Final Examination: Advances in Semiconductor Laser Mode and Beam Engineering

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Publications
Laser Mode and Beam Engineering

- Usually transverse modes define spatial brightness, and longitudinal modes spectral brightness.
- Many application specify spatial/spectral properties.
- Controlling lasing modes vital to engineering laser for application.

Orientation of modes and emissions in different diode lasers.
Motivation

Optical communications:

- Want larger bandwidths
- Partially limited by laser modulation response
- Vertical cavity surface emitting laser (VCSEL) arrays can exhibit Photon-photon resonance (PPR)
- PPR can increase modulation bandwidth (possibly 100’s of GHz)
- Effective PPR requires mode control/engineering
Contents

- Thesis covers:
  - General mode/beam engineering theory/concepts
  - VCSEL array modeling
  - Photonic crystal surface emitting laser modeling/design
  - VCSEL array experimental analysis
  - And more

- Presentation limited to VCSEL arrays:
  - Introduce structure
  - Theory of coupled modes and PPR
  - Waveguide modeling
  - Experimental results
  - Conclusions of VCSEL array work
  - Future PPR VCSELs work
Photonic Crystal VCSEL Arrays

- Photonic crystal (PhC) is triangular lattice of circular etches
- PhC lattice period (Λ) of 4-5 µm
- PhC “Fill-factor” (FF), or diameter to period ratio of 0.6
- 2 VCSEL cavities defined by missing-hole defects in PhC
- Ion-implantation isolates cavities for individual control

SEM image of a $2 \times 1$ PhC VCSEL array
Waveguide Array Coupling

**Identical (coupled)**

*Past coupled mode theory limited to symmetric arrays*

**Different index (uncoupled)**

**Different size (uncoupled)**

**Different index/size (tuned to couple)**
Photon-Photon Resonance

- Multi-mode effect, \( \geq 2 \) modes interfere
- Interference shifts power between cavities
- Coupled mode theory:
  - Quantified as “coupling coefficient” (\( \kappa \))
  - \( \kappa \) derived from modal effective index splitting
  - Limited to symmetric arrays
  - Previous method of choice
- Time-varying confinement factor (\( \Gamma \)) analysis:
  - Shifting field varies overlap with cavity gain
  - Derived from distributed feedback (DFB) laser work
  - Works with any lasers/arrays
  - Newly applied to VCSEL arrays
Supermode Beating and Confinement Factor

Power shifting due to supermode beating

Confinement factors with left and right waveguides
Time-Varying Confinement Factor: Rate Equations

- Laser rate equations for change in photon and carrier populations
- Inspired by DFB work
- Translate analysis to multiple cavities and array supermodes
- Small-signal modulation response derived from rate equations
- Time-varying confinement factor is driving term, like current modulation
Single VCSEL vs Symmetric Dual-VCSEL Array

Some enhancement in array due to higher power, not PPR (prior coupled mode analysis agrees that no PPR enhancement in symmetric arrays)
Symmetric vs Asymmetric Dual-VCSEL Array

Asymmetry enables photon-photon resonance at 30 GHz (now total array $\Gamma$ varies, not just single cavity $\Gamma$)
Varying Asymmetric in Dual-VCSEL Array

Varying cavity $\Gamma$ by factor of $1 \pm \gamma$ ($\gamma$ is asymmetry factor)

Greater asymmetry, stronger PPR

Even minimal asymmetry (e.g. fabrication tolerances) gives PPR effect
Varying Mode Suppression in Dual-VCSEL Array

Varying mode suppression ratio \( (MSR = \frac{P_{PrimaryMode}}{P_{SecondaryMode}}) \)

Dual mode lasing gives stronger PPR
Even “single-mode” lasing \( (10^3 = 30 \text{ dB MSR}) \) shows PPR effect
Varying PPR Frequency in Dual-VCSEL Array

Increasing PPR frequency

Resonance and modulation enhancement pushed outwards
Response between PPR and relaxation frequency drops
Reconciling PPR Analyses

Coupled Mode Theory (Coupling Coefficient) vs Time-Varying Confinement Factor Analysis:

- Real $\kappa$ (real modal effective index splitting) determines PPR frequency
- Imaginary $\kappa$ (modal gain splitting, confinement factor splitting, or mode suppression ratio) determines strength of PPR effect
- Array asymmetry determines total $\Gamma$ variation, determining strength of PPR effect (coupled mode theory assumes symmetric waveguide arrays)
Waveguide Modeling

