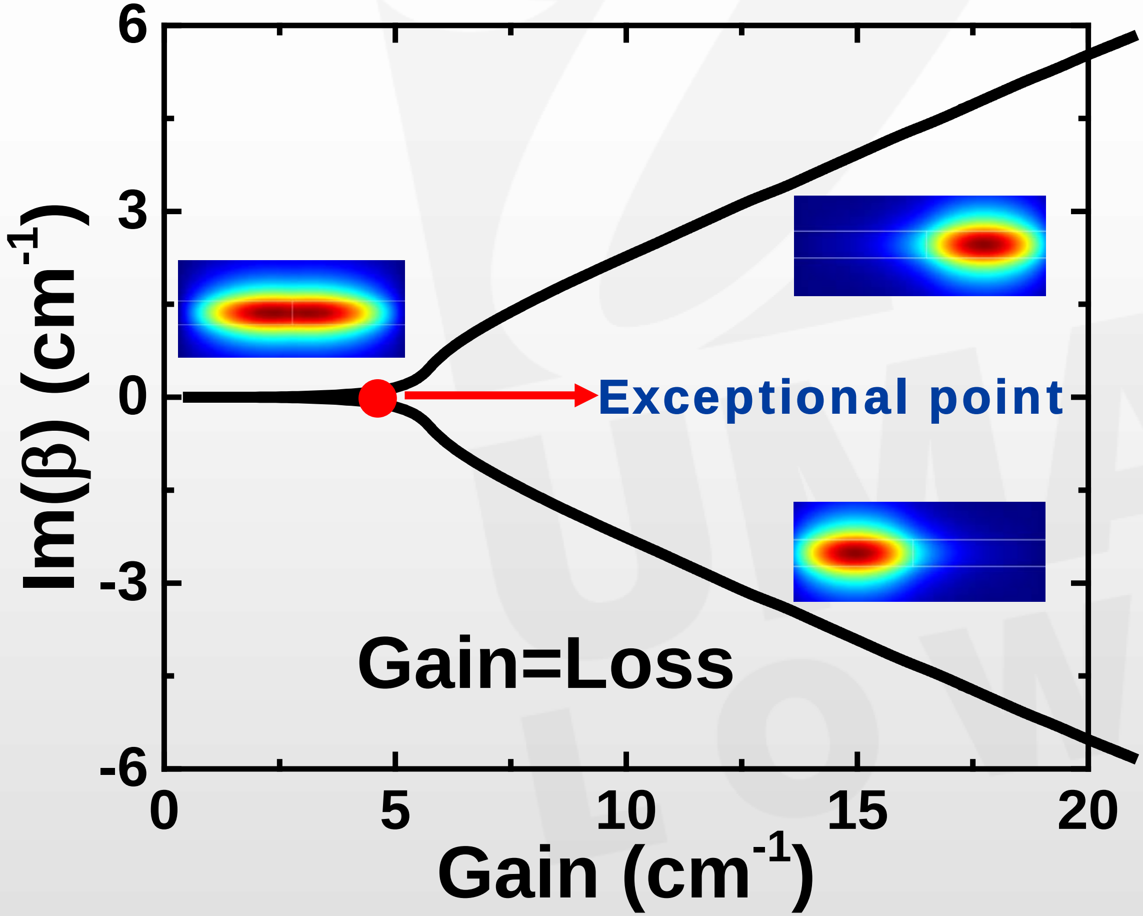
Model of Finite Element Method Simulation

Cross section

Active region

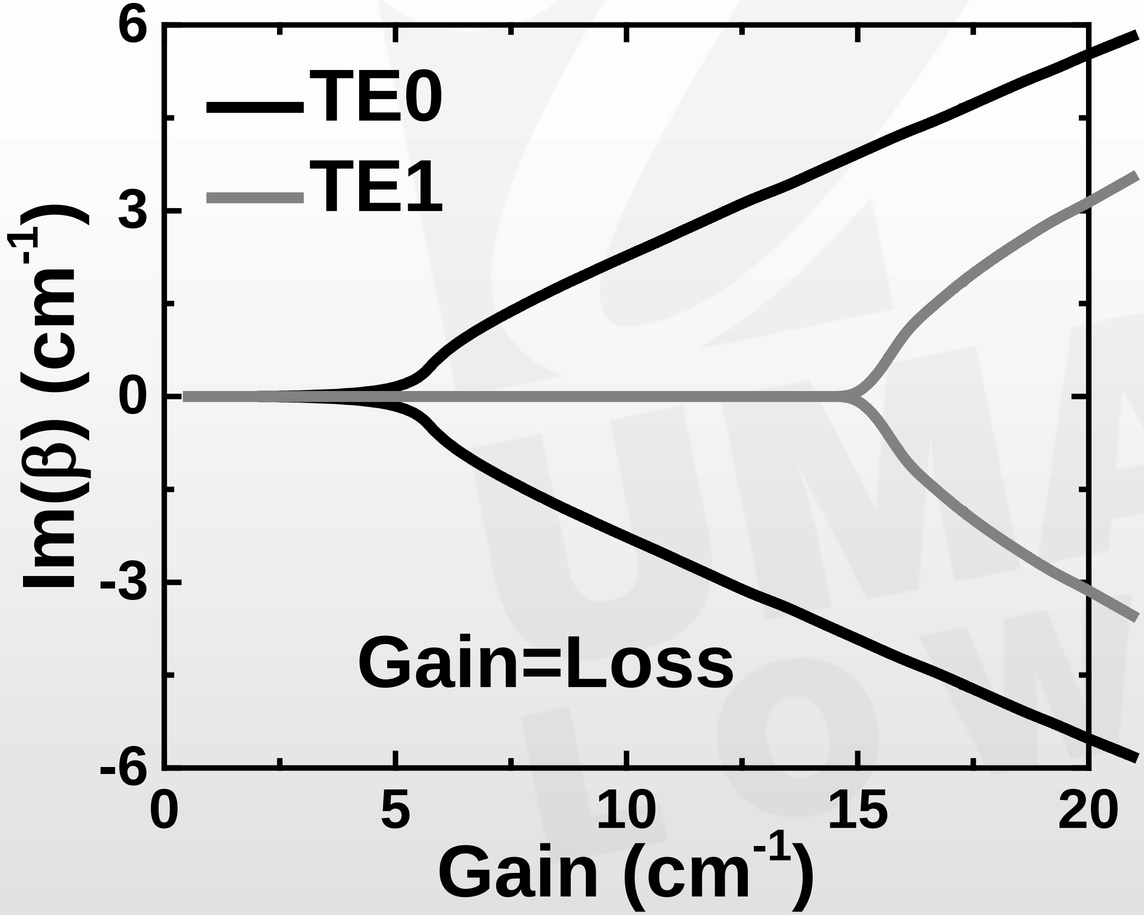
- Active region dimension:
  - Thickness=300 nm
  - Width=60 µm

