Guided Mode Expansion Analysis of Photonic Crystal Surface Emitting Lasers

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2021

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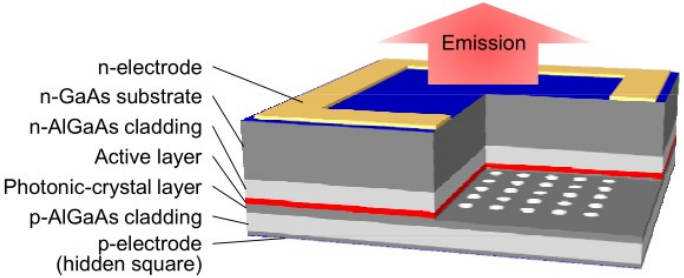
Background: PCSELs

The What

- Photonic crystal surface emitting laser (PCSEL)
- A type of semiconductor diode laser, driven by Susumu Noda (Imada et al, APL 1999)
- The optical resonance is in-plane (like edge-emitting lasers)
- The optical emissions are out-of-plane (like VCSELs)
- A photonic crystal (PhC) provides optical confinement/feedback, mode control, and out-of-plane emissions



Yoshida, CLEO 2018

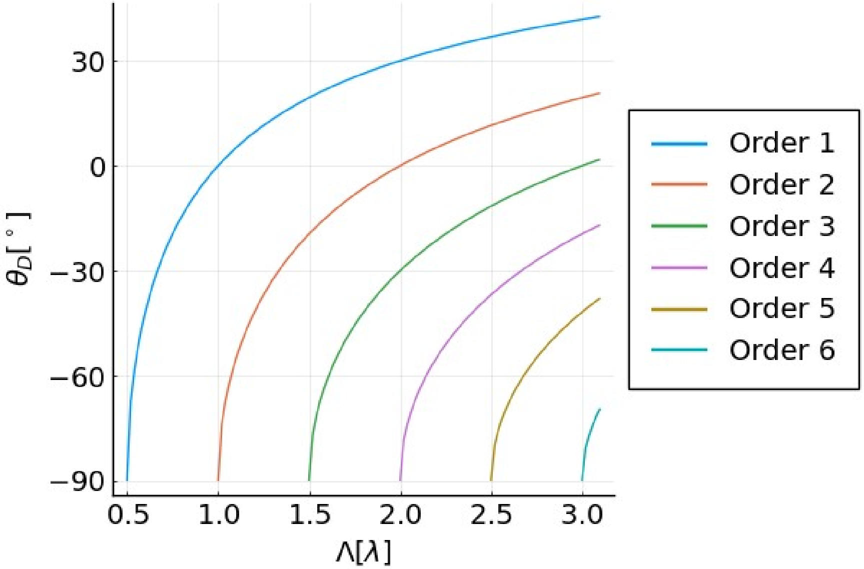
The Why

- Photonic crystal enables narrow spectral linewidth, broad area emission, high beam quality that scale to high power:
    - 200 µm diameter PCSEL, 1.5 Watts CW or 3.4 Watts pulsed, M^2=1 up to 0.5 Watts (Hirose et al, CLEO 2014)
    - 500 µm diameter PCSEL, 10 Watts pulsed with M^2<2.5 Yosida et al, CLEO 2018)
    - 3 mm diameter PCSEL, 150 Watts pulsed (Noda, PW 2021)
- Scale to larger area for higher power

The How

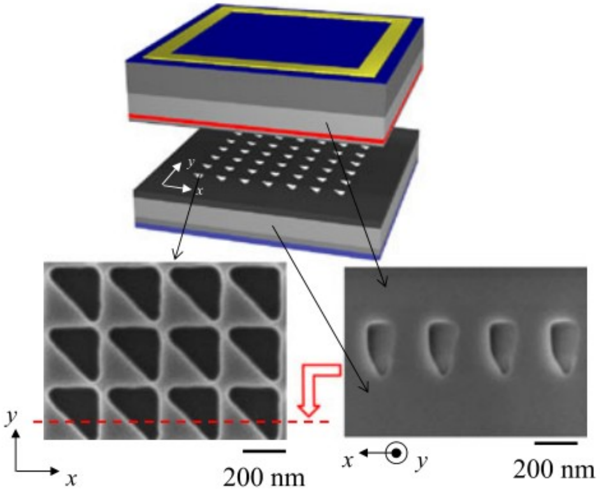
$$\Lambda=\frac{\lambda_0 m_B}{2 n_{eff}} \qquad \theta_D=\sin^{-1}\left(n_{eff}-m_D\frac{\lambda_0}{\Lambda}\right)$$

