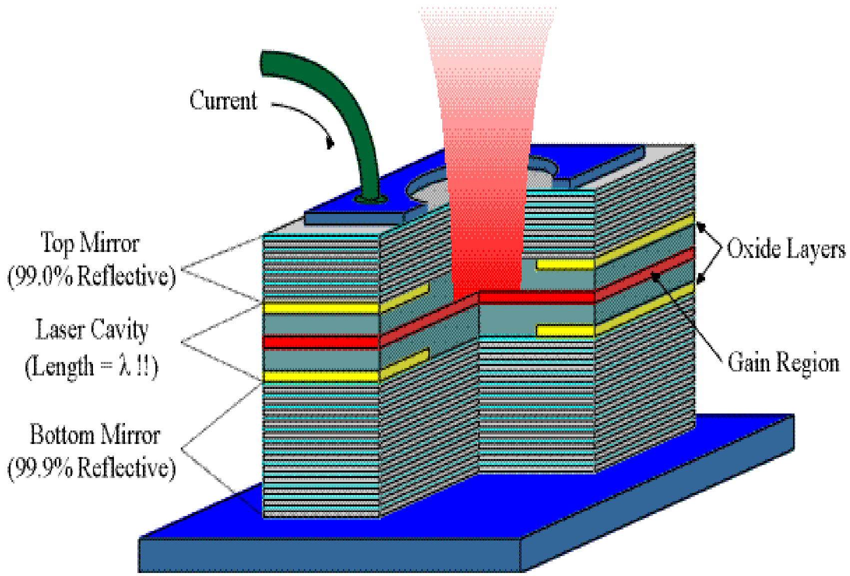
THE UNIVERSITY OF ARIZONA
Wyant College of Optical Sciences

The 22nd Mini-Conference Sponsored by the Coherent/II-VI Foundation

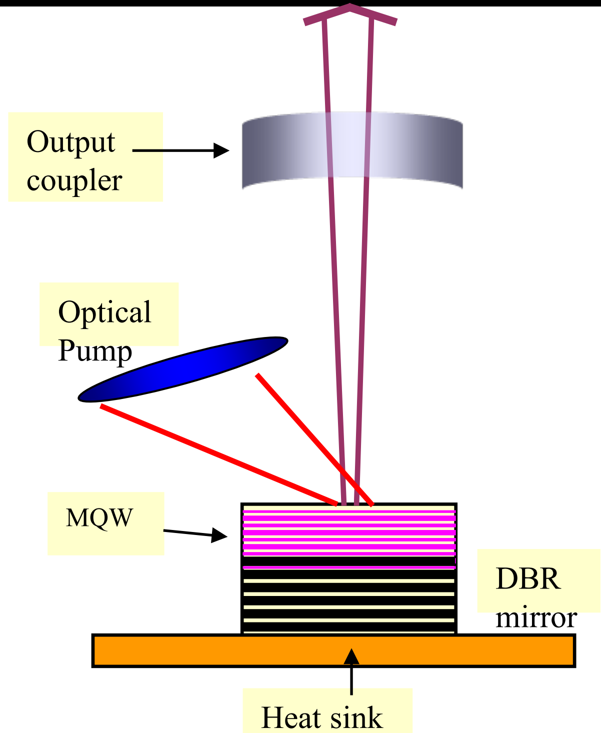
High-Order Laguerre-Gaussian Beam Mode-Locked VECSELs for Secure Free Space and Fiber Communications

- PhD Students: Nathan Gottesman
- Kelby Todd
- PI: Dr. Mahmoud Fallahi

Introduction to surface Emitting Lasers: VCSEL vs. VECSEL?



VCSEL (electrically pumped)

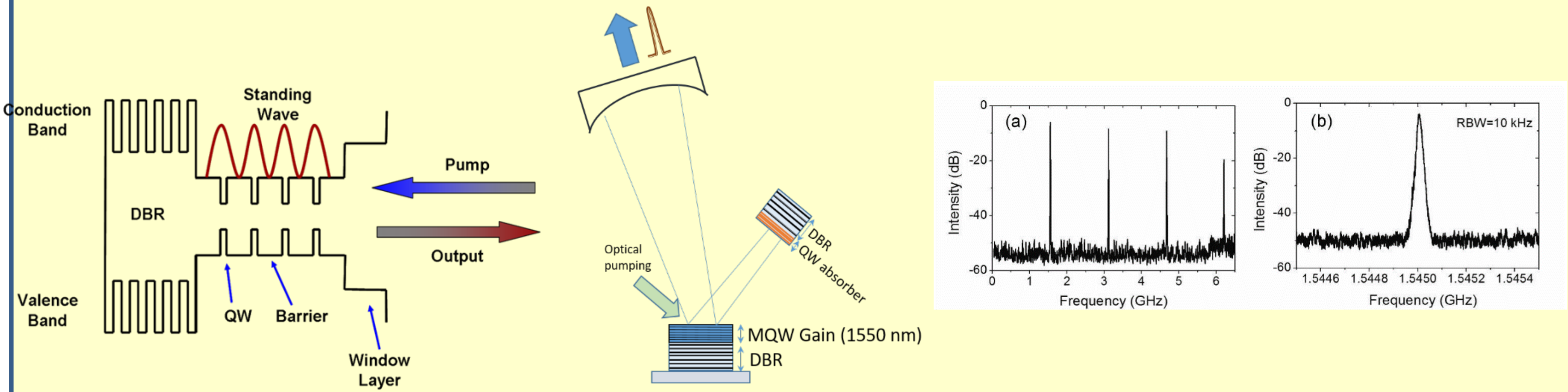


VECSEL (typically optically pumped)

Benefits of VECSELs

- **High Power and High Beam Quality**
- **Wavelength Tolerant Barrier pumping with low cost broad-area lasers**
- **Power Scaling by increased beam diameter**
- **Access to intra-cavity radiation (Wavelength tuning, mode locking, high-orders beams generation)**

Mode-Lock VECSEL for Optical Communication

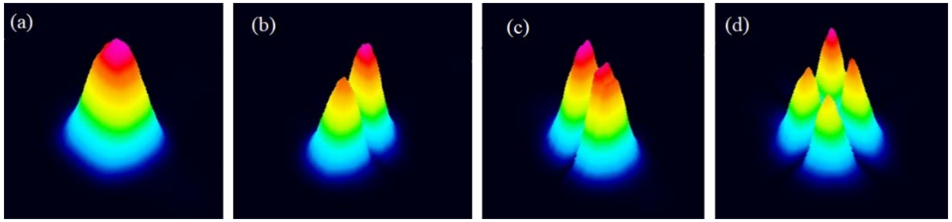


Schematics picture of the proposed mode-lock VECSEL with InGaAsP QW, and SESAM saturable absorber.

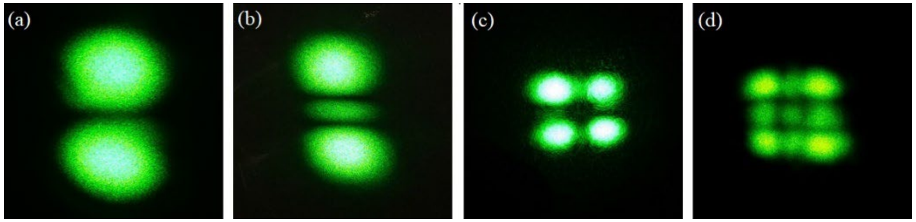
- Design, fabrication and characterization of high power, high-order mode-locked VECSELs in the 1050nm and 1310nm.
- The research will provide unique cross-disciplinary research opportunity for 2 PhD students: design and modeling SC lasers, Micro/nanofab., cavity design, nonlinear optics, high energy short pulse,…..

Watt-level Outputs of Higher HG and LG Modes

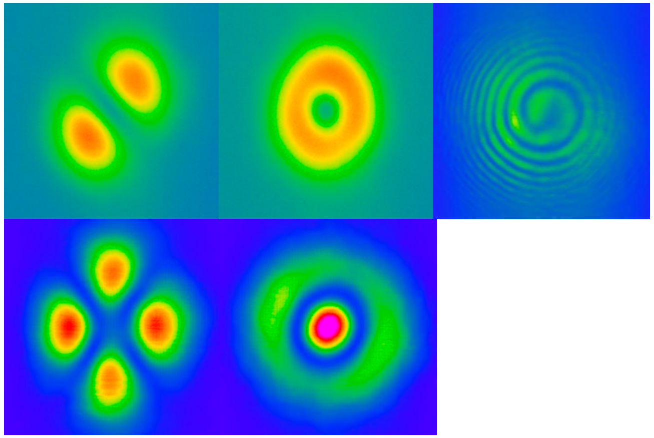
Applications: in fiber and free space communication, atom and particle trapping, manipulation of bilogical cells,…



3D profiles of fundamental wavelength Hermite-Gaussian modes



Images of green Hermite-Gaussian modes



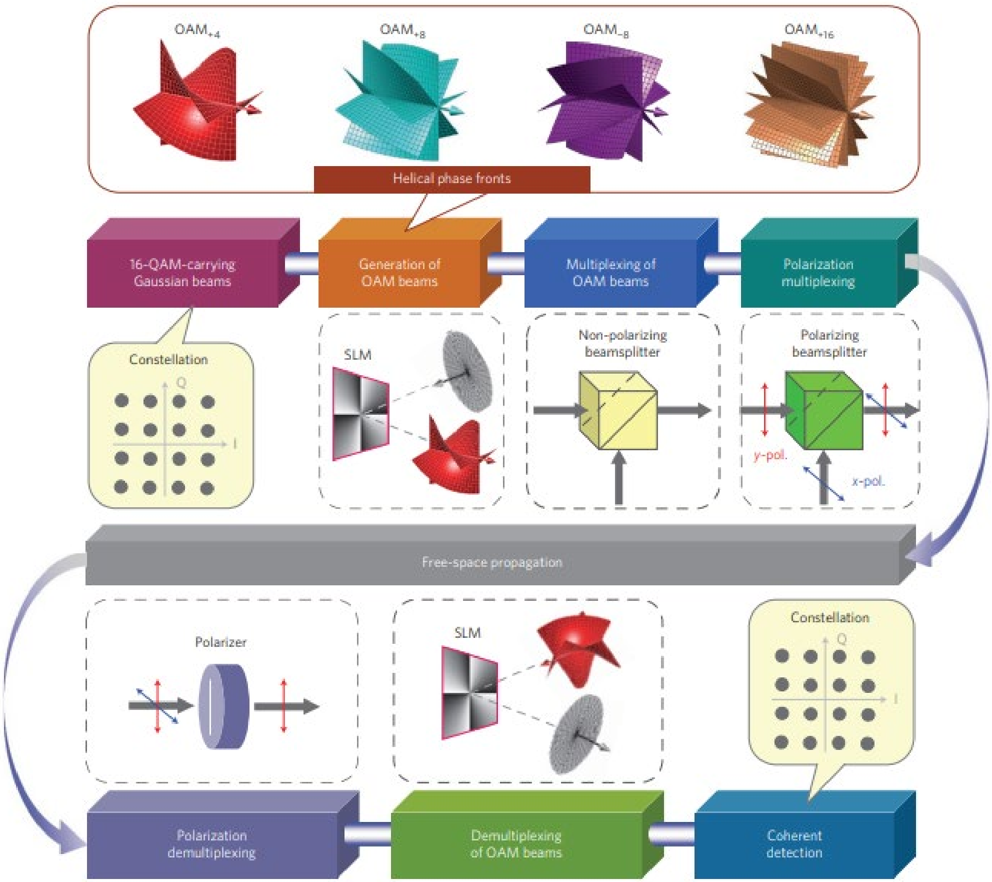
Images of HG_{10}, HG_{11} and their corresponding converted LG_{10}, LG_{01} modes; spiral interference pattern of LG_{01} mode with spherical wavefront.

