Guided Mode Expansion Analysis of Photonic Crystal Surface Emitting Lasers

Pawel Strzebonski, Kent Choquette
Photonic Device Research Group
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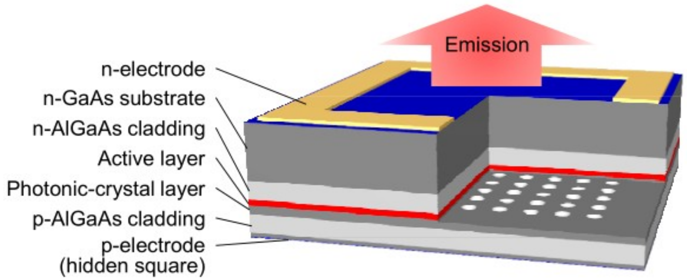
Background: PCSELs

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

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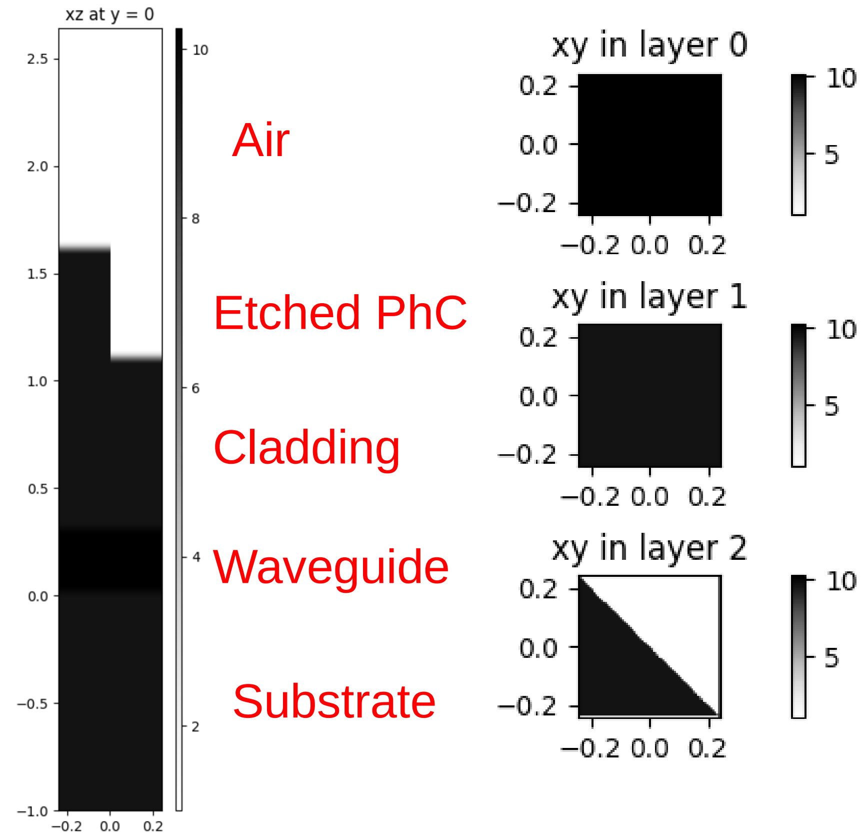
Computational Modeling