- Epitaxial waveguide confines in-plane mode
- Photonic crystal produces resonant feedback/confinement, diffraction
- Period Λ, wavelength λ_0, diffraction angle θ_D (angle from surface-normal), effective index n_{eff}, and Bragg/diffraction orders m_B/m_D
- Both in-plane resonance and surface-normal diffraction if $m_B=2m_D$

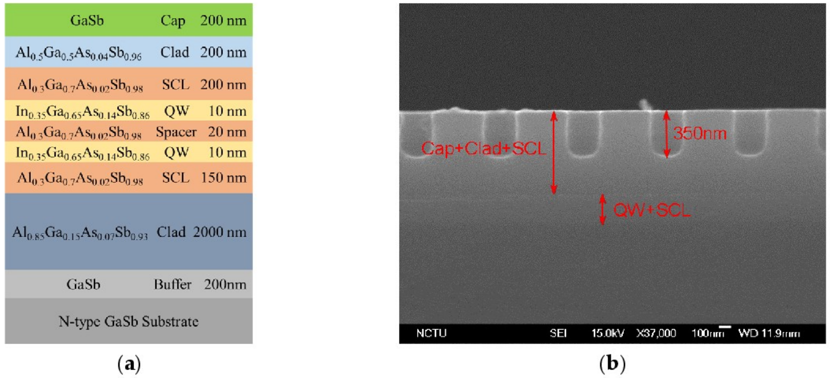


Diffraction angles as a function of PhC period (in terms of in-material wavelengths)

Structures



Noda et al, JSTQE 2017



GaSb	Cap	200 nm
$Al_{0.5}Ga_{0.5}As_{0.04}Sb_{0.96}$	Clad	200 nm
$Al_{0.3}Ga_{0.7}As_{0.02}Sb_{0.98}$	SCL	200 nm
$In_{0.35}Ga_{0.65}As_{0.14}Sb_{0.86}$	QW	10 nm
$Al_{0.3}Ga_{0.7}As_{0.02}Sb_{0.98}$	Spacer	20 nm
$In_{0.35}Ga_{0.65}As_{0.14}Sb_{0.86}$	QW	10 nm
$Al_{0.3}Ga_{0.7}As_{0.02}Sb_{0.98}$	SCL	150 nm
$Al_{0.85}Ga_{0.15}As_{0.07}Sb_{0.93}$	Clad	2000 nm
GaSb	Buffer	200nm
N-type GaSb Substrate		

(a) (b)

Li et al, Micromachines 2019

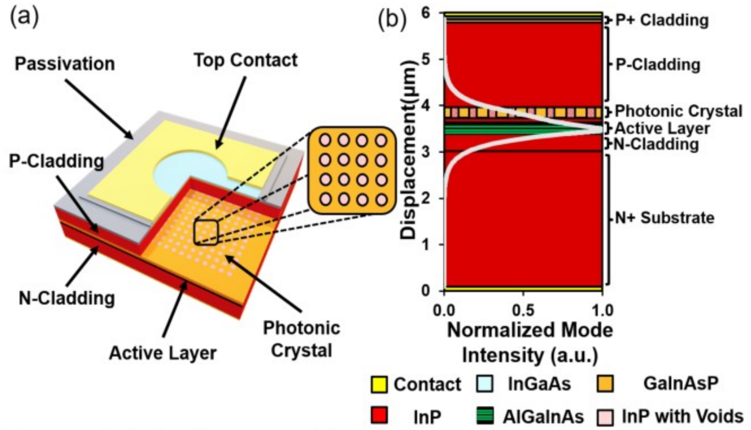


Figure 1 *a) A schematic of the device, with cut-out area showing*

Bian et al, IEEE PTL 2020

Numerous design variations:

- PhC shape (triangle, circles, ovals, …)
- PhC lattice (triangular, square, ...)
- PhC material (semiconductor/air, all-semiconductor)
- PhC location (surface, buried-layer)
- Many more

