Guided Mode Expansion Analysis of Photonic Crystal Surface Emitting Lasers

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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
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

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

- Epitaxial waveguide confines in-plane mode
- Photonic crystal produces resonant feedback/confinement, diffraction
- Period \( \Lambda \), wavelength \( \lambda_0 \), diffraction angle \( \theta_D \) (angle from surface-normal), effective index \( n_{\text{eff}} \), 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

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

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

- Quality, or Q, factor
- Many definitions:
  - In terms of complex resonance frequency
  - In terms of resonance bandwidth
  - In terms of cavity photon lifetime
  - In terms of stored energy in cavity E and power loss rate P
- Higher Q means lower losses
- Higher Q means lower modal threshold gain

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

\[
Q = \frac{\omega}{\delta \omega}
\]

\[
Q = \omega \tau_p
\]

\[
Q = \frac{\omega E}{P}
\]
Computational Modeling
The Objectives

• Desired features/capabilities for modeling software:
• 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
  - $\Lambda=496$ nm
  - First order
- Vary etch-depth (from surface)
- First 4 resonance wavelengths

![Graph showing etch depth vs. wavelength with two pairs of nearly degenerate modes.](image)
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

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

\[ \frac{1}{\tau_p} = v_g (\alpha_i + \alpha_m) = \frac{\omega}{Q} \]
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