FEM Simulation



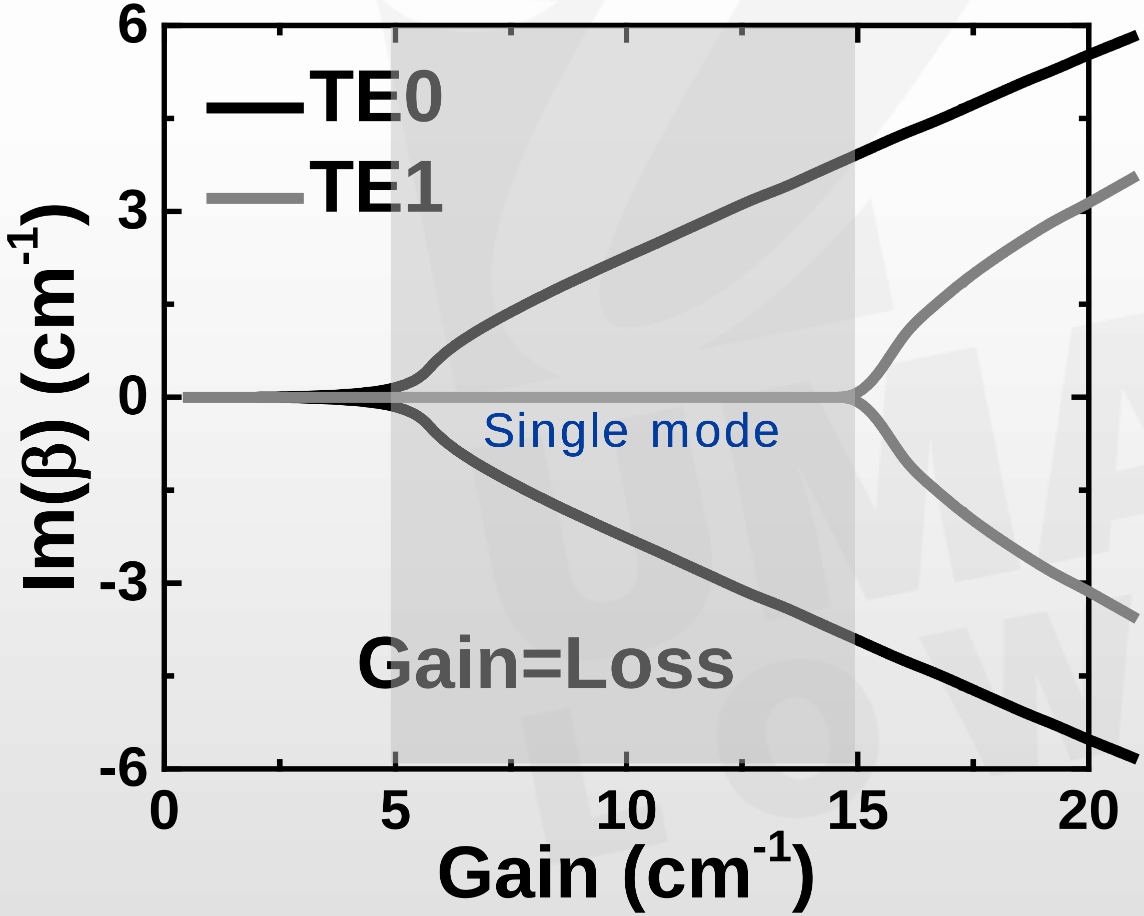
- Before EP, electric field oscillates
- After EP, mode bifurcates, either lase or absorb

FEM Simulation



- Each mode has separate EP

FEM Simulation



- Each mode has separate EP
- Single mode operation window 5 to 15 cm^{-1}

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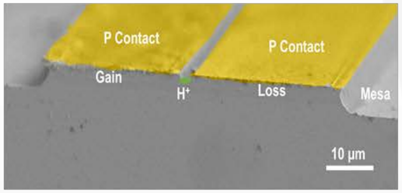
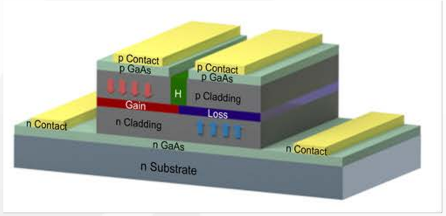
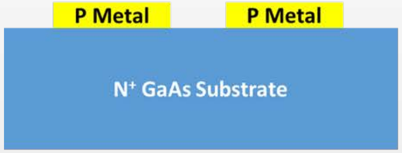
Device Fabrication