Q-Factors

- Quality, or Q, factor
- Many definitions:
  - In terms of complex resonance frequency

    $$Q=\frac{-\Re(\omega)}{2\Im(\omega)}$$

  - In terms of resonance bandwidth

    $$Q=\frac{\omega}{\delta\omega}$$

  - In terms of cavity photon lifetime

    $$Q=\omega\tau_p$$

  - In terms of stored energy in cavity E and power loss rate P

    $$Q=\frac{\omega E}{P}$$

- Higher Q means lower losses
- Higher Q means lower modal threshold gain

Computational Modeling

The Objectives

- <u>Desired features/capabilities for modeling software</u>:
- PhC mode frequencies (align to gain)
- PhC band diagrams (mode frequencies/slow-light)
- Mode Q-factor or threshold gain (mode control)
- Mode fields (near-field/far-field/beam)
- Full 3D structure (model both PhC and epitaxial design)

Some Options

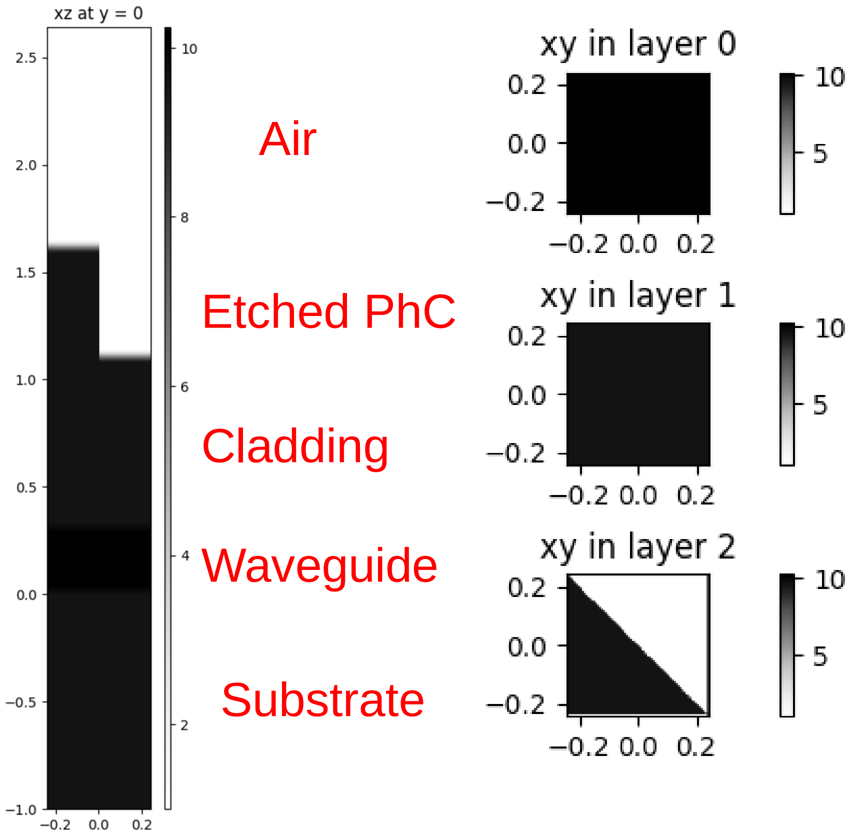
- Finite-difference time-domain (FDTD):
  - Very capable (3D structures, mode frequencies, fields, and Q)
  - Slow, more involved results analysis
- Plane-wave expansion (PWE):
  - Great for PhCs (mode frequencies, fields, band diagrams)
  - Not good for non-repetitive dimensions (epitaxial structure)
- Rigorous coupled wave analysis (RCWA):
  - Relatively capable (3D structure, mode frequencies, Q-factors)
  - Modal fields are trickier to analyze
- Guided mode expansion (GME):
  - Great match to problem (3D structure, mode frequencies, Q-factors, bands, fields are all straightforward to analyze)

My Choice

- Chose guided mode expansion (GME) implemented by legume
- legume is free and open source software from Shanhui Fan's group at Stanford University
- Programmatic Python interface
- Modeling process:
  - Define PhC lattice (period and crystal axes)
  - Define top/bottom interfaces (air/substrate)
  - Define epitaxial layers (with etched features, if relevant)
  - Define wave-vectors (normal DFB modes or surface-emitting modes) and modes indices (first order or higher order resonances) to solve for
  - Calculate modes
  - Analyze modal frequencies, Q-factors, fields, coupling coefficients to substrate/air, etc