PhD students:

- **Mr. Nathan Gottesman**
- **Mr. Kelby Todd**

Motivation

- Challenge: Higher bandwidth and data rates required as internet traffic continues to grow
- Solution: Mode Division Multiplexing (MDM)
  - requires a robust, tunable, stable, ultrashort pulsed high order laser source at telecom wavelengths (~1050 nm and 1310 nm) that is compact and inexpensive
- Approach: A custom VECSEL
  - Tunable for FSO (1030 nm – 1070 nm)
  - Tunable in the O-band (1290 nm – 1330 nm)
  - Ultrashort pulses (<10 ps)
  - High power operation (>1 W peak power)
  - Fast, flexible repetition rates (500 MHz-several GHz)
  - Higher Order Laguerre Gaussian and Hermite Gaussian modes
  - Compact package



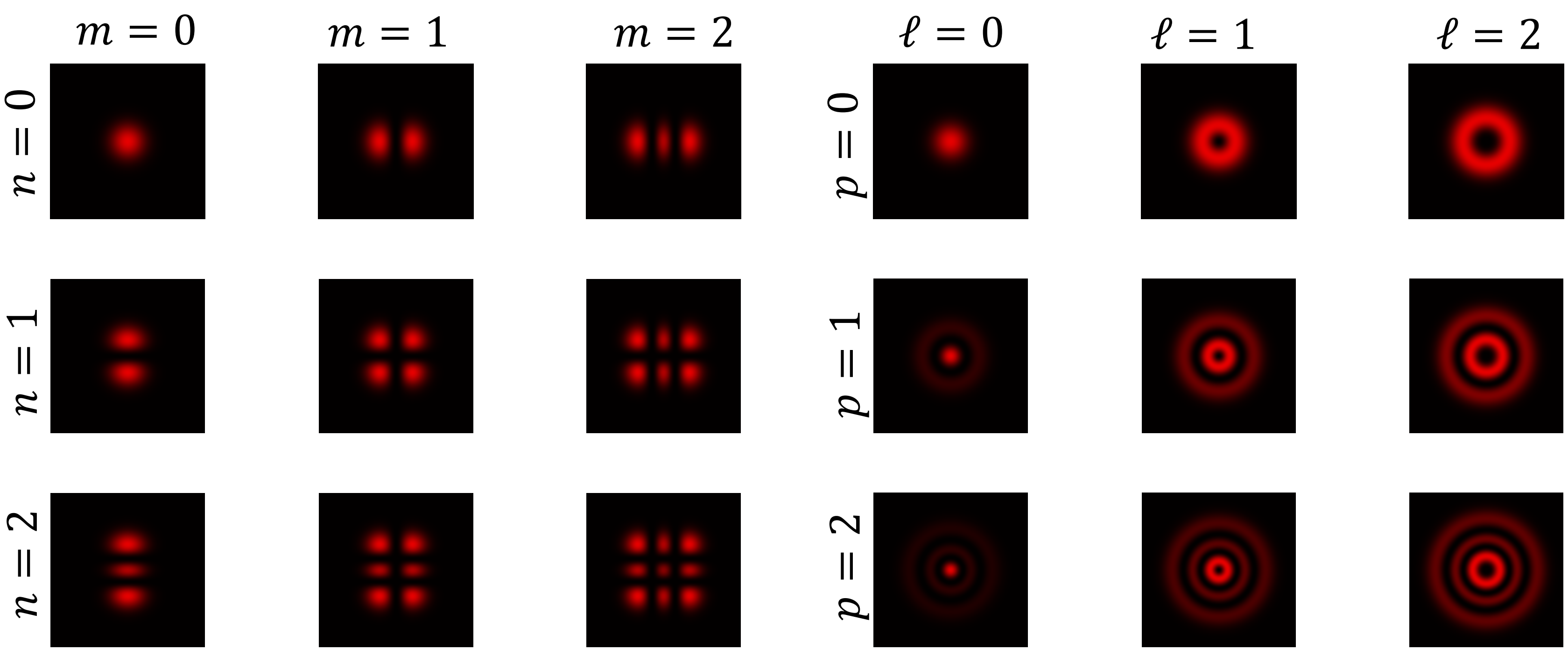
Ref. [1]

