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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
Computational Modeling
• 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
  - $\Lambda = 496$ 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 → 705 nm)
Higher Order Resonance

• Same wavelength vs etch depth trend as first order resonance

![Graph showing wavelength vs etch depth for different modes.]
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