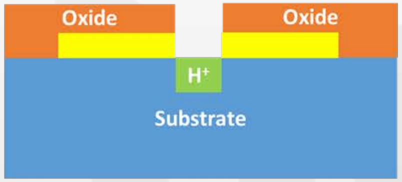
SEM image of the laser facet



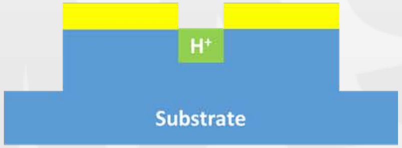
3D model of PT symmetric laser



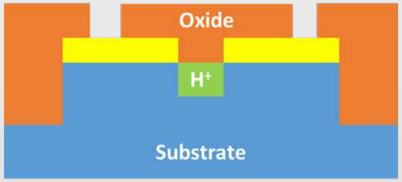
1) P Metal Deposition



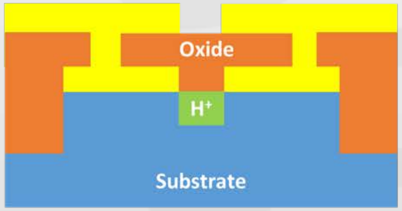
2) H+ Ion Implant



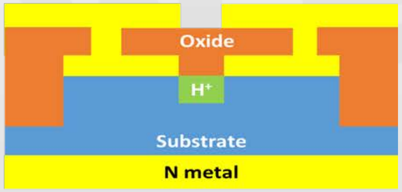
3) Mesa Wet Etch



4) Passivation PECVD

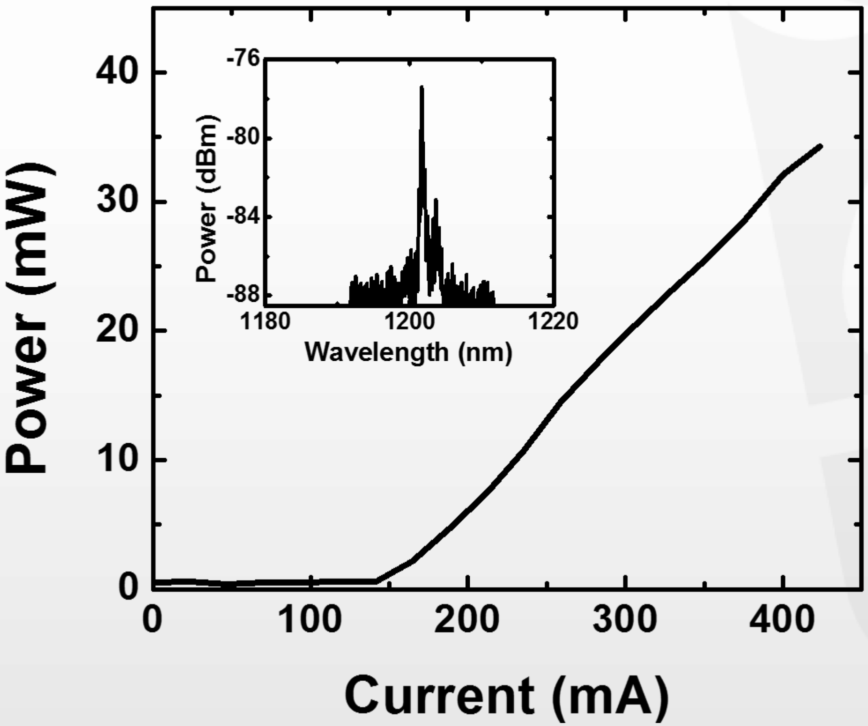


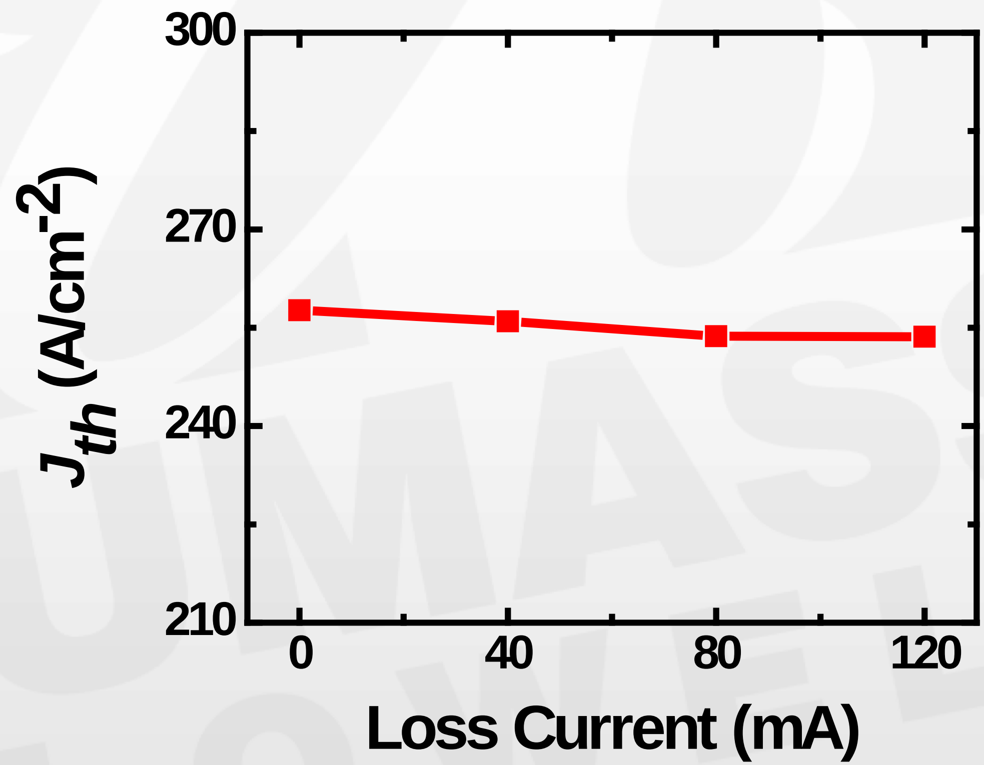
5) Interconnection Deposition



6) N Metal Deposition

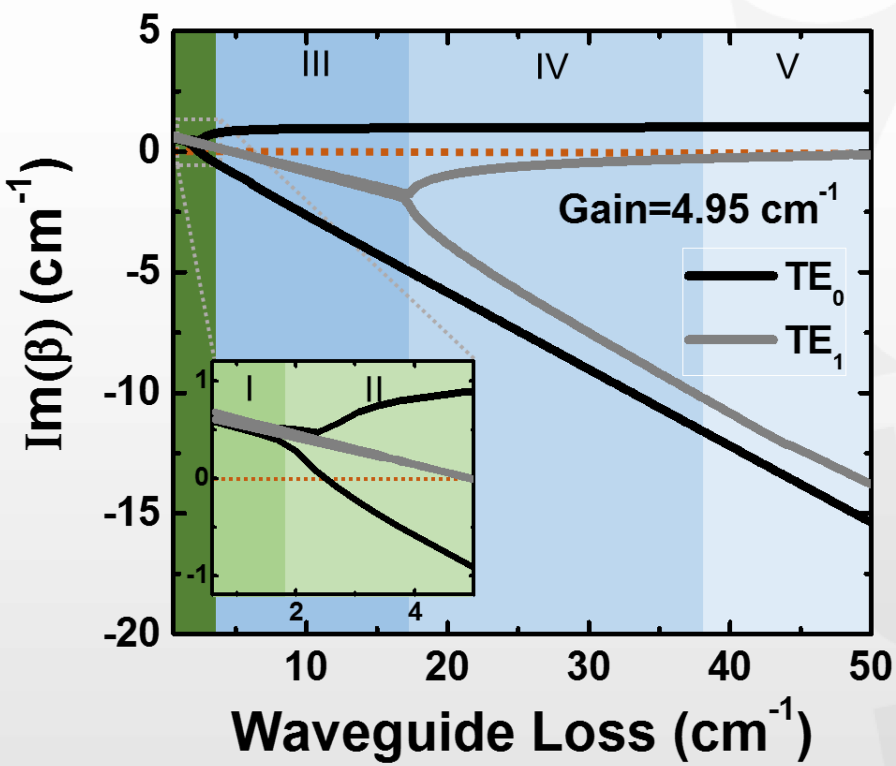
Electroluminescence and L-I



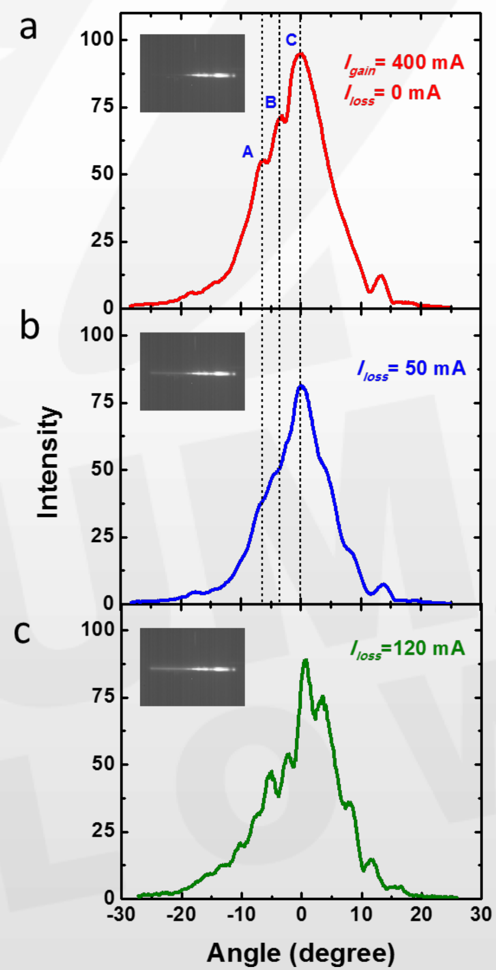


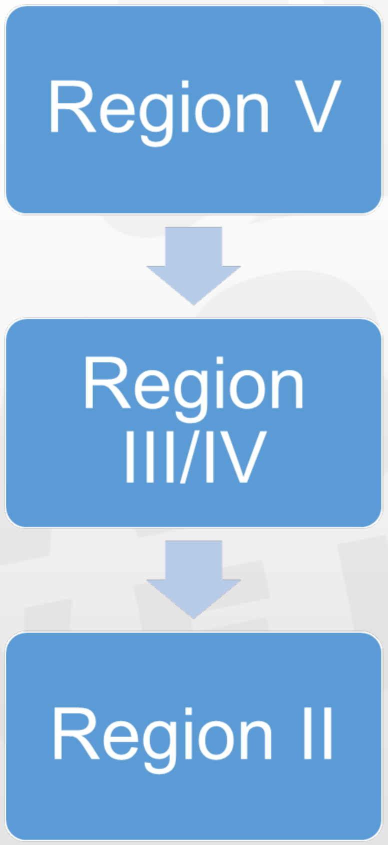
- The gain (loss) current is 400 (0 to 120) mA pulsed current of 1% duty cycle and 1 (10) µs pulse width
- The loss current always keeps below I_{th}
- J_{th} remains stable

Near- and Far- Field Characteristics



Phase Diagram





- A trend of milti→single→multi modes is observed which very well matches simulation