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

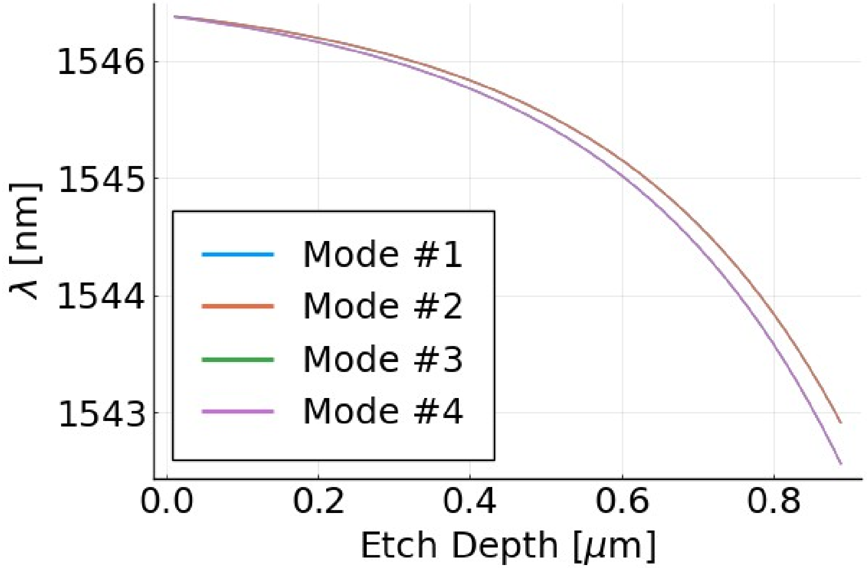


Structure cross-sections,
Shade is permittivity

Exploring Etch Depth: Results

Etch Depth and Wavelength

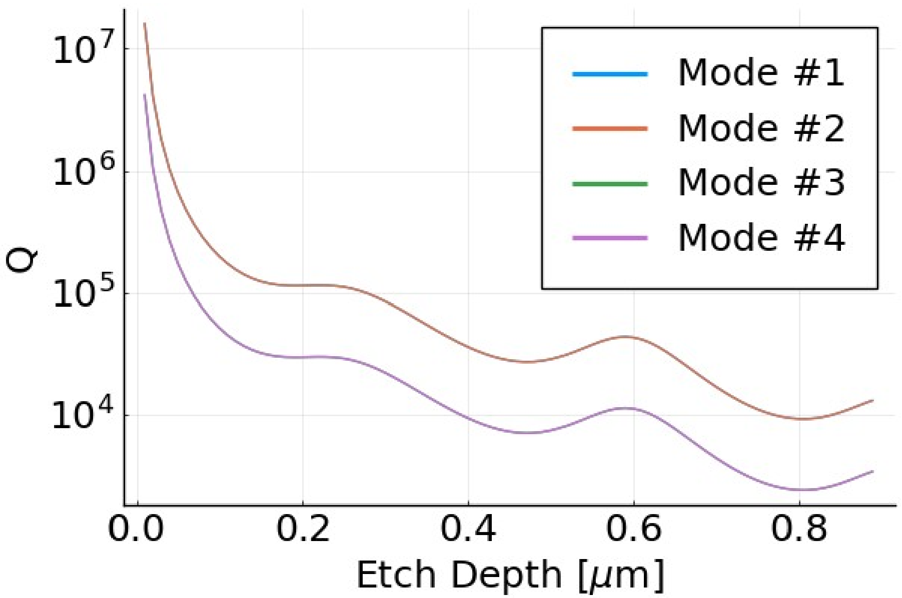
- Start with conventional PhC
  - Λ=496 nm
  - First order
- Vary etch-depth (from surface)
- First 4 resonance wavelengths