Higher Order Transverse Modes

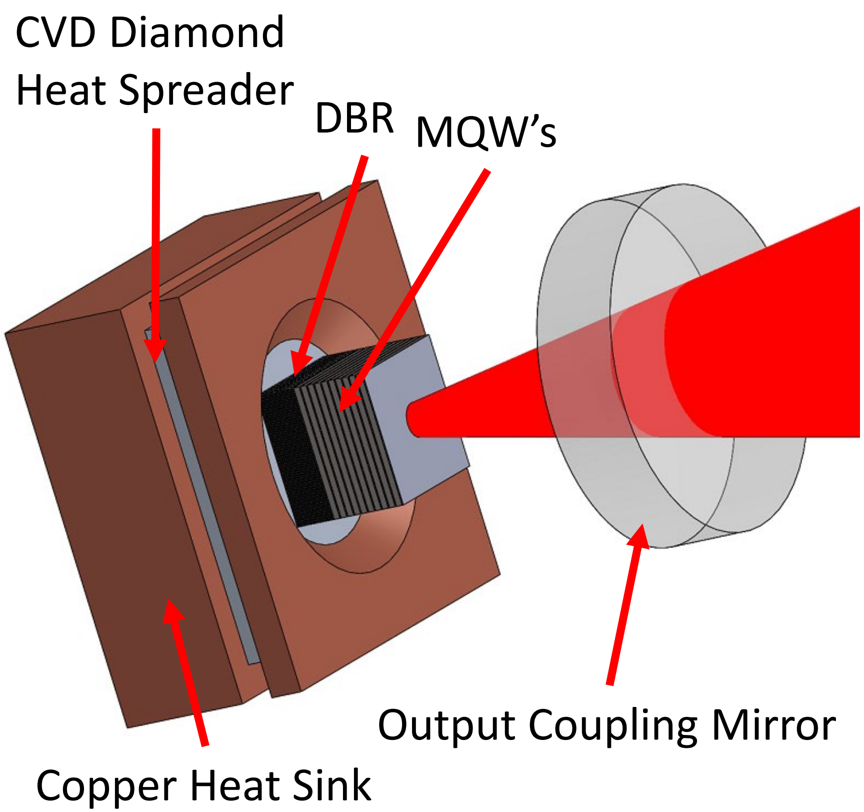
Paraxial Wave Equation

$$\nabla_T^2 \varepsilon + 2ik\frac{\partial \varepsilon}{\partial z} = 0$$

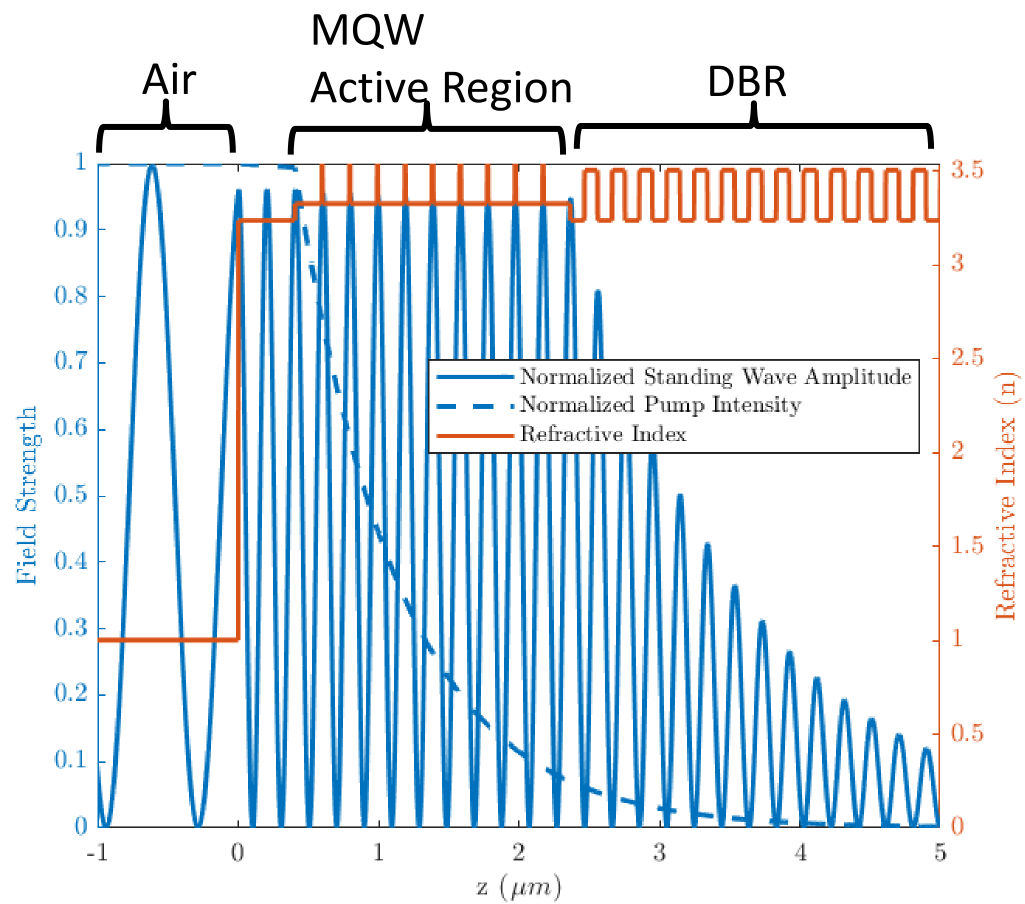
Hermite Gaussian **Laguerre Gaussian**



Vertical External Cavity Surface Emitting Laser

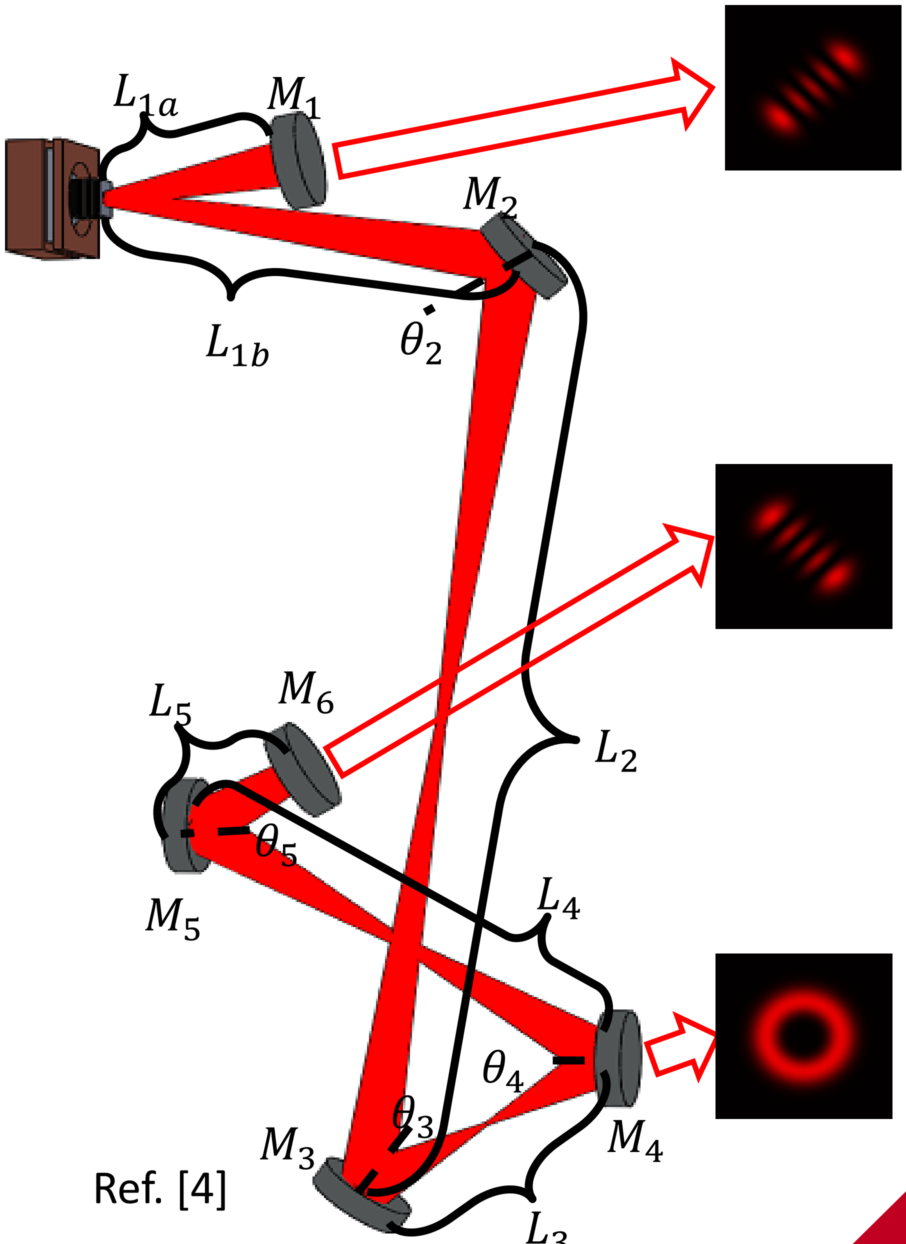


VECSEL Linear Cavity Geometry



Semiconductor Gain Chip Structure

CW Intra-Cavity Astigmatic Mode Conversion

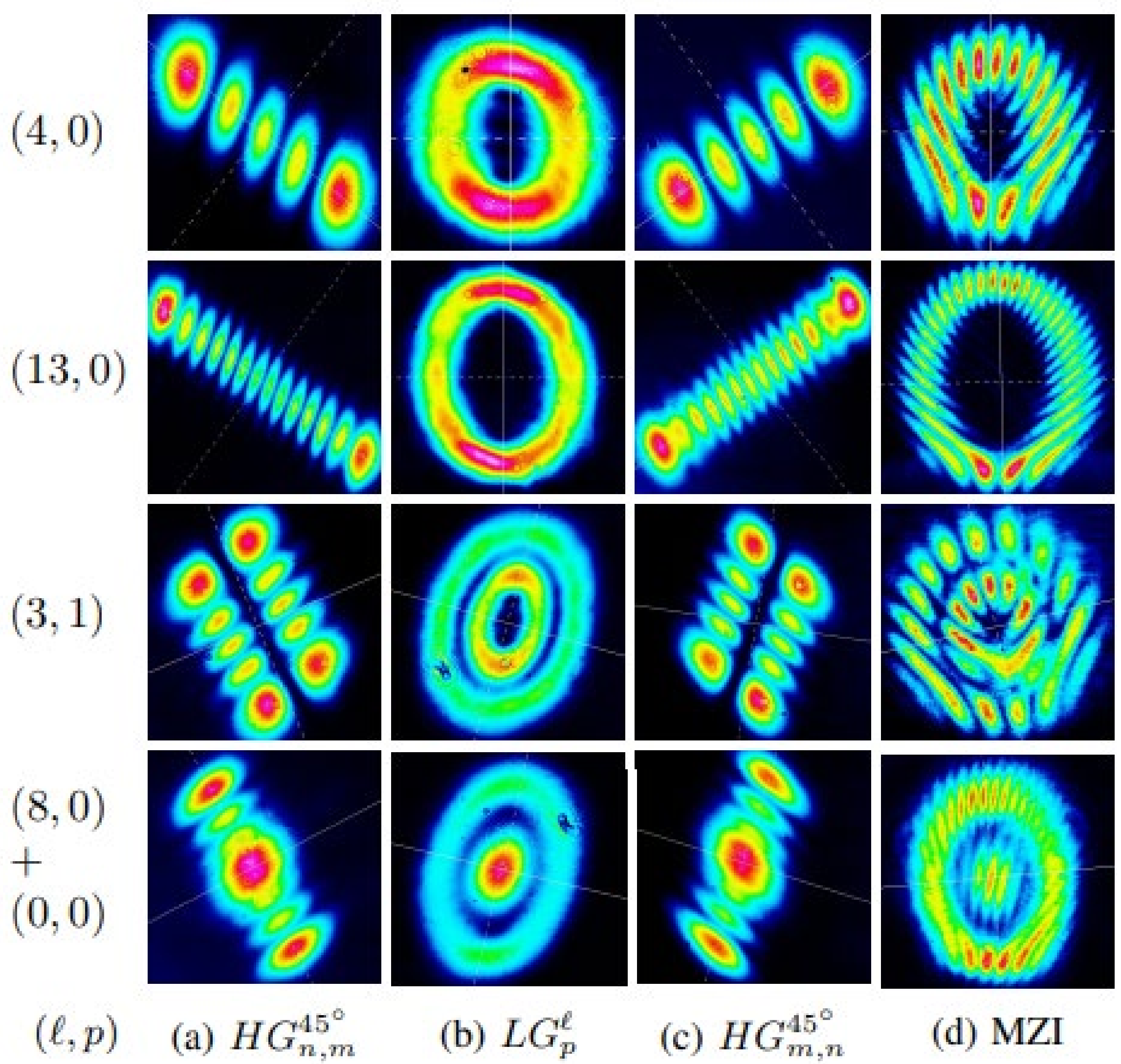


Ref. [4]

Proof of concept for Intra-Cavity Astigmatic Mode Conversion

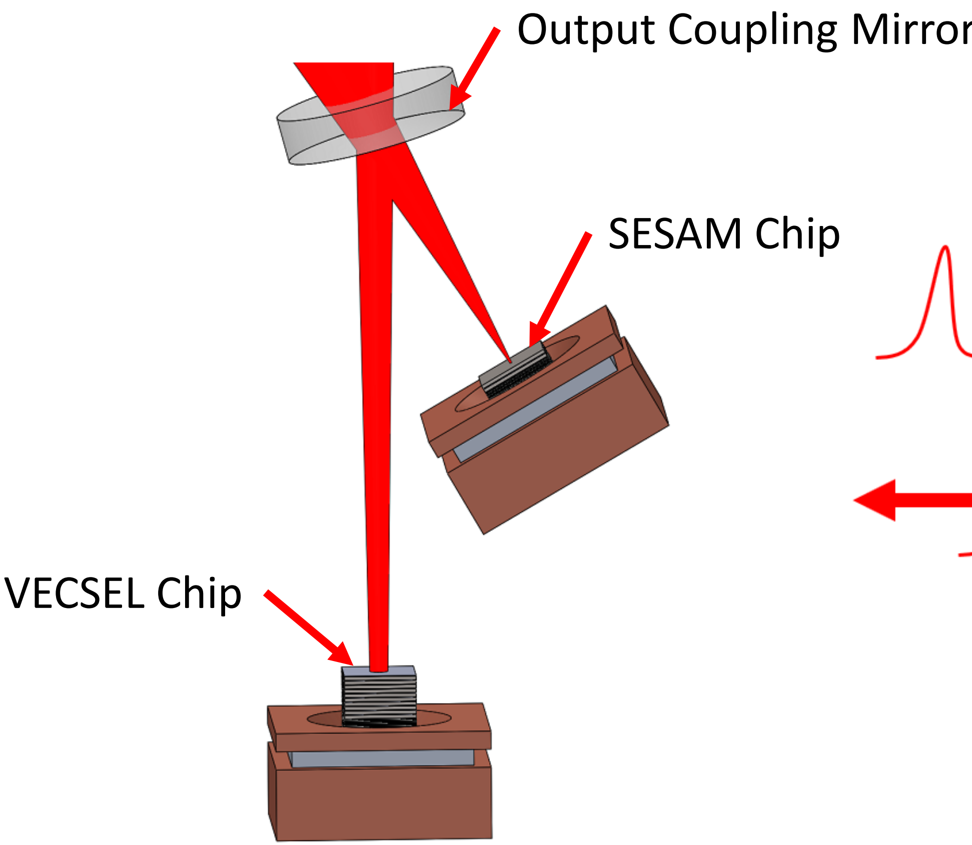
- Two Mirror Based Astigmatic mode converters will be used to for a cavity.
- The location of the VECSEL and pump displacement with control the mode.
- Permutations of this design will enable mode locking

Experimental Results

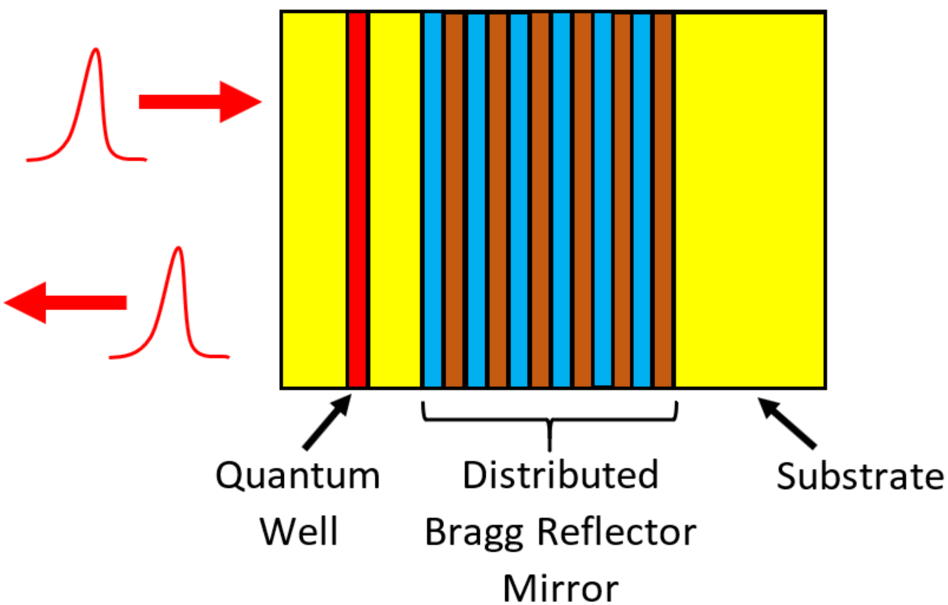


Ref. [4]

Semiconductor Saturable Absorber Mirror

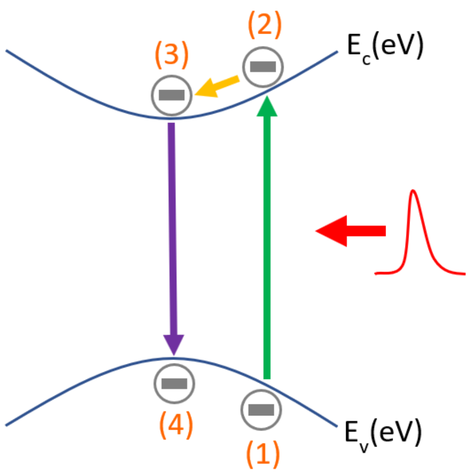


Mode-locked VECSEL V-Cavity Geometry

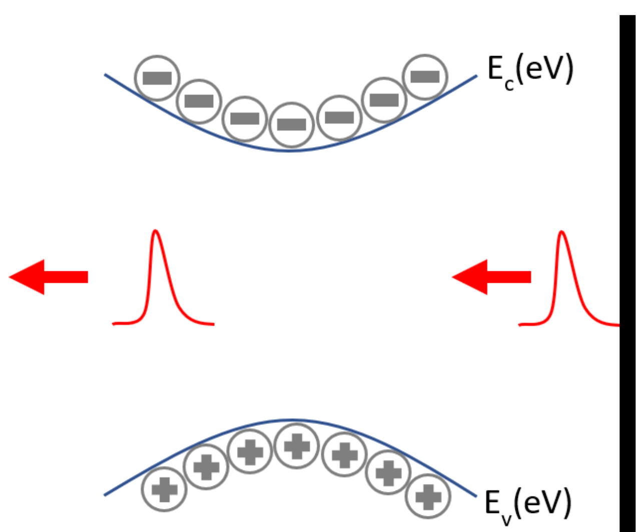


SESAM Chip Structure

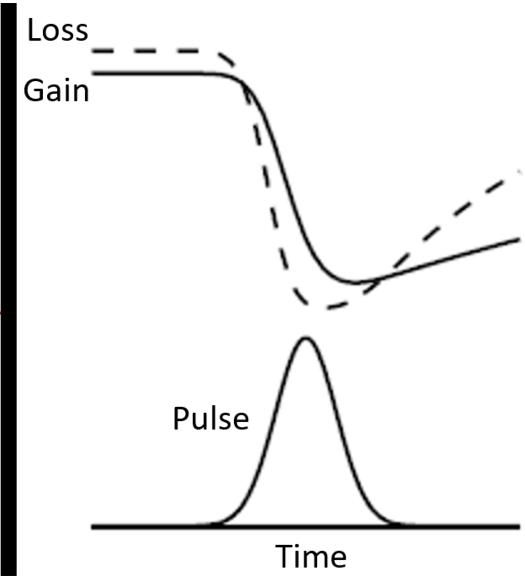
How Does a SESAM Work?