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Summary

- InAs Quantum Dot laser and SLEDs is an ideal candidate for integrations
- PT Symmetry is a novel concept for high-power laser applications
- Packaging is an alternative for integrations

Acknowledgement

Current Members:

- Prof. Zhao Hong (visiting professor, Qiqihaer University)
- Prof. Yuanyu Wang (visiting professor, Taiyuan University of Technology)
- Ruizhe Yao (PhD)
- Hang Li (PhD)
- Johnson Silverio (B.S)

Collaborators:

- Prof. Viktor Podolskiy (UML)
- Prof. Hualiang Zhang (UML)
- Prof. Stefan Preble (RIT)
- Prof. Xuejun Lu (UML)

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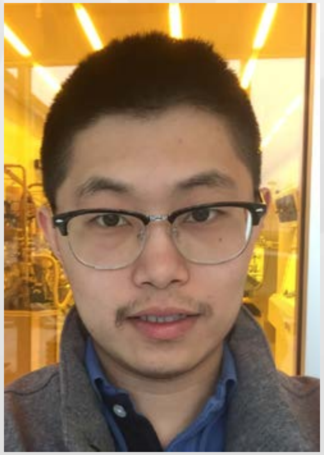
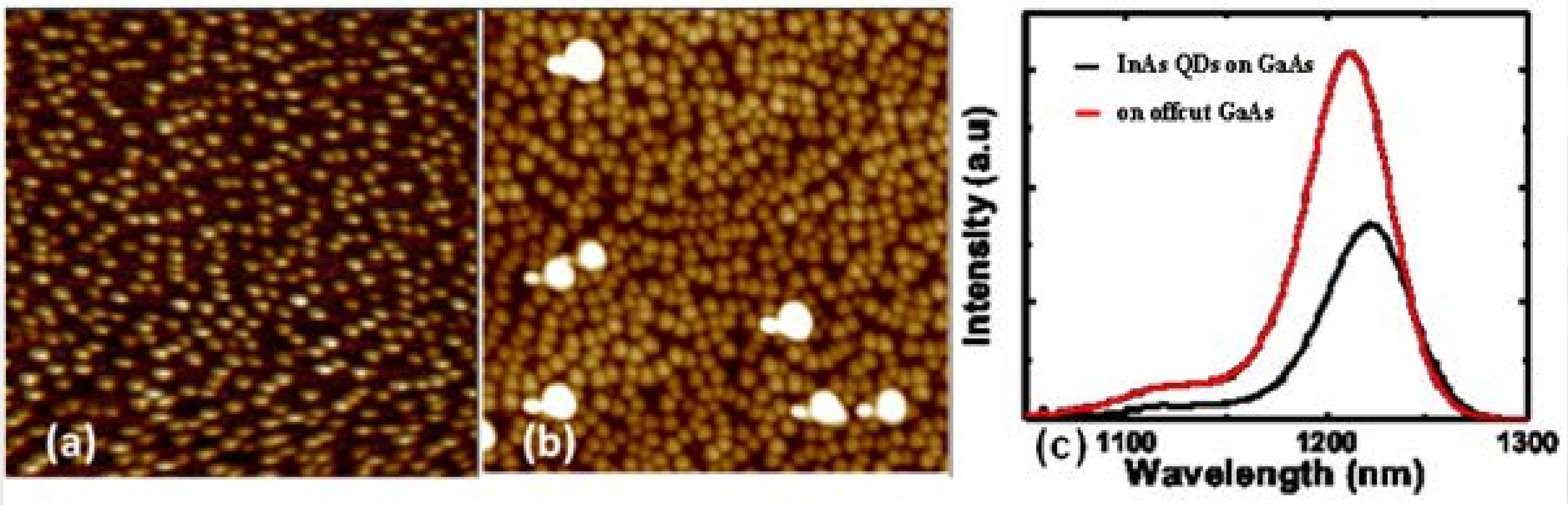


Ruizhe_yao@student.uml.edu

Acknowledgement

- Work was done CRF at UMass Lowell
- Work was supported by NSF under grant No. ECCS-1309230 and commonwealth of Massachusetts