Basic Assumptions and Structure

- Assume InP/InGaAs and aim for 1550 nm wavelength
- Epitaxy provides dielectric slab waveguide
- Surface-etching provides PhC
- Use triangular PhC etch on square grid



Structure cross-sections,
Shade is permittivity

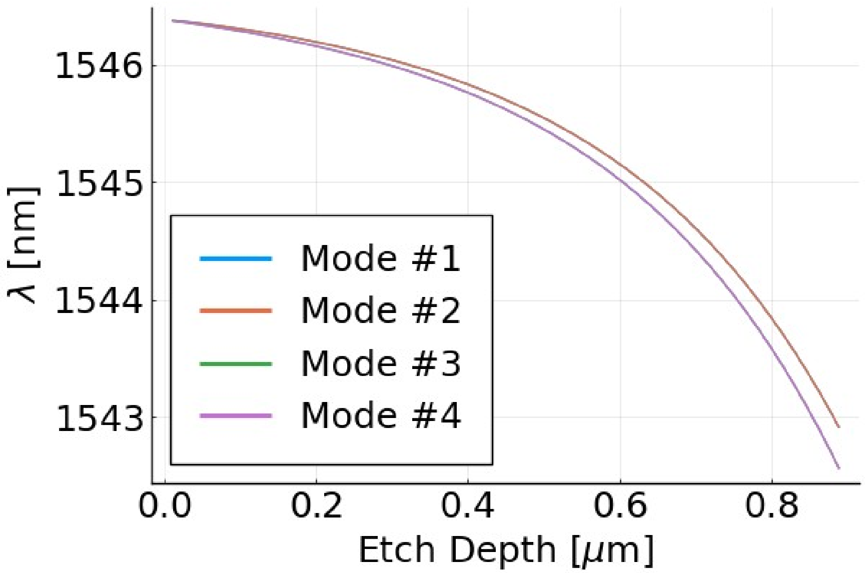
Some Questions

- What are the effects of etch-depth on:
  - Resonance wavelengths?
  - Q-factor (diffraction loss)?
  - Out-coupling to substrate/air?
- What about higher order PCSEL designs and resonances?

Exploring Etch Depth: Results

Etch Depth and Wavelength

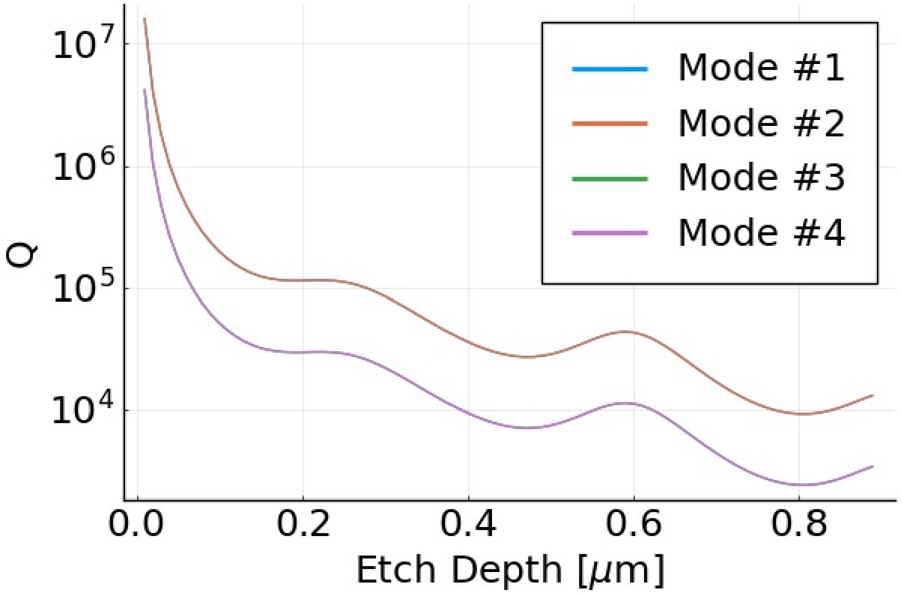
- Start with conventional PhC
  - Λ=496 nm
  - First order
- Vary etch-depth (from surface)
- First 4 resonance wavelengths