Before Saturation Fluence

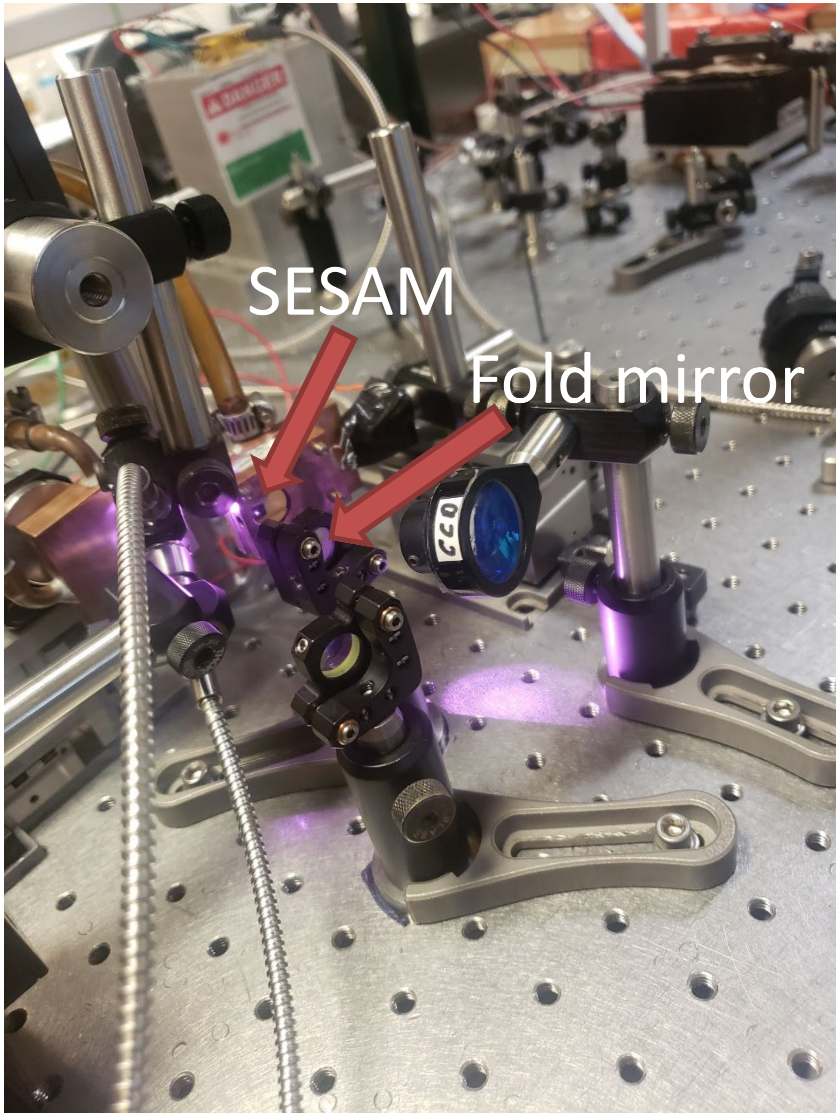


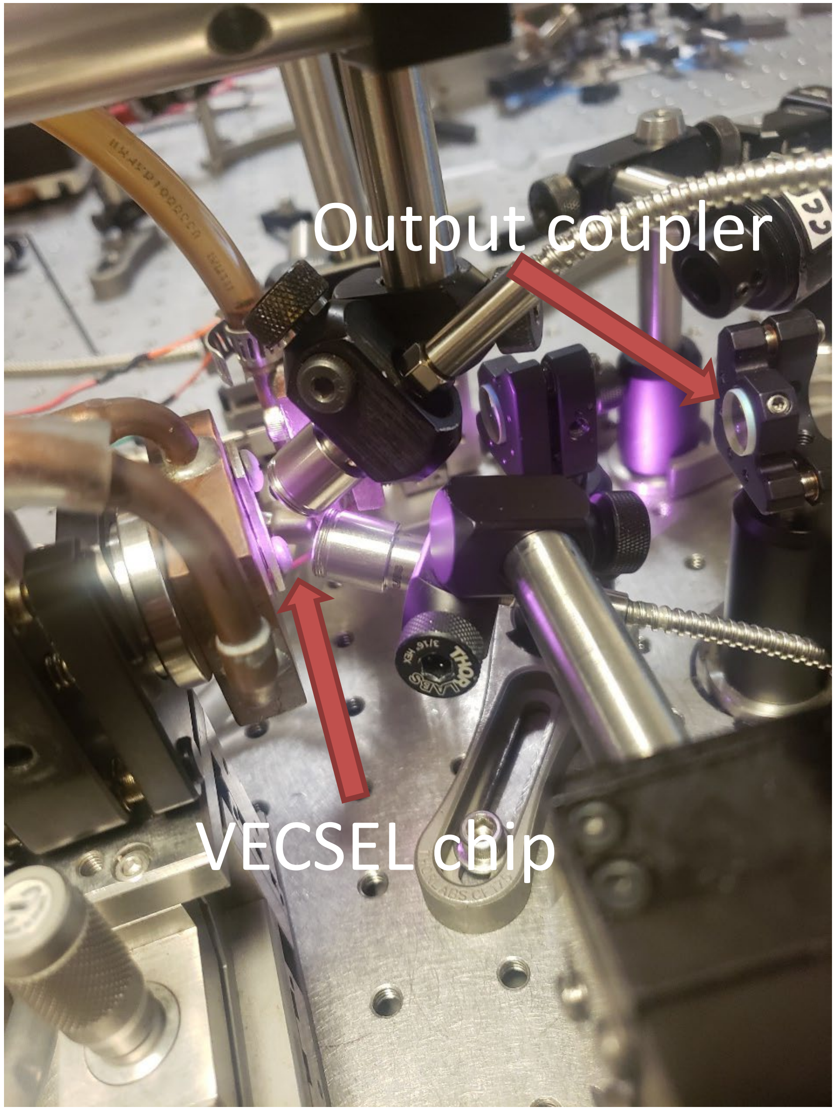
At Saturation Fluence



Gain/Loss Dynamics

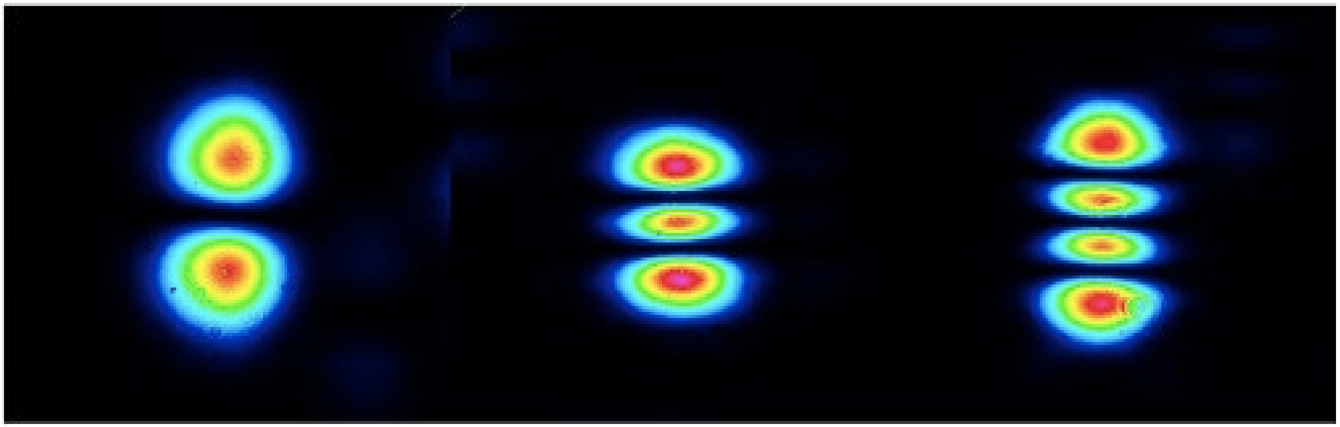
Benchtop cavity for mode-locking

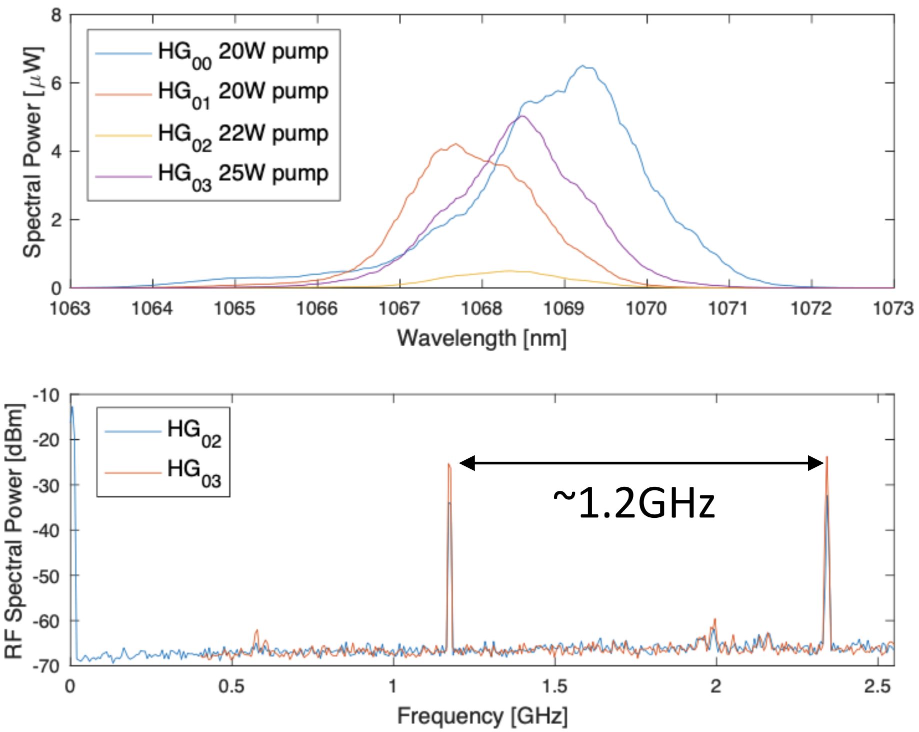




Observed HG modes

Observed HG_{0n} modes.

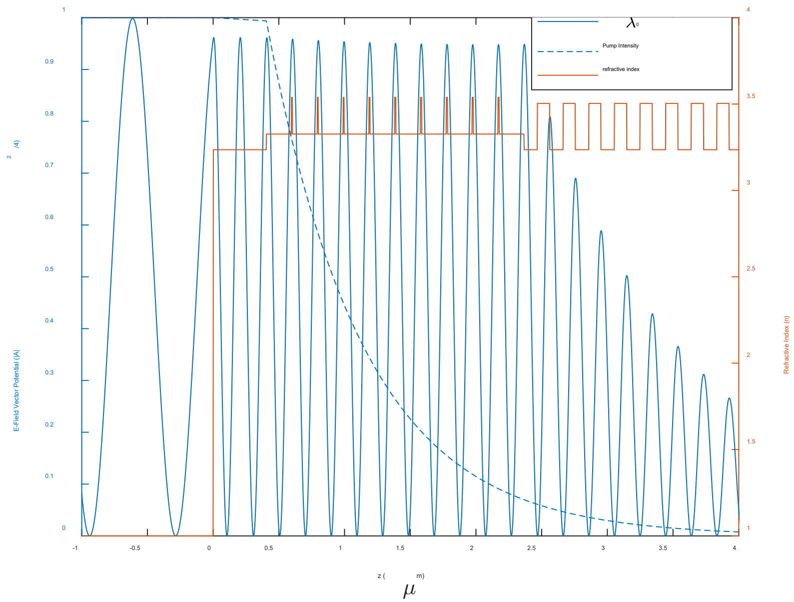




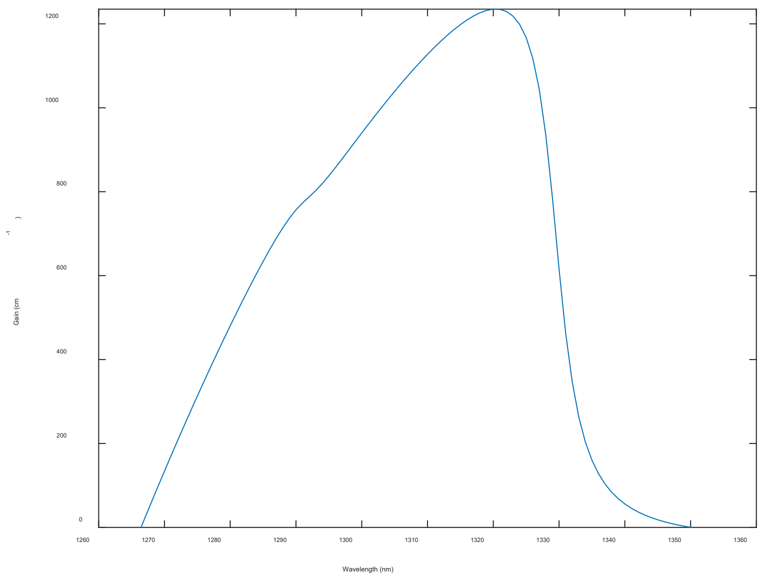
Optical spectrum (upper) and radio frequency spectrum (lower).