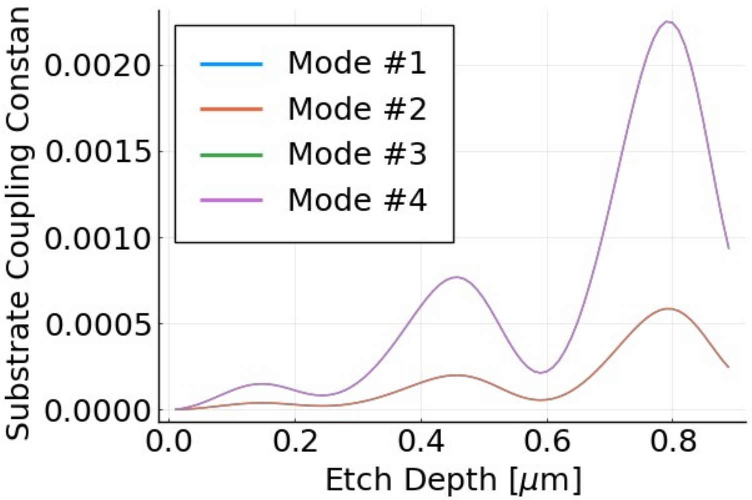
Two pairs of (nearly) degenerate modes

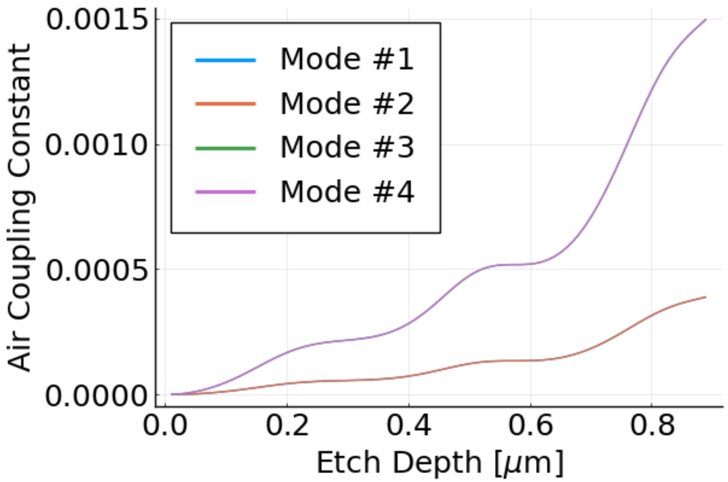
Etch Depth and Q-Factor

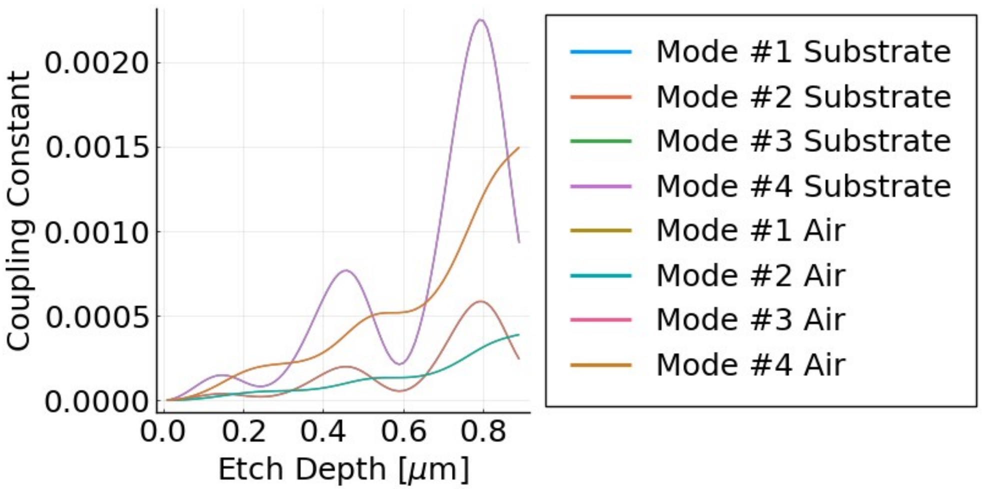
- Deeper etch:
  - More mode-PhC interaction
  - Stronger diffraction
  - More loss
  - Lower Q
- But why does Q increase periodically?