Two pairs of
(nearly)
degenerate modes

Etch Depth and Q-Factor

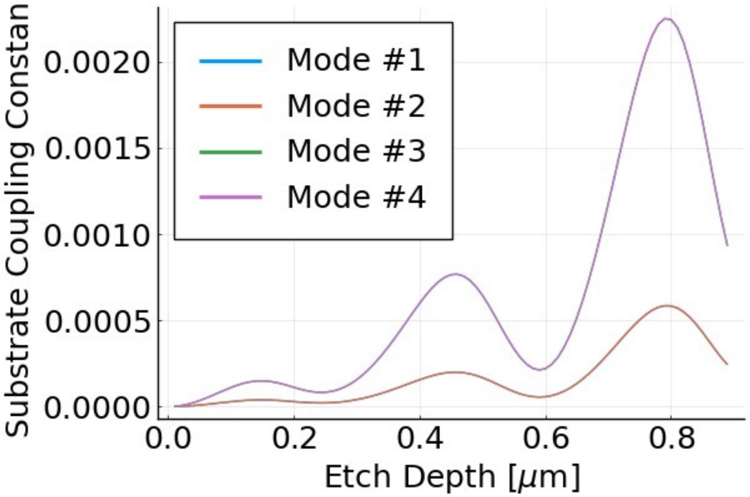
- Deeper etch:
  - More mode-PhC interaction
  - Stronger diffraction
  - More loss
  - Lower Q
- But why does Q increase periodically?

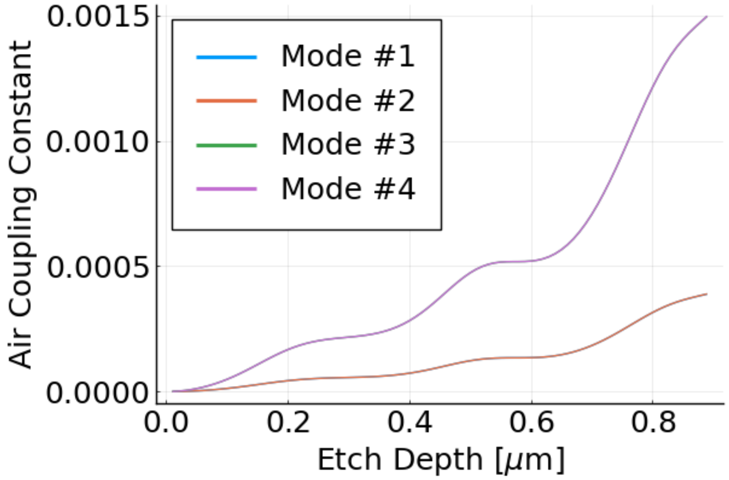


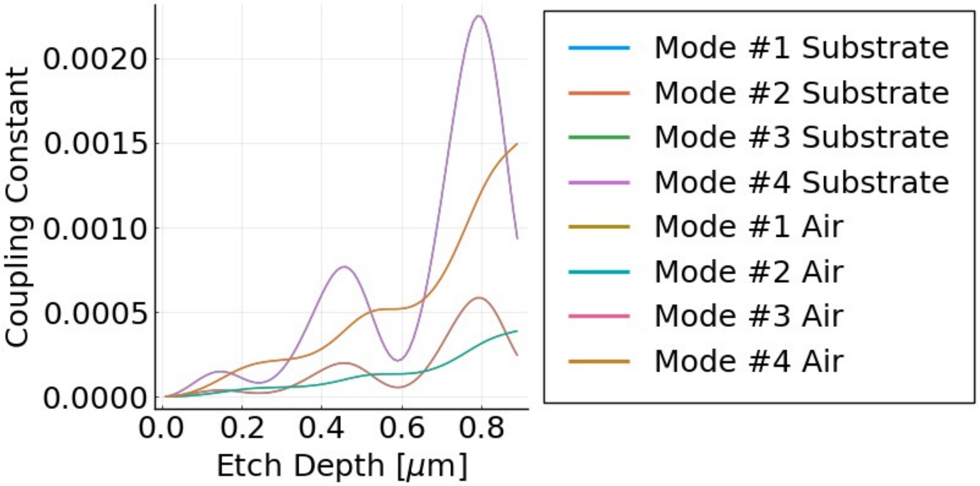
Coupling Coefficients

- legume also calculate modal coupling coefficients to substrate/air
- Higher coupling coefficient implies higher radiation into a layer
- Looking at coupling coefficients we can see where the power is going (where the periodic loss goes)