Modelling and Design: the 1310 nm Wafer

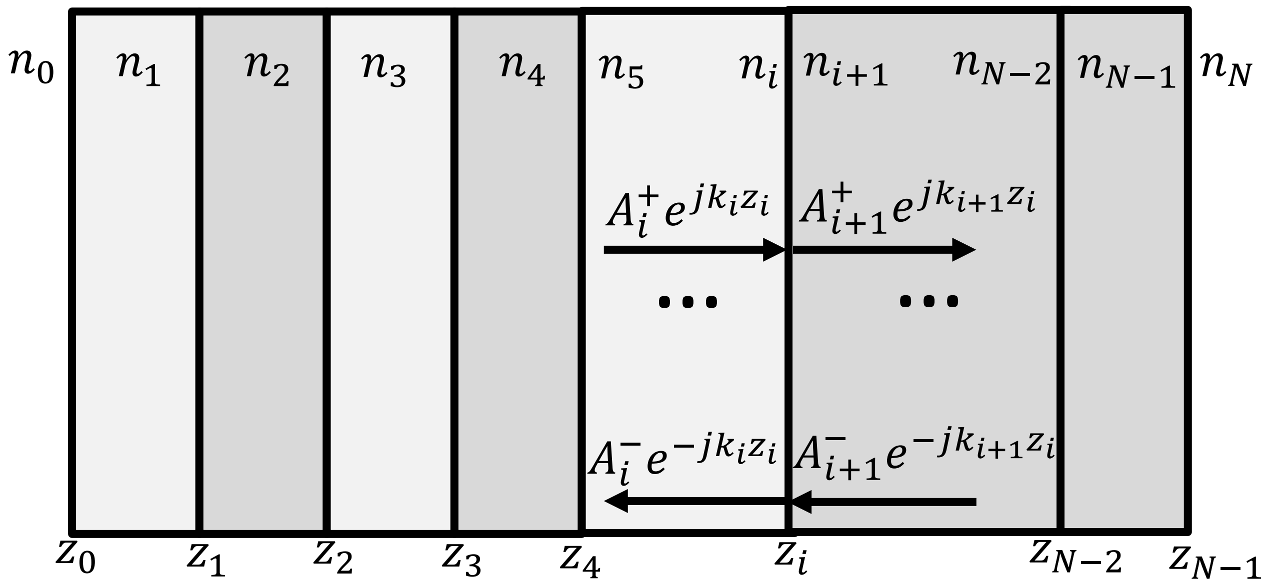
Design of the E-field Distribution



Design of the Quantum Well Gain



Design of the E-field Distribution

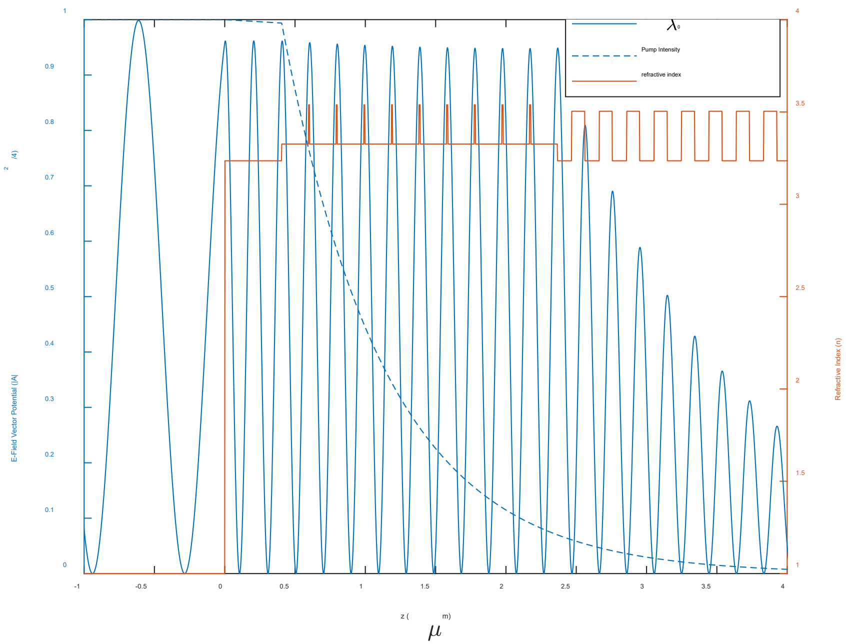


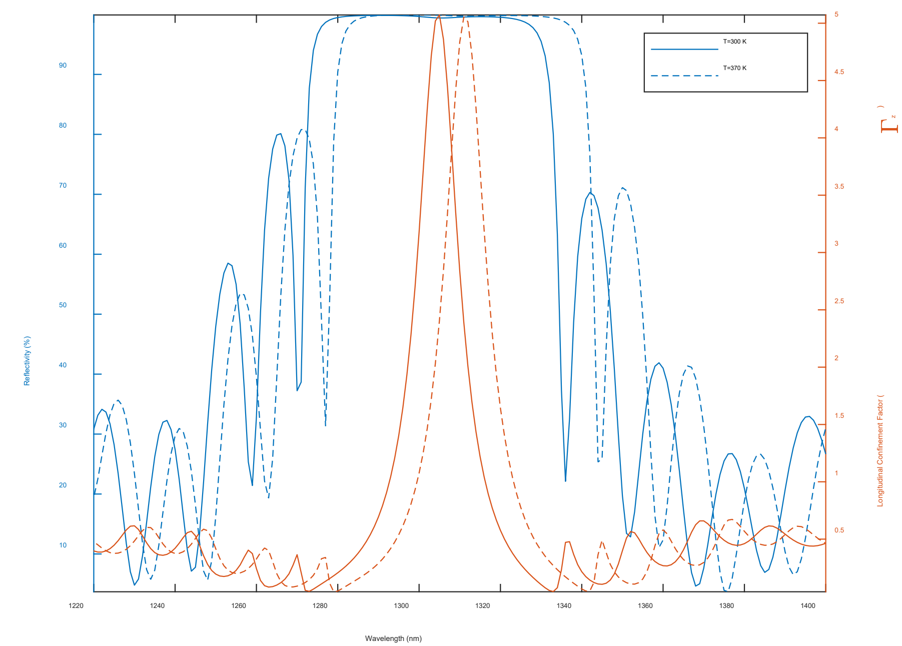
$$A = \frac{\partial}{\partial t} E$$

$$A_i(z_i) = A_i(z_{i+1})$$

$$\frac{\partial}{\partial z} A_i(z_i) = \frac{\partial}{\partial z} A_i(z_{i+1})$$

Design of E-Field Distribution

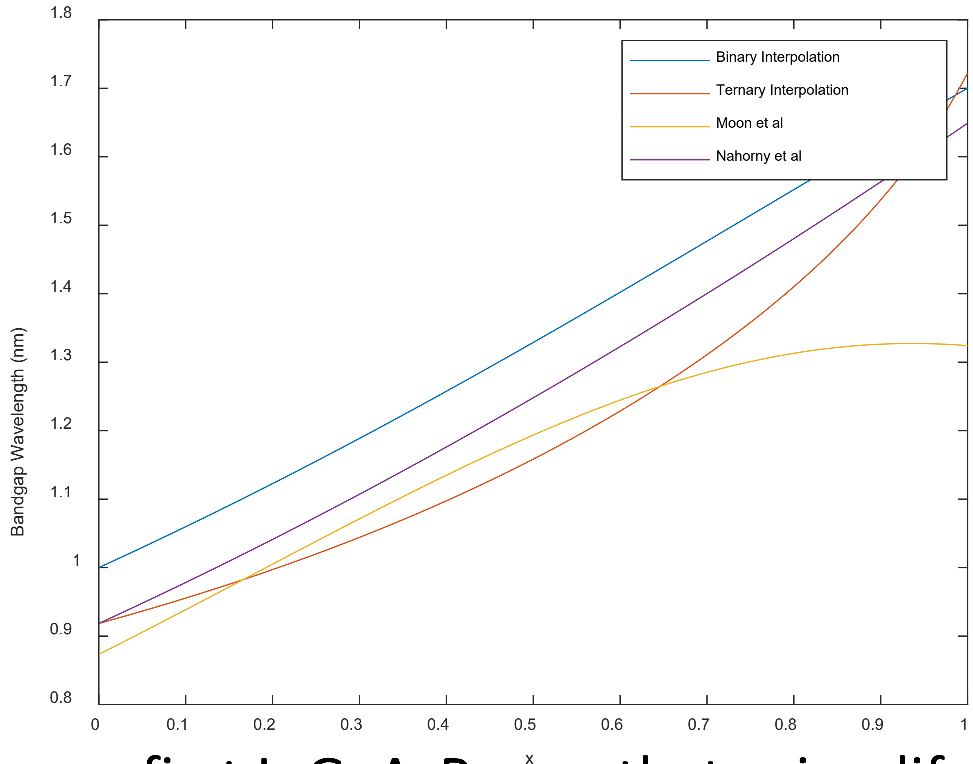




$$R = \frac{|A_0^-|^2}{|A_0^+|^2}$$

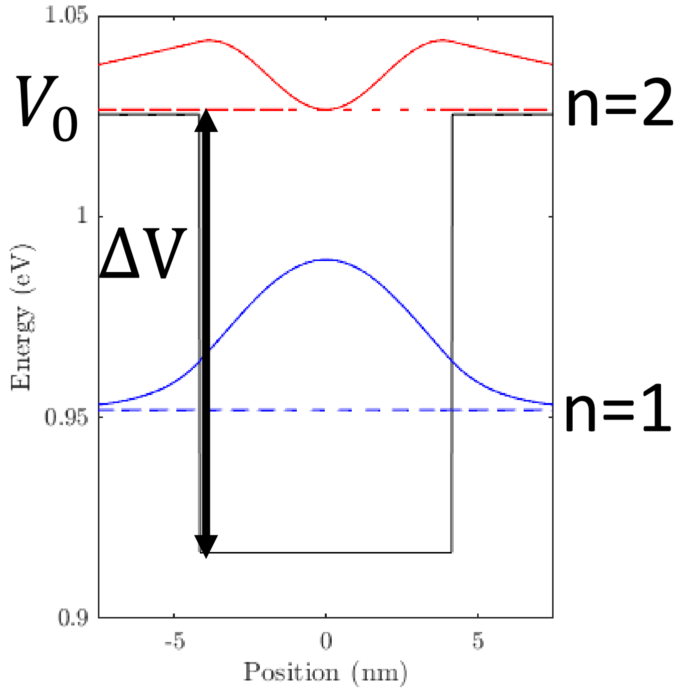
$$\Gamma_z = \sum_q \frac{\left|A_{iq}^+ e^{jk_{iq}z_q} + A_{iq}^- e^{-jk_{iq}z_q}\right|^2}{|A_0^+|^2 + |A_0^-|^2}$$

Design of the Quantum Well Gain
Band gap of $In_{1-x}Ga_xAs_yP_{1-y}$



- Since this is our first InGaAsP growth, to simplify calculations we fix x=0.47y to lattice match to InP