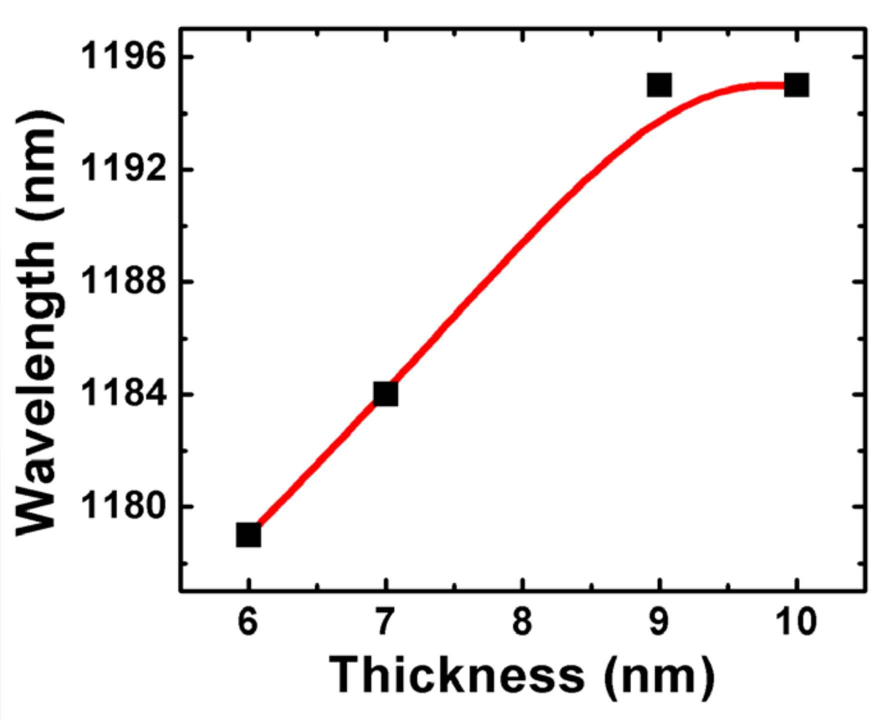
Optimization of InAs QDs

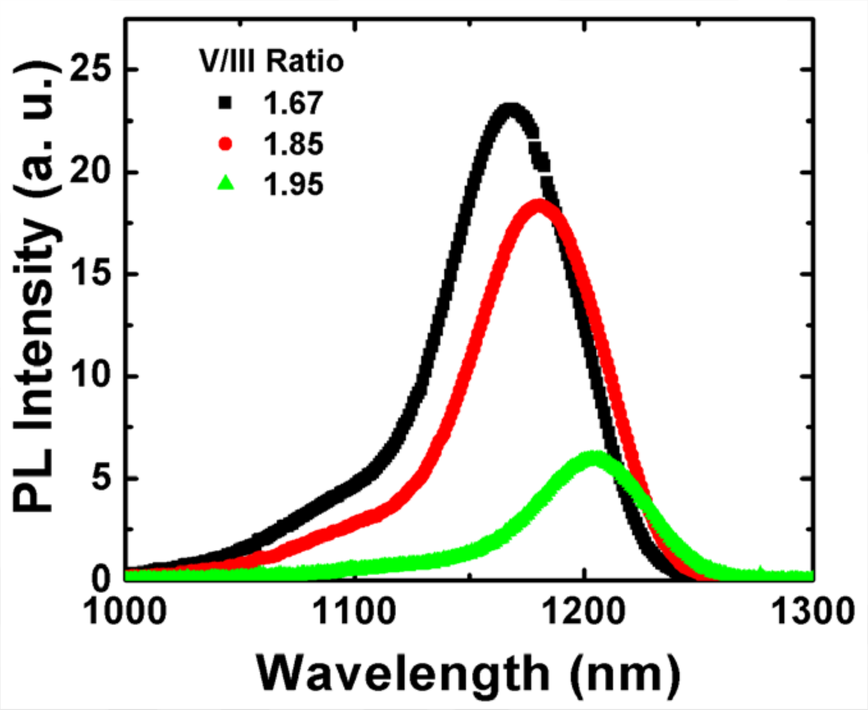


- InAs QDs grown on offcut GaAs substrates show improved PL intensity and improved dot uniformity

Guo et. al. Journal of Crystal Growth 451 (2016) 79–82

Optimization of InAs QDs





- The thickness and III-V ratio of the LT GaAs layer is playing a critical role of the dot performance

Guo et. al., Journal of Vacuum Science & Technology B, 34(4), 041223, (2016)

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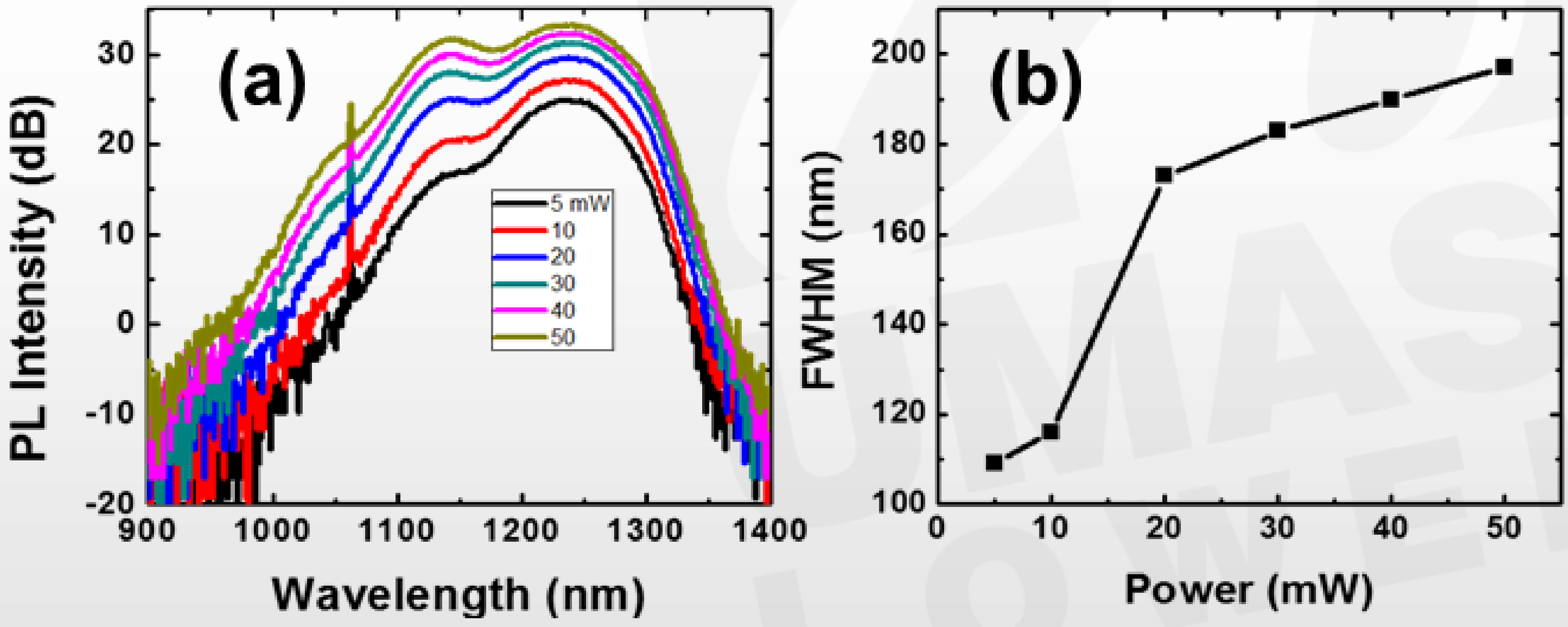
Chirped QDs with InAlAs SRLs