Etch Depth and Coupling Coefficients







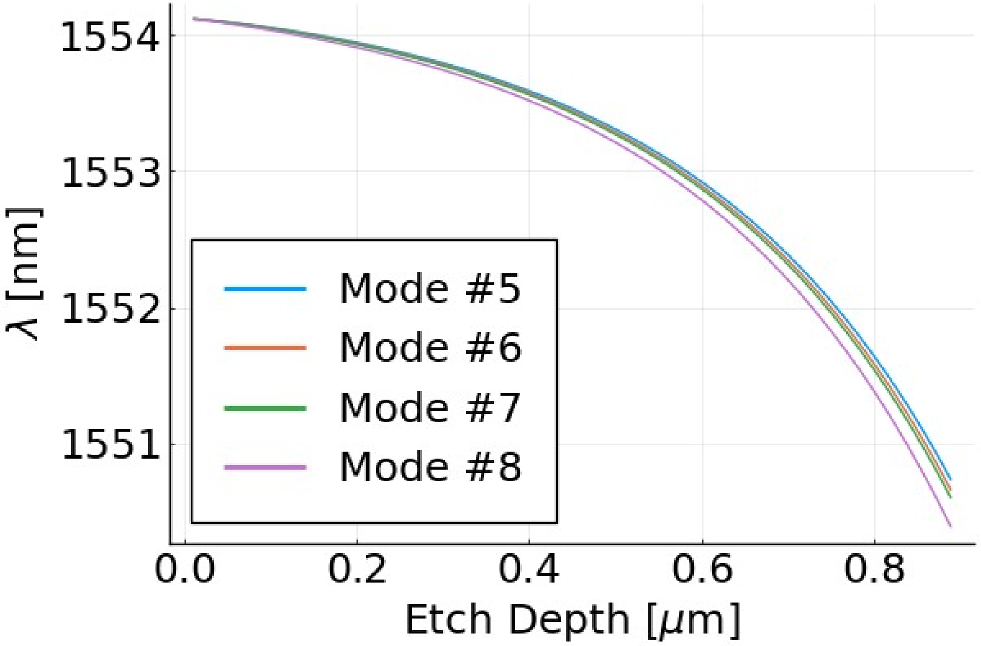
- Etching periodically varies power lost to the substrate
- We want primarily coupling to air, not substrate
- Prefer low substrate coupling → local Q maxima

Higher Order Resonances?

- High lithography requirements are common issue with PhCs
- Larger period PhC may have the correct wavelengths as higher-order resonances
- The second band of resonances requires about 1.4 larger features (496→705 nm)

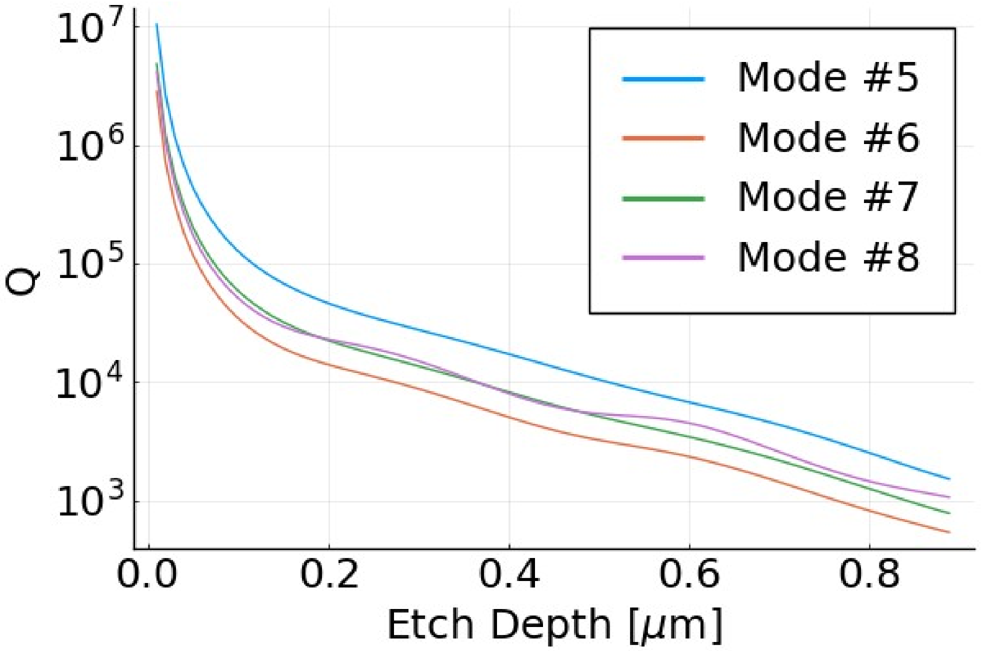
Higher Order Resonance

- Same wavelength vs etch depth trend as first order resonance



Higher Order Resonance Q

- Q is of decreases faster than in first order
- Periodic variation much less pronounced