Design of the Quantum Well Gain
Finite Quantum Well Problem

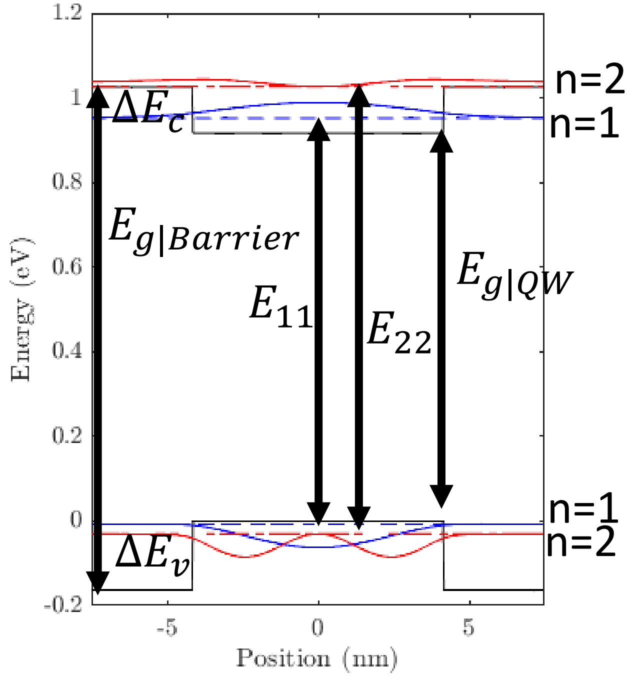


$$E|\psi\rangle = H|\psi\rangle$$

$$H = \frac{-\hbar^2}{2m_{c|v}}\frac{\partial^2}{\partial z^2} + V(z)$$

$$V(z) = V_0 - \Delta V rect\left(\frac{z}{L_z}\right)$$

Design of the Quantum Well Gain

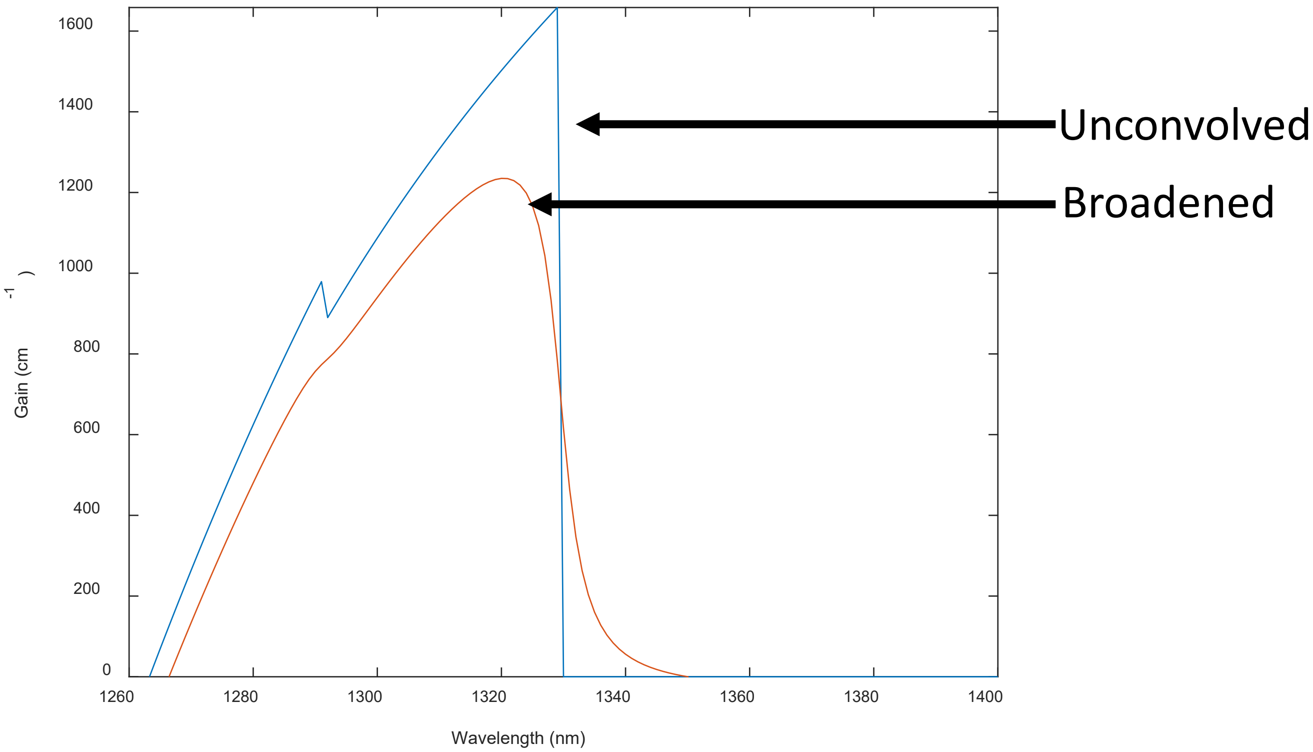


$$g_{ij}(E_p) = g_{max}(E_{ij})[f_i - f_j]$$

$$g_{max}(E_{ij}, E_p) = \frac{\pi e^2 \hbar}{n \varepsilon_0 c m_e^2} \frac{1}{E_p} |M_T(E_{ij})|^2 \rho_r(E_{ij})$$

$$g(E_p) = \sum_i \sum_j g_{ij}(E_p)$$

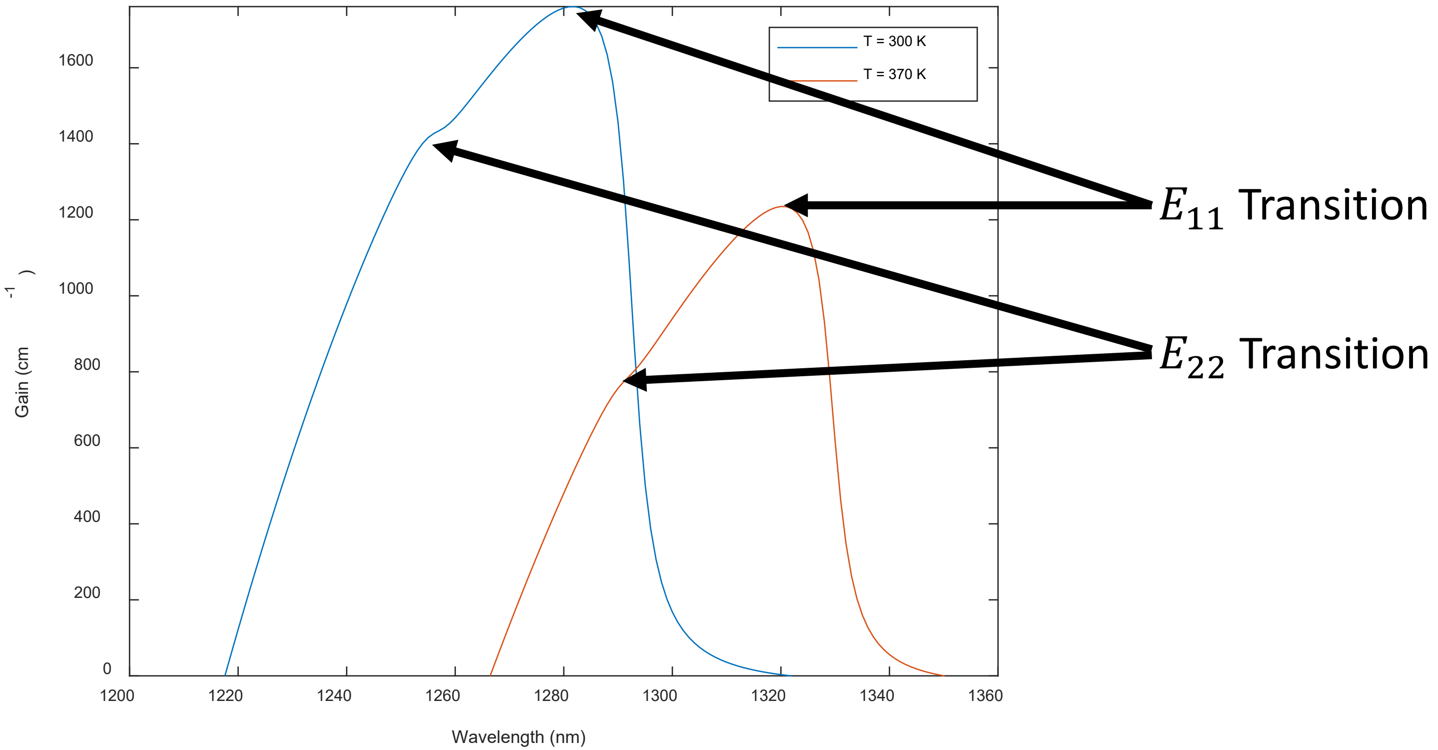
Design of Quantum Well Gain Line shape Broadening



$$g(E_p) = \int g_{ij} L(E_p - E_{ij}) dE_{ij}$$

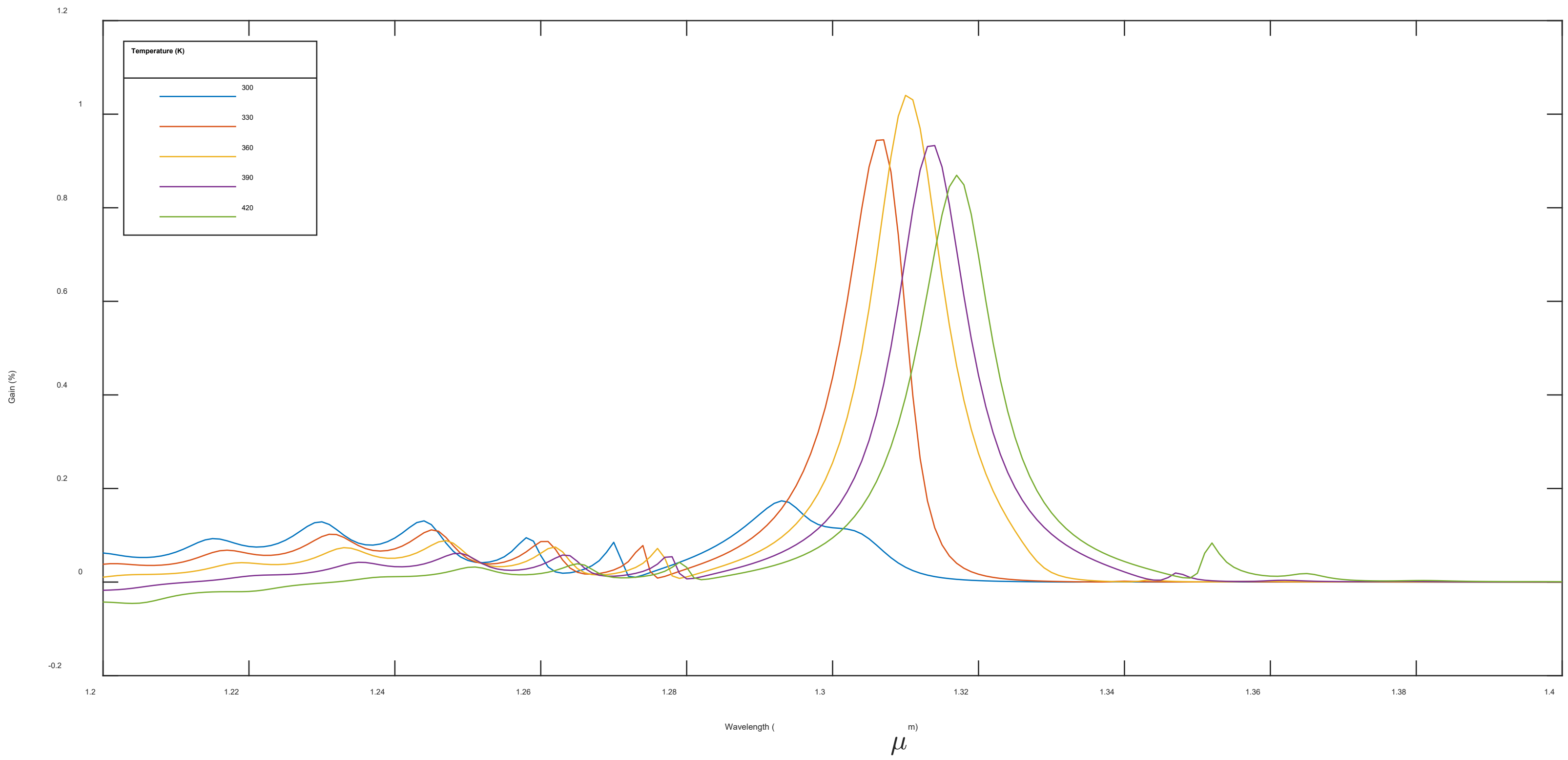
$$L(E_p - E_{ij}) = \frac{1}{\pi} \frac{\frac{\hbar}{\tau_{in}}}{\left(\frac{\hbar}{\tau_{in}}\right)^2 + (E_p - E_{ij})^2}$$

Design of the Quantum Well Gain



- Gain redshifts with temperature
- Driven by bandgap redshift with temperature $\approx -387\ \mu eV/K$