- By changing the SRL design, the GS and ES emission wavelengths can be tuned

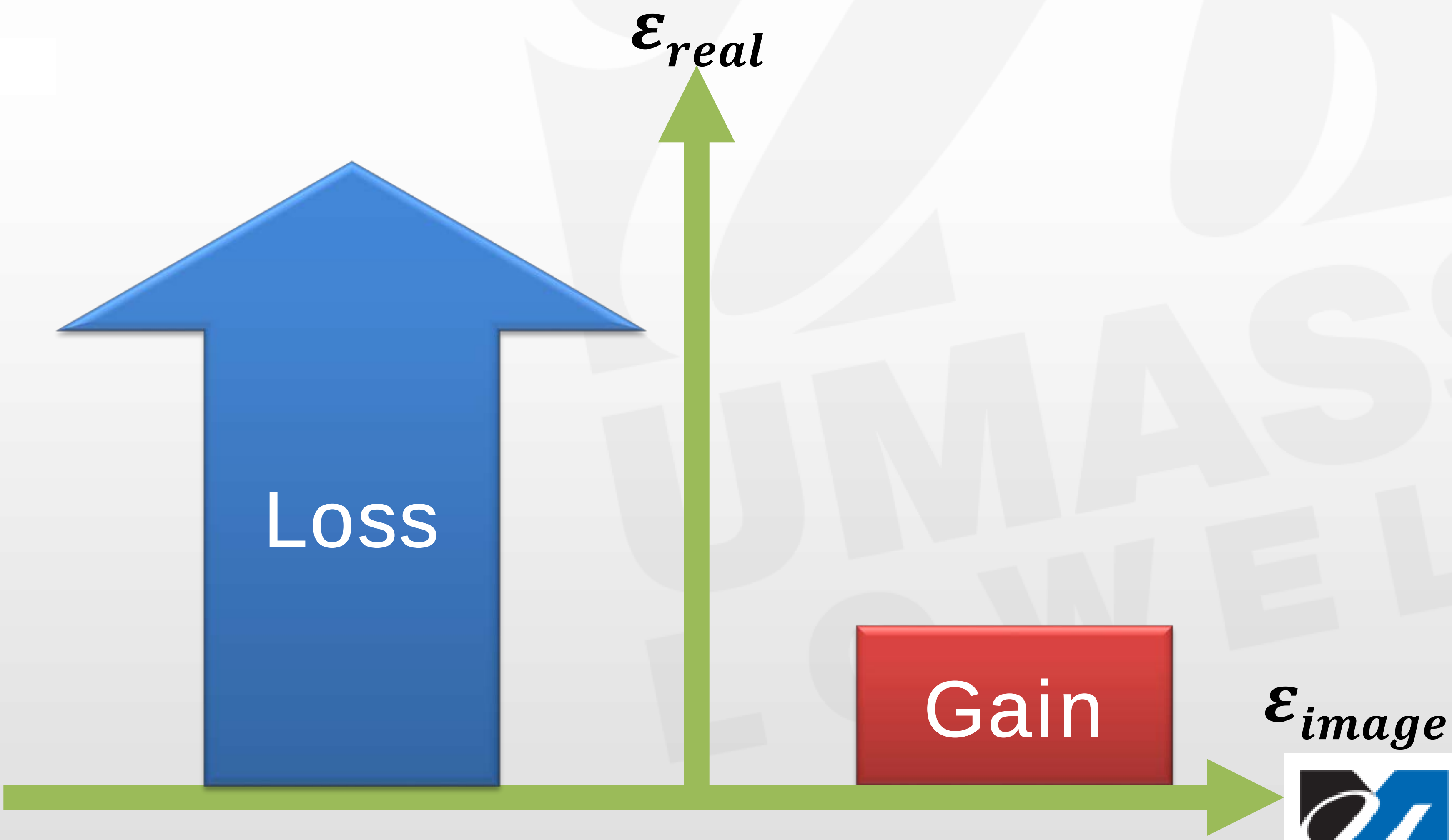
Lasing Condition

$$g_{th} = \overline{\alpha}_i + \overline{\alpha}_m$$

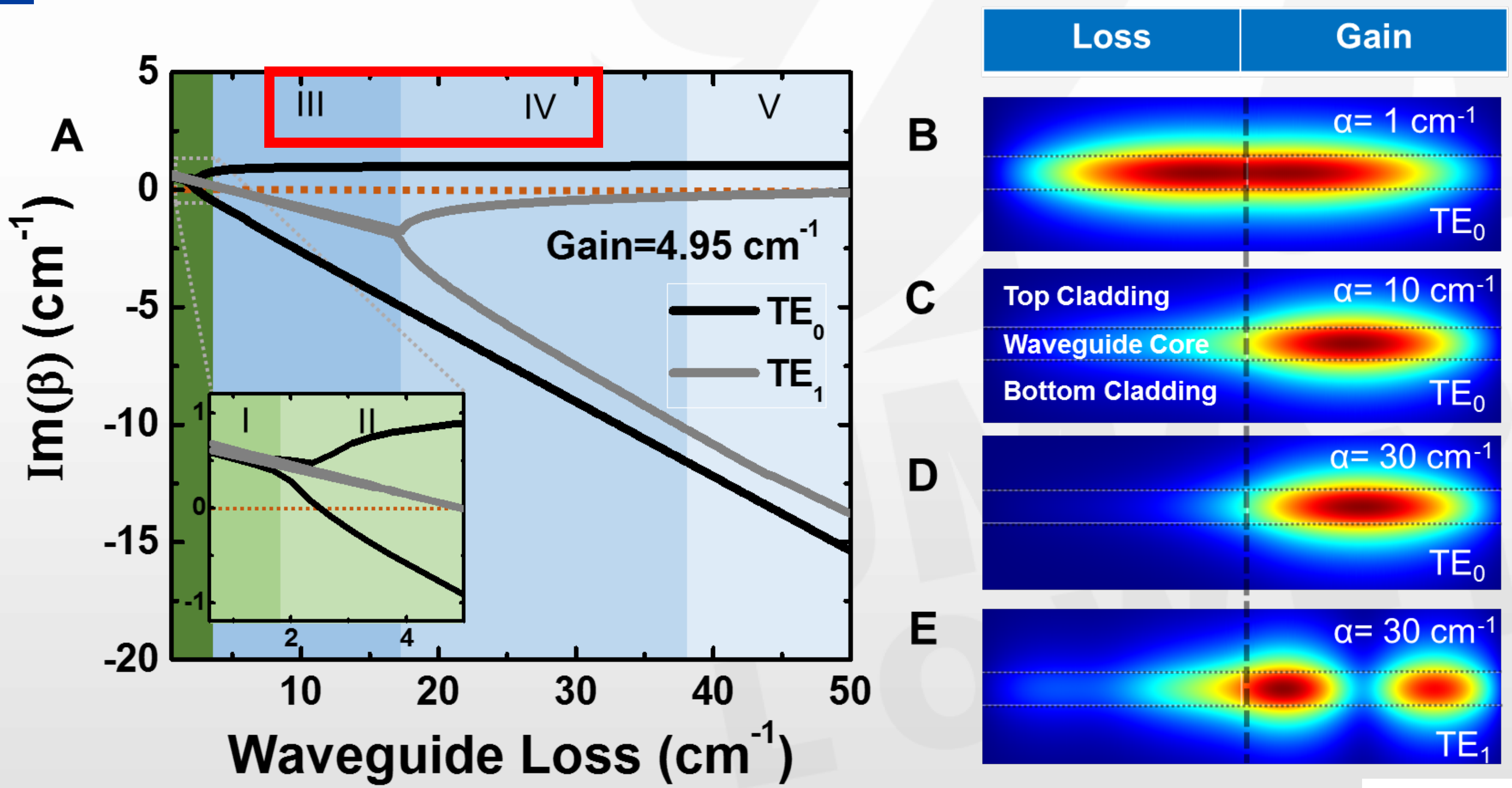
$$g_{net} = g_{th} - \overline{\alpha}_i = \overline{\alpha}_m = \frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right)$$