- 2D complex index waveguide model for $2 \times 1$ PhC VCSEL arrays
- Gain in cavities, loss outside
- Carrier injection causes index suppression in cavity
- Find 2 highest confinement factor waveguide modes
- Find $\kappa$ from complex modal effective indices
VCSEL Array Supermodes

Out-of-phase mode

In-phase mode

Mode and beam intensity profiles
VCSEL Array Supermodes with Increased Index Suppression (Carrier Injection)

**Highest $\Gamma$ mode:**

Increasing injection switches from out-of-phase mode to in-phase mode

**2nd highest $\Gamma$ mode:**
VCSEL Array Coupling with Index Suppression (Carrier Injection)

In-phase and out-of-phase modes switch at the dip in $\kappa_i$

Increase in $\kappa_r$ when third central lobe appears
VCSEL Array Coupling with PhC Period

Both components of $\kappa$ tend to decrease with $\Lambda$ (weaker coupling with larger separation)
VCSEL Array Coupling with PhC Fill-Factor

$\kappa_r$ and $\kappa_i$ counter-vary with fill-factor

Total $\kappa$ magnitude varies much less than $\kappa_r$ and $\kappa_i$ individually
VCSEL Array Coupling with Suppression (Injection) Asymmetry

**Confinement factor of favored mode**

**Frequency splitting**

Increasing index suppression in one cavity by $\delta n_{\text{suppression}}$ lowers $\Gamma$, increases frequency splitting.
VCSEL Array Modes with Increased Suppression (Injection) Asymmetry

*Highest $\Gamma$ mode*

Asymmetric injection breaks down coupling, transitions from array supermodes to individual cavity modes
VCSEL Array Modes with Increased Suppression (Injection) Asymmetry

**Highest $\Gamma$ mode beam**

Asymmetric injection deteriorates interference fringes in beam, induces beam-steering.

**2nd highest $\Gamma$ mode beam**
Experimental Analysis: Optical Power

- Driving currents $I_1, I_2$ tune array in-to and out-of coupling
- Optical power increases when coupled ($\Gamma$ greater for array supermode than individual cavity mode)
- Imaginary coupling coefficient related to power enhancement $\Delta P$ and un-enhanced power $P$
- $|\kappa_i| \approx \frac{\Delta P}{\alpha+\beta P}$ for coefficients $\alpha, \beta$
VCSEL Array Power Measurements

Design 1 (4 µm period):

Design 2 (4.5 µm period):

Design 3 (5 µm period):
VCSEL Array Power Enhancement Estimates

**Design 1 (4 \( \mu \text{m} \) period):**

![Graphs showing power enhancement estimates for Design 1]

**Design 2 (4.5 \( \mu \text{m} \) period):**

![Graphs showing power enhancement estimates for Design 2]

**Design 3 (5 \( \mu \text{m} \) period):**

![Graphs showing power enhancement estimates for Design 3]
Experimental Analysis: Optical Power Results

- Find max $|\kappa_i|$ for each array
- Plot individual and average imaginary coupling coefficients
- Larger PhC periods give smaller imaginary coupling coefficient (consistent with model)
- Some arrays show dip in $|\kappa_i|$ with increased current (consistent with model)
Experimental Analysis: Beam Profiles

- Coupling causes interference fringes in beam
- Past work has used “visibility” parameter to analyze beam profiles:
  - \[ V = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \]
  - Values from 0 (non-coherent) to 1 (very coherent)
  - Derived from beam profile minima and maxima
  - Accurate/effective usage requires tuning (noise removal, envelope removal, maxima/minima finding, etc.)
  - Uncertain if applicable to 2D profiles
- Proposed a Fourier method analysis of beam profiles:
  - No tuning
  - Noise resilient
  - Simpler effective implementation
  - Simple to apply to 2D profiles
  - Allows beam-steering analysis too
Experimental Analysis: Fourier Method Beam Analysis

Higher coherence shows as stronger side-peak in Fourier transform of beam

Ratio of side-peak to central peak is $\frac{1}{2}$ of visibility parameter

Phase of side-peak related to beam-steering
Experimental Analysis: Beam Analysis Compared