Full Structure Gain

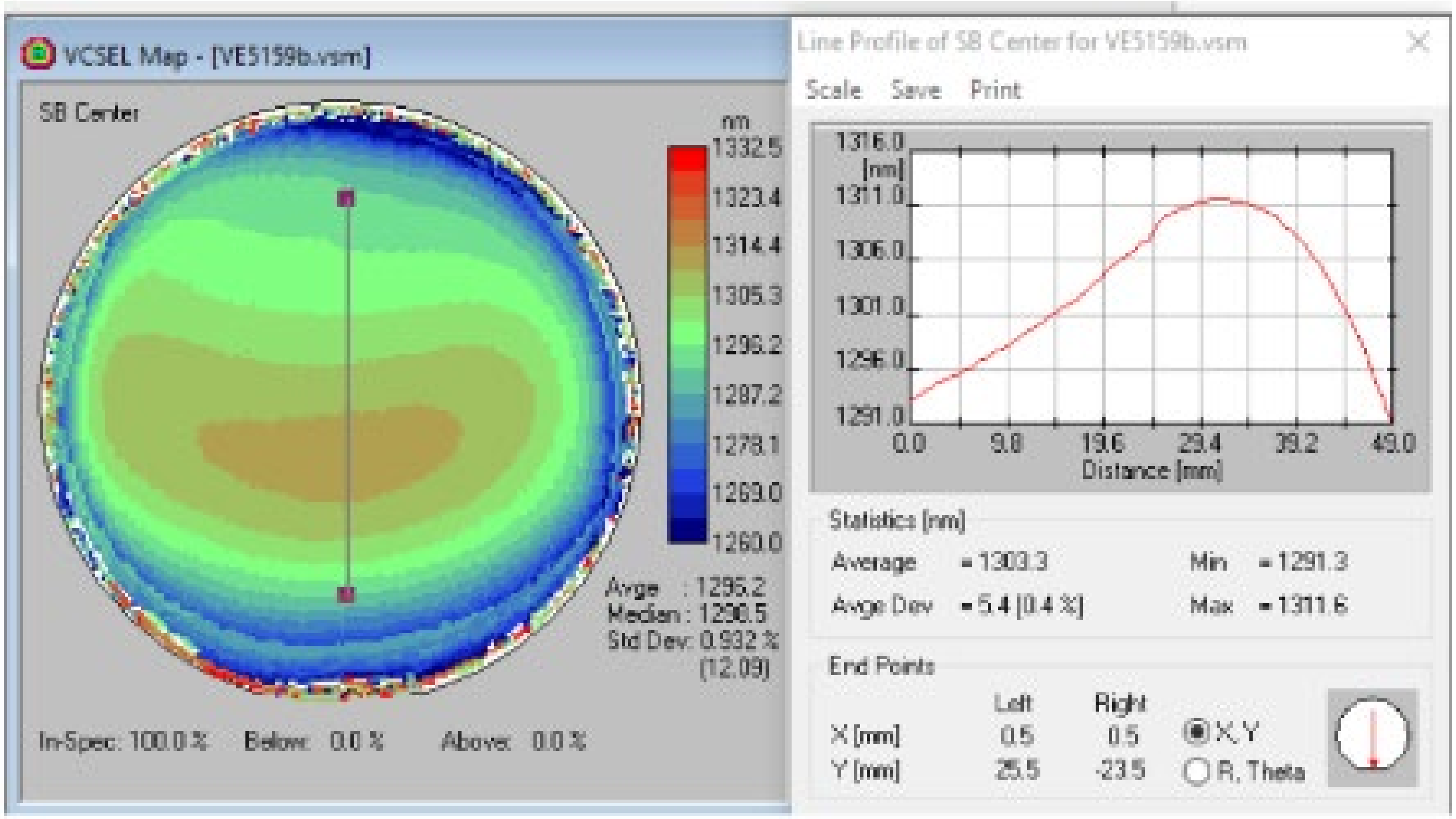


$$G = \Gamma_z e^{g_{QW} L_z}$$

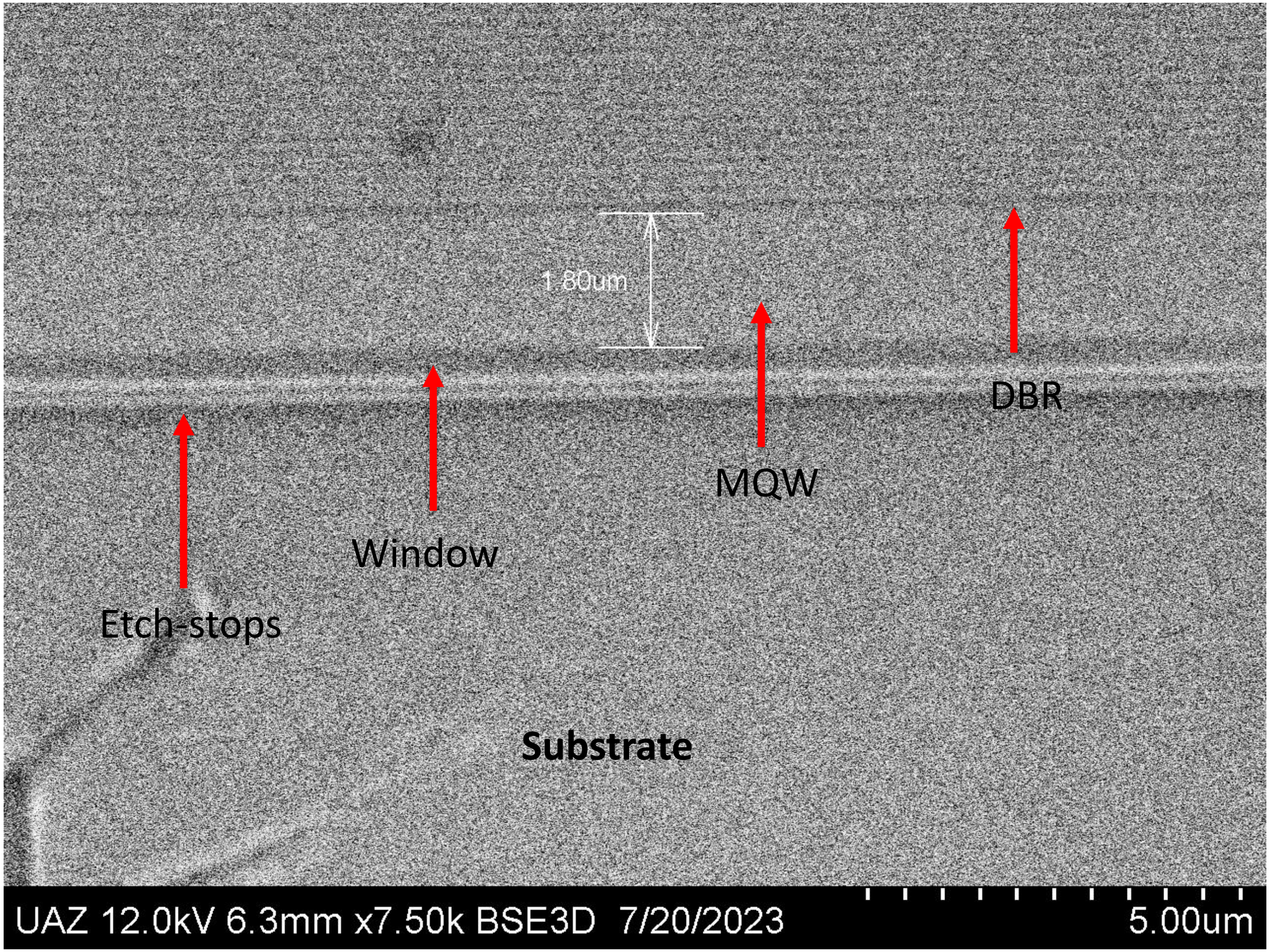
Microfabrication and Characterization

- Upon receiving the wafers from our industry partner, we began developing a procedure to process the wafers into chips.
- This involves several steps that will be covered in what follows.

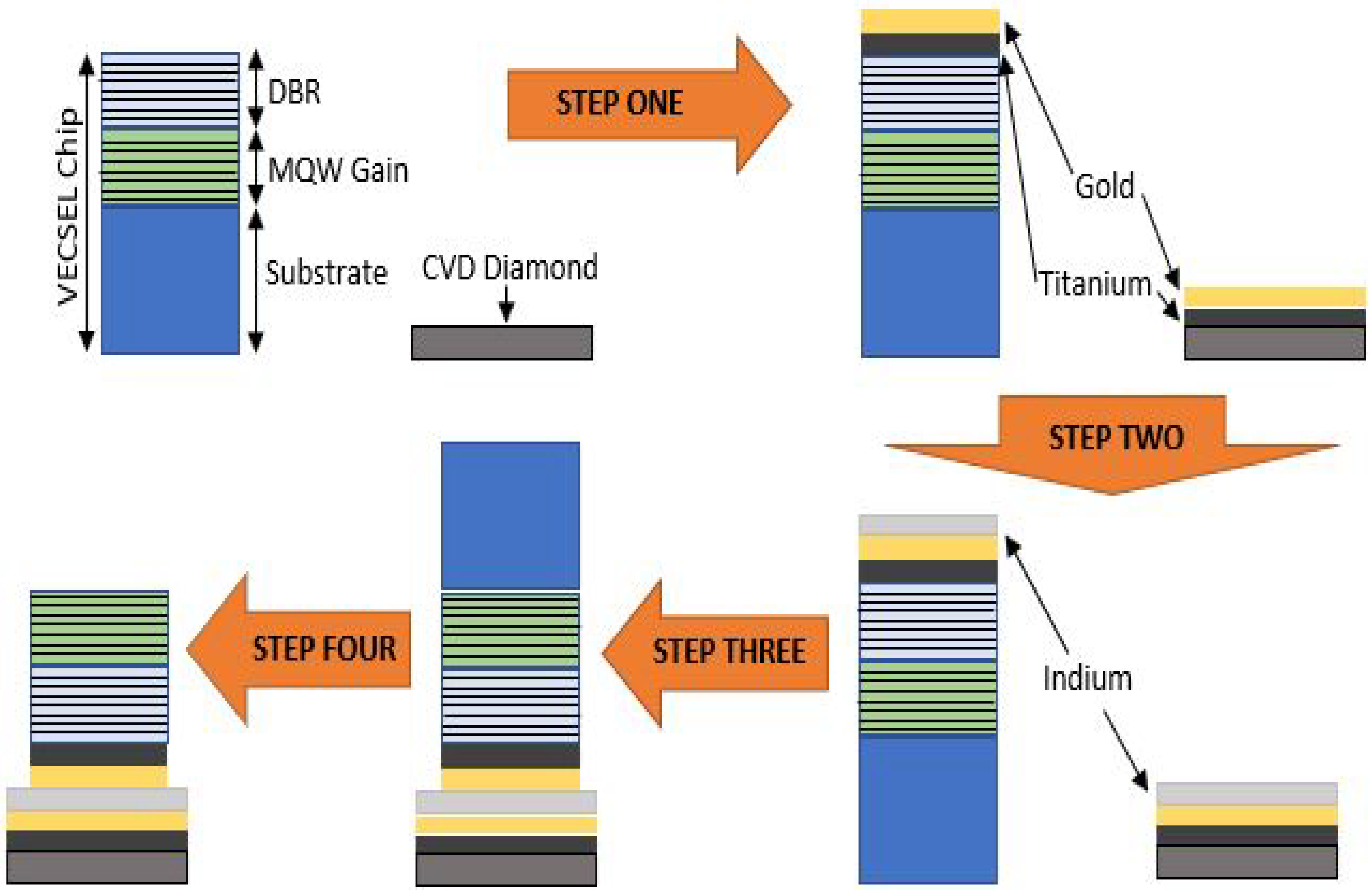
Wafer Map


VCSEL Map - [VE5159b.vsm]
SB Center
nm
1332.5
1323.4
1314.4
1305.3
1296.2
1287.2
1278.1
1269.0
1260.0
Avge : 1296.2
Median : 1296.5
Std Dev: 0.932 %
(12.09)
In-Spec: 100.0 %
Below: 0.0 %
Above: 0.0 %
Line Profile of SB Center for VE5159b.vsm
Scale
Save
Print
1316.0
[nm]
1311.0
1306.0
1301.0
1296.0
1291.0
0.0
9.8
19.6
29.4
39.2
49.0
Distance [mm]
Statistics [nm]
Average = 1303.3
Avge Dev = 5.4 [0.4 %]
Min = 1291.3
Max = 1311.6
End Points
Left
Right
X [mm] 0.5 0.5
Y [mm] 25.5 -23.5
X, Y
R, Theta

SEM

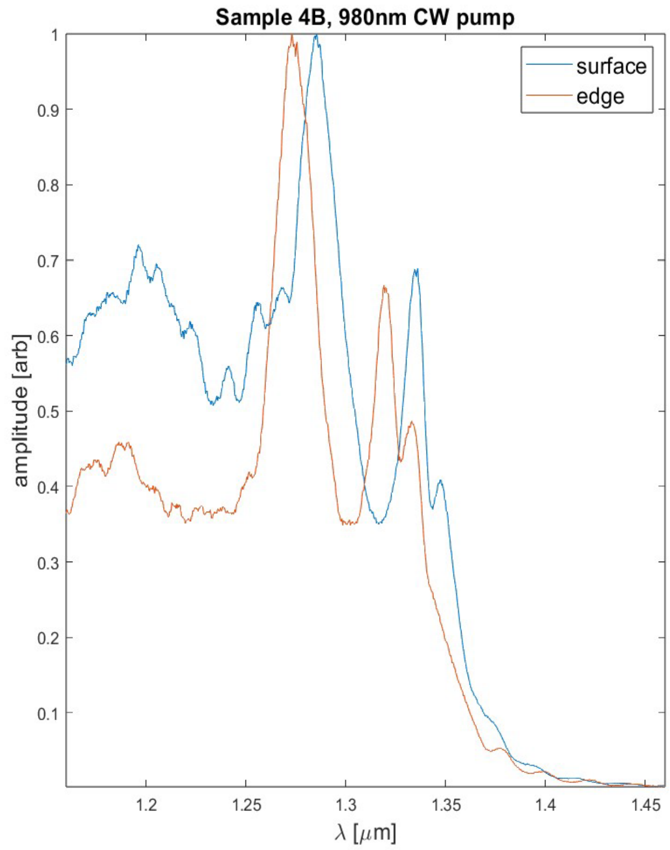

1.80um
DBR
MQW
Window
Etch-stops
Substrate
UAZ 12.0kV 6.3mm x7.50k BSE3D 7/20/2023
5.00um