- Hard to maintain gain=loss all the time
- Gain is clamped

Fix Gain and Tune Loss

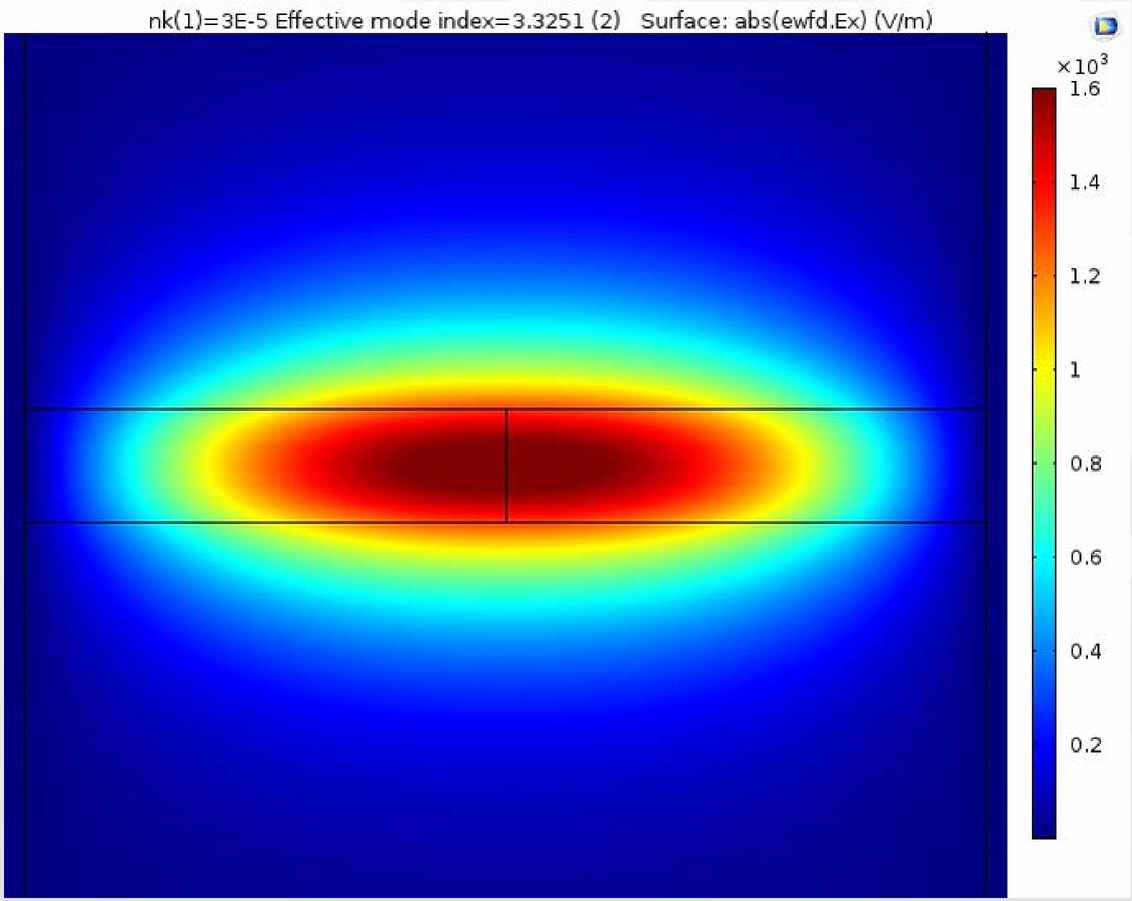


Mode Selection in PT Laser



- Region III & IV is the single Transverse-mode operation window
- TE_1 is not observable until into region V

FEM Simulation



Coupled Waveguide Theory

$$\frac{da_m}{dz} = i\beta_m a_m + i\kappa_m b_m + g_m a_m$$

$$\frac{db_m}{dz} = i\beta_m b_m + i\kappa_m a_m + g_m b_m$$

$$\rho_m = \frac{g_m}{\kappa_m}$$

- $\rho_m < 1$, β_m is real, PT is not broken
- $\rho_m > 1$, , β_m is complex, PT is spontaneously broken

Coupled Waveguide Theory

$$\frac{da_m}{dz} = i\beta_m a_m + i\kappa_m b_m + g_m a_m$$

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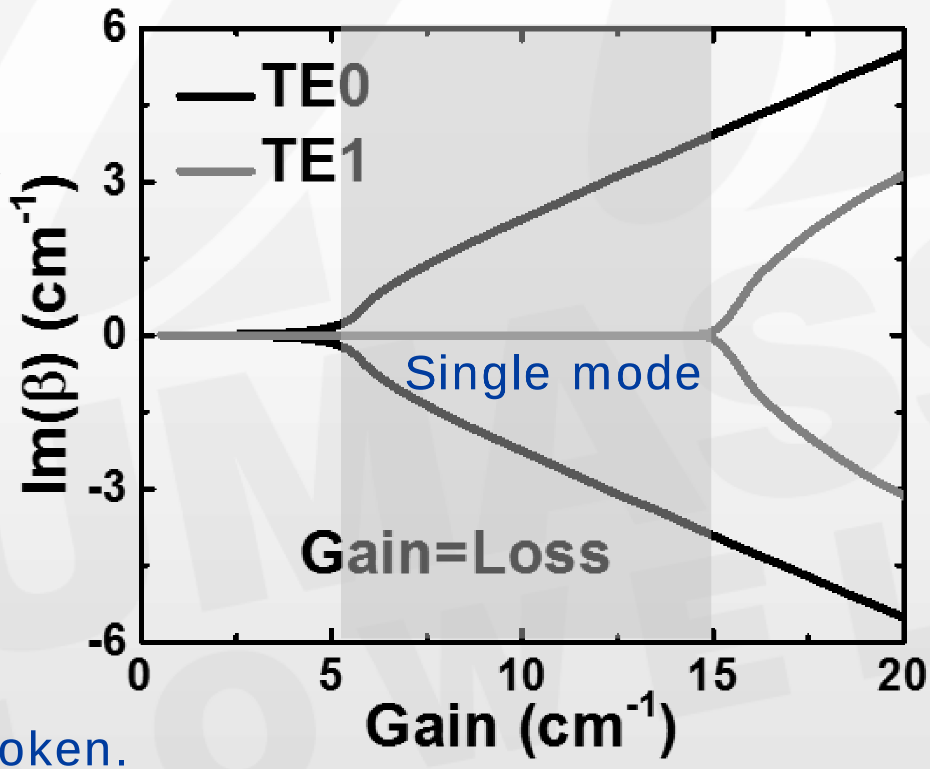
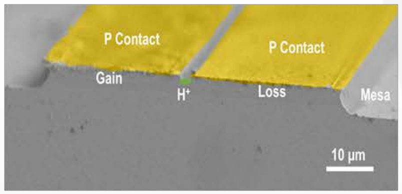
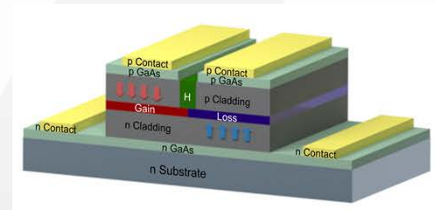


- $\rho_m < 1$, β_m is real. PT is not broken.
- $\rho_m > 1$, , β_m is complex. PT is spontaneously broken.
- κ_m increases with m.