Array power  Simple estimate  “Tuned” estimate  Fourier method

Visibility estimates are finicky, noisy (tuning involved)
Peak ratio needs no tuning, shows less noise
Experimental Analysis: Beam Profile Metric Interpretation

- Lower mode suppression ratio, lower visibility
- Asymmetric supermodes (asymmetric array or breaking coupling) lower visibility
- Consider supermode with \((1, \alpha)\) power in two cavities
Two coherent ridges visible in peak ratio
Phase varies smoothly across coherent ridge (beam-steering)
Large phase transition between the two (switch between in-phase-like and out-of-phase-like modes)
VCSEL Array Design 1 Beam Analysis

Locations of beam profiles marked

The two ridges show beam-steering and different beam profiles from the different supermodes.
Much narrower coherent ridge visible in peak ratio
Phase varies smoothly across coherent ridge (beam-steering)
VCSEL Array Design 3 Beam Analysis

Narrower coherent ridge visible in peak ratio
Phase varies smoothly across coherent ridge (beam-steering)
Ridge shows unusual low visibility features at center at some power levels
VCSEL Array Design 3 Beam Analysis

Rapid profile variation due to mode transitions:

Dip in visibility at center of a ridge (lowered mode suppression ratio):

Locations of beam profiles marked
Experimental Analysis: Beam Profile Results

- Fourier peak ratio analysis is effective (finds coherence when power enhancement cannot)
- Two coherent ridges of different supermodes, consistent with waveguide model
- Beam-steering across coherent ridge, consistent with waveguide model
- Find pockets of low visibility beams within coherent ridges:
  - Likely low $|\kappa_i|$ and MSR
  - May be great conditions for PPR modulation enhancement (response vs MSR below)
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- Publications
Results: 2 × 1 VCSEL Arrays

- Time-varying confinement factor analysis of photon-photon resonance:
  - Linked to coupling coefficient analysis
  - Predict stronger PPR modulation at lower MSR and higher asymmetry

- 2D complex index waveguide model:
  - Link PhC design and current injection to complex coupling coefficient
  - Predict mode switching and associated imaginary coupling coefficient reduction with varied current injection
  - Predict breakdown of coupling, lowered beam visibility, and beam-steering with asymmetric current injection

- Experimental analysis:
  - Show decreased peak imaginary coupling coefficient with increased PhC period (consistent with model)
  - Show mode switching and associated imaginary coupling coefficient reduction with varied current injection (consistent with model)
  - Develop improved Fourier method of beam profile analysis
  - Show decrease in beam visibility and beam-steering as current injection is varied off the coherent ridge (consistent with model)
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Experimental Validation

- Characterize small-signal modulation response and PPR frequency across multiple VCSEL array designs, driving conditions:
  - Verify model’s real coupling coefficient trends
  - Verify rate equation’s prediction of stronger PPR modulation enhancement with lower MSR ($|\kappa_i|$)
- Fabricate/characterize VCSEL arrays with different PhC fill-factors
- Apply characterization methods to larger VCSEL arrays (e.g. triangular three-element arrays)
Alternative PPR VCSELs: Composite Resonator Vertical Cavity Lasers

- Composite resonator vertical cavity lasers (CRVCLs) or dual-wavelength VCSELs
- Two epitaxially defined cavities separated by a middle DBR section
- PPR effect from the beating of two longitudinal modes
- More complicated epitaxy but may be simpler to tune/operate (needs only a single active cavity)
Alternative PPR VCSELs: Engineered Waveguide/Gain

- Can try to use PPR between modes of a single cavity
- Triangular waveguide modes can beat, shifting field between less leaky base and more leaky tip
- Challenge for triangle waveguide is lowering frequency splitting between modes
- Near-degenerate modes of rectangular waveguide can have correct frequency splitting
- Have to engineer active region (gain profile) to select for the correct two modes
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Publications
Published Publications I

ORCiD: orcid.org/0000-0001-5628-6296


Published Publications II


Published Publications III


Published Publications IV


Planned/Ongoing Publications

- Multi-cavity time-varying confinement factor analysis for VCSEL array PPR
- Derivation and theory of visibility and Fourier method peak ratio metrics for $2 \times 1$ VCSEL arrays
- Waveguide model and experimental validation of supermodes and coupling in $2 \times 1$ VCSEL arrays
- Guided mode expansion analysis of photonic crystal surface emitting lasers (journal version)