Etch Depth and Coupling Coefficients







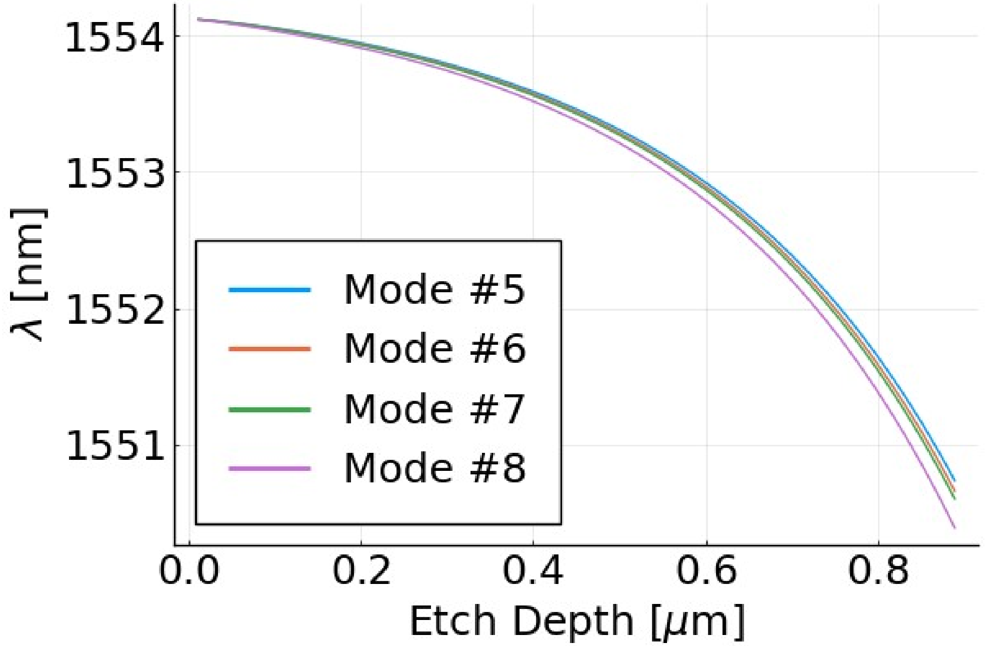
- Etching periodically varies power lost to the substrate
- We want primarily coupling to air, not substrate
- Prefer low substrate coupling → local Q maxima

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 $\rightarrow$ 705 nm)

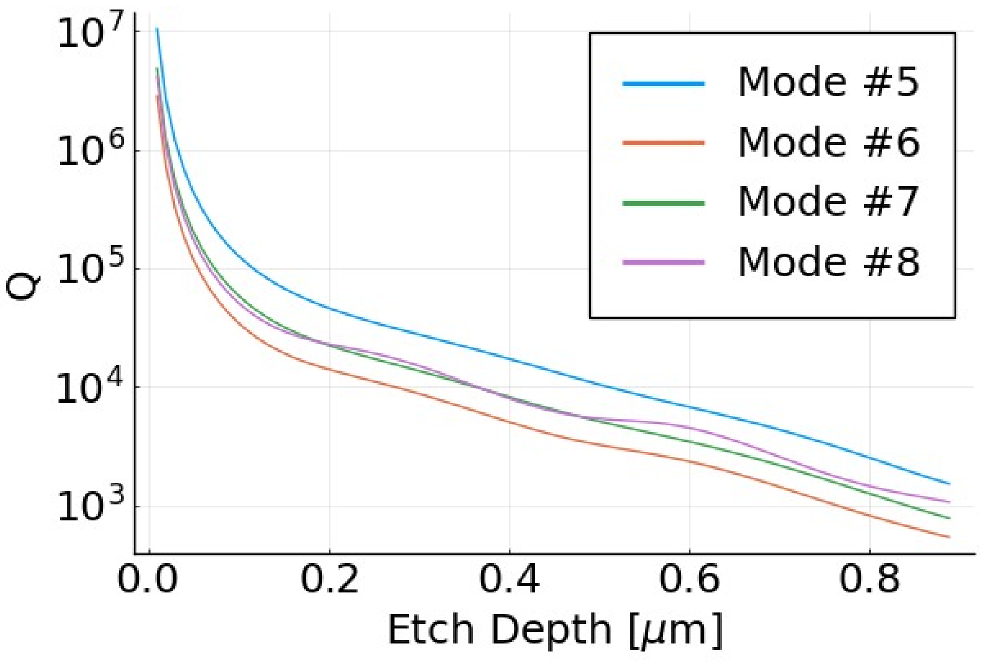
Higher Order Resonance

- 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



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
- Future work:
  - Experimental validation of models in fabricated surface-etch PCSELs
  - Experimental demonstration of higher-order PCSELs