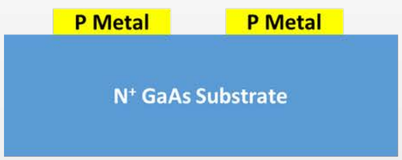
Device Fabrication



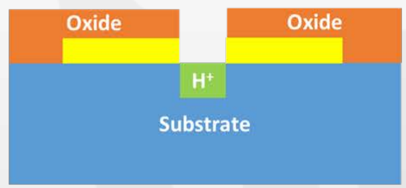
SEM image of the laser facet



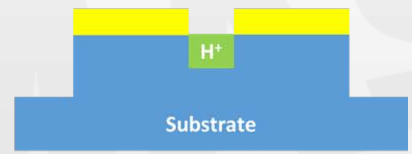
3D model of PT symmetric laser



1) P Metal Deposition



2) H+ Ion Implant



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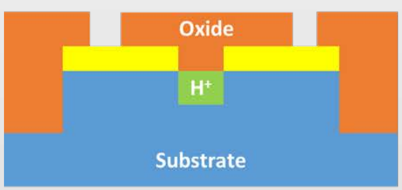

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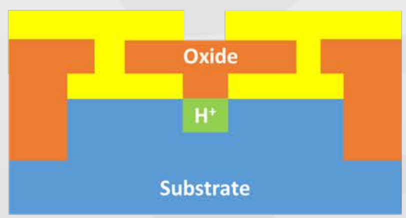

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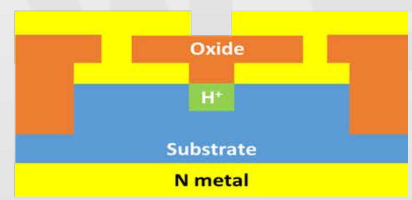
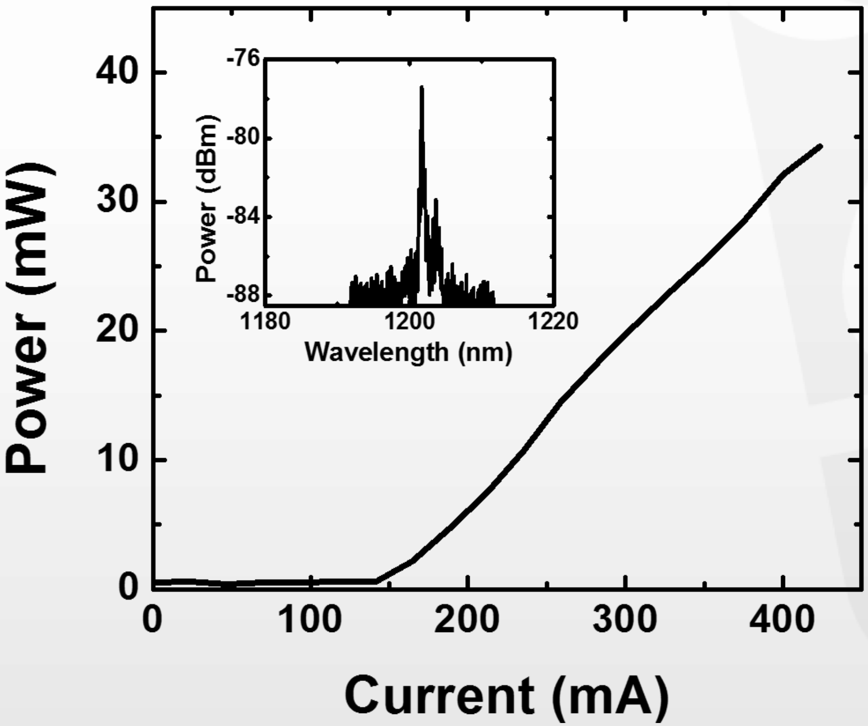
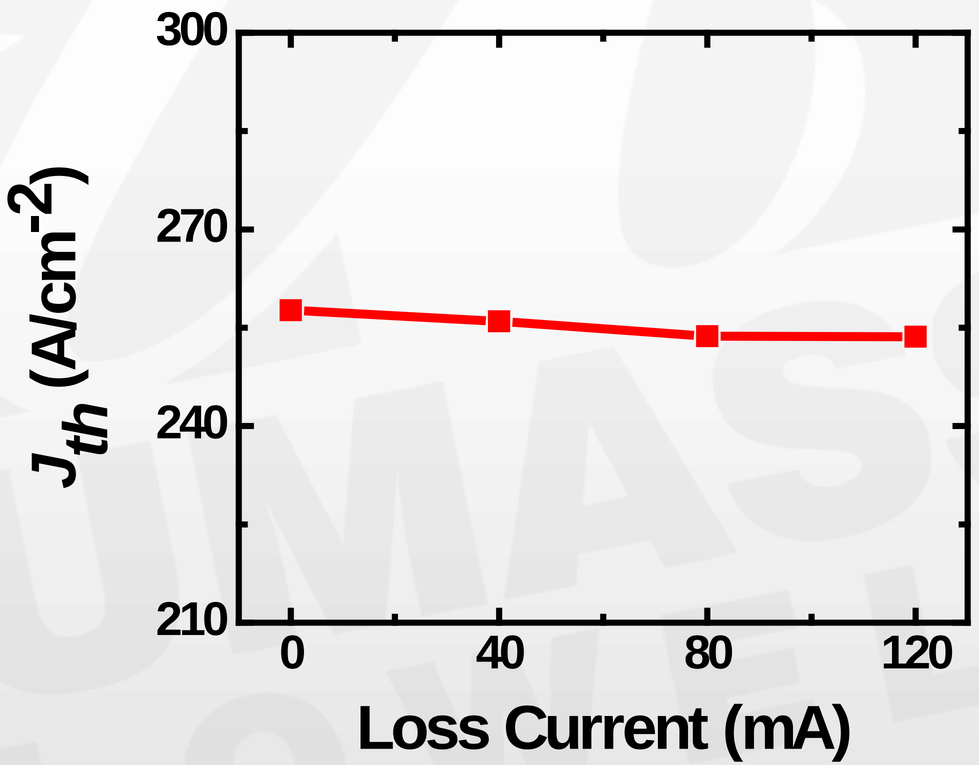


6) N Metal Deposition

Electroluminescence and L-I





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- The loss current always keeps below I_{th}
- J_{th} remains stable

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Near- and Far- Field Setup

- Schematic of near-field measurement

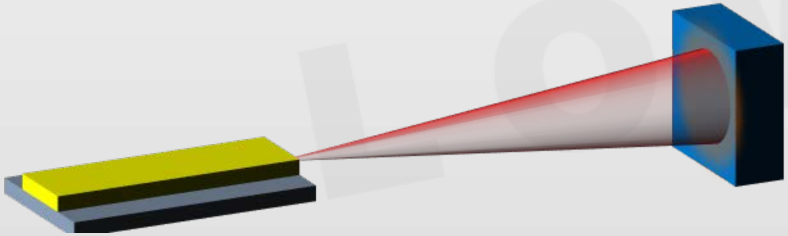
PT symmetric laser

Focus Lens

Near Infrared Camera

- Schematic of far-field measurement

PT symmetric laser



Beam Profiler