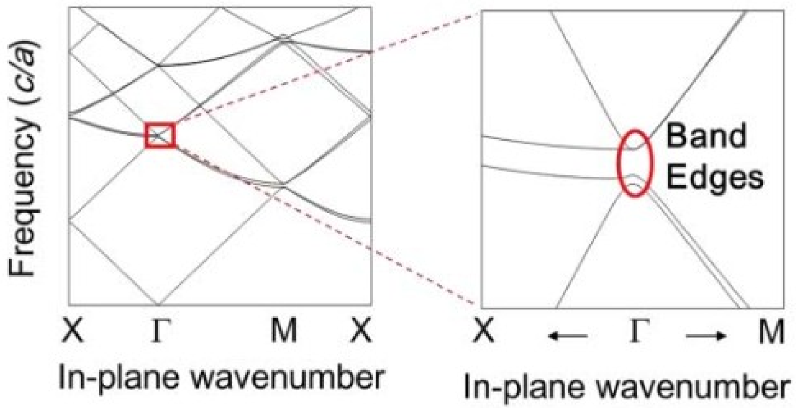
Future Exploration: In-Plane Modes

In-Plane PhC Modes

- Higher power → larger device area
- Larger device area → more in-plane PhC modes
- More in-plane PhC modes → reduced beam metrics
- How do we model device size and effects on in-plane modes?

In-Plane PhC Modes

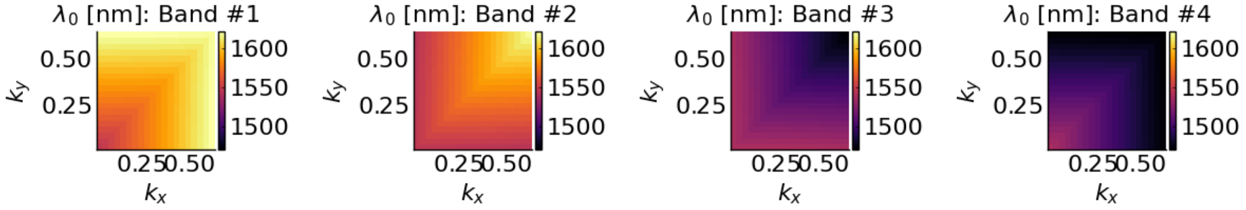
- Basic PCSEL theory states lasing at the Γ-point (surface emission)
- Higher order in-plane modes are points off-set from Γ
- Off-sets are wave-vector k_x,k_y perturbations

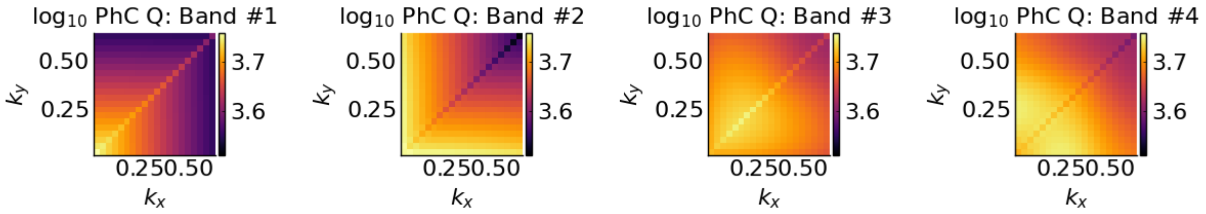


Zoysa, PTL 2017

In-Plane PhC Modes

- Moving off the band edge changes:
  - Resonance wavelength
  - Slope of band (related to group velocity)
  - PhC Q-factor