Microfabrication Process

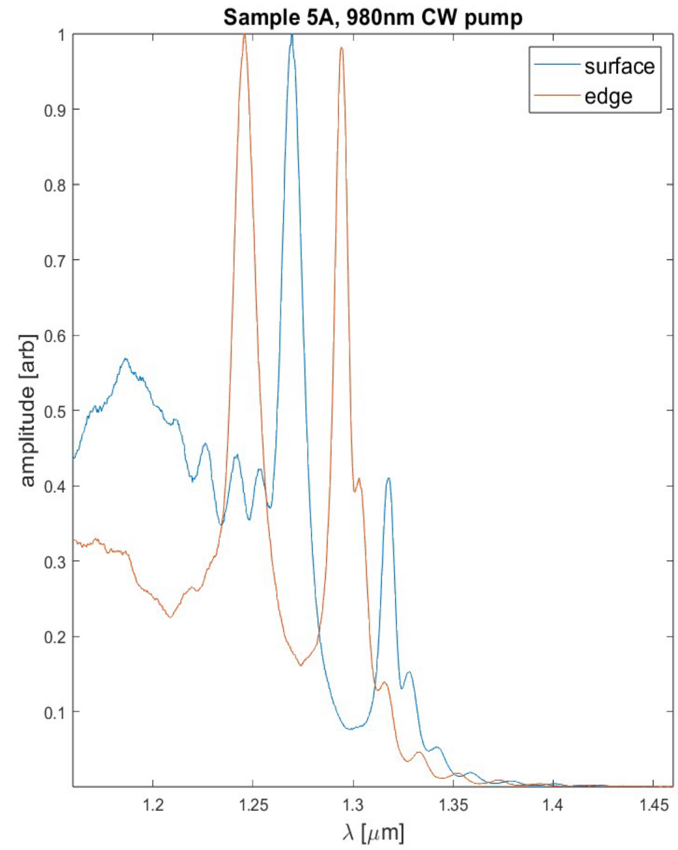


Characterization: PL Spectra

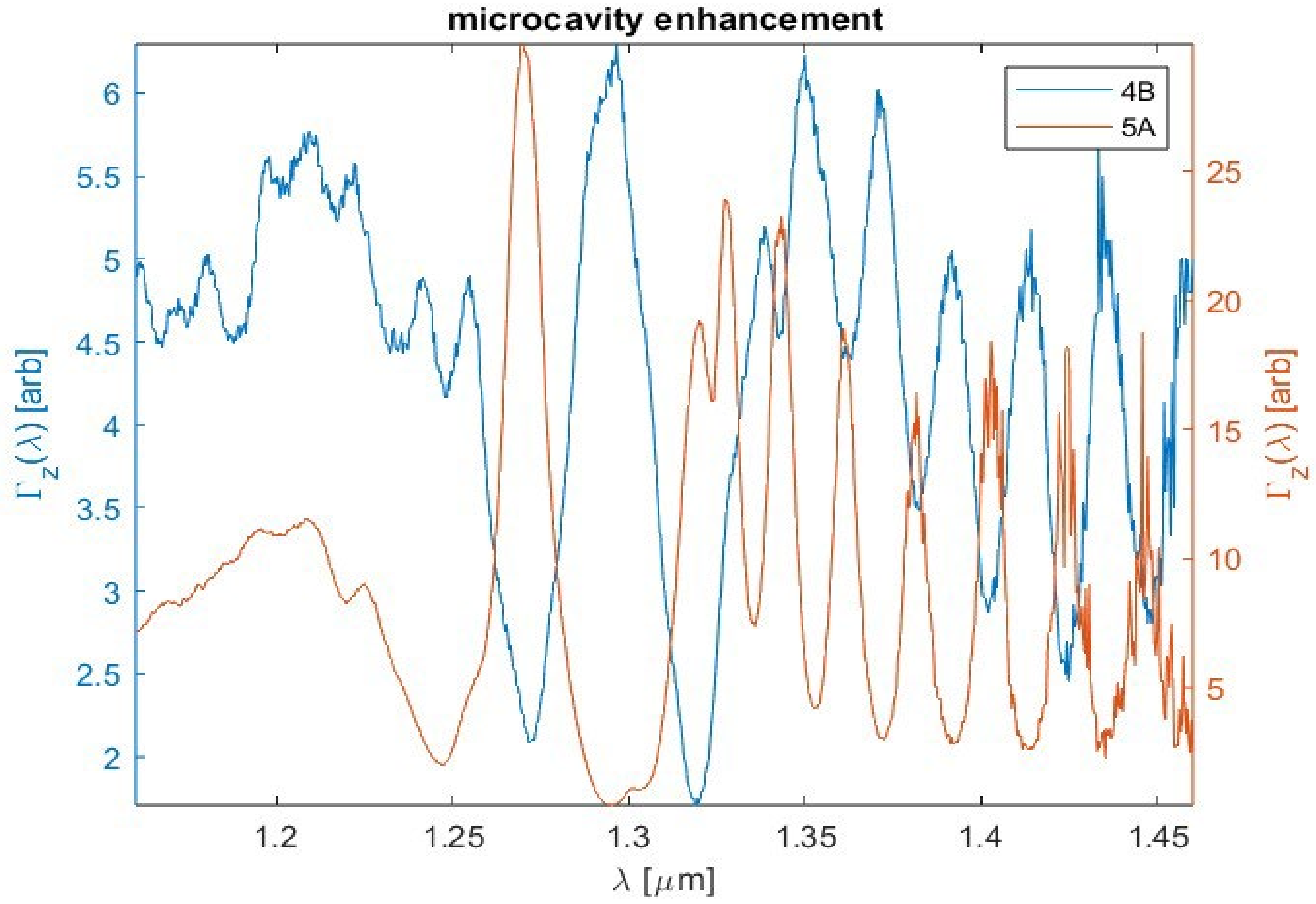
AR coated



uncoated

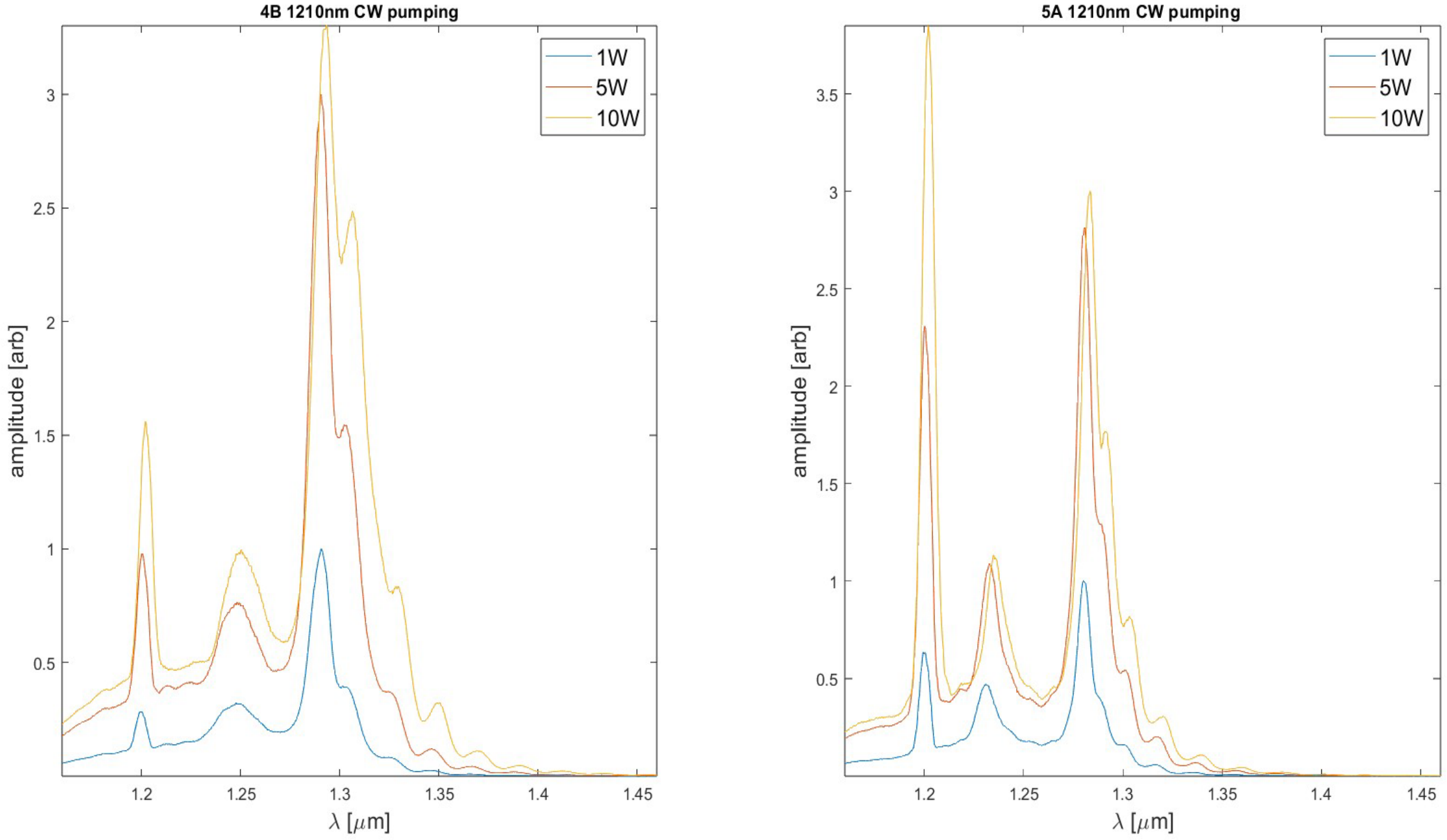


Sub-cavity resonance effect



$$\Gamma_z(\lambda) \propto \frac{I_{SPL}}{I_{EPL}}$$

Paths toward lasing: in-well pump



Paths toward lasing: Strain

- By introducing strain to our existing structures, we may be able to reach laser threshold.
- We will experiment with mounting techniques to do this.
- In future designs, we can design a strained QW active region.

Alternatives

- Additionally, we may explore alternative material systems such as InGaAlAs/InP, which is commonly used in telecom applications.
- InGaAlAs has a larger conduction band offset, leading to better electron confinement and a significantly reduced leakage current density.

Thank You!

Thank you to the Coherent/II-VI Foundation for providing us with this research opportunity!

Questions?

References

[1] Wang, J., Yang, JY., Fazal, I. *et al.* Terabit free-space data transmission employing orbital angular momentum multiplexing. *Nature Photon* **6**, 488–496 (2012).

[2] M. L. Lukowski, J. T. Meyer, C. Hessenius, E. M. Wright and M. Fallahi, "High-Power Higher Order Hermite–Gaussian and Laguerre–Gaussian Beams From Vertical External Cavity Surface Emitting Lasers," in *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 25, no. 6, pp. 1-6, Nov.-Dec. 2019, Art no. 1500406, doi: 10.1109/JSTQE.2019.2906256

[3] J. T. Meyer, M. L. Lukowski, C. Hessenius, E. M. Wright, M. Fallahi, "All-intracavity fourth harmonic generation for ultrafast UV emission," in Opt. Comm., doi: 10.1016/j.optcom.2021.127255

[4] N. S. Gottesman, M. L. Lukowski, J. T. Meyer, C. Hessenius, E. M. Wright and M. Fallahi, "Intra-Cavity Astigmatic Mode Converting VECSEL," in *IEEE Photonics Journal*, vol. 14, no. 4, pp. 1-6, Aug. 2022, Art no. 1538906, doi: 10.1109/JPHOT.2022.3186684.