In-Plane PhC Modes

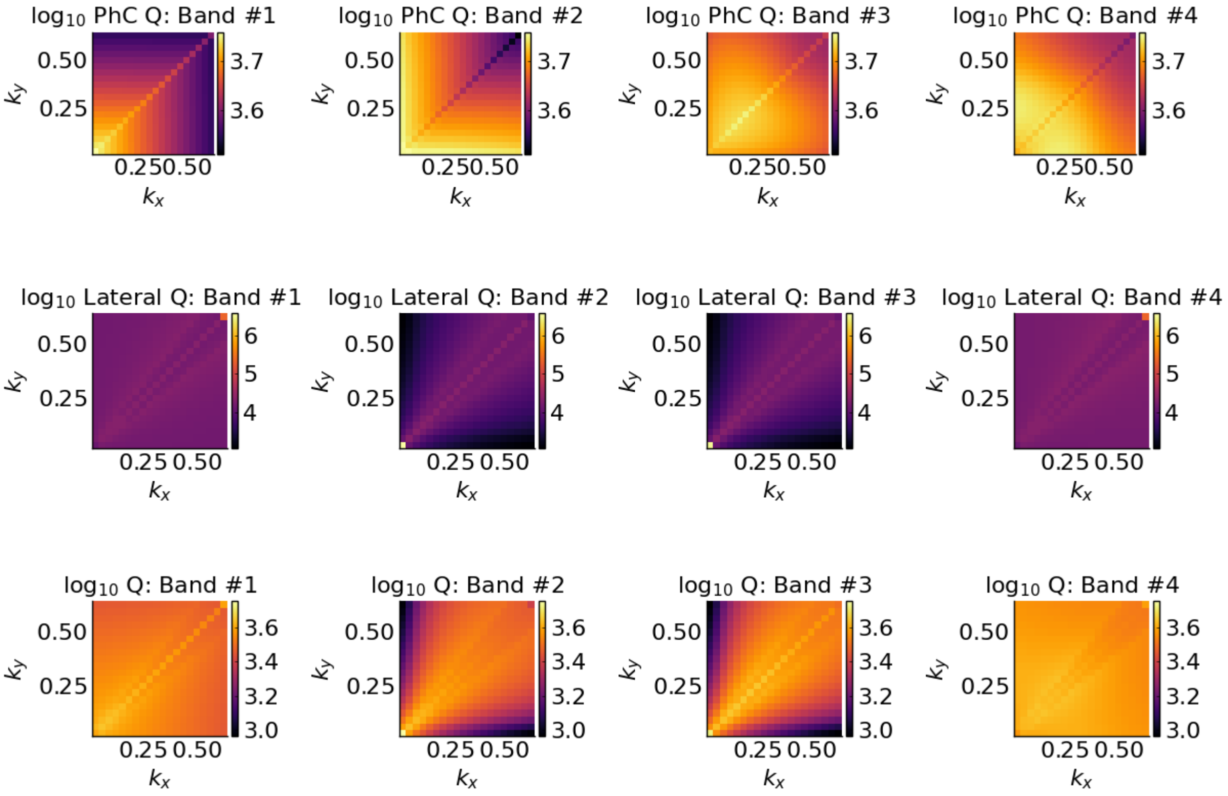
- Consider regions/forms of optical loss:
  - PhC scattering (good loss)
  - Leakage through device perimeter (bad loss)
- Try to quantify these losses:
  - PhC scattering → PhC Q (previously calculated)
  - Edge leakage → lateral Q
- How to estimate lateral Q?
  - Model in-plane structure as optical cavity (analogous to Fabry-Perot)
  - Calculate cavity mirror loss
  - Lateral Q from mirror loss and group velocity

$$\frac{1}{\tau_p} = v_g\left(\alpha_i + \alpha_m\right) = \frac{\omega}{Q}$$

- Higher modal group index (ie slow-light), longer photon lifetime and higher lateral Q

In-Plane PhC Modes

- Combine both PhC and lateral Q to get overall modal Q:



Conclusions

Summary

- Use GME to analyze PCSEL surface etch depth effects on:
  - Resonance wavelength shift
  - PhC mode Q-factor
  - Coupling to substrate/air
- Calculate higher-order resonances in larger period PhCs
- Develop potential method for GME analysis of in-plane modes of finite size PCSELs
- Future work:
  - Experimental validation of models in fabricated surface-etch PCSELs
  - Experimental demonstration of higher-order PCSELs
  - Further modeling analysis of in-plane PCSEL modes